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Challenges, Ideas, and Innovations of Joined-Wing Configurations: A Concept from the Past, an Opportunity for the Future

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Abstract

Diamond Wings, Strut- and Truss-Braced Wings, Box Wings, and PrandtlPlane, the so-called “Joined Wings”, represent a dramatic departure from traditional configurations. Joined Wings are characterized by a structurally overconstrained layout which significantly increases the design space with multiple load paths and numerous solutions not available in classical wing systems. A tight link between the different disciplines (aerodynamics, flight mechanics, aeroelasticity etc.) makes a Multidisciplinary Design and Optimization approach a necessity from the early design stages. Researchers showed potential in terms of aerodynamic efficiency, reduction of emissions and superior performances, strongly supporting the technical advantages of Joined Wings. This review will present these studies, with particular focus on the United States joined-wing SensorCraft, Strut- and Truss-Braced Wings, Box Wings and PrandtlPlane.

1. Introduction

Traditional monoplane configurations have extensively been adopted for many decades in both civil and military applications. The design has been improved reaching unprecedented levels of efficiency. This has been possible due to a constant progress of technology in the different disciplines and the adoption of increasingly sophisticated computational models with a combination of extensive structural and wind tunnel experimental campaigns. In some cases, airplane accidents shifted the attention to crucial aspects that needed further understanding, and modifications of previous practices were then implemented (e.g., address fatigue problems).

Thanks to this relevant experience in the design and improvements of these configurations, a large amount of historical and empirical data is nowadays available in the industry, making additional design enhancements relatively cost effective from a pure industrial/manufacturing point of view, but also from a certification stand point.

It is the opinion of many experts in academia, industry, and leading aerospace agencies that with the present technology and without a *dramatic* change of the design layout of airplanes (migrating from the traditional single-wing one) improvements in the different disciplines (e.g., better materials with superior mechanical characteristics) can only lead to *incremental* enhancements in terms of performances, fuel consumption and operative costs. This represents a major challenge for the aviation: globalization made the world interconnected and the demand for transportation of goods and people will make the existing airplanes inadequate and environmentally unsustainable. There is then a need for new aircraft able to meet the larger requirements of transportation and at the same time reduce noise, pollution, emissions, and use existing infrastructures (airports). As a consequence, the industry is facing a challenge due to the difficulty of completely migrating from previous consolidated design practices.

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Several concepts have been proposed by researchers completely changing the traditional wing-tail-fuselage airplane. Some ideas, such as the Blended Wing Body, will not be covered in this review, which actually focuses on the so-called joined-wing layout. “Joined Wings” will be here used to identify Diamond Wings, Strut- and Truss-Braced Wings, Box Wings and PrandtlPlane, see Figure 1.

The general concept behind Joined Wings is to add an interconnected wing to form a complex over-constrained system, with substantial increase of the design space and allowing more options in terms of aerodynamics, flight mechanics, engine integration, aeroelasticity etc. This is done in the hope that there is an optimum “far better” than the one available for traditional designs. And, indeed, this was the case from a pure induced drag perspective: a century ago Prandtl introduced the concept of *Best Wing System* and showed that a Box Wing, i.e., a wing with a rectangular path when seen from a frontal view, presents the lowest induced drag among wing systems that have the same wingspan, total height, and lift.

Subsequent studies conducted in the following decades added other relevant aspects (e.g., aeroelasticity, flight mechanics, stability and buckling), considered modifications to the above proposed layout, and made claims on the possible advantages/disadvantages compared to traditional configurations. These claims were substantiated with partial data and, often, also with incomplete studies due mainly to a lack of funding and long-term commitment from defense and aerospace agencies. Moreover, it was not uncommon to see statements that contradicted previous findings and a clear picture of the true possibilities/challenges inherent to the joined-wing design is still on debate. However, the need of addressing the aviation goals of having a better and more efficient transportation system makes the understanding of the true potential of Joined Wings a necessity.

This review has then the main purpose of presenting the major technical challenges and concepts that can be retrieved from a very vast body of literature. The available technical papers are organized addressing, in particular, the following configurations:

- United States joined-wing SensorCraft
- Strut- and Truss-Braced Wings
- Box Wing
- PrandtlPlane

The authors will provide a critical discussion on several scientific areas, with the aim of presenting problems from an unified point of view that interconnects the works done in several institutions worldwide. Despite their best effort, the authors are aware that not all very valuable contributions have been included in this review. For example, a relevant quantity of research was devoted to Diamond Wings in the US in the last decades of the 20th century, as summarized by Wolkovitch in his famous review work [356]. The present paper does not cover the above mentioned work, and for more details the reader is sent to Wolkovitch’s paper. Nevertheless, the authors hope that this review will spark debate and interest on a configuration that offers the potential to address several of the challenges the aviation is currently facing.

2. Joined Wings: Different Layouts

It is worth to introduce the layouts studied in this review, providing a brief description of them.

With reference to Figure 1, the Box Wing presents a structure with two wings having approximately the same span, and connected at their tips through a vertical (often tilted in the streamwise direction) element, called lateral/vertical joint or winglet¹. Thus, the front view reminds of a box shape. The concept of Box Wing is strongly tied to Prandtl [272], who investigated the theoretical advantages in terms of induced drag reduction for the box-shaped layout.

¹In the authors’ opinion the term “winglet” should be adopted only for tip devices used to improve the aerodynamic performance (in terms of induced drag) of traditional configurations, and not to identify the joints of a Box Wing.

Figure 1: Joined Wings: Diamond Wing, Strut- and Truss-Braced Wings, Box Wing/PrandtlPlane.

The Diamond Wing presents a direct junction of the wings. This junction is typically located in the outer part of the main wing. Moreover, the front wing is usually the “main” one, and is located in a lower position than the rear wing. A Diamond Wing with junction at the wingtips is very similar to a Box Wing. It is clear that aerodynamic advantages of the Box Wing are progressively lost as the wings junction falls inboard. However, the typical arrangement is intuitively associated with a stiffer structural design.

The Strut-Braced Wing features a main high wing, supported by a lower strut. Several elements, called juries, may reinforce the wing-strut system connecting them at several inboard stations. In the presence of juries, the layout is called Truss-Braced Wing. The strut has conceptually a structural function. Thus, the typical aerodynamic features of Box Wings and, to a smaller extend, of Diamond Wings, are lost. Nevertheless, the strut supports the main wing allowing higher aspect ratios.

Part I

United States Joined-Wing SensorCraft

The main proposer of the “joined-wing departure” from classical wings was Wolkovitch [356]. Investigations on structural design, flight mechanics and dynamics, wind tunnel tests showed that a smart design was needed to fully exploit the potential benefits of the joined-wing design.

Aircraft synthesis with a structural optimization, applied to a civil aircraft, was then carried out at the

beginning of the '90s [132–135, 194]. It was recognized the potential issue with aft-wing buckling, which could even jeopardize the advantages achieved in other areas. In the proposed designs the rear wing was mostly producing a down-lift; in other words, it behaved like the tail of a conventional configuration from a flight mechanics point of view. If it is true that closed systems offer an enhanced flexibility in terms of lift distribution and induced drag (as discussed later in sections 23.1 and 37.1), it is also true that having a large rear wing characterized by low wing loading and supporting the front wing in compression might, intuitively, not look as an optimal design.

Joined Wings were also considered for military applications especially in the 2000s, when the *joined-wing SensorCraft* [212] was studied in United States. Primary goal of that aircraft configuration was an efficient design for the *antenna*, directly integrated into the wing structure, to achieve superior high-altitude *Intelligence, Surveillance and Reconnaissance (ISR)*. The SensorCraft was designed to enable world-wide coverage without special deployment of the aircraft launch and recovery operations.

The joined-wing SensorCraft with its technical unique features/challenges is discussed next, covering also the evolution of the collaborative effort between government institutions and universities.

3. Evolution of a Collaborative Effort

3.1. Introduction

A brief description of the main contributions from universities, Air Force Research Lab (AFRL) at the Wright Patterson base, Boeing, and NASA is now provided, with indications of the evolution that characterized this effort in the years. In some cases different groups collaborated but showed only little interaction and often the research partners' contributions were not explicitly acknowledged.

3.2. Early Works and Collaboration Between AFRL, Boeing, NASA, and US Navy

Study of integrating the JW concept and sensing requirements were first explored driven by US Navy needs [70]. In fact, US Navy carrier battle groups depended strongly on early warning of incoming aircraft and missiles launched by beyond-the-horizon enemies. The early warning task was assigned to the Navy E-2C Hawkeye aircraft and its radar antenna. As response to the Navy program called *Electronics Experimental (EX)*, in the early nineties the Boeing Defense and Space Group's Military Airplane Division started a series of studies on a new joined-wing surveillance aircraft design (see Figure 2) as possible outperforming replacement surveillance aircraft option. Later, the Navy E-2C Program Office started a collaboration with

Figure 2: Artistic representation of the Boeing EX.

NASA Langley for testing of the Boeing EX configuration. Several tests were performed at the NASA's transonic tunnel to evaluate, *among others*, longitudinal and lateral aerodynamic characteristics and the effectiveness of various control surfaces. Several modifications followed and further CFD and wind tunnel tests were carried out to reduce flow separations (a critical area was the junction between rear wing and vertical tail), and, finally, drag was cut to a large extent.

In the 2000s the NASA's *RevCon* (Revolutionary Concepts in Aeronautics) was established. NASA's Office of AeroSpace Technology selected 9 revolutionary aeronautical concepts, among which the *Joined-Wing Integrated Structures Flight Demonstration*. The program set the following objectives for a 4-plus-year project: enable the integration of large radar apertures into smaller aircraft for improved detection range and resolution, reduce drag and weight for improved aircraft speed and endurance, and reduce costs of the system. Participants were NASA Langley (team leader), NASA Dryden, Boeing (Phantom Works), Naval Air System Command (NAVAIR) and AFRL for the development of Joined-Wing Flight Demonstrator (JWFD), which was designed by building upon past knowledge gained with the Boeing-Navy-NASA studies on the Boeing EX (see Figure 2). For example, forward and aft wings were very similar to those of the EX configuration. A large number of both experimental and numerical tests concerned aerodynamics and flight stability in low- and high-speed conditions. The thirteen control surfaces gave excellent possibilities for optimization of the handling qualities. The aerodynamic issues already noted in the EX program, i.e., separations and shock waves in the junction areas, were remarkably reduced, up to higher Mach numbers.

As suggested in references [49, 70], Air Force involvement was also favored by the rapidly growing interest in surveillance Unmanned Air Vehicles (UAVs). Within this research, the AFRL initiated limited CFD investigations using in-house codes. The quote from reference [70]

"results were inconclusive to the suspected critical conditions"

was perhaps driven by the lack of definitive and broad-spectrum results, as well as by a not accurate understanding of the main properties of flows around Joined Wings.

It is not clear if reference [349] was describing an ad hoc activity concerning AFRL contribution to RevCon; however, a comparison between experimental activity (carried out at NASA Langley Basic Aerodynamics Research Tunnel, BART) and numerical analysis on a joined-wing configuration (different than the EX-like one) was provided. Tests considering different angles of attack and dynamic pressures (with a variation of Reynolds number between the $0.25 - 0.95 \cdot 10^6$) were performed. CFD investigations (using the in-house software *Cobalt*) showed a reasonable agreement (within 5%) for the lift coefficient, but also a large discrepancy in the drag prediction. Large separations were spotted for angle of attack of -5° , whereas for positive values, initial separations were found at 8° . It is interesting to note that, according to the same reference [349], AFRL had a joined-wing baseline model consisting of two fuselages, see Figure 3. However,

Figure 3: Artistic representation of the AFRL twin-fuselage Joined Wing [328].

in order to take into account the size of the wind tunnel, the support/mount system and other restrictions, the studied joined-wing model was a single fuselage, reduced wingspan with changed airfoil camber.

According to reference [70], in 2001 *funding priorities* within the participating government agencies were directed *elsewhere*. The Navy and Air Force were unable to meet their shares of the required funding commitment and NASA terminated the *RevCon* at the end of September 2001.

3.3. The Air Force Research Lab Takes the Lead on SensorCraft Research

With the premature ending of the RevCon program, the AFRL continued the effort in the development of Joined Wings within the *SensorCraft* concept.

3.3.1. SensorCraft: background and general overview as deduced from the literature

The SensorCraft concept was initiated by the AFRL to inspire innovation and cutting-edge technology. The driving design objective was the integration of the sensing functionality into an unmanned aerial vehicle capable of 30 hours of endurance at 2000 nautical miles range. A good overview on the technical motivations (altitude, range, endurance, payload capacity and sensor fields) that led to the concept is provided in reference [212], which presented a discussion on the main challenges in terms of aerodynamic and structural nonlinearities, emphasizing the importance of taking into account *shocks and flow separations into aeroelastic analyses*; also the significance of *material and freeplay nonlinearities* remained to be discovered.

Work [177] presented the emerging technologies to produce UAVs configured and optimized to conduct multiple advanced sensing modalities integrated into an airframe that sustained an enduring theater presence. The paper assessed as the most innovative aspect the integration, into structural components of the aircraft, of a large antenna required for low frequency operations. It was observed that in lower bands the SensorCraft provided a *foliage penetration radar capability*. SensorCraft concept represented a diverse, multi AFRL Directorate shared vision to combine the emerging technologies associated with flight vehicles propulsion, sensors and information into a highly responsive thrust to provide revolutionary capabilities in ISR. According to reference [212], in the first years of the 2000s a series of contracts with Northrop Grumman, Lockheed Martin and Boeing produced preliminary design details for several different layouts, conceptually subdivided into three categories:

- *wing-body-tail configurations* (developed by Lockheed Martin's Skunkworks);
- *flying-wing configurations* (provided by Northrop Grumman);
- *joined-wing configurations* (provided by Boeing's Phantom works).

The main difficulty was indicated to achieve aerodynamic performances able to guarantee aggressive endurance goals, while providing payload capacity, power and cooling to support ISR sensor suite.

The *wing-body-tail SensorCraft* was designed for 40 hours of endurance at Mach 0.6 (payload capacity of 6000 lbs). Even if Lockheed Martin's layout was carefully designed to avoid transonic shocks at cruise conditions, it was argued that subsequent pushes past design conditions (like the case of Global Hawk) could make the wing experience transonic shocks and, consequently, flow separations. The question to be answered was then how such aerodynamic issue would interact with the highly-flexible wing structure.

Regarding the *flying-wing SensorCraft* studied by Northrop Grumman, the endurance was set to 50 hours at cruise Mach of 0.65 (with a payload capacity of 7000 lbs). The potential difficulties on effective control and dynamic stability properties of a tailless aircraft were pointed out; however, advantages such as reduced drag and weight, and simplified construction were claimed. Moreover, the possibility of having a 360° radar coverage by *integrating radar apertures into the skins as primary load-bearing structure* (essentially turning the large wings into antennas) was emphasized. One of the challenges with the flying-wing SensorCraft was identified to be the very low frequency of the first bending mode (1 Hz or less); this was associated to the very-flexible high aspect-ratio wings. The low frequency bending mode could then couple with the rigid body, short period mode to produce *body-freedom flutter* at low airspeeds.

The *Boeing joined-wing SensorCraft* (see Figure 4) was designed for 32 hours of endurance at cruise Mach of 0.8 (quite higher than the Mach number of the other two SensorCraft models), the payload capacity was 9200 lbs. The joined-wing SensorCraft was considered technically appealing for two main reasons:

- *first*, it allowed a full 360° coverage with sensors integrated into the wing panels;
- *second*, a potential reduction of wing structural weight and induced drag with respect to wing-body-tail competitor configuration was claimed to be possible (Wolkovitch's review paper [356] was cited to support these claims).

Figure 4: Artistic representation of the Boeing joined-wing SensorCraft.

The reasons why Boeing selected the joined-wing configuration for the SensorCraft were also outlined in reference [103]:

“According to Boeing, a joined-wing configuration promises to offer decreased life cycle costs (LCCs) when compared to other potential SensorCraft configurations (e.g., flying wing and conventional wing), based on a utilization rate (UTR) of 360 hours/month and the requirement of a 3000 nm radius of action (RoA). It achieves this savings by reducing squadron size, as only four vehicles are needed versus five for the other designs, due to increased speed and sensor visibility differences of the Joined Wing.”

However, this relevant point was stated [212]:

“Even without large aerodynamic improvements or weight savings, the joined-wing configuration is motivated for SensorCraft by sensor field of view performance alone”

Another advantage of the joined-wing version was the *availability of many potential locations for aerodynamic control surfaces* on both the front and rear wings.

3.3.2. Joined-Wing SensorCraft: brief overview of the technical challenges

Reference [212] discussed the potential problems expected to characterize the joined-wing SensorCraft design. The *aerodynamic nonlinearities due to the high speed* were predicted as important. More in details, the possibility of *flow separations in the junction areas* was considered as a unique problem of the layout.

Importance of properly taking into account geometric structural nonlinearities and non-traditional load paths in aeroelastic investigations was also stressed out. A very relevant issue regarding the nonlinearities of Joined Wings was mentioned:

“Such vehicles could be designed and built using linear methods with unknown nonlinear phenomena awaiting discovery in flight test. This puts the entire program at risk, and leads to expensive redesign work when nonlinearity produces problems”

According to reference [29], the design driver was represented by the *buckling of the rear wing* (the statement was based on results of efforts [132, 134], although they were obtained using structural models of limited fidelity).

More integrated and multidisciplinary conceptual design frameworks [29] were extensively used. In this sense, the utility of *accurate reduced order models* to bring down the computational cost was emphasized [212].

Work [224] discussed some key aspects of the SensorCraft concept, and some parts were dedicated to the application of the joined-wing technology. Practical constraints related to sensing requirements in the framework of ISR capabilities were analyzed. The prospective aft-wing buckling or flattening during gust loading was discussed, with emphasis on the possible weight penalty to prevent this instability. To investigate more in-depth stability issues and put them into an aeroelastic framework, plans of developing scaled aeroelastic wind tunnel and free-flight models were mentioned. In particular, it was stated that Boeing was working on an 8% scale, full-span wind tunnel model that could be free to pitch and plunge (to be tested in NASA Langley Transonic Dynamics Tunnel). The collaboration between AFRL’s Air Vehicle

Directorate, AFRL's European Office of Aerodynamics Research & Development, and Portugal's Instituto Superior Técnico to develop a free-flight model was also mentioned.

3.3.3. The Aero Efficiency Improvements program

Successive studies on Joined Wings remained centered on the ISR concept. AFRL awarded a series of contracts to Boeing, see reference [70] for more details. Among them, the *Aero Efficiency Improvements* (AEI) program addressed the aerodynamic and aeroelastic design of the joined-wing SensorCraft. Other than AFRL and Boeing, also NASA, Lockheed Martin, Northrop Grumman and other companies contributed to the AEI program.

The AEI consisted in two phases. According to reference [282], in Phase I aerodynamic optimization (see section 6.3) and structural sizing verified the potentials of meeting required performances, and found that the *airframe structural design was mainly driven by gust loads*: actively reducing these loads would have led to a 20% weight savings. Phase II was characterized by experimental investigations on a scaled model regarding the *active gust load alleviation*; aeroservoelastic wind tunnel tests were performed at NASA Langley facilities.

The efforts demonstrated controlled flight of the flexible model at CoG positions corresponding to +5% to −10% static margin, a 50% reduction in significant airframe gust loads at fundamental airframe symmetric mode frequency through the gust load alleviation, and validation of the flexible aircraft design process. Three sub-phases were identified. In the second and third ones, a redesigned support allowing a complete freedom of motion in pitch and plunge was used (see also section 8.2).

Overall, during this AEI program, a very large amount of numerical and experimental work was carried out. A good overview of the collaboration between Air Force and Boeing within AEI program (leading to a final 306-page report delivered by Boeing to the Air Force on 17 July 2006) is given in reference [103].

4. Multidisciplinary Optimization and Integrated Design Process

One of the early works describing the conceptual design framework used within AFRL for joined-wing *SensorCraft* was reference [29]. The effort reviewed the background of the joined-wing concept and the integration of computer tools for the design. A description of the AFRL MultiDisciplinary Technologies (MDT) center in the Air Vehicles Directorate was also provided. The UAV SensorCraft (see Figure 5) and its technical features were presented, with particular emphasis on the engine efficiency, aircraft empty weight and (high) efficiency (lift-to-drag ratio).

Figure 5: Artistic representation of AFRL SensorCraft concept.

Reference [26] was the *first publication* of a multi year collaborative effort between Blair and Canfield (at that time Canfield was a faculty at the Air Force Institute of Technology; a few years later he moved to Virginia Tech). The integrated design process of Joined Wings (AVTIE - Air Vehicles Technology Integration Environment), including structures, aerodynamics, and aeroelastic analysis was discussed.

The issue of buckling and the relevance of geometric nonlinear structures were emphasized. In particular, the possibility of leveraging nonlinear aeroelastic effects was outlined (see detailed discussion reported later in the technical part of this review, Part IV). An interesting point was raised in that work:

"It turns out that the joined wing concept requires special attention in pitch balance to avoid adverse trim with negative lift on the aft wing resulting in excess drag. This drives the requirement to maintain outboard wing sweep as an important design variable."

A discussion of the position of the center of mass and the benefit of a reduction of the outboard wing sweep angle was also provided.

References [298, 300] used the same integrated platform. The researchers optimized and trimmed an aluminum model and found large geometric nonlinearity below the critical buckling eigenvalue. It was concluded that nonlinear analysis was critical to correctly model the SensorCraft configuration.

Efforts [309, 319] showed the application of an integrated design process (based on the previous research within AFRL) for generating high-fidelity analytical configurations and weight estimation of JW concepts. The starting detailed model was taken from reference [26], and a reduced order model was built. A strong sensitiveness of the structural solution to the modeling of the joint was noticed. The lower order model provided a very good estimate of the 3-D displacement field (static responses) for slender configurations. Moreover, the model was used for some nonlinear dynamic analyses. Effectiveness of using control surfaces for lift and roll was also determined.

Reference [299] extended the work earlier presented in effort [298] and optimized a graphite-epoxy composite model that incorporated *Conformal Load-bearing Antenna Structures (CLAS)* as well as a graphite-epoxy model without CLAS material. Important geometric nonlinearities near the critical buckling eigenvalue were also observed. The CLAS composite model demonstrated significant weight savings over the aluminum design.

With the goal of weight minimization, different Joined Wings were investigated in references [274–277] by changing several design variables. The integrated design process was based again on AVTIE. The paper showed the importance of vertical offset as far as buckling of the aft wing was concerned. In particular, it was found that without vertical offset "localized" panel buckling became critical. In a lift distribution graph, it was shown that in the optimal configuration the tail was producing a large down-force.

Reference [27] presented an integrated process for the design. Elements of nonlinear structural, aerodynamic and aeroelastic analyses were incorporated. Goal of the work was to combine structural sizing that simultaneously satisfied the following: aerodynamic performance requirements with respect to range and loiter, equilibrium of integrated aerodynamic and gravity forces in pitch and lift, and structural stress in static equilibrium. The buckling analysis was based on an eigenvalue approach and was verified a posteriori. Taxi condition was found to be critical; large geometric nonlinearities were observed below the critical buckling eigenvalue. For some trim conditions, the buckling mode shape was characterized by a washout (unload) of the outboard wingtip. It was then stated that this effect could have been leveraged or passively induced to create an aeroelastically *fail-safe joined-wing design*. Reference [27] also focused on the control surface cutouts and indicated that they should not be placed on the major load path. Thus, it was suggested a *twist-actuated aft wing* instead of the classical trailing edge flap. It was also recommended to use, if possible, an unswept aft wing to facilitate the proposed twist-actuated design.

Reference [103] took Boeing's SensorCraft model and performed a perturbation of seven design variables to determine their effects on the Take-Off Gross Weight (TOGW). The sensitivity analysis showed that the TOGW was substantially affected by the wingspan, joint location, inboard sweep angle, and vertical offset respectively.

Development of a process that enabled high-fidelity MDO framework for future air vehicles was explored

in reference [165]. An application to the Joined Wing was presented, showing the robustness of the approach.

4.1. Optimization of Joined-Wing SensorCraft Using Equivalent Static Loads

Equivalent static loads method was largely studied as a mean to expedite the analysis (vital within an MDO). In efforts [202, 203] dynamic response optimization was carried out by using equivalent static loads; gust loads were included too.

Figure 6: Representation of the generation of equivalent loads for displacement constraints, as deduced from reference [186].

The equivalent static loads (shown for the static case in Figure 6) were calculated as follows. First, the nonlinear transient equation with the actual dynamic loads was solved and the displacements found. The displacement vector was then substituted into the *linear* static equation to find the equivalent static loads as the product between the linear global stiffness matrix and the vector of dynamic displacements. The optimization iterative procedure was then carried out by performing the transient analysis and calculating the equivalent static loads and, after, by solving a static response optimization with equivalent static loads (in which the design variables were updated).

The analyzed Joined Wing was made of aluminum and the system was subdivided into fore wing, aft wing, mid wing, and wingtip to identify the design variables. The optimization aimed to achieve mass minimization under dynamic loads. Linear structural analysis was performed but the importance of nonlinearity was recognized and planned for future works.

Extensions of the above researches were carried out in references [185–187]. An optimization process took into account the geometric nonlinearities by using equivalent loads, with significantly reduced computational costs. The importance of nonlinear analysis was justified by a study in which a gust loading condition at cruise speed produced a wingtip displacement five times larger than that predicted by linear analysis [186] (see Figure 7). The buckling instability calculation was performed for the optimized design (obtained using equivalent loads) and was not included as constraint in the process. It was claimed that the equivalent load method could be applied to large scale problems thanks to its computational efficiency (nonlinear response sensitivity was not required).

5. Control Surface Effectiveness, Wing Twist and Pitch Control

5.1. Layout of Control Surfaces

Within an integrated design process for generating high-fidelity analytical configurations and weight estimation of JW concepts, effectiveness of using control surfaces for lift and roll was determined in references [309, 319]. The most appropriate placement of control surfaces and their effectiveness at end of the mission profile were discussed, considering different locations on the outboard portion of the wing (in the very tip of the wing, in the middle of the outboard wing, and where the outboard wing meets the joint,

Figure 7: Representation of the deformation under the gust loading condition, as deduced from reference [186].

see Figures 5 and 8). Control surface reversal study showed that the placement on the *furthest outboard* location was the most critical.

Figure 8: Wing planform and different placements of the control surface. Artistic representation as deduced from reference [309].

5.2. Roll Control by Wing Warping

The conference paper [67] by researchers at University of Michigan showed a research activity supported by an AFOSR grant. A new formulation (strain based for structures, 2D unsteady for aerodynamics) for highly-flexible active vehicle capable of modeling the structural geometric nonlinearities was introduced and applied to a simplified model of the joined-wing SensorCraft. In particular, assessment of wing warping as a mean of roll control was carried out. Warping was achieved by anisotropic piezocomposite actuator technology - ATA. This technology was applied to the outer part (see Figure 9) of the wing for *assessing roll*

Figure 9: Layout of the Joined Wing; performances of a traditional aileron or warping of the outer part of the wing were compared. Artistic representation as deduced from reference [67].

control, and was compared to a traditional (passive) aileron concept. Baseline configurations were defined by considering different points in the mission profile (flight indices), and assessing the failure (based on first-ply failure) for a load factor of 2.5 g , the gust load failure and (linearized) flutter margin. The first condition was found to be the critical one, thus the thicknesses were redistributed for fully-strained design.

The roll response was then studied for both cases using a linear and also a nonlinear approach (the two methods could provide different results especially for the passive case). It was shown that the ATA technology would have given poor performances (in terms of terminal roll rate) compared to the traditional aileron, due to limited twist authority. Increasing the maximum free strain (almost 4 times) would have filled the gap. Further, effects of the *sweep angle of the outboard portion was examined and shown to deteriorate performances mainly due to the bending-torsion coupling*.

The study also explored larger load factors. The front-wing *deformation increased dramatically* approaching a certain speed, with a consequent drop in lift (note that the aircraft was trimmed only for the initial nominal speed). A more detailed discussion of these aspects will be presented later, when the snap-divergence phenomenon is discussed in the technical part of this review, see section 24.3.

5.3. Aeroelastic Active Wing Concept

5.3.1. Performance of load-bearing antennas

In references [325–327] the researchers studied the performance of conformal load-bearing antenna arrays embedded into the wing structure of a conceptual remote sensing joined-wing aircraft. In particular, when the structure was subjected to aerodynamic forces (maneuvering and gusts) large deformations of the wings resulted in a loss of accuracy of the antenna: distortion of the radiation pattern was not possible to be counteracted by simple phasing.

5.3.2. Active Aeroelastic Wing technology to enhance ISR performances

A collaboration between AFRL and Georgia Tech was established as discussed in references [279, 280]. The concept of *Active Aeroelastic Wing (AAW)* was explored for the SensorCraft (the study was considered one of the first AFRL configurations featuring a twin fuselage) to reduce deformations, an important requirement considering the ISR nature of the vehicle. A trim optimization was carried out in which the objective function was describing the entity of the displacements at the antenna's tip, and the constraints were on the aeroelastic trim for a user-defined maneuver, on control surface deflection limits, on hinge moment limits. Six control surfaces (see Figure 10) were considered, and a one-point mission condition was chosen for the optimization. It was ascertained how, with an optimal combination of deflections of mobile surfaces, deformations dropped of an order of magnitude in respect to the case in which trim was controlled by one mobile surface. Furthermore, two different objective functions were considered to minimize also the deformations at several locations, leading to different solutions.

Figure 10: Artistic representation of the examined twin-fuselage SensorCraft, as deduced from reference [280]. Six mobile surfaces were used for testing the AAW concept.

The jig-shape design (flat antenna at a certain mission-point) and a roll trim optimization were performed, to show the possibility of maneuvering while maintaining low level of deformations. Thus, the feasibility of AAW for improving antenna performances was ascertained.

In work [278], as continuation of the research carried out in reference [280], the *Mission Adaptive Wing (MAW)* and AAW technologies were adopted to enhance landing roll maneuverability of SensorCraft, which was previously found not to comply with the regulations. In fact, during this phase, the dynamic pressure was low since the design was first carried out considering the long loitering phase, leading to highly cambered wings. Twist actuation on the outer part of the wing was proven not to be feasible, whereas the AAW considering leading edge and trailing edge control approach led to reasonable results. In particular, performances were improving with the number of independent sections. Smoothness of the deflections was then added as a constraint since in practical situations having large gaps between adjacent mobile surfaces leads to an *increase in drag*, and *deteriorates antenna performances*.

Further studies on the concept of morphing were carried out considering cruise and loiter performances. Due to the inherent nature of the SensorCraft, loitering is unusually long, thus, an optimized design for the mid-cruise point may be penalizing since a large portion of the time will be spent in off-design conditions consequence of different trim necessities. This is true because the mission profile is not a cruise-climb but a constant altitude, constant Mach number cruise and loiter, with a large change in the lift coefficient. Results were showing an increase in the average efficiency, with consequent possible decrease of the structural weight and/or an increase in endurance requirements. From a quantitative point of view, gains were not spectacular within a military capability, but much more appealing for commercial flight operation. Overall, the application of the technology was successful.

5.4. Pitch Control by Twisting

The joined-wing SensorCraft is characterized by sensors built into the composite skin. The necessity of increasing the area available to sensors and avoid sensor interference demands a minimization or possibly elimination of control surfaces. With this in mind, references [31, 35, 36, 188] suggested to *control pitch by twisting the aft wing*. This twist was induced by an actuator located in the vertical stabilizer applying a force to the root of the aft-wing. To limit the force required to achieve the twist, *the torsional stiffness* was reduced with a spanwise slit (see reference [188] and Figure 11). Advantages of this solution were demonstrated by an increase of four and a half times the aft-wing twist compared to the baseline configuration. Wind tunnel tests [31, 35, 36] were conducted to assess the overall effectiveness of this technique. They were carried out in the Portuguese Air Force Academy wind tunnel on a 1 to 38 scale model SensorCraft. Twist-up condition was an effective mean to achieve pitch control over 20° angle of attack. Outside this range, and also in the twist-down case, separation effects were observed.

Figure 11: Pitch control by twisting the aft wing. Artistic representation as deduced from references [36, 188].

A flutter analysis [188] was then performed at sea level for a Mach number of 0.5. Critical speed without slit was 191m/s; with the addition of the slit the speed increased to 195 m/s.

Studies on the use of composite structures (CLAS, see Figure 11) were also conducted [188] to investigate their effect on the amount of twist induced to the aft wing for a given applied force (simulating an actuator load). It was found that the most effective mean to increase the twist was the slit, and the CLAS ply orientation effects were very small.

The potential of structural instability was also emphasized:

“No analysis of joined wing would truly be complete without some consideration of buckling”.

Eigenvalue-based buckling analysis showed that the addition of the slit made the wing more prone to instability. Some analyses on a new joint design indicated that the configuration was much stiffer and it was claimed that additional optimization could further improve the structural effectiveness. The authors note that in the same reference the following statement was provided in the conclusions:

“Although a major error was discovered in the setup of the analyses...”.

6. Aerodynamic Studies

6.1. Aerodynamic Investigations and Drag Prediction

Very preliminary studies have been conducted in efforts [243–247] and reported in details in [242]. In reference [244] a comparison between panel method and Euler code was given, showing a very good agreement in the distribution of the pressure coefficient (C_p): the panel method was assessed as a reliable tool as long as the peak suctions on the leading edge were not too large. Reference [246] performed similar studies considering different layouts featuring various disposition of the two wings. In effort [245] (see also reference [247]) a design with the aim of ensuring laminar flow at cruise showed prospective potentials for

the use of such a technology; junction areas, however, needed a very careful design. In reference [243], a high-speed preliminary study was carried out on a modified layout.

In the thesis [82] aerodynamic drag prediction of SensorCraft technology demonstrator was conducted via numerical methods. A single design environment, AVTIE, incorporating (see reference [26]) panel method (PANAIR) and airfoil analysis software (XFOIL) was created. A seven-point mission profile was considered; throughout the flight profile, the aircraft was aerodynamically trimmed using the aft wing as a pitch control surface, and then the drag force was determined. Results varied considerably depending on the drag prediction method. For example, different models predicted the last point of the flight profile to show the highest or lowest aerodynamic efficiency achieved throughout the whole mission. Also *Roskam's* formulas were adopted for the SensorCraft, and it was recognized that the estimates could not be reliable being past historical data based on completely different configurations.

In the general discussion, the cited work pointed out that Joined Wing's large (if compared to traditional configurations) horizontal control surface (the entire aft wing) producing *negative* lift greatly increased the parasite drag and limited the benefits coming from an induced drag reduction.

Another general observation made in reference [82] regarded the junction location, which was selected to be at 70% of the semispan. This was justified by referring to results earlier obtained by Kroo and Gallman [135, 194]. However, in the authors' opinion, the junction and its location should be determined with an optimization which is a case dependent process.

6.2. Aerodynamic Studies with CFD and Structural Analyses on Multifidelity Models

University of Cincinnati performed a series of CFD analyses. Aerodynamic loads were also used for structural analysis. In references [320, 321] some CFD analyses were performed with the AFRL code Cobalt (featuring RANS and also DES) for different Mach numbers and angles of attack. The junction areas showed some flow separation, and the flow in that region was very sensitive to grid resolution. The aerodynamic loads obtained with the above analyses were applied to structural models of different levels of fidelity (mainly provided by the AFRL) [220, 221, 248]. Those models ranged from lower fidelity (1D-Beam) to a detailed (ribs, spars, etc.) description. Treating the aerodynamic loads as mechanical ones, linear static and dynamic, modal, and eigenvalue buckling analyses were performed.

Work [322] continued the above investigations. At higher angles of attack, separation, as well as a drop in lift, were observed at the junction, on the trailing edge of the front wing. At $M = 0.6$, a weak oblique shock was noted at the trailing edge of the aft wing. The aerodynamic loads (for the undeformed configuration) were applied to the different structural models. Considering the higher-fidelity model, it was observed that the wing skin was wrinkling causing stress concentration in regions directly above the reinforcements. With the 1-D model, large deflections were found (tip displacement of about 16% of the wingspan).

Although the analyses were still not aeroelastic, in references [178, 179] a step forward was done: the aerodynamic actions relative to the nominal condition ($M = 0.6$ and $\alpha = 12^\circ$) were applied (through a low order and simple projection method) and both structural linear and nonlinear responses were tracked.

A small design optimization was pursued to redistribute the material in order to lighten the structure while complying with maximum-stress requirements. Linear and nonlinear analyses were performed on the optimized configuration: it was observed that nonlinear buckling analysis predicted a 18% smaller critical load (more discussion will be presented in section 24.1 of this review). A separate study of the junction was performed, finding some adverse structural behavior. A local design was also pursued for certain portions of the structure (optimization of the panel stiffness subjected to local failure constraints).

6.3. The Aerodynamic Efficiency Improvements Program: Aerodynamic Optimization

Following the contract FA8650-05-C-3500 granted by AFRL, called Aerodynamic Efficiency Improvements (see also section 3.3.3), in reference [199] transonic cruise design and optimization were investigated with the constraints required for antenna thickness and fixed planform. A "point of departure" configuration was chosen and analyzed. Then, an elaborated optimization process was pursued, using the adjoint method solver and the CFD *Overflow* program (see Figure 12). The optimization problem counted 60 variables on the complete configuration, trim (about a nominal transonic design condition) as well as manufacturing/feasibility (curvature), body volume (for fuel storage purposes) and rolling moments constraints. The

efficiency was improved by a large extent, in particular the separation induced by trailing edge break on both main wing and strut were significantly, though not completely, reduced. Letting also the planform to change was in the future plans, and could have potentially led to further improved results.

It was verified that the *optimal configuration* for the specific design point was carrying its advantages also in off-design conditions. It needs to be noted that calculations were done assuming a fully turbulent

Figure 12: Qualitative C_p distribution on the optimized and nonoptimized configurations. Artistic representation as deduced from reference [199].

boundary layer, which was in contrast with the laminar flow technology, keypoint of the SensorCraft design.

7. Buckling and Nonlinear Structural Studies

As outlined, nonlinearities and buckling were assessed as relevant for Joined Wings. In the early studies, even recognizing the importance of nonlinearities, buckling was approached with an eigenvalue analysis. Only later it was ascertained that a truly nonlinear stability analysis was needed to correctly characterize the response.

7.1. Buckling of Joined-Wing SensorCraft

In one of the early efforts [266] buckling of a Joined Wing was addressed with a *stochastic* approach. The areas of the Joined Wing that were considered more important were the wings root and the junction, and buckling was assessed by solving an eigenvalue problem. First, a sensitivity analysis was carried out by perturbation of the elastic modulus. Decreasing the elastic moduli (especially at the *aft-wing root area*) by a factor of ten produced a significant change of the buckling eigenvalue; decreasing them by a factor of one hundred produced a relatively high sensitivity of the buckling eigenvalue (mainly at the *front-wing root*). This “shifting of sensitivity” from one variable to another was interpreted as an indication that large variations in the junction stiffness could induce significant qualitative changes in the buckling behavior of the Joined Wing.

Then, Young’s modulus of these parts was modeled considering a Gaussian randomness. Stochastic analysis showed that the first and second buckling eigenvalues were only moderately correlated, whereas the first and third buckling modes were found strongly correlated.

Having recognized the importance of structural geometric nonlinearity in previous wind tunnel scaled model [28], reference [3] continued the collaboration effort with the Portuguese Air Force Academy tackling the structural stability of the Boeing joined-wing SensorCraft. Several analyses were conducted. The linear static investigation considered the load cases provided by Boeing and determined “the most severe” condition from a buckling perspective: gust load was found to be the most critical case.

Preliminary investigations showed a “localized” buckling (called “panel” buckling in reference [3]) taking place. Thus, an iterative process was employed to adjust the core thickness of the buckled panels and re-run

the eigenvalue buckling analysis. It was claimed that the model was not optimized for weight minimization, featuring a relatively stiff structure which made global buckling not a critical condition. The modal analysis of the free-free and the constrained (in one point) vehicle showed that the clamped case exhibited significant motion of control surfaces on the aft-wing.

In work [201] nonlinear aeroelasticity including buckling effects was investigated by adopting a generalized direct simulation method with discrete time-domain state-space approach for transient response. Nonlinearities were included by selecting some nonlinear parameters (modal stresses) that divided the nonlinear system into locally linear ones.

7.2. Nonlinear Structural Studies of Joined Wings: Experimental Works

References [32, 34] presented experimental analyses of a structure with large deflections (see Figure 13). In the experimental model the applied forces could follow the structure through a system of cables, and simulate (qualitatively) aerodynamic loads. The tested model was a scaled one, obtained including in the equivalence process also the buckling mode (in reference [32] it was claimed that this was done for the first time in the literature).

On the computational side, the team used Boeing's finite element model (which was delivered to Air Force in 2006) modified as discussed in reference [3] by increasing the panel thicknesses (to decrease the number of "localized" panel buckling modes and have a "non-local" buckling mode within the first 50 eigenvalues). The model was also modified to incorporate torsional compliance in the aft wing for pitch control purposes. An optimization followed to have the most flexible design without overstressing the structure. Regarding the finite element model delivered by Boeing and the technical difficulties associated with it, in reference [32] the following statement can be found:

"Upon further investigation, incorrect boundary conditions were discovered on the as-delivered model. The rotations had been incorrectly constrained in the wing in attempt to remedy convergence problems with nonlinear analysis".

No further discussion of this issue was reported later in other publications. After corrections the discrepancies

Figure 13: Artistic representations of the experimental tests on Joined Wings. Left, test performed as deduced from reference [34]; right, experimental setup as deduced from reference [40].

between the experimental and computational results were at most 15%.

References [38–40] presented an experimental set up for Joined Wings (see also Figure 13). The model was designed so that the wing experienced nonlinearities without material failure. The applied forces were not of the follower type. The main contribution was the publication of experimental data for comparison of analytical models. In the paper it was stated that

"the unique bend-twist couplings inherent in the structure require nonlinear analyses".

Reference [183, 184] conducted an experimental campaign on a joined-wing model, considering both conservative and follower forces. Displacements produced by the two different load regimes were then compared, showing that follower loads induced as much as 34% greater deflections. This result was in agreement with the theoretical findings of reference [60]. Nonconservative mechanical follower forces provide some indications on the nonlinear deformation of the system, however, as discussed in reference [60], they may misrepresent the true stability properties of the aeroelastic system.

8. Joined-Wing SensorCraft Models: Challenges and Approaches

As seen so far, the novelty of joined-wing design for SensorCraft poses several challenges that need to be accurately addressed and verified with both computational and experimental approaches. The design of an aeroelastically scaled model is a milestone towards an appropriate design of the actual aircraft, thanks to precious information that can be preliminary collected, for example, during wind-tunnel aeroelastic campaigns or remotely piloted flights. The AFRL and its collaborators in US and Europe performed a vast research effort in this direction.

8.1. The Air Vehicle Joined-Wing Technology Demonstrators VA-JWTD and VA-1

Reference [301] was conceptually part of the AFRL initiative to have an affordable, fast response scaled aircraft prototype. The effort described the load testing, structural failure, and redesign of the Air Vehicle Joined-Wing Technology Demonstrator (VA JWTD). The JWTD was a 7% scaled version of the joined-wing SensorCraft proposed in reference [27]; it was designed in the summer of 2002 and resulted in a 14-foot span model. The fore and aft wings had sweep angles of 30° and -30° respectively. JWTD was delivered on March 2003 by AeroComposites Inc (see Figure 14). The model was accepted by AFRL, but presented

Figure 14: Artistic representation of the Air Vehicle Joined Wing Technology Demonstrator.

higher-than-expected flexibility, making clear at that time that the airplane could not be flight-worthy in the aeroelastic sense. Several ground tests were then performed, among which a static load analysis. The system showed structural failure. JWTD wing geometry was then modeled and meshed with solid elements. The mounting conditions were modified and a fiber glass reinforcement was adopted at the inboard half of the fore wing. The computer model indicated that this design was safe. Tests (see reference [226] for more details) proved the effectiveness of the design modifications.

According to reference [227], in 2004 and 2005 AFRL Air Vehicles Directorate designed, built, and flew a scaled radio-controlled joined-wing aircraft, called VA-1, to explore structural integrity, aerodynamic stability and performance. VA-1 experienced a *deep stall during a turn*, resulting in hard landing. This motivated the work of reference [227], which represented the first research quantifying the flight handling qualities of the VA-1. Researchers experimentally measured the mass moments of inertia to perform the dynamic stability analysis, and evaluated also the non-dimensional stability characteristics. The spanwise lift distribution was analyzed to see where the stall might have occurred first. It was found that VA-1 had good longitudinal and lateral flight qualities for cruise flight; the vertical tail could also be removed without degrading the dynamic stability. Finally, the investigations showed that VA-1 could turn without stalling using bank angles smaller than 50° . The stall first occurred at the aileron immediately outboard the wings junction.

8.2. Aeroservoelastic Model for the AEI Program

Within Phase II of the AEI program (see section 3.3.3) aeroservoelastic experimental investigations on a full-span scaled model were performed in the NASA Langley facility (see Figure 15). The challenges were represented by the statically unstable vehicle with low frequency structural modes. This needed the redesign of the support allowing a complete freedom of motion in pitch and plunge. Paper [316] described such innovative model support in detail (contribution of *Millennium Dynamics Corporation* was relevant in this activity).

Figure 15: Artistic representation of the SensorCraft model used for the aeroservoelastic investigations within AEI program, as deduced from www.wpafb.af.mil and from reference [312].

The article [312] described systems, software, and procedures developed to perform experimental tests on the full-span aeroelastically scaled Joined Wing. Trimmed flight at -10% static margin and a reduction of structural response of at least 50% were successfully demonstrated.

In reference [160] the multisine excitation of a SensorCraft in an experimental (wind tunnel) framework was studied. The goal was to assess the frequency response more effectively than one-at-a-time excitation.

Details about the practical design of the model are shared in reference [310]. Fabrication (mainly carried out by *NextGen Aeronautics* company) and validation test procedures of the aeroelastically scaled full-span model of joined-wing SensorCraft, with particular focus on the hardware and the gust alleviation control system were described. An hydraulic actuation was used to control the 13 mobile surfaces. Analysis of the typical modes was also given. Some unexpected facts were found. For example, in-plane bending stiffness of the mid-forward wing as well as the vertical bending stiffness of tail boom was influencing to a large extent some modes. This is in line with findings on simplified joined-wing models [61, 62], for which the complex deformation was very sensitive to material and geometric properties, and this was also the case for the occurrence of instability phenomena.

8.3. Aeroelastic Scaling and One-Ninth Scale Remotely Piloted Vehicle Joined-Wing SensorCraft

Work [263] presented a *scaling technique* aimed to reproduce the aeroelastic equations of motion of a full-scale aircraft by adopting a wind tunnel model. The scaled model was developed by matching flight Mach numbers and reduced natural frequencies. Flutter speed of the scaled model reproduced the full-scale vehicle one, and the ground vibration test was also in excellent agreement. This work was clearly a preliminary effort to gain the necessary expertise which was used years later in the design of an aeroelastically scaled flying model of the SensorCraft.

Report [336] (which overlapped with the above reference [263]) described a theoretical formulation to achieve aeroelastic scaling. Two separate optimization phases were proposed. In the first phase the structure was subjected to representative aerodynamic forces and the optimizer had to change the stiffness distribution to minimize the error in the calculated displacements and scaled values obtained from the full-scale aircraft. In the second phase, the optimized model result of the first phase was augmented with concentrated masses and the optimization had to match the target mode shapes.

Reference [28] presented design plans for a low-cost aeroelastically-scaled flight test concept. This paper can be considered only a very preliminary work on the aeroelastic scaling, which was studied later by the same group in different publications (see for example references [33, 37] discussed later in this section). Several of the above activities (see references [28, 227, 301]) were summarized in the extensive report of AFRL [226].

A collaborative effort involving the AFRL, Virginia Tech, and Instituto Superior Tecnico in Lisbon (Portugal) is described in reference [294], discussing the design of a scaled *Remotely Piloted Vehicle (RPV)* SensorCraft based on Boeing's model (see Figure 4). Goal of the research was the creation of a 1/9th-scale *aeroelastically equivalent model* to investigate the gust response (note that later studies involved a larger multi-institution collaborative effort and the goals became more ambitious, targeting the nonlinear aeroelastic response in flight). Results were intended to be used to design gust load alleviation technologies which were going to be validated with the RPV. In addition, RPV was designed by taking into account allowances for fuel, avionics/sensors, landing gear etc.

The same work provided a theoretical introduction on the similarity issue for an aeroelastically scaled model. Two optimization strategies were discussed. In the first one the vibration modes of the real airplane and scaled model were matched (via genetic algorithm) at once by including both mass and stiffness in the optimization process. Some difficulties in the convergence of the procedure were noted and attributed to the coupling of mass and stiffness (i.e., if one area was made to be stiffer by the optimizer, it also became heavier and therefore required additional stiffness to support itself). This issue was not present on a two-step optimization method, which first determined the stiffness distribution and then optimized the concentrated masses to achieve the matching of the modes and total scaled mass. Reference [294] also stated that an improvement of the *mode matching procedure* was going to be obtained by integrating University of Michigan Nonlinear Aeroelastic Simulation Toolbox (UM/NAST) and a reduced order model to speed up the long run times associated with the genetic algorithm. However, later works showed an extensive use of Equivalent Static Loads (see section 4.1) in the optimization process.

The ongoing efforts towards the building of the aeroelastically scaled RPV model are shared in reference [293]. Cost-effective flying models were presented. UM/NAST was adopted to provide a starting point for subsequent optimizations of higher-fidelity models. The *Dutch roll mode was found slightly unstable* and concerns regarding the lack of yaw control authority were raised due to absence of a rudder surface in the configuration.

The goals of the multi-institution effort towards the testing of a flying piloted model were outlined in references [1, 291]:

"By experimentally demonstrating, investigating and measuring the aft-wing buckling response in flight, future flight test programs will be able to design active aeroelastic control and gust load alleviation systems to reduce the structural and aerodynamic effects of the nonlinear responses".

The final state of the project aimed to subject (during the flight) the aeroelastically scaled RPV to a series of tests designed to *load the aft wing to a point where the nonlinear response could be achieved, observed*

and measured.

Several practical aspects needed to be solved. They were discussed in reference [290] in which ground tests, instrumentation and flight testing of a 1 to 9 geometrically-scaled model (having, however, *rigid wings*) were presented. Some interesting technical information were also provided; in particular, the forward-swept wings and lifting center body were designed to generate 85% of the overall required lift in flight. The remaining 15% was produced by the aft wing which was joined at approximately 60% of the aircraft semispan.

Reference [107] focused on a methodology to scale the *linear* aeroelastic response (flutter) of the full-scale model [1]. Six vibration modes were matched. In the first, fourth and fifth modes an extraneous pitch rotation, not present in the target full model, was observed. An aeroelastic flutter analysis was also conducted for both the scaled and target Boeing's models. The correlation with the target model was found unsatisfactory; in fact, even though predictions of flutter speed were in very good agreement, there was a 26% error on the flutter frequency and the predicted flutter modes were different.

8.4. Nonlinear Aeroelastic Scaling

References [33, 37] formulated the problem of scaling real Joined Wings in wind tunnel models, with the preservation of *aeroelastic similarity* even in the presence of geometric nonlinearities. The main idea of the work was to scale natural frequencies and modes, buckling eigenvalue and corresponding modal shape. The investigations were done on a classical rectangular wing (Goland wingbox) which was then "transformed" into a Joined Wing by adding a strut. In reference [37] it is possible to read:

"The hypothesis was that if the critical buckling eigenvalue is matched, then nonlinear analysis will yield similar results for both models".

In the authors' opinion this needs to be verified case by case. In fact, matching "just" the first buckling eigenvalue *can be considered a kind of reduced order model*. Thus, all the problems and difficulties of reduced order modeling for Joined Wings apply here [91, 100, 342]. This is also implicitly recognized in reference [37], in which *matching of more buckling modes* was suggested to improve the accuracy in the case of relatively large applied loads.

The challenge represented by nonlinear aeroelastic scaling was also addressed in reference [286]. Previous results showed the difficulties in having a satisfactory response when nonlinearities were not included in the scaling procedure or when the matching involved only the buckling mode and eigenvalue (in addition to the vibration modes). Thus, reference [286] considered trim-like loads and *matched the nonlinear static deflections*. Matching of vibration modes was achieved in a two-step procedure similar to the one proposed in reference [294]: a first optimization phase matched the stiffness distribution so that linear static-scaled deflections could be achieved. The second optimization process matched the frequencies and modes by changing non-structural masses. However, in reference [286] the first optimization phase included the matching of *nonlinear static deflections*. This had obviously an expensive computational cost which was substantially reduced by adopting *Equivalent Static Loads*. The aeroelastic scaling also required the matching of the modes which were evaluated in the undeformed state (thus, the change of stiffness matrix with the deformation was not included).

New algorithms designed to overcome difficulties relative to nonlinear aeroelastic scaling were discussed in references [284, 287], in which linear and nonlinear static responses were matched with the satisfaction of modal frequency constraints. The computational costs were reduced by adopting the Equivalent Static Loads previously used by the same research group. This new method *simultaneously designed the vehicle stiffness and non-structural masses* instead of having a two-step optimization procedure. Results were, thus, significantly improved and a good matching of the nonlinear static aeroelastic response was obtained.

Reference [292] continued the multi-institution effort aimed towards the creation of an aeroelastically scaled RPV [290, 291, 293, 294]. The goal was to investigate if the existing forward wing could be reused with an aeroelastically tuned aft wing to demonstrate the geometric nonlinearities. The finite element analysis showed that the aft wing, required to support the existing forward wing, would need to be overly stiff, making the corresponding nonlinear response too small to be measured in flight.

The contribution provided by the AFRL on the scaled flying model is very valuable because it ad-

vanced the knowledge in different areas, including optimization and aeroelastic scaling in the presence of nonlinearities.

9. Other Aeroelastic Investigations

9.1. *Body-Freedom Flutter vs Cantilever Flutter of Joined Wings: an Early Conceptual Work*

Efforts [200, 353], partly sponsored by AFRL, investigated the *body-freedom flutter* (which involves the interaction between the elastic modes and the aircraft rigid modes). This work represents an important contribution since it explains relevant physical aspects related to the joined-wing concept. It was concluded that rigid-body modes must be included in structural optimization because flutter involving the vehicle motion can be an *active constraint*. It was also shown that the placement of the rear-wing root junction of the Joined Wing above the plane of front wing reduced the weight and *deactivated the flutter constraint*.

The above cited efforts provided a conceptual separation between *body-freedom flutter* and *cantilever² flutter*. It was demonstrated that for small values of *fuselage pitch inertia* the mode of instability was body-freedom flutter; when the pitch inertia was increased the mode of instability changed from body-freedom to a cantilever fixed root event. It was also observed that body-freedom flutter speeds were higher as the rear-wing root vertical offset distance increased and this was linked to the nonplanar effects and the resulting *increase of stiffness*. In fact, it was stated that:

“When body-freedom flutter is a constraint, a large weight penalty can result. This penalty is more pronounced when the Joined Wing is planar and the rear wing does not provide out-of-plane stiffening of the configuration.”

The optimization procedure and the change of instability mechanism were conceptually linked:

“While the optimal design began with body freedom flutter as a critical mode, formal structural optimization not only has reduced weight, but it has moved the critical flutter mode from body freedom to cantilever flutter”

The above references also claimed that swept-forward wing appeared the driving mechanism for the joined-wing body-freedom flutter:

“The presence of a swept forward wing segment (the rear wing), because of its well-known aeroelastic flexibility, appears to be the driving mechanism for joined-wing body-freedom flutter”

However, *formal proof of this statement was not provided* and this could be a fundamental research area for new work on Joined Wings.

On the aerodynamic side, there was no mention of the fundamental Prandtl’s work (see reference [272]) on the Best Wing System and its superior characteristics on induced drag reduction; however there was a discussion on the work conducted by Letcher [205], almost 50 years later, on the induced drag of *diamond-shaped closed systems*. The reader should note that the aerodynamic efficiency improvement is actually limited for Diamond Wings, as also reported in references [89, 90, 96–99].

9.2. *Effects of Flexible Fuselage and Vertical Tail*

Following previous work carried out in reference [67], in effort [68] effects of *flexible* vertical tail and fuselage (and also inner wing) were selectively assessed when studying the roll response, and dynamic and static stability of a joined-wing SensorCraft model. In the first case, the fuselage flexibility brought oscillations in the roll-rate response, even though roll angle did not show a significant reduction, whereas vertical tail deformability led also to a reduction in roll angle.

When studying flutter, the not-fully-flexible aircraft appeared to keep the same corresponding unstable modes throughout all considered flight conditions. On the contrary, the fully flexible (fuselage and vertical tail) model showed a change in the flutter mode with flight condition. As a general trend, flutter speed was seen to drop. Thus, *flexibility of fuselage and tail did show to have a relevant influence on the aeroelastic response of Joined Wings*.

²The term “cantilever” is used in this context to indicate a model fixed in the space.

As far as static stability analysis was concerned, an initial flight condition was chosen and the speed was increased (without retrimming the aircraft) until a drop in lift generation was found (maximum load factor was about 1.6g). This was associated with large deformations causing high ply-failure. Moreover, flexible vertical tail led to the highest instability speed, whereas flexible fuselage had the opposite effect.

In reference [257] a procedure to effectively model (within a reduced order concept) the dynamics of active slender structures (including joined-wing SensorCraft) with embedded actuators and sensors was introduced, with the main objective of enhancing parametrization.

9.3. Aeroelastic Static Instability

In work [281] the preliminary structural design of the joined-wing Sensorcraft and an aeroservoelastic wind tunnel test program were discussed. Moreover, the activities carried out in Phase I of the AEI program (see section 3.3.3) to mature the structural design of the Joined Wing were reviewed. After an aeroelastic modeling, aeroelastic stability analyses showed a symmetric flutter mechanism, however, minimum flutter speed margins were found well in excess of 15%.

Static aeroelastic analyses were performed at several flight conditions (maneuver loads) and considering gusts (down gust with low fuel loading and up gust with high fuel at low Mach low-altitude flights were reported as critical conditions). A structural design was carried out considering linear analysis to guide resizing efforts to have positive margins of safety, whereas nonlinear geometric analysis was performed to verify the stability of the airframe under critical gust loads: the mechanism leading to a possible instability was a *flattening of the overall configuration* rather than the usual previously-observed buckling of the aft wing due to compressive loads (this is extensively discussed later, in part IV).

The AFRL carried out additional research on joined-wing SensorCraft with a different group [6]. Results were obtained on a model that was also experimentally tested within the AEI program. The aft wing was designed relatively stiff to meet the safety standards required for wind tunnel testing. Flattening of the SensorCraft was observed, as found by different studies (e.g., [281]). Interesting enough, reference [281] was not explicitly cited and it was not actually specified who first obtained the flattening of the wing. Moreover, no work from Blair's team at AFRL was mentioned or cited (and vice versa in subsequent works).

9.4. Limit Cycle Oscillations

Reference [21] introduced a framework (OpenFSI) to couple the unsteady vortex lattice method (developed at Virginia Tech) and MD NASTRAN. The wake roll-up was modeled and the compressibility effects taken into account with corrections (for the steady case using Prandtl-Glauert correction, for the unsteady case Morino's approach). The analyses involved nonlinear static deflection with increasing load factors from 0 to 16. The following statement was presented:

"when $N_z < 9$ we see a sudden increase in deflection, it is believed that this is when the rear wing buckles". This statement was actually not supported by evidence.

9.5. Aeroelastic Studies of a Twin-fuselage Joined-Wing SensorCraft

In paper [328] a loosely coupled procedure for static aeroelastic analysis of HALE joined-wing aircraft was presented. A finite volume Navier-Stokes solvers was coupled with a linear mode-based structural solver. *Twin-fuselage* joined-wing SensorCraft (see Figure 3) was analyzed, and the structural model was the one first used in reference [279] (also adopted in reference [221]). The importance of structural nonlinearities was recognized (although not justified), however, the aeroelastic analyses were more directed towards a familiarization with the problem rather than a real quantitative result. In this regard, the need of a large number of cells was necessary in order to correctly evaluate the forces.

10. Miscellaneous

10.1. *Gust Loads and Certification Challenges of Joined Wings*

In references [285, 288, 289] the issue of gust-load analysis in the framework of design and certification of novel-configurations was addressed. The investigations regarded Joined Wings and other HALE configurations. Quasi-static, transient, and continuous turbulence methods for the simulation of gust were discussed. It was concluded that Pratt's method provided a *reasonable preliminary analysis tool for joined-wing applications*, though detailed design and certification would have required more accurate procedures.

10.2. *Joined Wing Adopted as Test Cases to Assess the Accuracy of Various Techniques*

In publications [148, 149] the geometrical exact beam theory was used for the structural modeling of Joined Wings. It was claimed that the cost of the optimization was reduced by orders of magnitude. The 3D nonlinear analysis was split into 2 parts: the 2D linear analysis of the cross section and the 1D nonlinear analysis along the axis of the beam.

References [206, 207] presented an application of continuous sensitivity analysis. The Joined Wing was modeled using nonlinear 1D beam elements.

The paper [329] presented the first step towards the creation of an in-house aeroelastic code for highly-flexible aircraft including Joined Wings. The structural model was based on fully-intrinsic equations. Linear potential flow was adopted for the aerodynamic model.

Part II

Independent Research on Joined-Wing HALE and SensorCraft

11. Early Conceptual Work

Reference [261] was one of the first works underlining the importance of a conceptual understanding [60, 62, 64, 87, 88] of Joined Wings with their unique features (overconstrained nature, highly complex geometric nonlinearities). Some discussions were reported on the geometric nonlinearities:

"The rear wing, especially in the non-planar case carries some compressive load and is thus able to constrain the vertical motion of the main wing at the joint. The compressive load can lead to buckling of the rear wing. The likelihood of buckling increases with decrease in the rear wing thickness."

This statement was actually *not* supported by the results presented in the paper. It was also in theoretical disagreement with the findings of other models [61, 62], in which making the compressed wing stiffer was found to be detrimental (although the examined Joined Wing had a different geometry). Reference [261] attempted to further investigate the matter by changing the thickness of the rear wing. A reduction of thickness was observed leading to a higher deformation of the main wing and a buckling-like shape. However, the actual buckling [88] was not observed because of convergence problem of the Newton-Raphson procedure. The reason of this failure was not discussed, and continuation methods were not taken into consideration.

The conclusions section of the paper ended by outlining that "structural nonlinearities were quite negligible". Some researchers used that statement in subsequent works and claimed that nonlinearities are not important in Joined Wings. However, this is a case-dependent statement and should be carefully considered when Joined Wings are analyzed.

12. Analysis of Joined Wings Using Fully-intrinsic Equations and Incremental Method

Efforts [330, 331] show a fully-intrinsic formulation, to which an incremental method was added to circumnavigate the inherent problem of solving a steady overconstrained system. This method was added to an aeroelastic computational framework comprehensive of an unsteady 2D aerodynamic solver. As an application, a joined-wing geometry for which experimental and numerical (mixed-formulation) results were available [261] was selected. The investigators plotted the nonlinear response with applied mechanical loads, and studied the linearized stability properties. Moreover, in reference [330] a parametric study and a (linearized) flutter analysis were conducted.

13. Works in Europe and Australia

13.1. Morphing Joined Wing

In effort [52] an independent study on a 5-meter model of Joined Wing (see Figure 16) was performed within the NOVEMOR FP7 project, focused on implementing novel morphing concepts on UAV.

Figure 16: Artistic representation of the joined-wing baseline model as deduced from reference [52].

Four different morphing capabilities were considered: outboard sweep angle, dihedral change, telescopic rear wing and morphing vertical tails (see Figure 17). A reference mission was chosen, and thanks to the

Figure 17: Artistic representation of the morphing capabilities of the joined-wing model, as deduced from reference [52].

CEASIOM/NeoCAS software, flight mechanics/dynamics, structural and aeroelastic analyses were carried out. Some preliminary formulas were considered to give a prediction of the range, minimum level turn and pull-up radii, take-off distance and landing distance.

Performances of the modified configurations were compared to the baseline ones. With the aid of eloquent spider plots, the morphing vertical tail (between 20° and 50°) was more effective in improving the flight

parameters, with the exception of range/endurance at high speeds (for which outboard sweep and telescopic rear-wing solutions were more successful).

13.2. Optimization of Joined Wings Using the Bacterial Foraging Optimization

Work [136] showed the application of an optimization technique to a JW: the Bacterial Foraging Optimization (BFO) and a hybrid variant were applied to match the aeroelastic responses of wind tunnel model with a full-scale aircraft. The wind tunnel model needed to behave aeroelastically the same as the full-size model, and to do it at different wind speeds (3 m/s at sea level, and, also, at the actual airplane operative condition, i.e., cruise speed of 130.41 m/s at altitude of 19812 m). Actually, the finite element model of the real airplane was not available to the researchers. Thus, they built it with a two-spar-per-wing design (located at 1/4 and 3/4 chord). The objective function to minimize was the mismatch of measures providing correlations between static and dynamic responses of the models (aircraft mass, reduced frequencies and static tip deflection), the parameters were the internal structures and thicknesses. Among the tested methods, the researchers claimed that the Particle Swarm Optimization method had better performance. It is relevant to notice that 3 frequencies were matched.

13.3. Studies of a HALE Joined Wing at the Italian Aerospace Research Center (CIRA)

CIRA performed, within the *Italian Aerospace Research Program - UAV Chapter*, research on a joined-wing concept of UAS (see Figure 18). The main objectives concerned the development and validation of advanced modeling methodologies for flexible aircraft, and aimed at providing the scientific community with a valuable testing platform supporting validation of flight technologies.

Figure 18: Artistic representation of the unmanned joined-wing HALE studied at CIRA, as deduced from references [16, 258].

In effort [168] a first look at the program is given in general terms. After a feasibility study of a HALE vehicle having a 80 m wingspan and able to flight 20 days at 30 Km altitude, a high-altitude performance demonstrator (HAPD) was conceptually designed. The HAPD had a wingspan of 16.5 m for a maximum take-off weight (MTOW) of 184.4 Kg. A rational analysis of the principal requirements (operational, airworthiness, etc) was given, with a subsequent discussion about implications of lower-level requirements. Inherent challenges of this class of vehicle (HALE Joined Wings) were then identified. It was stressed out the importance of preserving the representative properties of high-altitude flights maintaining Reynolds and Froude similarities with some reference HALE configuration, while exhibiting the same peculiarities in terms of vehicle dynamics. The effort also underlined the importance of the junction, which could significantly alter the structural and aeroelastic responses when its properties are slightly perturbed. Thus, uncertainties in manufacturing should be kept as small as possible.

The control architecture introduced difficulties due to the different needs during low- and high-speed operations. For this reason, ailerons, rudder and elevators were split into different parts. This choice proved also to be interesting for modulating control actions in order to limit the excitation of structural modes.

Reference [101] focused on the difficulties of the design. It was noted that:

“The high aspect ratio and the low structural weight requirements lead to a non-negligible flexibility of the wing; furthermore, for this kind of structure, the elastic-body dynamics can have natural frequencies quite close to typical flight mechanics rigid-body frequencies of the vehicle. So, basic aeroelastic investigations must be introduced early in the design process.”

This led to an integrated design methodology, capable of performing the analysis of a flexible trimmed aircraft.

In the paper, an application was shown in which the maximum load factor and gust effects were considered. Interestingly, the strength analyses showed the landing phase to be the most critical condition. Buckling analysis considering the load at gust condition was pursued through an eigenvalue approach, showing an instability occurrence; to prevent this event, the front wing was stiffened. Flutter analysis was then performed on blocked mobile surfaces or also considering a finite hinge stiffness value. The same paper showed some details about the structural realization of HAPD.

In effort [259] the concept of active control system was explored on the HAPD. A formulation for symmetric and balanced maneuvering load alleviation (aircraft flexibility was considered as well) was shown. The principal bending moment at a chosen design section was the variable to be *minimized*. The aerodynamic model was based on a DLM; CFD assessed the small effects of fuselage which was then neglected during aerodynamic analyses. Airfoil camber and aerodynamic corrections caused by viscous effects were retained, calibrating the zero angle-of-attack aerodynamic values (aerodynamic zero effect).

Junction was placed at 70% of the wingspan, and some unconventional structural solutions were provided. A very significant assumption was done: since the tip deflection at a balanced maneuver for maximum load factor was in the order of the one usually registered on conventional aircraft (10% of the semispan), it was speculated that the *use of linear analyses was appropriate*:

“The joined-wing configuration is a valid alternative to a flying wing configuration for solar powered HALE vehicles, not only for its higher structural stiffness and its larger solar array area but also for the possibility to rely solely on linear analysis, thus resulting in a cheaper design process.”

This particular topic about small deformations and nonlinearities will be tackled in the critical discussion, section 26.

Ailerons outboard of the junction area were used as alleviation control. The maximum deflection of aileron was bounding the maximum value of the alleviation factor; particular caution had to be paid towards the design at V_A (design maneuvering speed), since an increase in angle of attack consequence of the load alleviator might lead to stall when aircraft was at its maximum attitude. Aeroelastic effects changed also the distribution of the loads, suggesting that paradigms based on considering rigid structures might not apply. Good level of alleviation factors were reached, however, in some situations the stress far from the wing control section (chosen to be the front-wing root) was actually rising.

In study [258] the impact of the HAPD with the ground during the landing phase was studied. Due to

the high flexibility, it was decided to alleviate the stresses equipping the wing junction with an elastic device able to absorb the impact loads. The study was conducted using the *large mass* method, popular in the seismological studies. Although the device was linear, the force-displacement response was not. Different absorber geometries and stiffnesses were tested to reduce the loads, whereas the chosen condition complied with the CS-VLA regulations. Drop tests confirmed the calculated values of the peak time duration. The design was pursued finding a compromise between a flexible absorber (which meant a higher mount point) and the necessity to avoid the mechanical stop.

In reference [16] a large review of the project was given, starting from the feasibility study of the full-scale 80-meter HALE propelled with 8 electric motors. The investigators revisited also the calculations presented in their previous works regarding structural loads, strength and buckling analyses, adding interesting information. The spar web cap had to be redesigned since strength analyses showed larger-than-allowable stresses. The same action was taken to prevent buckling (studied only with *linear* analysis) observed in the more critical condition (case of discrete gust load). The *out-of-plane* bending stiffness of the front wing was the driving parameter, thus the decision to increase spar-cap thickness of about 60%.

Both divergence and flutter analyses showed a strong dependence on the juncture stiffness, which was initially designed for strength only. Flutter analysis found the third elastic symmetric mode to be unstable; the relative mode shape was a torsion of the front and rear wing and the bending of the outer portion of the front wing. Control surface freeplay was then considered, assuming a backlash of the actuator shaft of $\pm 0.24^\circ$. Equivalent stiffness at the hinge line was evaluated by using harmonic balance method. The design was flutter-free.

Failure of a servoline at time was also investigated. Critical was the case concerning the central elevator, which had then to be equipped with a balancing mass collocated on the control surface, slightly ahead the hinge line. Also a *closed-loop* flutter analysis was carried out to assess if the control law dynamics was inducing instability. This analysis was suggested by the closeness of elastic mode and flight mechanics frequencies. At nominal open-loop flutter speed, with active control, the response was damped (no flutter occurring).

A large part of the effort was devoted to technical and manufacturing details, landing gear, prototyping and testing.

Part III

Strut- and Truss-Braced Wings

Strut- and Truss-Braced Wing concepts *could* be considered as an improvement of the classical monoplane, or also as a *particular type of joined-wing configuration*. As discussed later, Truss-Braced Wing (TBWs) have the final goal of reducing TOGW, increasing performances and reducing fuel consumption and pollution. Some researchers [137] claim that this layout would be well received by the public:

“The SBW is likely to have a more favorable reaction from the public than other configurations, especially for those who suffer from a fear of flying. Affirmative passenger and aircrew acceptance is probable because other than the addition of a visually innocuous strut and a high wing, there is little to distinguish the SBW from the existing airliner fleet. Radical appearances of the blended-wing body, Joined Wing³, or other candidate configurations may cause apprehension in many flying patrons.”

There is a relatively vast body of literature which will be addressed in this review. To understand the terminology followed in the text, the reader should refer to Figure 19 (in the literature, however, this terminology has not been always strictly followed). One may notice that the SBW is a particular case of the more general TBW. According to reference [22], the conceptual difference between SBW and TBW is in

³In reference [137] the term “Joined Wing” did not include TBWs and SBWs. In the present review paper the authors conceptually consider TBWs and SBWs to be Joined Wings.

Figure 19: Strut- and Truss-Braced Wing concepts: terminology used in this work.

the number of members supporting the wing. For example, a 0-member truss defines a classical monoplane configuration, a 1-member truss defines a SBW, and so on. The juries depicted in Figure 19 are rectilinear, however, the designer may consider different options (for example Y-shaped juries as possible mean for improving aeroelastic properties).

14. Early Work

14.1. First Works in the Second Half of the Past Century

One of the earliest TBW concepts was proposed in the '50s by Pfenninger [267] for transonic transport. He remained a strong proponent of the layout [268, 269] for the following decades, until he retired. An artistic representation of Pfenninger's concept is shown in Figure 20.

Figure 20: Artistic representation of Pfenninger's TBW concept in the '70s (see reference [268]).

Later, at the end of the '70s, Boeing and Air Force compared TBW with a baseline model [196]. The analysis showed potentials for lower gross weight, lower empty weight, and reduced fuel consumption. Flutter calculations were not included, but aeroelastic effects were considered by using beam theory for the structural part, and lifting line model for the aerodynamics. Structural analyses indicated that a *jury* should be located at midspan of the main strut.

The same effort also reported an interesting discussion on effects of maneuver load alleviation. In particular, an upper deflection (trailing edge up) of the *outboard aileron* and a lower deflection (trailing edge down) of the *inboard flap* were investigated in an effort towards the *reduction of the wing root bending moment*. It turned out that due to aeroelastic effects (flexibility of wings) the aileron deflections did not produce the desired result, whereas the deflection of the inboard flaps was recommended for an effective shift of the wing lift loading inboard.

Reference [176] investigated transport aircraft designed for long-range military missions. Traditional configuration and one-jury TBW were compared. Using statistical data a cost comparison was performed and TBW showed a slightly worse performance in terms of weight. On the contrary, analytical calculations showed superiority of the TBW, indicating smaller operating and life-cycle costs; the TBW was also found to be 4% lighter. Advantages of TBW design in terms of reduced taxi wing deflections were also observed. The interdisciplinary nature of designing a new configuration was outlined:

“To fully determine the performance and economic potential of the strut-braced wing configuration, coordinated detailed structural and aerodynamic studies are necessary”

14.2. The '80s

In the '80s NASA [347] conducted a study on a transatlantic-range business jet (the baseline model) which was modified with a truss-braced design (an artistic representation is given in Figure 21). The

Figure 21: Artistic representation of NASA TBW business jet concept [347].

truss-braced airplane presented higher cruise lift coefficients and aerodynamic efficiency than a conventional configuration, the larger wing decreased the wing loading. One of the main features of the design was that the smaller chord length determined a lower Reynolds number (less than half of the corresponding baseline airplane wing) favoring thus laminar flow.

The study showed a 20% fuel saving with the truss-braced design in a comparison made for the same payload and range. Considerations about additional construction costs, due to the wing size and complexity, were also provided.

NASA contract report [348] discussed the advantages of TBW in terms of aerodynamic performances: increasing the wing aspect ratio of a classical monoplane configuration to minimize the induced drag would significantly increase the weight, whereas the use of strut could alleviate stress and reduce weight. A parametric study was conducted with common fuselage, engine, fuel load, and wing area; several wing aspect ratios (between 10 and 30) were also considered. The baseline model was represented by a jet powered high-altitude configuration. TBWs were found lighter for the same wing area and aspect ratios, particularly at higher aspect ratios.

Reference [180] presented an aeroelastic study (the “Keldysh problem”) of a simplified SBW (see Figure 22). The wing had high aspect ratio, was rectangular, and with no dihedral. Under the assumption of incompressible flow, constant bending and torsional stiffnesses, *perfectly rigid strut*, and using the aerodynamic strip theory, the wing was found aeroelastically *stable* for a wing-strut junction at 0.47 of the half wingspan (or larger) distance from the root. However, references [214, 215] showed that for junction located

Figure 22: Keldysh’s problem.

at a larger distance, the instability was of the divergence type. For joint located exactly at 0.47 of the half wingspan, the flutter and divergence speeds coincided, whereas for joint located at a smaller distance the flutter was the critical instability.

15. Multidisciplinary Design Optimization

15.1. Early Studies at Virginia Tech

References [145–147] presented a comprehensive summary of accomplishments of the research group at Virginia Tech and University of Florida on TBW. In June of 1996 NASA Langley funded a research to perform a thorough feasibility study of a transonic TBW concept using an MDO framework (previous works did not use this approach). References [146, 147] summarized the main findings up to year 1998.

One of the main advantages of the TBW was claimed to be the *structural efficiency*: the support for the wing allowed larger wingspans without an increase in wing weight or thickness. The increased span reduced the *induced drag*. Moreover, it was possible to decrease the thickness so that the *transonic wave drag* was reduced. A smaller chord (possible thanks to the improved structural efficiency) determined a smaller Reynolds number, favoring laminar flow and a reduction of the parasite drag.

Another relevant discussion was about the design of *tip-mounted engines* for further cutting induced drag (and promoting inertial relief for the wing structure), see section 15.4.

The TBW was assumed best suited to a *long-range mission* in which the increased efficiency could be fully utilized and exploited. Thus, a typical mission profile of the Boeing 777-200IGW was selected for the study (range of 7,380 nm at Mach 0.85 and 305 passengers, plus 500 nm were added to satisfy the reserve fuel requirements). Several design variables were considered (e.g., wingtip chord, strut sweep, wing

semispan) and the optimization was carried out with several constraints (e.g., range, engine-out, wingtip deflection at the taxi bump load condition). The optimization procedure included 3 disciplines: structures, aerodynamics, and performance. Due to the absence of actual coupling between aerodynamics and structures (aeroelasticity), the aerodynamic calculations were done off-line when needed. One of the main results was the significant induced drag reduction achieved by the TBW.

15.2. Collaboration Between Virginia Tech and Lockheed Martin Aeronautical Systems

In April 1998 [238, 239] NASA funded Lockheed Martin Aeronautical Systems (LMAS) to further investigate the TBW concept; Virginia Tech was a subcontractor. In the above references, a preliminary design and weight estimate for a SBW were carried out.

The study showed that 18% reduction of the wing weight and 9.4% reduction in TOGW were possible without sacrificing performances. Among others, the concept of telescoping sleeve strut as a way to overcome

Figure 23: Qualitative sketch of the telescoping sleeve mechanism in a SBW.

the buckling issue of the strut was extensively discussed (see in particular Figures 2.4 and 3.1 of reference [239] and Figure 23, as well as section 15.3, of this review paper).

Reference [152] continued and extended the works earlier presented [146, 147, 239]. In particular, the collaboration with LMAS played an important role, improving the analysis with the addition of realistic constraints in the MDO procedure [222], and manufacturing and certification aspects. LMAS collaborated to upgrade, calibrate, and validate the Virginia Tech MDO code which was used for the optimization of conventional and SBW aircraft. Reference [152] also presented an excellent discussion on the different design options regarding the engines placement: wingtip, underwing and T-tail fuselage mounted (see section 15.4).

The SBW was found to be 9.2-17.4% lighter, to burn 16.2-19.3% less fuel, to require 21.5-31.6% smaller engines and to cost 3.8-7.2% less *than an equivalent classical monoplane aircraft*.

The collaboration between Lockheed Martin and Virginia Tech produced also works [150, 151], and the MDO studies on SBW [152] were updated. Compared to the traditional configuration, SBW showed superior properties. When the objective function to minimize was the TOGW, SBW showed a 8.1% reduction for the case of fuselage-mounted engine; the reduction was even more significant (9.1%) for wingtip engine. However, for such case, engine-out problems represented a serious challenge, as discussed in section 15.4.

The advantages of the SBW were emphasized with respect to the classical monoplane configuration:

"...the greatest virtues of the SBW may be its improved fuel consumption and smaller engine size. These results indicate that the SBW will cost less, limit pollutant discharge and reduce noise pollution for urban airports. Advantages of the SBW increase with range, suggesting that this configuration may be ideal for larger, long-range transports."

15.3. Possible Solutions Against Buckling

The *potential issues with buckling* [81] under $-1 g$ load condition was discussed to be a critical challenge for the single-strut configuration. References [146, 147] suggested to allow the strut to be inactive in

Figure 24: Artistic representation of arch-shaped strut configurations proposed in references [146, 147].

compression (a telescoping sleeve mechanism was mentioned as an option, see the conceptual representation in Figure 23). Other than the telescoping sleeve mechanism, references [146, 147] proposed an innovative design concept to specifically address the compression of the strut and the risk of buckling. The configuration had an arch-shaped strut (see Figure 24), and was actually similar to other joined-wing concepts presented in the literature [355]. The following statements can be found in reference [147] regarding this solution:

“However, instead of buckling under compression like a straight rigid strut, it simply acts like a spring and helps to relieve the bending load. In fact, it takes at least 180° of rotation to actually buckle the arch-shaped strut!” and

“Additionally, the two struts complement each other by allowing one to be in tension when the other strut is likely to be in compression, thus alleviating the strut buckling problem.”

Also other studies [239] focused on the concept of telescoping sleeve strut.

15.4. Challenges of Tip-mounted Engines

References [146, 147] proposed the tip-mounted engines for a reduction in terms of induced drag and for inertia relief (see Figure 25). Difficulties were arising in the case of *engine failure*: to maintain equilibrium of flight at the engine-out flight condition, circulation control needed to be used on the vertical tail, to increase its effectiveness. A possible solution was to blow air through slots or to combine the slots with a deflection flap for redundancy.

The study [152] confirmed that the tip-mounted engines provided a significant inertia relief on the wing and a substantial induced drag reduction at take-off and cruise. However, the issue of engine-out constraint suggested a compromise constituted by an engine placed under the wing in a generic location. This could avoid the need of circulation control on the vertical tail (as suggested in [146, 147]). The T-tail fuselage-mounted engine option did not provide inertia relief on the wing. The inboard-of-the-strut engine could determine engine exhaust blowing on the strut, thus, it was not considered in the study.

Problems related to the engine-out condition for the tip-mounted engine solution were also emphasized in the paper [151] (see also the discussion reported in reference [45]):

Figure 25: Artistic representation of optimal SBW configuration with tip-mounted engines as deduced from reference [146].

“Although the tip-mounted engine case is the lightest of the SBW cases, it is currently the highest risk case. This is because of the severity of the engine-out condition, the need for a circulation control system on the vertical tail and the need for detailed structural analysis with the engine mounted on the wingtip”

A possible solution was also suggested:

“One possible way to counter the engine-out problem for the tip-mounted engine configuration would be to have a more powerful engine on the centerline. If one of the tip engines fails, the other can be shut off, and the centerline engine would provide the necessary thrust for the critical cases. This may raise unique dilemmas when attempting to certify this configuration because it is essentially a twin-engine aircraft from an engine failure point of view, but there are physically three engines”

15.5. The Role of Constraints

References [189, 192] addressed several aspects of the MDO technique applied to SBW, and the MDO framework [137] was improved. The sensitivity of the design with respect to the individual constraints was assessed. The *range constraint* was identified to be the one to which all the designs were most sensitive. On this regard, it is possible to read in the references [189, 192] the following statement:

“An investigation of the effect of the design constraints of the different configurations was performed. It was found that in all the design configurations, the aircraft range proved to be the most crucial constraint in the design. However, results showed that all three SBW designs were less sensitive to constraints than the cantilever⁴ wing aircraft.”

Reference [138] summarized the research on SBW at that time and five years earlier. The main results of references [191] and [192] were reported and discussed.

15.6. SBW and Double-deck Fuselage

The double-deck fuselage SBW design (see Figure 26) was investigated to increase the angle at the strut and, thus, to reduce the interference drag. This design was also a favorable option due to the increased maximum allowed wingtip deflection (from 20 ft of the single-deck case to 25 ft of the double-deck case)

⁴The term “cantilever wing” referred to the classical monoplane configuration; throughout this part on SBWs and TWBs, it has to be always intended in this sense.

Figure 26: Artistic representation of double-deck fuselage design cabin layout as deduced from reference [192].

which could lower the wing skin thickness and the TOGW. Savings of 10%-14% in TOGW over a similar traditional wing optimized design were obtained, whereas with single-deck fuselage the gains were smaller (9%-13%).

15.7. MDO Studies of SBW with Fuselage-mounted Engines

The MDO studies of SBW and comparison with traditional designs continued in reference [141]. Central part of the work was the study of *fuselage-mounted engine SBW configurations* (see Figure 27). The importance of the wing-strut junction in transonic flow (shock waves and regions of separated flow) was addressed by using off-line CFD calculations and a curve fit. The interference drag penalty was shown to be linked to the strut arch radius (higher radius determined smaller drag), see also section 19.1. Benefits in terms of reduction of TOGW and fuel burn compared to a traditional configuration were highlighted. A relevant aeroelastic potential problem was mentioned: the high aspect-ratio wings typical of SBWs were more susceptible to aileron reversal and additional studies were planned to cover this aspect.

15.8. Multidisciplinary Design and Optimization Including Noise Constraints

Reference [204] addressed the MDO by including the noise level constraint. SBW with fuselage-mounted engines was investigated. It was found that the noise level was similar (slightly smaller) than the traditional reference aircraft (however, in regions close to the strut-fuselage and strut-wing intersections it was possible to have three-dimensional vortex shedding that could generate noise; this source of noise was neglected in the study).

16. Strut- and Truss-Braced Wings: a Comparison

The NASA chief scientist D. Bushnell engaged the Virginia Tech group to further expand their previously conducted studies on Strut-Braced Wings and address the Truss-Braced Wing configurations [146].

Figure 27: Artistic representation of the SBW T-tail design with fuselage-mounted engines, as deduced from reference [141].

16.1. Improvement of the MDO to Take Into Account TBW

The approach previously developed in reference [142] for SBW was extended in reference [22] to handle TBW configurations. Moreover, high-fidelity representation of the wingbox structure was also introduced by means of shell elements. Reference [22] emphasized the importance of nonlinear investigations:

“...the analysis require the following capabilities: steady and unsteady aerodynamic analyses capability; trim load calculations; use of trim loads to calculate linearized buckling eigenvalues and geometric stiffness for use in modal analysis, flutter solution”.

At that time, there was a plan to include in the MDO capability the flutter constraint.

Several relevant findings are here summarized.

- The difference between the optimized wing mass obtained from rigid and flexible trims becomes significant as the wingspan increases; this is even more important when the mid-chord sweep is higher, due to the bending-torsion coupling.
- There is a significant change of natural frequencies if the wingspan is increased. At 80 ft semispan the first mode occurs at 2.3 Hz. This reduces to 0.1 Hz as the span is increased to 240 ft. Reference [22] made then the following statements on this regard:
 “The modes have very low frequencies as compared to those observed in present day airliners. This raises the possibility of coupling of rigid-body modes and wing deformation modes”
 and
 “Increasing the span reduces the natural frequencies of the wing structure and also makes it more susceptible to flutter”
 (It should also be noted that the supporting truss structure enables higher wingspans). The flutter analysis of reference [22] did not take the rigid-body modes into account.
- The flutter mode was observed to be a combination of the wing chordwise and spanwise bending modes.
- For configurations with only one strut (i.e., the SBW designs) it was observed that dimensions of the strut were *driven by its buckling*. When more truss members were added, the buckling constraint became inactive because the length of the added truss members decreased.

Reference [22] discussed the relevance of *geometric nonlinearities* and compressive forces. With explicit reference to the SBW configuration, the following statement was reported:

“...the portion of the wing inboard of the wing-strut junction will remain in compression during level flight. This leads to a geometric stiffness effect that would lower the structural natural frequencies and potentially influence the flutter characteristics of the wing”

In the authors’ opinion this statement should be regarded conjunctly with the theoretical discussion on the buckling of the aft wing of the SensorCraft (see dedicated technical part of this review, section 24).

Finally, reference [22] mentioned the on-going effort towards the inclusion of active and passive flutter-suppression techniques.

16.2. Transonic Long-range Case

References [156, 157] applied the MDO framework described in reference [22] to 3 configurations: traditional wing, SBW and TBW (see Figure 28). In all cases the engines were located on the fuselage. Vehicle

Figure 28: Artistic representation of the traditional wing, SBW, and TBW considered in references [156, 157].

mission was similar to that of the Boeing 777-200LR, with a range of 7730 nm and 305 passengers.

The studies showed relevant potential improvements of the TBW compared to SBW. For the case of minimum TOGW objective function, both SBW and TWB presented lower wing-weight with similar span and aspect ratio compared to a traditional wing baseline model. While maintaining similar TOGW, TBW could achieve a 32% reduction of fuel consumption. The TBW showed very high aspect-ratio wings with spans over the typical airport limit of 80 m. A *folding mechanism* was then considered, with relative weight penalty.

The optimization did not consider aeroelastic coupling. However, a parametric flutter analysis with Doublet Lattice aerodynamics showed that adding more jury members increased the flutter speed.

Reference [154] showed additional improvements of the Virginia Tech MDO capability with a new aeroelastic module (however, the flutter was not treated as a constraint in the optimization procedure) and other modifications to make easier the study of TBW cases [155]. On the technical side, 4 different configurations were optimized and compared: traditional, SBW, one and two juries TBW. The savings in fuel consumption and reduction of TOGW were confirmed. Particularly relevant were the effects of adding additional truss members: the wingspan increased, the chord decreased, the chord of the main strut decreased, and the *strut-wing intersection was pushed toward the wingtip*.

16.2.1. Upgraded modeling for TBWs: multiple jury cases

Reference [313] presented the results of investigations carried out with an updated (compared to previous capability [157]) MDO framework. In particular, the aerodynamic module was upgraded and the analysis of complex *three-jury* TBW was then possible with more realistic spanload aerodynamic distributions. The optimization cost function was represented by the (minimum) TOGW. Traditional, one-jury, two-jury, and three-jury TBWs were compared. The lowest TOGW was achieved with the one-jury TBW, whereas the

lowest fuel consumption was obtained with the two-jury TBW. Another interesting result regarded the three-jury TBW: the *structural weight of the optimal wing* was practically equal to the one of the traditional configuration. However, the TOGW, fuel consumption, and aerodynamic efficiency were significantly improved. The new updated MDO capability predicted more aerodynamic load on the strut and less on the inboard part of the wing. No aeroelastic effects were discussed in the paper.

16.3. Transonic Medium-range Case

References [228, 229] adopted the MDO framework previously developed at Virginia Tech [154, 155] but instead of investigating the TBW concept for Mach 0.85, long-range case (Boeing 777-200ER), the focus moved on the examination of benefits of the TBW for a Boeing 737-800NG-like *medium-range mission*. Both SBW and TBW were considered and fuselage- as well as wing-mounted engines were analyzed. Possibility of storing fuel in the strut was also introduced. TBW and SBW showed to be superior than the traditional counterpart; however, no significant performance differences between the optimized versions were found for both minimum TOGW and fuel cost functions. Regarding aeroelastic phenomena and instabilities, the study did not perform any flutter analysis.

Reference [317] presented an MDO analysis of a medium-range (3115 nm), transonic ($M = 0.78$), Boeing 737-700 NG-like aircraft carrying 162 passengers. Traditional layout, SBW and one-jury TBW were compared. Two objectives were considered: L/D (to emphasize aerodynamic efficiency) and wing weight (to emphasize structures). For less efficient airplane, the optimizer found a shorter and more-swept wing, with a change in taper of the trailing edge occurring at 75% of the half span. For the most efficient aircraft, the span was much larger and the maximum chord length was found at 33% of the semispan before tapering out to a smaller tip chord. Increasing aerodynamic efficiency was found to be penalizing in terms of wing weight and, to a smaller extent, also to TOGW. Several optimal designs were compared and assessed. A

Figure 29: Artistic representation of selected “best” designs for traditional wing, SBW, and TBW considered in reference [317].

summary of the main findings (see Figure 29) critically discussing the “best” design cases was also reported in reference [317]:

“Some might look at this and judge the SBW with the wing engines as the overall winner, based on low fuel

weight (and therefore emissions), good L/D , low wing weight and acceptable TOGW. Others might consider the TBW with wing engines as a better design since it combines low TOGW with a moderate increase in fuel consumption, and does not go to the high cruise altitude of the SBW design."

16.4. Subsonic Military Transportation Case

Reference [153] modified the type of airplane used to assess the benefits of SBW and TBW designs. In particular, the study focused on the subsonic Lockheed Martin C-130J-like aircraft with a cruise Mach number of 0.60, 1800 nm range and a maximum payload of 40000 lbs. The cost function was the fuel weight. Three configurations were investigated: traditional, SBW, and TBW. It was found that the SBW option actually provided a better performance than the TBW: with SBW the fuel reduction was 10.7%. However, a TOGW penalty of 4.2% was also observed (results compared against the traditional configuration, see Figure 30). The TBW showed a 4.5% decrease in fuel weight but also an increase of TOGW by 11%

Figure 30: Subsonic Lockheed Martin C-130J-like aircraft: artistic representation of selected "best" designs for traditional wing, SBW, and TBW considered in reference [153].

(compared against the optimized traditional configuration). This was explained in the study by the fact that the optimizer found for the two designs (SBW and TBW) similar aspect ratio but the TBW, having a jury, had a larger interference drag. Moreover, a second effect was outlined: the analyzed configuration had multiple engines on each semispan of the wing, providing inertia relief and bending moment reduction, especially for the SBW (thus, reducing structural weight). In the TBW case, the effect was less pronounced because the accommodation of the engines and jury required a longer strut inducing a weight penalty.

16.5. Subsonic Ultra Green Aircraft Research (SUGAR) $N+3$

References [69, 240, 241] used MDO to study TBW optimized for *minimum fuel consumption*. The investigation was conceptually part of the *SUGAR N + 3* study (see the dedicated part on the topic, section 17), which selected TBW concept as the most promising configuration. SBW and TBW with one and two juries were explored. For a given wingspan, it was found that adding a single jury to a SBW provided lower wing-weight. Adding a second jury had a marginal improvement due to the penalty in aerodynamic drag. Thus, it was concluded that there was no need for investigating more complex truss systems such as three- or four-jury TBWs.

Reference [69] analyzed the mission-level impact of aircraft cruise speed. Consideration was given to both mission block fuel and operating costs, and both fuel-optimal and cost-optimal designs for a range of cruise speeds. A monotonic reduction of cruise L/D was observed as well as an increase of sweep angles (see Figure 31). The breakdown of the aerodynamic drag indicated the dominant role of the friction angles at the examined Mach numbers. The induced drag showed a reduction with the Mach number due to a reduction in lift coefficient at cruise. The interference drag was constant across the Mach numbers used in the investigation. Finally, the wave drag became more important at relatively high Mach numbers.

Figure 31: Artistic representation of the fuel-burn optimized TBW designs and drag breakdown, as deduced from reference [69].

17. Truss-Braced Wing and Boeing Subsonic Ultra Green Aircraft Research

17.1. Aviation Challenges and NASA Technology Goals to Achieve Efficiency

Long distance travel can be safely and effectively achieved by air transportation. Indeed, air travel is rapidly expanding providing an unprecedented level of freedom and economic opportunity around the globe. However, the increase of world demand of this type of transportation poses relevant challenges due to the diminishing supply of natural resources (which implies higher fuel costs: in 2000 the fuel price increased nearly four times compared to the prices of previous decades [42]). Furthermore, commercial aviation share of CO_2 global production is about 2% and, thus, an environmental concern needs to be taken into

account by designers. Airport capacities, airplane noise, and air pollution are also relevant factors which new technological development should address to achieve a sustainable transportation system. NASA, then, set ambitious technology goals for future subsonic vehicles to address these aviation challenges.

In this framework, the technological level is labeled with the “ N ” to indicate how far is in the future a given proposed technology. According to reference [42], the 737NG vehicle and CFM56 engine technology are *the in-service standards* and thus defined as “ N ”.

The technological improvements to achieve NASA aircraft efficiency goals are defined using levels indicated as $N + 1$, $N + 2$, etc. as shown in Figure 32.

Technology Benefits	Technology Generations		
	$N + 1$ (year 2015)	$N + 2$ (year 2020)	$N + 3$ (year 2025)
Noise	–32 dB	–42 dB	–71 dB
LTO NOx Emissions	–60%	–75%	–80%
Cruise NOx Emissions	–55%	–70%	–80%
Aircraft Fuel/Energy Consumption	–33%	–50%	–60%

Figure 32: Artistic representation of the NASA noise, emissions, fuel, and energy goals as deduced from reference [43].

17.2. Truss-Braced Wings within SUGAR $N + 3$

Reference [42] summarized the work accomplished by SUGAR (Phase 1, period October 2008-March 2010). Members of the team (see also reference [108]) were Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech. Several concepts were evaluated in detail, including the 765-095 SUGAR High (2020 Advanced Strut-Braced High Span). Standard methods used to estimate the wing weight were not considered adequate to account for all of the advanced technologies. Therefore, it was stated that there was high wing-weight uncertainty and significant, although unproven, potential for weight reduction. The following recommended activities were given for Phase II (Phase II is discussed in reference [43]):

“We recommend a comprehensive study of high aspect ratio strut/truss braced wings, accounting for coupled aerodynamics, structures, materials, propulsion, and control. Making this wing aerodynamically effective while controlling weight is the key to enabling this high L/D configuration. A detailed finite element model is needed, and an aeroelastic test is necessary to validate the structural analysis and to determine the weight of the wing. The high cruise lift coefficient required at Mach 0.70 for high aspect ratio wings requires additional analysis, optimization, and experimental validation.”

In Phase II a TBW configuration was studied for future Boeing 737-size transports [5]. Phase II included higher-fidelity finite element models and aeroelastic analyses with the goal of reducing the uncertainty in the potential benefit prediction [311]. Flutter weight penalty for the flexible TBW design was considered critical and a 15% dynamically scaled aeroelastic wind tunnel model (built by NextGen Aeronautics) was tested at NASA Transonic Dynamics Tunnel. Wind tunnel tests were completed in April 2014 [311]. The primary goal was to identify the open-loop flutter boundary and then demonstrate flutter suppression. A secondary goal was to demonstrate gust alleviation.

More details and results carried out in the project can be found in different sections of this review, e.g., sections 18.6 and 19.6.

18. Aeroelastic Investigations

18.1. Preliminary Considerations

Reference [154] showed improvements of the Virginia Tech MDO capability with a new aeroelastic module (however, the flutter was not treated as constraint in the optimization procedure) and other modifications to make easier the study of TBW cases [155].

References [228, 229] adopted the MDO framework previously developed at Virginia Tech (see references [154, 155]). Regarding aeroelastic phenomena and instabilities, the study did not present any flutter analysis. However, the following was stated:

“An implicit assumption behind all of these studies is that the wing and strut flutter, if not alleviated by passive means, will be controlled by an active control system. No data were available to permit including weight or cost estimates for such a system.”

Moreover, an interesting option for TBW was suggested to improve the aeroelastic behavior:

“Split struts could be used to control wing twist as well as passively control the wing aeroelastic behavior. A split or branched strut like a Y where it intersects the wing would allow passive wing stiffening in bending and torsion with active control of the upper wing twist if actuators are placed in each branch.”

18.2. Flutter Sensitivity Analysis for SBWs and TBWs

Reference [333] provided an extensive sensitivity analysis for SBWs. In a first study flutter and divergence speeds sensitivity to the strut position in the longitudinal direction was assessed. The *flutter speed was observed to increase* as the strut-fuselage junction moved *forward* along the fuselage axis; in all conditions, the design was divergence free.

The second sensitivity analysis was related to the investigation of the variation of the flutter speed when the wing-strut junction position changed along the spanwise direction, as shown in Figure 33. For wing-

Figure 33: Artistic representation of the flutter speed as a function of the spanwise and chordwise position of the strut junction at the wing, as deduced from reference [333].

strut junction position smaller than 70% of the semispan a gradual decrease of the flutter speed was noted; a substantial drop of the flutter speed occurred for wing-strut spanwise position larger than 80% of the semispan. For intermediate values, an increase of the flutter speed occurred. This was justified as follows:

“The increase is related to the fact that the flutter mode switches from a torsional mode outside this region to a

bending mode inside this region. This trend may indicate that the aeroelastic stability system of the strut-braced wing is not dominated by the lower order modes."

The third sensitivity study performed in reference [333] regarded the variation of flutter speed when the location of the wing-strut junction changed along the chordwise direction (see Figure 33). Three possible positions for the strut support were investigated: wing elastic axis, front spar and rear spar. The strut support at the rear spar gave the lowest flutter speed.

Additional studies regarded the influence of the different lengths of the offset beam connecting the wing and strut, and the impact of *fuel load* and flight altitude.

Several parametric studies were conducted years later in references [24, 25] in which wing geometric characteristics that mostly affected the flutter speed were analyzed. The study was conducted on SBW and TBW configurations. The primary parameters considered were the wing semispan, strut sweep, spanwise location of wing-strut juncture, and the number of truss members. The main findings are here summarized.

- For a SBW the best flutter performance occurred when the wing and strut had the same sweep angle.
- For TBWs a *swept-forward strut provided the best flutter performance*. It is interesting to note that the juries modified the bending-torsion coupling between the main wing and the strut. Thus, in the authors' opinion it could in principle be possible to achieve the same flutter benefits by adopting an appropriate aeroelastic tailoring. However, the impact on the weight needs to be investigated in an MDO study.
- The sensitivity of the flutter speed of TBWs with respect to the strut sweep increased with the spanwise intersection location.
- An increase of the spanwise intersection location increased the wing weight due to critical buckling constraint (however, it should be noted that this constraint was imposed via eigenvalue analysis and this may not be an accurate estimate of the actual instability properties of the system, as discussed in section 24.1).

18.3. Aeroelastic Modeling Including Chordwise Bending

Reference [46] analyzed a two-dimensional airfoil modeling of a high aspect-ratio wing. The model was based on Theodorsen function aerodynamics. The novelty of the simplified framework was in the inclusion of chordwise bending, motivated by the high aspect ratio typical of TBW designs. Under some values of the parameters of the model, the flutter behavior was shown to be negatively affected. However, validation of the procedure with more refined models was not presented.

An additional study was conducted to assess the effects of *ballast masses* as methods to increase the flutter speed (passive flutter suppression). The examined case was a SBW optimized for minimum TOGW. The optimal location for the concentrated mass (2% of the total wing weight) was at 36% of the span and 58% aft the elastic axis, and was leading to an overall increment of flutter speed about 1% only.

It was noted that the sensitivity to ballast mass placement was actually a function of the weight of the ballast mass; thus, several values for the mass were considered. However, the flutter speed did not show a strong sensitivity.

18.4. Multidisciplinary Design and Optimization with Flutter Constraint

18.4.1. Long-range aircraft case

Reference [23] augmented previous MDO capability [154] with the addition of dynamic aeroelasticity. The framework was used to study aircraft in the same class of the Boeing 777-200ER. Flutter, calculated via strip theory and with the inclusion of the geometric stiffness matrix, was a constraint in the optimization. Buckling was included with a more realistic representation, the eigenvalue problem (instead of just using Euler's formula, approach which was found to be too conservative). Three layouts were studied: traditional monoplane, SBW and TBWs. The initial configurations were the ones obtained from previous MDO studies [156, 157] (see also Figure 28). For the SBW case, inclusion of buckling constraint increased the optimal

wing-weight by 10% and resulted in a flutter-free design. For the TBW, addition of buckling constraints raised the optimal wing weight by 2.5%. Addition of flutter constraint further raised the optimal wing mass by 8.2%. The inclusion of geometric nonlinearities in the flutter calculation did not significantly change the results.

A more recent study [217] on an aircraft designed for a flight mission similar to Boeing 777-200LR, showed that adding the flutter constraint determined a penalty of 7-8% on fuel burn. Thus, it was proposed the use of the so-called Novel Control Effector (NCE) consisting in a wingtip mechanism which can sweep forward and aft relative to the wing, see Figure 34. For certain conditions a swept NCE tip would prevent flutter and simultaneously provide sufficient capability for roll control. The final TBW design with NCE predicted 12% lower fuel burn than its optimized traditional counterpart.

Figure 34: Artistic representation of the Boeing Novel Control Effector as deduced from reference [217].

Additional studies on long-range aircraft were presented in reference [218]. The design considered *fuselage-mounted engines*. Linear flutter studies were performed on an optimized TBW (minimization of fuel weight without applying any constraint on the flutter) considering a 2.5 g maneuver load case with full fuel. The wing and the strut were considered as the only lifting members. It was found (see Figure 35) that modes 3 and 5 participated in the flutter. As deduced from Figure 35, mode 3 was the second primarily out-of-plane bending mode, whereas mode 5 was the first primarily torsion mode.

After these studies, optimization was carried out with the inclusion of the flutter constraint. When the *objective function was the TOGW*, adding the flutter constraint brought a 3.2% penalty. When the objective function was the *fuel consumption* a substantial increase (+7.5%) was observed.

18.4.2. Long-range aircraft case: TBW compared with traditional layout

Optimized TBW designs (including flutter constraint) introduced important fuel consumption savings, when compared with optimized traditional configuration, see Figure 36. The study showed also that the traditional optimized long-range aircraft *had the flutter constraint inactive*. This is also a result found for the medium-range aircraft discussed later.

18.4.3. Mid-range aircraft case

Reference [216] considered the medium-range vehicle and improvements of the TBW design (see references [228, 229]). One-jury TBW and wing-mounted engines were selected. This last choice was justified in reference [218], reporting that a previous study [229] revealed that wing-mounted engine TBW designs outperformed fuselage-mounted versions in minimizing both TOGW and fuel weight when a medium-range type of mission was considered (although reference [216] focused on the minimization of TOGW only).

Figure 35: Artistic representation of the V - g and V - f diagrams, and relative modes, as deduced from reference [218].

Objective function: <i>minimum TOGW</i>			Objective function: <i>minimum fuel</i>		
	Optimized traditional configuration	Optimized TBW		Optimized traditional configuration	Optimized TBW
TOGW (lb)	488,700	479,700 (-1.8%)	TOGW (lb)	502,000	482,000 (-4.0%)
Fuel weight (lb)	163,500	148,000 (-9.5%)	Fuel weight (lb)	156,000	146,400 (-6.0%)

Figure 36: Long-range aircraft: optimized TBW compared against optimized traditional layout as deduced from reference [218].

The flutter constraint was included in the MDO procedure resulting in 1% weight penalty [216]. A comparison between a configuration that violated the constraint and one that satisfied it, showed that in the first case the jury increased in length and also increased its inclination angle (see Figure 37). The strut was attached to the mid chord of the main wing. However, it was suggested to attach it to the front spar as previously done for a SBW study (see for example reference [335]). A discussion regarding the importance of active flutter suppression was also emphasized:

“It has been observed that cantilever designs are not affected by flutter constraint and hence the TBW loses some of its benefits over the cantilever due to the penalty faced by the latter. An application of active flutter suppression may lead the TBW configurations to regain some of the benefits in TOGW over cantilever designs”

As a side note, the unsteady aerodynamic model adopted for the flutter analysis was based on Theodorsen’s strip theory and Prandtl-Glauert correction for compressibility. No other aerodynamic effects were modeled.

Reference [218] was an extended version of the conference paper [216] with additional insights and studies. The following approach was adopted to include flutter in the optimization procedure:

- The designs were obtained *without applying the flutter constraint* to serve as baseline for comparisons.
- These designs were chosen as *initial points* and the flutter constraint was included within the optimization procedure.

When minimizing the TOGW, inclusion of flutter constraint determined an increase of take-off weight (about

Figure 37: Artistic representation of the minimum TOGW optimized TBW configurations as deduced from reference [216]. A negative value of the flutter margin means that the flutter speed is included in the flight envelope.

1.5% for a selected design point⁵). The bending stiffness increase was considered the most important factor which suppressed flutter. It was also observed that to satisfy the flutter constraint the optimizer moved structural material from outboard and inboard sections *toward the wing-strut junctions* (implicitly confirming the result presented in Figure 37).

Similar study was conducted for the *minimum fuel objective*: achieving a flutter-free design determined a 5% increase of fuel consumption. Exploration of active flutter-suppression mechanism was suggested for both cases:

"The cost of the reduced fuel burn against the weight penalties and efficiency of an active-flutter-suppression mechanism to increase flutter speed by 10% may be worth investigating."

18.4.4. Mid-range aircraft case: TBW compared with traditional layout

For the same type of aircraft, it is relevant to compare the benefits in terms of TOGW and fuel weight when the objective function (to minimize) is the TOGW and when, alternatively, is the fuel weight (see Figure 38). In the first case, there is a small reduction in weight (-0.6%), whereas the fuel consumption is significantly reduced (-3.5%). In the second case, there is a consistent reduction (-6%) of the fuel weight, however, the TOGW is not affected.

The studies of reference [218] showed also that the traditional optimized medium-range aircraft *had the flutter constraint inactive*. In other words, the flutter constraint did not play any part in changing the feasible designs. An attempt to explain this was provided:

"The results show that the ratio of the first bending and torsion modes for the cantilever is further apart than the frequencies of the second out-of-plane bending and the first torsion mode of the TBW. Based on the notion that the flutter velocity drops to its lowest when the frequencies of the modes come closest to each other, it is believed that this is the prime reason why cantilever wings do not flutter, whereas the TBW configurations do".

⁵This finding is not identical to the one reported in the earlier version of the same paper, reference [216], probably because a different point in the design space was considered.

Possible additional studies regarding aeroelastic behavior of TBWs compared to traditional layouts were suggested:

“However, it is interesting to note that the cantilever designs optimized for minimum fuel may have very low first-bending frequencies, which may lead to body freedom flutter. Although such an analysis performed for a free-free vehicle is beyond the scope of the existing analysis, such an event would also constrain the performance of cantilever designs, and make TBW configurations even more superior”.

18.5. Aeroelastic Analysis Including Structural Geometric Nonlinearities

References [333–335] investigated *aeroelastic effects on the SBW* with the inclusion of geometric nonlinearities. The main idea was to extend the work presented in the past [180, 215] and analyze how the position of the wing-strut intersection (and many other parameters) influenced the flutter speed. *Geometric nonlinearities* were also taken into account with an in-house code based on a tapered bar element on the structural side and on a modified DLM (different than the formulation proposed by Rodden [303]). The wing-strut system was idealized (see Figure 39) with a space frame structure composed of tapered beams. Importance of geometric nonlinearities, discussed later in the technical part of this review (see sections 24.1 and 25) was recognized [333]:

“For the strut-braced wing (SBW) aircraft design, however, the compressive force may have a significant influence on the flutter analysis due to the unconventional nature of the wing”.

and

“Studying the influence of this compressive force on the structural response of the strut-braced wing is thus of paramount importance”.

The procedure described in reference [333] involved first the trim of the SBW. A modal analysis was then performed *including the effect of the compressive force* and the flutter equation of the K method was modified by including an additional term (taking into account both the force and geometric stiffness matrix). Sensitivity analysis was then performed varying the spanwise position of the wing-strut junction, the offset beam length in the wing-strut junction, and the altitude. It was observed that the compressive force lowered the flutter speed practically for all the examined strut spanwise location (see Figure 40). A dip when junction location was approximately at 40% of the semispan was found. This was attributed to a switch of the flutter from the bending to torsion mode.

Flutter speed was calculated also for the wing with and without strut, being higher in the latter case. A possible explanation related this phenomenon with the compressive force reducing the stiffness of the inboard part of the wing. Other studies specifically addressing the structural buckling were presented in reference [334].

On a side note, it was also claimed that the aeroelastic analysis code was accurate and fast enough to be implemented in an MDO environment. The second author of this review implemented the Doublet Lattice formulation (in an unpublished work) proposed by Sulaeman, however, he found the original formulation proposed by Rodden [4] and revised in 1998 [303] to be significantly faster.

References [72, 73] used the same theoretical approach also presented in the paper [201]: the nonlinear system was subdivided into several subdomains, and within each subdomain, the system was assumed to be linear. The nonlinear parameters that divided the nonlinear systems into locally linear systems were selected according to the buckling load of the wing and the strut, respectively. The first 20 buckling modes were considered sufficient to represent the structural deformation. As a note, the SBW did not present a telescopic sleeve mechanism as the one proposed in other studies from the Virginia Tech group.

Additional studies on effects of nonlinearities on the aeroelastic properties were presented in reference [218]. Linear and nonlinear flutter analyses were conducted on a long-range aircraft. Modes were calculated using the configuration corresponding to the 2.5 *g* maneuver load case with full fuel. In both linear and nonlinear analyses the participating modes were the third and fifth ones. Comparison of modes with and without the geometric nonlinearities is presented in Figure 41. The linear and nonlinear aeroelastic analyses produced similar flutter velocities and frequencies, with smaller values in the nonlinear case (see Figure 41). Reference [218] also conceptually compared the found results with the findings of reference [80]

(discussed in detail in section 18.6.1 of this review). In particular, it is possible to read the following statement:

“A nonlinear prestressed flutter analysis was performed in another paper [80]. However, these results⁶ cannot be compared directly to those results, because an iterative methods was used by Cogging et al. in [80], which cannot be incorporated into an MDO framework because of its huge computational cost. Also, the results were obtained for a wind-tunnel model with different load cases and boundary conditions than what is simulated in the MDO”.

Another interesting comparison between linear and nonlinear flutter analyses was presented for both medium- and long-range airplanes. In all cases, NASTRAN nonlinear predictions presented smaller flutter speeds and frequencies compared to the in-house linear ones (see Figure 42).

Structural nonlinearities have also been considered in the aeroelastic design within the SUGAR program, as it will be shown in the next section.

18.6. Aeroelastic Analyses within the SUGAR Program

18.6.1. Effects of structural nonlinearities

Reference [80] investigated the *effects of nonlinearities* on the aeroelastic stability properties of the wing system. The Boeing company created a finite element model of a TBW within the SUGAR program in order to simulate the corresponding wind tunnel model fabricated by NextGen Aeronautics. Flutter simulations, conducted with NASTRAN, were performed in both linear and nonlinear regimes. The nonlinear analyses adopted the vibration modes evaluated with the pre-stressed structure (determined via nonlinear static large displacement analysis). Coalescence of the third and fourth frequencies was observed when the flutter occurred. The aerodynamic model (VLM) was also corrected with some weighting factors obtained from CFD. The main results can be summarized as follows:

- The structural geometric nonlinearity increased the flutter speed; the reader can notice an *opposite effect* in respect of what seen in Figure 41.
- The model that took into account structural geometric nonlinearity and aerodynamic weighting corrections to the VLM did not even present the flutter.
- At higher angles of attack flutter speed increased (however, the mode shapes for the linear case and for the pre-stressed model were not shown and the nonlinear static response curve was not presented).
- The flutter was found to be quite sensitive to the mass of the system.

This study confirms that structural geometric nonlinearities may be *relevant* not only for SensorCraft-like Joined Wings, but also for TBWs. This is not necessarily a negative aspect: an appropriate design of the nonlinearities may be beneficial. The difficulty is in the actual modeling when the MDO preliminary design is conducted (computational costs).

Reference [5] addressed the importance of nonlinear effects with both a dynamically-scaled aeroelastic wind tunnel model (see reference [311]) and a full-scale TBW finite element model (only a single jury and a wingspan of 170 ft were considered since they corresponded to an MDO-optimized configuration). Structural nonlinearities were modeled by including preload and large displacement effects in the flutter solution. The study demonstrated that the flutter boundary was nonlinear and varied when the angle of attack was changed.

Modal properties of the finite element models were compared to data obtained by ground vibration tests [311], and an excellent correlation with the experiment was observed for at least the first seven modes. The two primary open-loop flutter modes were found to be mode 3 (second wing bending) and mode 4 (wing/nacelle torsion). An artistic representation of the modes is provided in Figure 43.

Flutter suppression was successfully demonstrated for control laws designed using aeroservoelastic models derived from both experimental data and from finite element models.

⁶They were referring to reference [218].

18.6.2. Combined effects of structural and aerodynamic nonlinearities

Reference [359] coupled linear unsteady aerodynamics (DLM corrected with aerodynamic correction factors obtained from CFD to capture transonic effects) with structural finite element model. The geometric nonlinearities were retained. For high angle of attack the nonlinear analysis predicted an increased flutter margin of 20%-30% and in some cases the flutter instability was not even present. Reference [359] also investigated the sensitivity to ballast masses. Even small changes (3.36% of the TBW weight) resulted in large deviations of flutter speed (around 20%).

The sensitivity of the Limit Cycle Oscillation and flutter to the angle of attack was also found in reference [13], and it was attributed to the transonic effects associated with mean shock location. The importance of nonlinearities was clearly stated:

“At least static, if not dynamic, aeroelastic analyses with nonlinear structure and nonlinear aerodynamic effects (at least through correction factors) are necessary to adequately predict the behavior of the TBW vehicle”

Reference [14] studied Limit Cycle Oscillations with main focus on the aerodynamic nonlinearities by coupling a high-fidelity Navier-Stokes solver (FUN3D) and linear NASTRAN structural model. Results were also compared against experimental aeroelastic investigations carried out on the earlier described dynamically scaled model manufactured by NextGen. The flutter mechanism evaluated by using both linear and nonlinear aerodynamic solvers was found to be the coalescence of the 3rd and 4th modes (see Figure 43).

18.6.3. Adaptive aeroelastic technologies

According to reference [344], aeroelastic interactions can result in adverse aerodynamics on the aircraft and lead to drag increases. Thus, Adaptive Aeroelastic Shape Control (AASC) technologies such as the Variable Camber Continuous Trailing Edge Flap (VCCTEF) were proposed for TBW design (see Figure 44). The trailing edge flap deflections were optimized to achieve load alleviation and drag reduction. In particular, reference [71] performed size optimization subjected to flutter and strength constraints with the objective of achieving minimum weight for the SUGAR vehicle. VCCTEF could satisfy the above constraints without paying weight penalty while optimal control surface scheduling at the cruise condition could achieve an 11% drag reduction over the baseline SUGAR.

19. Aerodynamic Studies

19.1. Strut Inclination and Drag Effects

One of the challenges of MDO procedures applied to TBW is represented by a reasonable estimate of the strut contribution to the drag. This is the reason why references [339–341] addressed the problem using CFD solvers. Changing the angle the strut formed with the wing substantially changed the drag. In particular, an arch-shaped strut was found better (in terms of drag) with respect to a straight one (see Figure 45). Moreover, increasing the radius was beneficial. Finally, an equation was fitted for the drag estimate (to be used in MDO studies).

19.2. Aerodynamic Design of the Strut-wing Junction to Weaken the Shock

In 1999 the Virginia Tech group suggested a demonstration of the SBW concept through the RevCon (Revolutionary Concepts in Aeronautics) program funded by NASA. This proposal, in partnership with LMAS and the NASA Langley Research Center, suggested to demonstrate the SBW concept through the flight testing of a re-winged A7 aircraft (using the SBW design). References [190, 191] used CFD to carry out the aerodynamic design of the demonstrator. Aerodynamic studies on the transonic effects of the wing/pylon/strut junction were conducted and the flow physics explained, providing design improvement and guidelines. The initial design showed ($M = 0.85$) several shocks located in different areas. A strong shock was observed near the trailing edge of the wing upper surface (see Figure 46), and another one on the wing lower surface near the trailing edge of the pylon. The strut top surface also had a strong shock (not the bottom surface though). Similar problems related to compressibility effects were also found on the inboard surface of the pylon.

It was observed that the flow in the juncture was behaving like a nozzle. Thus, to overcome this problem, some design modifications (see Figure 47) were proposed:

- top surface halved (flat top surface, 4% thickness over chord) (see Design # 2 in Figure 47);
- flat top surface, rounded nose, added thickness to the bottom surface (8% thickness over chord) (see Design # 3 in Figure 47).

The solutions, especially the second one, were particularly effective and it was concluded that the shock could have been weakened or even eliminated by flattening the upper surface of the strut near the intersection.

19.3. CFD Analysis for Intersecting Struts

Reference [106] analyzed the interference drag produced by two struts intersecting at different angles. The aerodynamic model was based on RANS solver (with Spalart-Allmaras turbulence model). Fully turbulent flow was assumed. It was found that when the struts intersected at 90° there was an “unexpected” drag rise compared to smaller intersection angle cases (see Figure 48). This drag rise was caused by flow separation on both sides of the strut intersections. At lower intersection angles the flow tended to separate only on the acute angle side.

19.4. Aerodynamic Considerations in the Design of TBWs

References [158, 159] analyzed the two-jury TBW with a previously developed MDO capability at Virginia Tech [154]. Focus of the efforts was the aerodynamic design. The study considered both wing and fuselage aerodynamic improvements. One of the main findings regarded the sweep angle. It was claimed that reducing the sweep angle increased the laminar flow and this had positive effect on the drag; on the other hand, the same geometric modification of the wing increased the wave drag substantially. This was thought to be the reason for which in all studies a significant sweep angle was retrieved by the optimizer.

Additional potential benefits were also observed from other modifications such as the Goldschmied fuselage design (see Figure 49) and a tailless configuration. The latter eliminated the tail wave and friction drag with substantial fuel and weight reductions.

An interesting result was also the effect of the winglets on the total drag. It was concluded that winglets contribution to induced drag reduction was counterbalanced by the increase of friction drag due to the larger wetted area, thus, the total drag of the two configurations (with and without winglets) was similar.

19.5. Induced Drag of Several Layouts

Reference [337] showed the aerodynamic efficiency of various nonplanar systems as far as induced drag was concerned. For the SBW case, it was numerically calculated that when the distance (evaluated at the centerline) between the strut and the upper wing was 20% of the wingspan, the aerodynamic efficiency increased 4% with respect to traditional design (see Figure 50). For $h/b = 0.1$ (see Figure 50 for the definition of h/b) the upper wing was carrying 80% of the load. Some general statements regarding the advantages of SBW were presented:

“Given the very modest increase in predicted Oswald Efficiency of this configuration, it would appear to be favorable only in circumstances where its structural benefits in feasibility and weight outweigh its demerits overall wetted area. In fact, a non-lifting strut combined with an optimal non-planar main wing may prove to be advantageous in terms of overall system performance”.

As a side note, in the authors’ opinion the minimum induced drag studies of any wing system should be presented adopting the *optimal aerodynamic efficiency ratio* [90, 94, 96, 98] rather than the peak of *Oswald Efficiency*.

19.6. Aerodynamic Analysis within SUGAR

Reference [175] analyzed the Boeing SUGAR truss-braced wing from an aerodynamic point of view. In particular, *variable geometry raked wingtip novel control effector* (VGRWT/NCE) was investigated. The fully swept geometry is shown in Figure 51 whereas a sketch of the pivot concept is depicted in Figure 34. The VGRWT/NCE was justified as follows. Ideally, the wingspan should be maximized during take-off and landing. However, during transonic cruise the drag needs to be reduced with a swept wing. VGRWT/NCE was considered a compromise between these two needs: the wingtip is swept at an angle to achieve improvements in all flight areas. The large moments produced by the VGRWT/NCE tip were suggesting the application of such a device for wing roll control, gust load alleviation, and flutter suppression.

Regarding gust simulation and aeroelastic investigations, NASA Langley Research Center developed a CFD-based gust model for TBW [12]. In particular, a reduced order gust model was developed with the intent of using it in closed-loop aeroservoelastic design of a gust load alleviation control law. The reduced order model was obtained by using proper orthogonal decomposition combined with a convolution of the gust response. The focus of the analysis was a flight condition (Mach = 0.7, altitude of 19k ft) at which Boeing analyses showed the largest gust-induced wing bending moment.

Aerodynamic studies within the SUGAR program have also been conducted at NASA AMES. In particular, reference [344] proposed a conceptual vortex-lattice aerodynamic tool and an aerodynamic superposition approach (without including the aerodynamic interference effects occurring between components) aimed to have an efficient initial analysis capability for the MDO framework.

20. Supersonic Commercial Transport

Reference [314] reported the concept of SBW in the framework of *supersonic commercial transport* (see the extreme arrow wing concept [193], represented in an artistic view in Figure 52) with focus on Pfenninger's work [269] and emphasis on the importance of laminar flow on the wings. Regarding the extreme arrow concept, effort [45] explained the main benefits:

"This shape minimizes wave drag due to lift, increases aspect ratio and reduces wetted area and wing chord, thereby reducing wing Reynolds number and enhancing the payoff of suction laminar flow control."

Application of the *area rule* was discussed and shown. This was not the case for the previously seen studies on transonic SBWs, in which transonic area rule was not explicitly mentioned. Of course, such criterion is of foremost importance in the aerodynamic design of aircraft operating at regimes in which compressibility effects cannot be neglected.

21. Flexibility and Load Alleviation

References [140, 142] studied the flexibility of SBW and potential effects in relation to load alleviation: " ...depicts one major advantage of the strut-braced wing from the aeroelastic point of view: a chordwise offset of the strut attachment to the wing box produces a twist moment acting on the wing. By attaching the strut to the wing-box front spar instead of the wing elastic axis, this moment literally is twisting down the wing leading edge. As a result, even more load is shifted inboard, producing a much higher load alleviation effect than for a conventional wing."

The *passive load alleviation* was also discussed in the conference paper [139]. With reference to Figure 53, it was found that for the strut attached *at the elastic axis of the wing*, the SBW exhibited the same load alleviation behavior of the traditional wing. A chordwise offset of the strut-wing attachment produced a moment acting on the wing. By attaching the strut to the leading edge instead of the wing elastic axis (see Figure 53), this pitching moment twisted down the wing leading edge. A larger portion of load was then shifted inboard, producing a more effective load alleviation. The opposite happened for a strut-wing junction at the trailing edge: in that case the moment twisted the wing upward, thus increasing the aerodynamic loads on the outboard wing sections. The benefits of attaching the strut to the front spar were confirmed for the fuselage- and wing-mounted engines. In the case of tip-mounted engine there was a small weight penalty

due to the flexibility. This was attributed to the combination of larger inertia and smaller aerodynamic load due to the wash-out.

22. Other Research on Truss-Braced Wings

22.1. Investigations Carried out in China

Reference [358] addressed the TBW with a preliminary optimization study. The structural model was represented by an I-beam with variable cross sections along the span, whereas aerodynamics was modeled by a lifting line formulation. The advantages in terms of induced drag were emphasized.

22.2. Investigations Carried out in Europe

Reference [53] presented the preliminary work on SBW conducted within the ALBATROS project (ON-ERA). The chosen reference mission reflected the one of the Airbus A320 or the Boeing 737. The aeroelastic calculations (based on DLM) showed a static divergence problem.

Part IV

General Concepts and Technical Discussion on Aerodynamics, Structures and Aeroelasticity

The previous sections of this review addressed a large number of research works carried out by several institutions worldwide on Diamond Wings (mainly HALE and SensorCraft Design) and Strut- or Truss-Braced Wings. Different aspects were outlined regarding various aeronautical disciplines with particular emphasis on the uniqueness, difficulties and challenges relative to these configurations.

This part aims at augmenting the previous ones with a more in-depth discussion about theoretical concepts relative to aerodynamics, structures and aeroelastic stability properties of Joined Wings. Based on a vast literature on the subject, the crucial relevance of nonlinearities will be underlined, showing how a new paradigm is needed for the design of such configurations.

23. Aerodynamics

Major claims have been made on aerodynamic benefits of Joined Wings. Although true in principle, some distinctions needs to be made regarding the real advantages.

23.1. Potential Advantages in Terms of Induced Drag

Earlier works describing the aerodynamic performance of Joined Wings (Box Wings, actually) in terms of induced drag can be found back in the 20th century [272, 351]. Figure 54 shows a qualitative representation of the aerodynamic load achieving the optimum for the particular case in which the upper and lower wings are equally loaded. However, the joined-wing SensorCraft considered by the AFRL in the US is quite different than a Box Wing [29] (see also Figures 5 and 55).

In particular, the location of the joint is not at the tip of the wing and this limits the aerodynamic advantages: the circulation must be zero at the tip (as it happens in a traditional layout) with relatively large gradients and, thus, adverse effects on the induced drag. Moreover, the configuration discussed in reference [29] (and depicted for convenience in Figure 5) presents a relatively small *vertical aspect ratio* [89, 90, 94, 96, 98]. Thus, some claims about aerodynamic advantages (in terms of induced drag) need to

be carefully scaled back. However, it can be observed that a relatively high aspect ratio⁷ can reduce the induced drag, as it happens for typical HALE configurations.

Another relevant point is the uniqueness of the optimal aerodynamic load which minimizes the induced drag. On this regard, reference [103] reported an interesting discussion on the aerodynamic performance of closed systems:

“Some of the theoretical issues the Boeing team contended with were that the joined-wing optimum is not unique, and shifting of a constant load from rear wing to front should have an effect on pitching moment only, with no effect on induced drag”

In the authors’ opinion and experience (see references [89, 90, 94, 96–99]) what discussed above has solid theoretical ground when the system is closed (e.g., Box Wing). For the joined-wing configuration adopted in the SensorCraft model there is an outboard wing (see Figures 4 and 5) which makes the discussion about aerodynamic optimum more complex. In fact, in these portions of the wing system it is not possible to add a constant circulation without penalty (compared to the optimum) on induced drag: at the tips the circulation must be zero and there is then no margin for adding any nonzero constant circulation. However, it should be observed that the “diamond part” of the Joined Wing is a closed system. Thus, even if this has not been formally proven in the literature, the authors’ opinion is that the optimal aerodynamic load is not unique, as stated in reference [103].

23.2. Role of Wake Roll-up

When assessing the aerodynamic field with panel methods, noticeable differences in the aeroelastic response have been observed for different wake modeling approaches. With reference to efforts [64, 65], preliminary analyses on Joined Wings showed that aerodynamic loads at the tip of the wing were sensitive to the modeling; moreover, aeroelastic analyses showed large differences in predicted flutter speeds. Thus, it was speculated that, contributing the forces in the tip regions largely to the bending moment, the overall aeroelastic response was significantly affected by the redistribution.

24. Static Structural and Aeroelastic Stability

24.1. Buckling Eigenvalue Analysis or Nonlinear Response?

The unique layout of Joined Wings interested many scientists and engineers who were concerned with the *buckling instability* under certain conditions. In references [298, 300] *large displacements below the critical buckling eigenvalue* were found and it was then concluded that nonlinear analysis was necessary to correctly investigate the joined-wing SensorCraft response.

Although the importance of nonlinearities was correctly stressed, referring to the buckling eigenvalue is in the authors’ opinion not fully representative of the structural instability. In fact, the buckling load evaluated via eigenvalue analysis is often nonconservative and may miss the underlying physics. Indeed, the buckling eigenvector (the so-called buckling mode) is in general different than the shape corresponding to the actual instability (if present). A conceptual representation of these aspects is shown in Figure 56, describing the stability behavior of a joined-wing configuration subjected to pressure loads when geometrical height of the joint is modified (parametric study). Not only is the (real) critical load value lower than the one predicted with buckling eigenvalue, but, the modes are also completely different (for more details the reader is referred to reference [88]).

The possible ineffectiveness of eigenvalue buckling analysis for Joined Wings may be interpreted as a sign of relevant nonlinearities. On this regard, reference [27] stated that

“a HALE uninhabited air vehicle will have very flexible wings due to high aspect ratio for optimal L/D. Therefore, HALE concepts experience large deflections, large enough that the assumption of geometric linearity is violated”.

This may induce to discard the structural nonlinearities for small deflections of the wings. However, Joined

⁷The terms “aspect ratio” and “vertical aspect ratio” do not represent the same physical quantity for a given wing system.

Wings may have significant geometric nonlinearities even for relatively small displacements. This could be assessed if one attempts to use a reduced order model (for example with a basis of vibration modes) and tracks the nonlinear response. As shown in references [342, 343], adding modal derivatives in a reduced order model greatly improves the quality of the approximation since the very beginning of the load-displacement curve. In other words, nonlinearities in Joined Wings may be important and have relevant effects long before they are actually “evident” (i.e, when significant displacements occur). Thus, although references [202, 203] stated that the nonlinearities should be considered when the deformation is large enough, it is the authors’ opinion that focus needs to be shifted from “large enough displacements” to “relevant enough geometric nonlinearities”.

An interesting discussion of the structural instabilities of joined-wing SensorCraft can be found in references [274–277]. In particular, the importance of the wings’ vertical offset was demonstrated, as far as *buckling of the aft wing* was concerned. When there was no vertical offset, “panel buckling” was found. However, again, the buckling analysis was conducted via eigenvalue approach which, as previously discussed, presents limitations in assessing the actual instability of the system.

A fully nonlinear response analysis to assess stability of Joined Wings in a vast conceptual design space was performed in the same period (see references [61, 62, 88]). The so-called *snap-buckling* phenomenon was found for some configurations. That is, tracking the load-displacement curve, at a certain point (corresponding to a singular tangent stiffness matrix) the structure was not able to carry any infinitesimal load increment without assuming a not continuously adjacent deformation, and, de-facto, snapping. More on this will be explained in section 25. That scenario represented the “real” instability, although some other practical form of instability (not directly linked to a mathematical event like the singularity of the tangent matrix) may also arise.

The structural instability and its interpretation was also attempted in other studies conducted at the Air Force Research Lab. Reference [26] discussed the relevance of geometric nonlinear structures and proposed a possible leverage of nonlinearities in the design:

“...the buckling mode shape tends to unload the outboard (for washout). We are curious if this effect can be leveraged to produce an aeroelastically fail-safe joined-wing design”.

The concept was also discussed in reference [27] which emphasized that for some trim conditions the buckling mode shape was found to unload (washout) the outboard wingtip.

It is the authors’ opinion that what was proposed in these two references is indeed an interesting possibility for design improvements with respect to classical wings. However, as shown a decade later in reference [88], the buckling mode may actually be different than the true deformation at the instability point, see for example Figure 56. Thus, the concept presented in references [26, 27] would need to be supported by fully nonlinear investigations.

To the best of the authors’ knowledge, this idea for a fail-safe design was not pursued by the SensorCraft research group in subsequent works or by other researchers, but presents a potential for aeroelastic tailoring studies.

Eigenvalue analysis to detect buckling was also used in reference [16] and it was found that the *out-of-plane bending stiffness* of the front wing was the driving parameter, thus the decision to increase spar-cap thickness of about a 60% was made. References [61, 62, 88], featuring nonlinear analyses, showed that indeed the bending stiffness has a relevant effect on the stability properties. Actually, the bending stiffness ratio (between the two wings) was shown to provide relevant information on how to reduce the likelihood of having structural instabilities (these findings were of course directly linked to the particular joined-wing layout examined in those works, and for different configurations additional insights could be found).

Following the previous discussion regarding the buckling analysis, it is in the authors’ opinion that a fully nonlinear response study is required to assess where the structure needs to be actually stiffened (see reference [16]), since the buckling eigenvalue analysis may not provide complete information of the true nonlinear structural behavior.

In support of the above considerations, experimental studies, like those carried out in references [38–40], led to the conclusion that:

“the unique bend-twist couplings inherent in the structure require nonlinear analyses”.

24.2. Is the “Aft-wing Buckling” Representative? Is the Instability a Local or a Global Phenomenon?

In the literature on Joined Wings and in particular when the SensorCraft is discussed, the potential problem of *aft-wing buckling* due to the *compressive forces* that develop during the flight is emphasized. There is an implicit vision of the buckling as a *local* phenomenon, and an interpretation using Euler’s column analogy is often provided to explain the instability. The actual picture is much more complex and is now discussed in detail.

Here, and for the rest of the paper, with *local* instability the authors are referring to the approach in which the instability is studied and conceptually related to the aft-wing loading condition only, whereas the overconstrained nature of system would rather suggest to consider the lifting system as a whole.

Reference [67] investigated Joined Wings and presented some relevant results showing large displacements beyond a certain freestream velocity. A passage reads:

“For joined-wing aircraft, the first sign of failure may be in the buckling of the aft members as the structure is softened. Flutter and divergence may also become a problem in these members due to the reduction in structural frequency as they go into compression.”

and

“The tendency for buckling and divergence in the aft member is of major concern when trying to reduce the weight. The finding of rear-wing divergence to be more critical than flutter is counterintuitive since the aft wing is supported at the joint. This phenomenon seems to be associated with a reduction in structural stiffness due to in-plane compressive loads in the rear members.”

The focus is clearly on aft-wing buckling. Moreover, especially from this last statement, it may appear that the buckling instability is considered as different than the aeroelastic (true) instability (this will be discussed more in detail in section 24.3).

A subsequent work from the same group [68] shared the same vision of reference [208] regarding buckling, divergence, and flutter of Joined Wings. Moreover, there was a discussion about instability mode (probably that was referred to the deformed shape at instability) explaining how the forces transmitted to the aft wing changed. It may be argued that the observation did not entirely describe the real behavior of the Joined Wing, since, being the system overconstrained, the interaction between wings is mutual.

Different researchers (see reference [330]) presented exactly the same statement quoted above from effort [67]. The major role played by the compression of the aft wing was also outlined in the introductory part of reference [103]:

“The aft wing mainly resists the lifting bending moment and acts as a compression strut. This has the effect of reducing the wing structural material required to resist the bending moment caused by lift, but premature buckling is a concern due to axial compression of the aft wing”

Similar considerations can be found in reference [3] where the structural stability of the Boeing joined-wing SensorCraft was specifically addressed. In particular, it is possible to read the following statement:

“By joining the forward and aft wings of the SensorCraft, bending and torsion in the forward wing is resisted by axial stiffness of the aft wing and vice versa. This further advocates the critical loading condition as the upward gust, because by displacing the forward wings up and forward, axial compression are induced in the elevated aft wing. This creates a buckling critical condition through axial compression”.

While this statement is relatively intuitive, it attributes the buckling instability to the axial compression, whereas it has been shown in a conceptual study [62] that the bending moment transferred through the joint also plays an important role. This is not a conclusive interpretation because changing the geometry and stiffness distribution may dramatically modify the physical mechanism driving the instability. In any case, linear eigenvalue analysis and intuitive interpretations of the instability are insufficient to truly characterize the behavior of the system.

A different perspective on the “local” vs “global” views on the stability properties of Joined Wings was provided years later in the *enlightening contribution* [281], which presented a more clear interpretation of the instability characterizing the joined-wing SensorCraft. In particular, the mechanism leading to a possible instability was shown to be

“...a flattening of the overall configuration, rather than the previously observed buckling of the aft wing due to

compressive loads⁸...”.

Figure 57 qualitatively summarizes the concept expressed in reference [281]. Comparing that image with those presented in efforts [60, 62, 87, 88], the deformation of the configuration is closely resembling systems on the verge of snap-buckling, indicating possible analogies between the different cases.

The flattening of the SensorCraft reported in Figure 57 was also observed in reference [6] (research conducted at the Air Force Research Lab). However, reference [281] *was neither explicitly acknowledged nor cited*. Interesting enough, reference [6] also *did not acknowledge* other instability studies, performed via eigenvalue analysis, carried out in the same research institution and discussed previously in this review (see for example references [274–277, 298, 300]).

In the authors’ opinion, the appropriate interpretation of the instability should consider the Joined Wing as a whole, instead of focusing on the buckling of the aft member: such a “conceptual” subdivision of the system into parts can lead to misleading results, not taking into account the overconstrained nature of the system (enhanced when nonlinearities are relevant). A very eloquent example is shown in reference [62], in which, in order to completely overcome instability issues, it was necessary to reinforce the wing that was not experiencing compressive loads.

This fundamental point regarding the instability involves also other types of Joined Wings, such as the Truss and Strut-Braced Wings. In particular, references [146, 147] introduced an innovative design concept to specifically address the compression of the strut and the risk of buckling. The proposed configuration was actually more similar to other joined-wing concepts present in the literature [355]. The innovative solution was constituted by an arch-shaped strut (see Figure 24). The following statements can be found in reference [147] regarding this concept:

“However, instead of buckling under compression like a straight rigid strut, it simply acts like a spring and helps to relieve the bending load. In fact, it takes at least 180° of rotation to actually buckle the arch-shaped strut!”

and

“Additionally, the two struts complement each other by allowing one to be in tension when the other strut is likely to be in compression, thus alleviating the strut buckling problem.”

It is the authors’ opinion that the buckling of the strut arch-shaped should also be regarded with a global point of view as discussed for the joined-wing SensorCraft.

A more global view on the structural stability of Joined Wings could be deduced from references [38–40], in which an experimental set up for structural testing was discussed. It was stated that:

“Typically, a joined-wing design like this experiment is considered buckling critical, but the wing does not buckle in the way most people would perceive as buckling. In a typical beam, when the structure buckles, it can no longer handle an increase in load. In a Joined Wing, when the structure is undergoing its global buckling case or the bend-twist coupling, the beams are still resisting the load”.

This agrees with the findings of references [61, 62, 86–88] which investigated the instability with a fully nonlinear analysis. Moreover, it implicitly confirms that the interpretation of Euler’s column-like instability is “not the way to go” when Joined Wings are studied. As seen in previously discussed cases, despite the correct observations made in references [38–40] regarding the instability, reference [6] (which was also a research carried out in the AFRL at WPAFB) was neither acknowledged nor cited. Related and very significant Boeing’s contribution (reference [281]) was not cited either.

Reference [27] claimed that the *aft-wing buckling* was more critical than

“forward wing buckling for the most severe gust load. Hence, more material was needed to stiffen the aft wing”. The buckling was calculated via eigenvalue approach, which presents limitations as previously discussed (see Figure 56). Moreover, the system was conceptually represented by two parts, the aft and forward wings. The need to reinforce the aft wing should be proven with a more computationally demanding fully nonlinear analysis as a structure with stiffer parts could actually *promote* the snap-buckling (true nonlinear static instability). See reference [62] for more details on this and other counterintuitive behaviors of Joined Wings.

⁸The “local” point of view, following the analogy of Euler’s column subjected to compressive forces.

24.3. Structural or Aeroelastic Problem?

An aircraft is subjected to aeroelastic actions during its missions. Thus, the investigations should focus on aeroelastic instabilities and how to avoid them. However, analyses employing mechanical forces (often of a follower type) have been used to provide some qualitative indications [38–40, 86, 87, 183, 184]. Considering the particular issues encountered by Joined Wings (static structural instabilities discussed above), the temptation of using results obtained with structural analyses to characterize also the real aeroelastic behavior should be carefully meditated upon. In fact, the complex bending-torsion structural coupling (due to both geometry and aeroelastic tailoring [200]) and the high sensitiveness of the aerodynamic forces to the twist of cross sections may actually lead to completely different responses than those predicted by using mechanical loads. Attempts to link the structural buckling to the aeroelastic instabilities such as *divergence* (and, in some cases, *flutter*) are also methodologically questionable. Also, from a mathematical point of view this is conceptually incorrect: the aerodynamics completely changes the aeroelastic stiffness of the system (Joined Wing, in this case) and what *is* relatively prone to buckling under aerodynamic-like mechanical loads may actually become quite *far from being unstable* in an aeroelastic setting.

In the literature, several cases confirmed the “vision” described above. For example, in reference [86], in some cases snap-buckling phenomena were found when mechanical loads were considered; however, no associated instability was characterizing the aeroelastic system. In references [86, 87] the opposite situation was also found. A so-called “*snap-divergence*” was observed; for a certain speed, the system (aerodynamic + structural) tangent matrix was singular. On the contrary, when trying to simulate the aerodynamic actions with mechanical loads, no instability was found (for the same lift).

It needs to be remembered that in a true design dynamic aeroelastic instability assessment is mandatory since the snap-divergence may not even be reached (the flutter speed may be lower than the snap-divergence one).

An interpretation of the structural/aeroelastic instabilities is mentioned in the introduction of reference [330], where the compression of the aft member was directly linked to the potential problems represented by divergence and flutter. As discussed above, this kind of interpretations needs to be augmented with an aeroelastic study, which should emphasize the true complex interactions (the compression of the aft wing is in general accompanied with bending moment transfer [62], and this in some cases was shown to play a determinant role). Future studies may address this aspect.

The importance of conceptually addressing the aeroelastic instability is also evident after a careful examination of reference [266], in which one may find the following statements:

“This [the joined-wing] non-traditional design might induce coupling between buckling and aeroelastic instabilities”

and

“...global buckling and post-buckling response of major lifting surfaces, such as the aft portion of the joined-wing configuration, become coupled with potentially critical aeroelastic responses, such as flutter and divergence”,

which may induce interpretations for which information regarding structural buckling can be used when aerodynamics is included in the model. Another concept reported in reference [266] is the following:

“The current analysis uses static aeroelastic loads as prescribed static load distribution for input to the buckling analysis, but ignores any subsequent variations in the load distribution and the associated deflections that are caused interaction between the aerodynamics and the deflected structural shape. This is extremely difficult goal to achieve that will require an extensive modification of the analysis algorithm to facilitate iteration between NASTRAN and PANAIR. Because the aerodynamic loads are not updated during the solution of the nonlinear buckling eigenproblem, the analysis accounts only for geometric nonlinearity. A more complete analysis would need to update the tangent stiffness matrix, compute new deflections, adjust the aerodynamic loads, and iterate to convergence.”

This approach in which aeroelasticity and structural response are considered similar phenomena characterizes also other efforts. In work [201] nonlinear aeroelastic analysis as well as buckling effects were investigated by adapting a generalized direct simulation method with discrete time-domain state-space approach for transient response. By referring to reference [266], the following was stated:

“They indicated that the possibility of coupling between buckling and aeroelastic instabilities and stated the necessity of nonlinear buckling analysis including aeroelastic interaction”.

A relevant aeroelastic study of Joined Wings is represented by reference [68], in which an instability with a *simultaneous drop in load factor* and increase in displacement was observed (see Figure 58). From the presented speed-displacement response, it is not clear if the snap-divergence as defined in references [86, 87] manifested, although a practical instability is evident.

Further work towards the correct characterization of static aeroelastic instability is presented in references [178, 179]. The nonlinear response was not completely tracked and, thus, no complete indication on the postcritical instability properties was provided.

It is interesting now to recall the issues presented in section 24.1 regarding the use of “linear” buckling analysis (i.e., calculated as an eigenvalue problem). The discussion mainly considered mechanical loads, however, even if aeroelastic stability analyses were pursued, solutions obtained with the eigenvalue approach were shown not to be reliable. This is for example studied in references [86, 87], comparing classical divergence and snap-divergence, and in reference [64], in which classic and nonlinear flutter analyses were carried out. Prediction with classic approaches (linearization about reference configurations) were nonconservative; even linearizing about a deformed configuration at speeds close to the critical ones (snap-divergence, or real flutter) led to inaccurate results. These results further substantiate concepts and conclusions presented in section 24.1.

Some efforts studied aeroelastic dynamical cases as buckling problem (adopting thus an eigenvalue approach applied to a purely structural system). Gust is a dynamic load which needs to be addressed in the design [285, 288, 289] especially when highly-flexible configurations are considered [262]. In the case of joined-wing SensorCraft, several authors emphasized the importance of gust loading and consequent aeroelastic response from both computational and experimental points of view (see references [294, 312]). A technical question that may arise is, then, what the aircraft behavior would be, when gust is encountered during the flight (see reference [21]) with particular concern on its alleviation and/or possible aeroelastic instabilities. A study of stability properties due to dynamically-induced forces on the airplane structure is the work presented in reference [101], in which a *buckling calculation with the load induced by gust* was performed. The dynamic response was not tracked with a transient analysis in the time domain and actually a static eigenvalue analysis was preferred. As already underlined, such an approach can provide some indications, but the previously discussed limitations hold. Moreover, the true aerodynamic-structural coupling and dynamic effects need to be modeled for a representative analysis which reflects the response of the system under gust.

25. Discovering the Complex Scenario

The *static* aeroelastic/structural response is far more complex to just think of safely assessing stability properties with a buckling analysis via eigenvalue approach. Concepts like snap-buckling and snap-divergence are intrinsically tied with presence of bistable (or multistable) regions. In fact, following the postcritical static branch, what is observed is the presence of a stable part below the critical load, where with “critical” is intended the condition associated with the snap, see Figure 59. Limiting for now the discussion to the pure structural case, this means that for an interval of subcritical values of the load there is *bistability*.

Presence of bistable regions, however, can hardly be accepted in aeronautics. In fact, in such situations, a vanishing perturbation may theoretically induce the system to alternatively settle on one or the other equilibrium point (states *A* and *C* in Figure 59). To guarantee a safe design, the operative conditions need to be outside *multistable regions*; otherwise, it has to be demonstrated that no possible perturbation (encountered in the operative conditions) may trigger this *branch-jumping* (see references [59, 60] for an extensive treatise on this possible issue). This highlights the importance of knowing the boundaries of multistable regions. In the above example, the whole postcritical response needs to be tracked with a continuation method. It should be kept in mind that this process is costly and is prone to numerical failures (arc-length techniques can have convergence issues and back-tracking).

Some “pathological” issues are also possible, as shown in reference [60]. A detached equilibrium branch, called *isola*, may appear for certain combinations of parameters, see Figure 60. Multistability is naturally associated with its presence. However, *being completely detached from the main branch, the usual path-tracking method is not able to capture these regions*. On the contrary, one possibility is to use dynamic perturbations trying to settle to an equilibrium point on the *isola*, and, starting from it, track the response. This procedure, however, is very impractical, and cannot be easily automated.

Technically, from a dynamical system perspective, the snap point represents a saddle-node bifurcation in the load-displacement parameter space. Cases for which an *isola* detaches show a response in the load-displacement plane that has four saddle-nodes (called in some literature *mushroom-shape*). For a certain combination of a third parameter two of these saddles-nodes coalesce, and a branch is detached. Further increasing (or decreasing) this parameter the *isola* shrinks into a point (*isola center*).

When considering also dynamic aeroelastic phenomena, the scenario becomes more complex, as discussed in section 25.4.

25.1. Tracking the Whole Response in Nonfeasible Regions?

Before asking ourself how to bridge these findings with a complicated realistic scenario, it is worth to discuss about postcritical branch tracking. In fact, the configuration may experience tension levels above the yielding point, thus, continuing tracking the response seems to be a pure academic exercise. However, if this is pursued, some postcritical regions may be associated to lower level of load and to smaller tensions, within the yielding limit. This suggests that, in order to detect a bistable region, one should momentarily avoid to think about stress level during the tracking process.

It is possible that perturbations inducing a branch-jumping are always associated to material failure during the dynamic response. In such case, the limiting factor is not the bistability itself. However, knowing that at the same load an equilibrium state “far” from the initial one exists, may intuitively suggest that for ad hoc perturbations the transient response can be characterized by large stress/deformations.

25.2. Static Aeroelastic Case

Aeroelastic investigations applied to wind-tunnel-like models, as those reported in references [64, 65, 86, 87], showed snap-divergence. For the particular case under investigation, the bistable region was generally smaller, nevertheless, the same pathological issues discussed before apply (although now the load parameter is the flow speed). In particular, it is interesting to notice that a correct definition of the instability should focus on the *speed-displacement diagram*, instead of the *load-displacement* one. In fact, in the latter case, it may well happen that an increase in speed will dictate also an increase in total lift, even though an instability is observed. This is clearly shown in Figure 61 and reference [87], for which the configuration after snap-divergence is associated to a larger lift. In some other cases, see for example reference [68], the drop in lift was almost simultaneous with the large deformations. This led to identifying the instability with a simultaneous drop in load factor and an increase in the displacement.

These last observations further substantiate what expressly stated in section 24.3 on the importance of carefully avoid to transfer stability results of structural analysis to the real aeroelastic case. In particular, effort [87] showed a comparison between the aeroelastic and pure structural cases in which similar trends were observed for the applied load (either aerodynamic and structural) vs displacement curve. However, in the aeroelastic case, an instability (snap-divergence) occurred.

Trim of the aircraft needs also to be taken into account. In such a situation, definition and study of the (global) stability properties becomes more challenging, already from a conceptual point of view.

25.3. Reduced Complexity Models to Unveil the Response with Computational Efficiency

The above scenario has been outlined and demonstrated for models whose stiffness and mass distributions did not correspond to “realistic” ones [60, 62, 65, 87, 88]. The temptation to describe these results as an academic exercise may be reinforced by the fact that the same models were also not representing in detail (e.g., wingbox with spar, ribs, etc) a typical aeronautical structure.

Nevertheless, evidence is in support of the use of those simplified models. With reference to Figure 58 of this review paper and Figure 37 of effort [68], an (almost) snap can be observed. Actually that curve was not tracked with a continuation method, thus, the real snap and part of the postcritical branch were not recognized. Figure 34 of reference [68] depicts also the deformed shapes, showing how the instability had a global flavor rather than being a local (to the aft wing) phenomenon. These results were obtained with an aeroelastic analysis of a beam model based on a “realistic” stiffness distribution of a SensorCraft (the work was sponsored by an AFOSR grant), where with “realistic” one has to intend as derived by a detailed plausible model.

Although a well known and accepted approach is to synthesize the details, describing only an equivalent global level behavior, one may still argue that the above example suffers from lack of representation. In general this is a weak argument, however, it can be partially accepted here due to the exhibited strong sensitivity to the parameters. Thus, also small differences in the model, enhanced by the overconstrained nature of the system and inherent nonlinearities, can theoretically drive different responses. It is then conceptually relevant to discuss cases in which a more “realistic” approach was pursued by adopting very detailed models describing the typical features of wing structures, and referring to specific SensorCraft cases. Figure 7 of reference [298] clearly shows a *snap phenomenon*. The same can be stated about Figure 9 of work [179], obtained by a mechanical loading evaluated starting from reference aerodynamic analyses. The curve was not completely tracked. Moreover, experiments described in reference [281] show an instability at global level featuring a deformation (Figure 14 of reference [281] and Figure 57 of this review) which reproduces typical traits observed in the simplified models, stating that

“...the mechanism leading to a possible instability was a flattening of the overall configuration rather than the usual previously observed buckling of the aft wing due to compressive loads”.

These analyses carried out on “realistic” models give credit to the concepts gained on the less detailed ones, reinforcing the scenario outlined above, at least for very-deformable (e.g., HALE) type of aircraft. A more thorough discussion about possible applicability to small-displacement (like civil aircraft) cases can be found in reference [60].

25.4. Dynamic Aeroelasticity and Postflutter of Joined Wings

There are several points that characterize dynamic aeroelastic response of Joined Wings. One can notice that the complexity is exacerbated by the overconstrained nature of the layout: bending-torsion coupling strongly modifies the aerodynamic forces when the structure is deformed; moreover, the geometric nonlinearities play a major role especially for highly-deformable configurations. Low frequencies of the natural vibration modes may also contribute in complicating the whole scenario.

Airplanes are designed to be flutter-free in the entire flight envelope. However, understanding the theoretical mechanisms of the aeroelastic response even after the flutter point may provide relevant information; existence of multiple equilibrium states may pose a danger in case of perturbations induced, for example, by gusts.

25.4.1. Low frequency and rigid-body mode interaction: body-freedom and cantilever flutter

Flutter is often evaluated constraining the configuration in the space. In such case, only elastic vibration modes are considered in the analysis. Flutter evaluated with this method has been assessed as “cantilever”⁹ (see reference [353]). The underlying assumption is that the rigid-body modes (not included in the analysis) do not interact with the elastic ones.

Relatively low natural frequencies have been observed for the first vibration modes of Joined Wings. On this regard, the case of classical diamond-wing layout is discussed in references [281, 353]; values have been also presented for different architectures: SensorCraft [263], Box Wing (or PrandtlPlane) [105, 198, 353], and Truss-Braced Wing [22]. Thus, joined-wing configurations are potentially prone to have an interaction

⁹*Cantilever* refers specifically to the fact that the configuration is constrained; the reader should carefully discern between this use of the word cantilever and the one did in the section devoted to Strut- and Truss-Braced Wings, in which the word referred to a single wing architecture.

between the elastic and rigid-body modes [209, 257, 353]. An instability characterized by such interaction has been called in literature “body-freedom flutter”.

In reference [353] the importance of free-flying¹⁰ analysis was outlined, especially on optimized (and thus, weight efficient) configurations. It was also observed that the weight penalty resulting from the body-freedom flutter constraint was more pronounced when the Joined Wing was planar and the rear wing did not provide the out-of-plane stiffening to the configuration. Moreover, the body-freedom flutter speed was found to be lower than for the cantilever case.

References [56, 57] studied a box-wing layout and showed an increase in flutter speed as opposed to the relative cantilever analysis. This was the result of having a fuselage with pitching moment of inertia in an appropriate range; in the limit of larger values, the cantilever flutter was observed, with coalescence of the first and second elastic modes. In the lower limit, the critical instability was the body-freedom flutter, with coalescence of the pitching and first elastic modes. When the value was falling between the two limit behaviors, either the pitching-first elastic or the first-second elastic modes coalescence were postponed to higher speeds (eventually out of the flight envelope). This will be better outlined in section 40.

25.4.2. Postcritical dynamic aeroelastic analysis and limit cycle oscillations

The discussion focuses now on highly-deformable cantilever configurations presented in references [64, 65]. As it will be shown, different layouts of Joined Wing can have completely different dynamic aeroelastic responses.

Figure 62 shows the static aeroelastic response and four freestream speeds (Speed 1, 2, 3, and 4 respectively) chosen for the dynamic analysis (see Figure 63). One can also notice the snap-divergence below Speed 1. For each fixed freestream speed the angle of attack is slowly increased until it reaches the sought value (the time history of the nominal angle of attack is depicted in Figure 63). When simulations are carried out for larger speeds than the flutter one, then a steady state is not observed (this is not necessarily obvious, as it will be shown in the next example). Time histories suggest that the flutter speed lies in the Speed 1 – Speed 2 range, probably closer to Speed 2. In fact, the LCO observed at this speed has a very limited amplitude, indicating that the state is one immediately following a Hopf’s bifurcation. With a small increase in speed (Speed 3), the LCO has a larger amplitude; with a further increment of speed (Speed 4), the response does not seem to have any periodicity (an in-depth analysis is eventually needed to affirm and demonstrate that this last behavior is chaotic).

A very similar process is now repeated on a SensorCraft-like configuration. The extreme nonlinear aeroelastic static response presents a sequence of softening and stiffening, as shown in Figure 64. In the first stiffening region (for the wingtip), the deformation of the upper wing produces a bending moment transmitted directly to the lower wing, such that the tip of the wing does not experience any vertical displacement for a wide range of speed.

Results of the transient are presented in Figure 65. At Speed 1 a LCO develops; the trajectory described by the point on the junction is the usual wave-like response whereas, this does not hold for the wing’s tip. In fact, considering a period, during the ascending part the motion is temporary reversed and some higher frequency oscillations of smaller amplitude establish before continuing again the ascending motion. The descending motion does not show such a pattern.

If the speed is slightly increased to Speed 2, the same pattern is observed, however now the oscillation within the ascending motion increases its amplitude. It is natural then to repeat this process for higher speeds and investigate what happens: Speed 4 is considered. The response does not show any aeroelastic instability. This result is unexpected and underlines, once again, the difficulties inherent to the design of such a configuration. With the aid of Figure 66 this property is further demonstrated: starting from a stable situation, the speed is slowly decreased until a critical condition is reached. It can be appreciated that at Speed 3 (which is lower than Speed 4) the response immediately loses its stability (in the static sense).

¹⁰Among others, a real free-flying analysis should consider the trimmed aircraft and evaluated the modes in that deformed configuration. Here with free-flying it is intended an analysis in which rigid-body modes are considered.

25.4.3. Joined Wings: a dynamical system perspective

This section shows the complex picture relative to the aeroelastic response of highly-deformable Joined Wings described from a dynamical system perspective (see references [64, 65]). Different kinds of bifurcations are detected when tracing the *stability diagram*. The selected model is a boxplane-like Joined Wing (a wind tunnel-like model), set at 0° angle of attack; there are no aerodynamic forces (neglecting the drag) in the undeformed (basic) configuration, which is then an equilibrium (fixed point) configuration for all speeds. With reference to the bifurcation diagram of Figure 67, in which the vertical displacement of the tip of the lower wing is chosen as the characteristic variable, and the parameter is the flow speed, these configurations are represented by points on the ordinate.

If the freestream speed is increased V^{sd} is reached. This speed is associated with *saddle node bifurcations* occurring on branches far from the fundamental one. What happens is the inception of two fixed node points on each of the nonfundamental branches. That is, if the speed falls between V^{sd} and V^{bf} , there are *five possible equilibrium configurations*, and three of them are *stable*, see Figure 67. Thus, a so-called *tri-stability* is in place. With the aid of Figure 68, a speed in this range is chosen and the equilibrium points are represented with small circles, full (empty) if they are stable (unstable). Consequence of multistability have been already explored and discussed for joined-wing layouts (see also references [59, 60]). This property is demonstrated in Figure 69a by giving different vanishing perturbations in angle of attack, and observing that after the transient the configuration can settle to three different equilibrium states.

When speed approaches V^{bf} there is a bifurcation that leads to a change of stability of the main branch: the undeformed configuration becomes unstable. The typical phase-space diagram which is in the range $V^{\text{bf}} \div V^{\text{hb}}$ is depicted in Figure 68. There is a bistability, being the stable states on branch I and II. There are also two unstable poles, the first being on the undeformed configuration and the other one on branch II. Transients showing this behavior are represented in Figure 69b.

When the speed is increased, an Hopf's bifurcation (flutter) is found (speed V^{hb}). This bifurcation pertains to the branch II only. The fixed static solution becomes unstable, and a stable LCO is developed. The properties of the points on the other branches do not change. Thus, for a speed which is in the range $V^{\text{hb}} \div V^{\text{fb}}$, typical responses to perturbations are transients as depicted in Figure 69c.

The largest bifurcation speed found in this analysis is V^{fb} , for which a flip bifurcation (also called period doubling) occurs. For speeds slightly larger than V^{fb} , considering that the only other stable point lies on the branch I, there is still a bistability. This is shown also in Figure 69d. The existence of period doubling could be assessed noticing that, immediately after the bifurcation point, the period of the closed orbit doubles compared to the one of the LCO established at slightly lower speeds, as depicted in Figure 70.

When speed is further increased, the response associated with the branch detached from the period doubling bifurcation *seems to have a chaotical nature*, as shown in Figure 71. In-depth analyses are needed to confirm transition to chaos; the branch I stable fixed point is still present (Figure 67).

25.4.4. "Bad" limit cycle oscillation

The complexity of aeroelastic dynamic response is also emphasized in reference [21], where a so-called bad-LCO (subcritical bifurcation) was observed on a SensorCraft, triggered by a gust load. That is, an ad hoc perturbation triggered an aeroelastic dynamic instability at lower speeds than the "critical one".

Considering this rich scenario and the possibility of existence of multiple branches, highly-deformable Joined Wings may present some challenges for the FAA certification. This difficulty is perfectly summarized in reference [212], in which, regarding the Joined-Wing SensorCraft, the following statement can be found:

"Such vehicles could be designed and built using linear methods with unknown nonlinear phenomena awaiting discovery in flight test. This puts the entire program at risk, and leads to expensive redesign work when nonlinearity produces problems."

Figure 38: Medium-range aircraft: optimized TBW compared against optimized traditional layout as deduced from reference [218].

Figure 39: Artistic representation of the SBW model used in reference [333].

Figure 40: Artistic representation of the flutter speed as a function of the spanwise position of the strut junction at the wing as deduced from reference [333].

Figure 41: Effect of structural geometric nonlinearities on flutter and artistic representation of the modes participating in flutter, as deduced from reference [218]. Note that, differently than the herein shown values, in the original paper the reduction of flutter speed and frequency were assessed using an in-house capability for the linear case, and NASTRAN for the nonlinear one.

Objective function: <i>minimum fuel</i>						
Medium-range aircraft	Velocity (KEAS)			Frequency (Hz)		
	Linear	Nonlinear	% Change	Linear	Nonlinear	% Change
Optimized configuration without flutter constraint	372.60	355.30	-4.6%	3.25	3.04	-6.5%
Optimized configuration with flutter constraint	417.20	412.30	-1.2%	4.26	4.10	-3.8%

Objective function: <i>minimum fuel</i>						
Long-range aircraft	Velocity (KEAS)			Frequency (Hz)		
	Linear	Nonlinear	% Change	Linear	Nonlinear	% Change
Optimized configuration without flutter constraint	315.38	301.34	-4.5%	2.55	2.32	-8.2%
Optimized configuration with flutter constraint	377.30	393.22	-3.8%	3.46	3.34	-3.5%

Figure 42: Effect of structural geometric nonlinearities on flutter of optimized medium-range and long-range aircraft, as deduced from reference [218].

Figure 43: Artistic representation of the flutter modes. Note that the vibration frequencies are the ones corresponding to the ground vibration test (see reference [311]).

Figure 44: Artistic representation of the structural deformation of final VCCTEF at negative 1 *g* push-over condition, as deduced from reference [71].

Figure 45: Artistic representation of the strut-wing intersection as deduced from reference [339].

Figure 46: Main aerodynamic features of the strut/wing/pylon location (see reference [190]).

Figure 47: Artistic representation of the spanwise cross section near the pylon of three different designs that were created to reduce and eliminate the strong shock at the wing/pylon/strut intersection, as deduced from reference [190].

Figure 48: Artistic representation of the axial velocity contours near the intersection region for NACA64A005 at Mach number of 0.85, as deduced from reference [106].

Figure 49: Artistic representation of the Goldschmied apparatus as deduced from reference [159].

Figure 50: Artistic representation of the induced drag performance of a SBW as deduced from reference [337].

Figure 51: Artistic representation of the variable geometry raked wingtip novel control effector as deduced from reference [175].

Figure 52: Supersonic SBW: artistic representation of the strut-braced extreme arrow wing configuration as deduced from references [193, 314].

Figure 53: Artistic representation of the spanload distribution for the wing-mounted engine SBW in a 2.5 g maneuver, as deduced from reference [139].

Figure 54: A “rough sketch” of the optimal aerodynamic load of a Box Wing, as deduced from Figure 81 of reference [351].

Figure 55: Definition of vertical aspect ratio for Joined Wings.

Figure 56: Drawbacks of buckling calculation based on eigenvalue analysis: lower critical load level and different critical modes (see reference [88]).

Figure 57: Boeing SensorCraft: artistic representation of the elastic instability mechanism according to reference [281].

Figure 58: Artistic representation of the instability mechanism according to reference [68].

Figure 59: Typical snap response, bistable region. Conceptual representation of mono- and bistable regions on a dynamic system perspective. See also references [59, 60].

Figure 60: Static response showing an isola, i.e., a detached equilibrium branch.

The aeroelastic instability *cannot be seen* in the load-displacement diagram. The freestream velocity needs to be considered in the diagram

Figure 61: Conceptual comparison between aerodynamic and mechanical forces and static instability (see references [86, 87] for details).

Figure 62: Aeroelastic static response.

Figure 63: Time response and phase-space trajectory for different flow speeds. The angle of attack is increased linearly.

Figure 64: Aeroelastic static response of SensorCraft-like Joined Wing. Vertical displacements of tip and joint points are taken into consideration. The vanishing perturbation applied to excite the dynamic response is also shown.

Figure 65: Time response for SensorCraft-like Joined Wing configuration, at different flow speeds. Vertical displacement of both tip and joint points are considered.

Figure 66: Time response for SensorCraft-like configuration, when the speed is decreased from Speed 4 to Speed 3, and the angle of attack is maintained constant. Vertical displacements of the wingtip is considered.

Figure 67: Bifurcation diagram. Solid (dashed) lines represent stable (unstable) fixed points, full circles stand for stable limit cycle oscillations (the largest value is depicted) and the full complex star stand for stable bicyclic closed orbit (largest value is depicted in the graph).

Figure 68: Phase space at different speeds.

(a) Tristability. The system can settle down to static equilibrium on main branch, branch I or II.

(c) Bistability. Either the static solution on branch I or the limit cycle oscillation are approached after a transient.

Figure 69: Starting from the initial undeformed configuration different vanishing perturbations in angle attack are given, and the transient is tracked.

Figure 70: Time responses for speeds slightly higher and lower than flip bifurcation speed V^{fb} .

Figure 71: Time response when a vanishing perturbation in angle attack is given: the response does not show any periodicity.

25.5. Nonlinear Aerodynamic Effects

In the literature, little emphasis has been given to the effects of aerodynamic nonlinearities (due to compressibility effects) on the aeroelastic response of JWs. This is actually not surprising, as the computational and experimental efforts to carry out such studies are prohibitive for the typical needs of the early design phases. However, phenomena like *transonic flutter* need to be taken into account as they can strongly limit the flight envelope and turn the design into a noncompetitive one when compared to traditional configurations. This topic could be an interesting future research direction.

26. Stiffness, Deformability and Flexibility: Clarifications

26.1. Stiffness Vs Deformability: A Dichotomy?

In a large number of papers, some statements regarding the concepts of *stiffness* and *flexibility* of Joined Wings are reported and often they appear to be in contradiction. The possible confusion and misunderstanding rise from not clearly pointing out the ground of comparison when stiffness and flexibility are discussed.

It is true and very intuitive that, in Joined Wings having the aft wing connected to the front one inboard, front-wing deformation (in particular tip-displacement) is expected to be considerably lower as opposed to the front-wing-only corresponding configuration (this conceptual comparison is implicitly made assuming the same aerodynamic loading for the front wing). However, depending on the application, meaningful comparisons are usually carried out considering other criteria. In one of the pioneering efforts [304], the Joined Wing was lighter, and also the tip displacement was smaller compared to a traditional layout operating at the same lift (and overall weight) and drag. In the above design, the Joined Wing had smaller wingspan.

A comparison based on different paradigms (for example if drag has to be minimized) may give more deformable Joined Wings with consistently larger aspect ratios. In some other cases, there is no direct comparison with a traditional layout, but it is observed that the configuration is highly deformable just after stating that Joined Wings are stiffer. See for example references [52, 261].

Considering the above reported references, the reader should note that the meaning of “stiffer” needs to be assessed with a reference configuration and with precise indication of the parameters that are assumed to be identical (e.g., aspect ratio, wingspan) for both layouts.

26.2. Multidisciplinary Design Optimization and Flexibility

Imprecise statements about the use of an integrated approach in the early design stages due to nonnegligible flexibility of the system are often encountered. Sometimes, geometric structural nonlinearities are considered negligible because the deformations are quite close to typical values observed for large conventional aircraft [259]. Some key points need then to be addressed.

First, the need of an early integration of different disciplines originates from an inherent property shared by Joined Wings. In fact, due to the characteristic layout, relatively small modifications to the initial configuration to comply with constraints or to improve performances in one direction (for example aerodynamics), may actually have nonnegligible effects invalidating the whole design¹¹. This is *not necessarily related to large deformations*. The intimate connection between all the disciplines may induce “small modifications” to have amplified effects.

Second, if large deformations are present, then issues are related to nonlinearities which need to be properly addressed. Obviously, if nonlinearities are significant the above interconnection between different disciplines can be exacerbated.

Third, even for “small” deformations, nonlinearities may be important for Joined Wings (see references [212, 270, 342]).

As far as introducing aeroelastic investigations early in the design process the following comments apply. It is true that having very small natural frequencies [22, 105, 198, 263, 281, 353] evokes (although it is

¹¹Although true also for conventional aircraft, Joined Wings are much more sensitive to this property.

not a sufficient condition) the need of a flutter analysis considering also rigid-body modes (or, following a different terminology, free-flying models). And, for Joined Wings, also in non-highly-deformable cases (as, for example, the ones studied in references [105, 198]) low frequencies have been observed. This suggests only that flutter analyses should consider also the rigid-body motion. What, on the contrary, justifies early aeroelastic analyses is the joined-wing layout, requiring an integrated design approach *ab initio*.

27. Reduced Order Modeling applied to Joined Wings

27.1. The Role of Reduced Order Models

The preliminary phases of the design require fast and reliable tools. In fact, the design space is so large that exploring it using higher-fidelity and expensive tools is not a feasible option. On the other hand, previous sections have discussed how the use of fast lower-fidelity procedures may lead to unreliable results, due to nonnegligible nonlinearities.

A possible way to reduce computational costs and retain the dominant physical properties of a system is to use the so-called reduced order models (ROMS). The idea is to be able to predict the relevant response of the system by describing it with a reduced “basis”. The difficult part is to understand how the basis evolves as the system changes.

A good example outlining the issue for aeroelastic applications is the case of traditional frequency domain flutter analysis [4, 302], which adopts a set of mode shapes. These modes represent the basis. Usually, a relatively small number of modes is enough for a reliable prediction. However, if structural nonlinearities are relevant, the modes cannot be approximated as being constant. Prediction of their variation maintaining low computational costs is the challenging part of the method.

Success of ROM has been limited and the studies showed how geometrically nonlinear effects need to be retained for Joined Wings. This is outlined next.

27.2. Investigations Using Modally-Reduced Aerodynamics and Detailed Full Nonlinear Structural Model

Alternative approaches to deal with aeroelastic problems in which the geometrically nonlinear effects are the dominant physical aspects have been proposed [92, 93] for Joined Wings. The idea is to reduce the order of the aerodynamic model (classical modally-reduced aerodynamics based on the concept of generalized aerodynamic force matrix) but keep the structural nonlinearities at full order level; thus, the structural model is *not* reduced in order and, therefore, the difficulties inherent to the reduction are avoided. An advantage of such an approach [92] is in the possibility of using well established and reliable nonlinear structural codes (such as NASTRAN, ANSYS etc.) and linear unsteady modally reduced aerodynamics [303, 360] for new accurate descriptions of the aeroelastic behavior of Joined Wings.

References [92, 93] followed the above method employing an energy approach and the Least Square Method (LSM) technique.

27.3. Aeroelastic Investigations with Structural Reduced Order Model

27.3.1. Importance of geometric nonlinearities

The reduction of the structural model would greatly reduce the computational cost: the linear systems that have to be solved during the iterative process would involve a very small number of generalized coordinates with potentially large CPU time savings. Modal order reduction procedures for geometrically nonlinear structures (see references [166, 249, 250, 315, 324, 345, 346]) have been introduced based on mode shapes of the structure. A basis built by adopting structural tangent modes (which are calculated from the solution of a free vibration problem with the actual tangent stiffness matrix) is often enriched with the use of *higher order* modes (see references [166, 324, 345, 346]). The basic idea is to have a basis which takes into account the *variability* of the modes due to nonlinear effects. Results can be improved if the basis is updated during the evolution of the system.

In work [91] accuracy greatly improved when second order modes [345, 346] were considered for the structural model. Moreover, updating the modes was found to be more efficient than increasing their number, confirming the relevant structural nonlinearities of Joined Wing.

Based on the observation that a small number of modes, if frequently updated, can provide an excellent approximation even for challenging cases characterized by significant nonlinearities, reference [100] focused on a mathematical description of how the basis of tangent modes changes with the applied aerodynamic pressure. This was accomplished via Proper Orthogonal Decomposition (POD) up to an assigned aerodynamic speed V_{POD} . For each structural tangent mode the POD analysis provided a set of POD coefficients and modes (different than the tangent modes), and the variation of each tangent mode with the aerodynamic pressure was reconstructed. The procedure was not satisfactory for loading conditions relatively far from the range in which the POD basis was obtained.

27.3.2. Performances of several reduced order models

Figure 72: Description of the wind-tunnel-like joined-wing model and reduced order bases, as deduced from reference [343].

Additional studies in the direction of implementing an efficient ROM were presented in references [270, 342, 343]. Several strategies were investigated (see Figure 72). In particular, vibration modes, static modes, modal derivatives (MDs), Ritz vectors, and trial solution and correction vectors (TSCVs, see Figure 73) were analyzed. In all cases the nonlinear static analyses were conducted by recalculating the reduction basis (when needed) and augmenting the previous basis. This assured an excellent accuracy of the different analyzed

Figure 73: Definition of the TSCVs, as deduced from reference [343].

methods (the selected Joined Wing is shown in Figure 72). The most efficient basis was constituted by Ritz vectors and modal derivatives calculated at the beginning of the simulation when no load was applied as summarized in Figure 74. On this regard, an explanation of this computational performance was provided in reference [343]:

“The MDs always contain information about the non-linearities of the structure. It is then useful to include them in the basis when the load is zero, because both the vibration and static modes do not contain any non-linear

Figure 74: Analysis of the computational effectiveness of the bases, as deduced from reference [343].

information at that point. With the inclusion of MDs the error at the first load step is significantly reduced and the number of Newton-Raphson iterations in the beginning and the calculation time are reduced as well."

However, a reduction of 20% in respect of the full order solution is really an insufficient advantage for practical industrial applications. In fact, a successful ROM should reduce computational costs of orders of magnitude (referring to cases in which nonlinearities are important), if they are supposed to be integrated into a MDO.

The effectiveness of these models, especially for complex dynamic responses (see for example Figure 67), is still an open question and could be a relevant research direction for an effective preliminary design of Joined Wings.

27.3.3. Possible significance of geometric nonlinearities already for "small" deformations

The quote from reference [343] regarding the importance of the inclusion of MDs since the beginning (undeformed configuration) has a relevant implication. Giving MDs information about how the system is changing its properties, their early inclusion suggests that even for relatively small deformations, nonlinearities are not negligible. Of course, this may not be the case for all joined-wing configurations, however, the designer should be aware of this possibility and call into question the paradigm "small deformations are characterized by negligible nonlinearities". Thus, it is in the authors' opinion that the geometric nonlinearities may be important not necessarily only in the presence of very large displacements.

27.3.4. Conclusions about ROMs for Joined Wings

Summarizing, ROMs applied to Joined Wings showed several challenges and difficulties. Studies on this subject provided relevant indications:

- Geometric nonlinearities may need to be included even at "small" level of displacements. Inclusion of the modal derivatives at the beginning of the iterative process provides great benefits since the variability of the modes due to nonlinearity is effectively taken into account.
- A satisfactory reduced order model which is computationally efficient for aeroelastic investigations (with standard tools adopted by industry) has not been achieved yet.

Part V

Box-Wing Layout

This part of the paper is devoted to the review of the work carried out on box-wing layouts. Although differences among Joined Wings (the term is intended in its broader sense) can sometimes be a matter of interpretation, the authors will refer with Box Wings to those layouts featuring two wings of approximately the same span, connected at the tip through a vertical element (the joint), so that, in a front view, the wings arrangement looks like a box, see Figure 1.

It is important to understand that this architecture is the one proposed by Prandtl [272] as the Best Wing System, featuring the lowest level of induced drag among all possible configurations having the same

span and carrying the same lift. This concept inherently characterizes Box Wings, differently than Diamond Wings, where focus is more on combined aero-structural advantages.

It should be noted, however, that often it is hard to have a clear separation between a driving conceptual advantage and its application: although Box Wings are primarily characterized by having lower level of induced drag, they can be designed to transfer the prospective aerodynamic advantage to other fields (structures). For example, the same level of (induced) drag can be achieved with a smaller wingspan (relative to the monoplane case). Likewise, SBWs, which do primarily have a structural advantage, permit to have wings with higher aspect ratio, with consequent aerodynamic benefits.

The *PrandtlPlane* configuration, as designated by Frediani [109, 117], recovers the box-wing layout and focuses on how the design should be tuned to exploit all advantages, instead of just considering a new lifting system applied to a traditional concept.

The presentation of the work in this area is organized as follows. First, research carried out in the US in the 20th century is chronologically introduced. Then, efforts presented worldwide in the current century are considered, with a logical subdivision based on research groups. Work performed on *PrandtlPlane* has been dedicated a specific part, following this one on Box Wings. Finally, an ad hoc section summarizes all these efforts on Box Wings in a critical technical discussion.

The authors are aware of some preliminary research carried out by the Moscow Institute of Aviation in the '40s, in which the wings of a biplane were joined together, as briefly stated in [219]. However, they were not able to retrieve these documents (or translated copies). Despite the authors' best efforts to have a comprehensive and complete literature survey, there is the possibility of existence of additional work not discussed in this review. In such case, the authors apologize in advance for the missing information, and are happy to receive communications with the spirit of improving future efforts on the topic.

28. The Fifties in the US

One of the first works on Box Wings is described in the NASA report [47], summarizing wind tunnel investigations carried out at NASA Langley. Different subsonic and transonic (in two different wind tunnels) experiments were performed on two box-wing models (one very rough and a second one slightly more refined in terms of joint fillets) featuring an high front wing and a low rear wing, as shown in Figure 75.

Figure 75: Artistic representation of one of the models investigated in the NASA report [47].

A reference monoplane layout employing the same sweep angle (swept-back wing), same tapering and total aspect ratio was chosen. An observed positive feature was the nose pitch-down of the boxplane, as opposed to the classic abrupt pitch-up tendency typical of the reference swept-wing monoplane. This was attributed to different characteristics, mainly the downwash of the front wing. It was also observed a decrease of the static margin with Mach number, again, as opposed to the reference monoplane case. The lift-slope was considerably lower, whereas the drag coefficient was higher for the very rough model (which, other than having poor junctures, employed also inefficient airfoils).

Roll moment induced by sideslip angles (related to the aerodynamic derivative $C_{l\beta}$) was found not to change for different lift coefficients, suggesting that a dihedral fine-tuning would be enough to achieve the target response at almost all lift coefficient conditions.

For transonic regimes, a near equal drag coefficient (as for the monoplane) was observed. At zero lift, the boxplane drag coefficient was smaller, and this was attributed to the different transition location.

To better understand the lift-dependent drag contribution more tests were needed in the higher lift coefficient range, however, this was not possible since the refined boxplane model was built having an airfoil thickness ratio t/c of 4%, as opposed to 6% of the reference layout, because it was thought that the overconstrained nature would have increased the stiffness. Moreover, as pointed out in reference [356], there was no special structural design to counteract the tilted flexural axis. For this reason, only low-lift conditions were investigated.

A high pitch damping was expected (but not demonstrated), and controls on the root of the rear wing were suggested to provide effective longitudinal control. Since the tip region of rear wing had unseparated flow until angle of attack of 28° , it was expected that ailerons effectiveness would have been maintained to very high-lift coefficients. A final note was given about low-speed conditions: installment of high-lift devices on the front wing would have required positive elevator loads to trim, increasing thus the maximum trimmed lift. However, as suggested in reference [356], to pursue this condition a very careful design should to be carried out.

29. The Seventies in the US

29.1. Miranda's Patent

The first patent featuring a Box Wing was taken out in 1974 [232], for an application to military aircraft (although it was also stated that the general concepts could have been applied to civil transport aircraft too). The primary objective was the incorporation of Prandtl's [272] and Munk's [236] theories. However, other

Figure 76: Artistic representation of the boxplane shown in Miranda's patent [232].

objectives were pursued, as controllability and maneuvering with direct force control, reduction of trim drag, reduction of aerodynamic interference at transonic operation and wave drag at supersonic ones, exploitation of compact design, increased structural efficiency (stiffer solution), and increased roll-rate capability.

Detailed and intensive studies were claimed (but not directly cited). As far as control was concerned, mobile surfaces located on both wings were thought providing direct-control power, poststall control and high values of pitch control. Potentials advantages of the layout could be an increased ride quality and better pilot performance in low-level high-speed maneuvers, and its employment as a stable configuration for weapon platform.

Regarding transonic and supersonic performances, the smoother lift distribution (compared to the mono-plane case) was claimed to be, theoretically, favourable for transonic wave drag. However, a careful design needed to be pursued in the junction areas (wingtip-joint and wing-fin corners). The reduction in induced drag was demonstrated by wind tunnel experiments (probably this claim referred to Lockheed's internal report [231], cited also in reference [198]).

Structural rigidity was claimed, with benefits also on aeroelasticity for achieving an high roll rate, especially considering the reduced wingspan. Other claims concerned the compactness of the design, with various advantages, including for example the ability to be transported within a cargo aircraft.

29.2. Lockheed's Transonic Box-Wing Concept

Following a contract between Lockheed Georgia and NASA, report [198] was the first in-depth conceptual investigation of a Box Wing (and Joined Wing in general) featuring an aircraft synthesis and tackling also aeroelastic phenomena.

A very first baseline configuration was established, having the same aerodynamic efficiency, cruise Mach number (0.95), payload (400 passengers), range (5500 nm) and airport performances (10000 ft runway length) of a monoplane previously developed within the framework of NASA ATT (Advanced Transport Technology). A parametric study was conducted with the purpose of developing a minimum-weight configuration for the design mission.

The final configuration was featuring a slightly smaller ramp gross weight compared to the reference case. However, it had both symmetric and antisymmetric flutter (associated with low frequency modes) occurring well below the acceptable speed. Several modifications and also a gull-like configuration were developed in order to overcome the aeroelastic issues; however, all attempts were unsuccessful.

Foundations of the study were admittedly Prandtl's [272] and Munk's [236] works. Low-speed wind tunnel tests, performed by the same company, *confirmed* the theoretical results on induced drag. Other than induced drag reduction, also several other benefits of the configuration were expected, like later stall with nose-down pitching moment, avoidance of increase of dihedral effect with lift coefficient, no need for fuselage indentation for area ruling, lower wave drag in supersonic regime due to a greater longitudinal spread of the lift distribution, and noise reduction due to the improved lift-to-drag ratio during take-off and landing.

Considering that this effort was the first one organically studying an innovative box-wing layout, the following quote appears valuable, and gives insight into the difficulties that were encountered:

"Because of the complexity of the transonic biplane¹² configuration, proper assessment of airplane characteristics utilizing this concept can only be accomplished by use of rather elaborated analytical procedures for aerodynamic, structural loading and aeroelastic characteristics."

Figure 77: Artistic representation of the transonic boxplane concept of reference [198].

¹²The term "biplane" was used to indicate the Box Wing.

29.2.1. Aerodynamic Design

Aerodynamic design was based on a parametric study relying on in-house aerodynamic codes, calibrated on internal wind tunnel data [231] (showing that analytical results were reproduced for low-medium lift coefficient, for high-lift conditions separation at the fuselage-wing junction was noticed). Several wing planform parameters were considered in order to establish optimal neutral point, trim drag and cruise induced drag. Studies on sensitivity of induced drag to lift repartition showed that off-design conditions led to small penalties. Also neutral point and trim were carefully investigated, driving in part the sweep angle value of the wings. The optimal configuration needed a small wash-out on the front wing, and a small wash-in on the rear one.

High-lift design was carried out using the mutual interference between the wings, data from monoplane wind tunnel tests, and in-house correction formulas. It was suggested that sophisticated high-lift devices were required, as double-slotted trailing edge flap and leading edge slat of advanced design. As a general direction, the front wing needed to stall at slightly smaller angles of attack than the aft wing, obtaining a nose-down pitch and good recovery characteristics. Moreover, an high C_L for the rear wing at the front wing stall angle was sought, maximizing the total lift without creating adverse trim effects. Different configurations were designed in sequence to achieve satisfactory performances, finding that fully flapped front and aft wings (being the inner and outer parts used as roll and pitch control too) were necessary for obtaining the required maximum lift coefficient and trim the aircraft (see Figure 78).

Figure 78: Studied flap configurations [198].

Drag in the high-lift regime was also assessed. One of the problems was the fuselage interference. For the configuration with full-span flaps it was possible to achieve an improved load distribution, with lower drag levels.

29.2.2. Design Integration

No indentation of the fuselage was required to reduce the wave drag. The joints were also thought as a possible location for the wing tank. Engines were mounted on the front wing, smooth area distribution was guaranteed, ventral pod to store the landing gear (allocated thus in the fuselage) were designed.

Wings were tapered in the inner side, untapered on the outer side (structural studies indicated that this solution yielded the lowest TOGW). Specific details (very comprehensive) about wing, fin, joints, flap mechanism and materials were also given.

29.2.3. Structural Analysis

Continuous structures were used at the wingtip-joints and aft-wing root-vertical fin intersections. Regarding weight prediction it was well underlined that:

“Weights of the biplane¹³ wing structure could not be estimated with conventional weight-estimating techniques because of the redundant load paths and the unknown stiffness requirements for flutter prevention.”

For this reason it was developed a parametric weight equation by sizing a baseline configuration for static loads. Points for developing the equation were obtained varying the wing taper and wing bat area. Simplified finite element (beam) tool was set up to compute the load distribution, and iterations were performed to adjust the structural size and stresses (ultimate stresses were held to levels which provided adequate fracture and fatigue resistance). Structural sizing was completed for several configurations, see Figure 79. The “interim configuration” proved to be slightly lighter than the reference monoplane (even though it was never mentioned if nonsymmetric wingbox¹⁴ was considered, prerequisite for a weight-efficient structural solution according, for example, to references [84, 356]).

The design load criteria accounted for the flight envelope, considering a 1.5 safety factor coefficient. Variations of the CoG within 12-27% of the medium aerodynamic chord were studied. Aerodynamic loads were applied, and inertia relief was considered for all the parts of the aircraft. It was noted a bending inflection point on each wing where bending moment was zero.

Weight breakdown showed an heavier fuselage (whereas other independent works on Joined Wings suggested exactly the opposite, see section 39.2), “suspiciously low” wing weight and propulsion system of the same weight of the monoplane.

However, the selected final configuration, as well as modified versions, did not comply with flutter requirements. Symmetric and antisymmetric (and relative rigid-body motions) analyses were considered, and modified Theodorsen as well as DLM were employed for the aerodynamic part. Unfortunately, low frequency symmetric and antisymmetric modes became unstable at speeds considerably lower than the limit one (270 m/s). The antisymmetric mode was similar to the classic T-tail flutter, in which yawing, rolling and lateral translation with the aft wing associated with lateral bending and torsion of the vertical stabilizer. The symmetric mode was inherent to the box-wing layout: fuselage pitching about a point near the nose with out-of-phase bending of the wings and vertical stabilizer such that relative little motions occurred at the wingtips. According to the paper, “this mode resembles a highly modified, flexible, short-period mode”. It was also noted that, because of the low frequency, flutter could have been probably suppressed by an active control system.

Large part of the work was devoted to find a configuration still exploiting box-wing layout advantages and complying with flutter requirements. Relocation of large discrete masses was also pursued, however engine integration did not change the flutter speed to an adequate extent. Also a layout not featuring the typical box shape was considered, see Configuration 6 of Figure 79. Other than small penalties in the induced drag, also less flexible off-design conditions were observed. All this without significant benefits in flutter speed.

29.3. Further Wind Tunnel Investigations

In report [161] further investigations on aerodynamics of Box Wing were performed at NASA Langley facilities. Experimentations were not completely devoted to the box-wing layout, being different parts (front/rear wing, lateral joints) selectively removed. The box-wing layout was obtained from the tandem arrangement joining the wings at the tip by a flat plate (definitely not the appropriate way to fully exploit Box Wing aerodynamic advantages), see Figure 80. Wings were twisted and cambered, designed with a vortex lattice procedure for minimizing vortex drag at the design point ($M = 0.3$, $C_L = 0.35$, $C_M = 0$ and $Re \simeq 1.94 \cdot 10^6$). Thickness ratio was $t/c = 6\%$. Leading edge slats maneuvering devices were attached to the wings, capable to deflect up to 20° . A monoplane having the same wing surface and sweep angle was chosen as reference configuration.

¹³The term “biplane” was used to indicate the Box Wing.

¹⁴The reader should not confuse the words Box Wing and wingbox, referring the first to the aircraft layout, and the second to the typical wing internal structure.

Figure 79: Configurations considered in report [198]. Configuration 5 was the interim one.

Tests were performed on a large range of angles of attack (0° - 20°) and sideslip ($\pm 4^\circ$). For the complete configuration, separation occurred at 6° , stall was observed at 12° . Before stall, the pitching moment coefficient exhibited a linear behavior, whereas, after, a strong nose-down pitch moment developed.

As said, the joints were roughly designed, thus they had the effect of increasing the drag. It was stated that, with a better design, they would have contributed in reducing the drag.

Leading edge flap deflection delayed flow separation with an increase in lift at higher angle of attack accompanied by a decrease in induced drag. However, at maximum lift, the lift-to-drag ratio remained approximately the same.

Figure 80: Artistic representation of the boxplane used for subsonic wind tunnel tests of reference [161].

Full configuration directional stability and positive dihedral effect were registered throughout the test angles. The end plates contributed to a destabilizing effect in C_{n_β} .

30. The Eighties in the US

30.1. Wind Tunnel Experiment

The most relevant work about box-wing layout in the eighties is represented by report [130], later expanded and published in paper [131], in which aerodynamic numerical and experimental investigations were carried out. The effort was not thought as a direct study on a Box Wing, but more as a study on a

Figure 81: Artistic representation of the biplane-winglet model studied in references [130, 131].

biplane with the tip joined, see Figure 81. In fact, the starting configuration chosen as the reference one was an optimized biplane (taken from previous efforts done on the topic), and the research focused on how the aerodynamic properties were changing when joints (called in the paper winglets) were added. For these reasons, symmetric airfoils were chosen (although they are notoriously not optimal for biplane, for which curved airfoils are required for optimal performances, see the review [356]), lower Reynolds number effects ($5.1 \cdot 10^5$) were not corrected (registering thus high overall drag values). What was observed was a reduction of induced drag (up to 13%), which became dominant in an overall drag perspective for lift coefficients

higher than a critical one. It was also measured an increase of the lift coefficient for a given angle of attack, the maximum lift and the lift-slope coefficient.

Stall behavior was also found to be smooth (for both the biplane and the Box Wing) due to the non-simultaneous stall of the two wings, unless the relative twist (decalage) was such that the stall happened simultaneously.

In the attached flow regime, where the numerical predictions based on potential flow theory were adequate, there was good agreement with experimental results.

30.2. Summary of Previous Research

In the last years of the decade, Lange, after 14 years, revised the work previously carried out in reference [198] as an extension of the NASA/Industry Advanced Transport Technology (ATT) program completed in 1972. His contribution was part of the conference proceeding published in [332] and also in the paper [197].

31. The Nineties in the US

As for the previous decade, most of the works on Joined Wings were devoted to the diamond-like configurations (and SBWs too), being only few efforts specifically dedicated to Box Wings.

Among them, conference papers [8, 9] numerically analyzed (through a panel method with added viscous capabilities) different box-wing layouts, focusing in particular on wing gap, on the positive or negative stagger, and on the interconnection between the wings (joint). Positive stagger, i.e., front wing higher than aft wing, gave the best aerodynamic performances. Cant angle (angle between the joint and the wing in the front plane) and twist distribution were also studied, providing directions on how to optimize efficiency. Moreover, it was shown that an equally (or more) efficient (considering also viscous drag contribution) Box Wing had a smaller aspect ratio and wingspan compared to the reference single wing having same total wing surface.

32. Years 2000s

Starting from the new millennium, works on Joined Wings in the US mostly focused on SensorCraft-like configurations, see part I. Thus, besides sporadic investigations or internal company studies (see, for example, report [223] within the Environmentally Responsible Aviation project), journal and conference publications on Box Wings were very few. Recently, some interesting studies have been performed in Canada, all of them having an MDO flavor.

On the contrary, in Europe, thanks mainly to investigations carried out by Università di Pisa and academic and industrial partners on the so-called *PrandtlPlane*, research was flourishing. Besides these activities, few independent works on the same topic were also carried out, however, for a short window of time and with reduced impact in terms of results.

The PrandtlPlane will be reviewed in the next dedicated part.

32.1. Work Performed in the US

PhD thesis [200] partly tackled aeroelasticity of Box Wings, showing how body-freedom flutter could become critical: in such cases the common approach of studying flutter on the constrained model would not be adequate. Most of the work, however, was devoted to Diamond Wing-like configuration, see part I of this review and, specifically, section 9.1.

32.2. Work Performed in Canada

32.2.1. Aero-structural optimization

An aero-structural optimization was carried out in reference [170], following the work performed in effort [264]. The minimization problem was formulated as a single-level one. Gradient-free optimization method (ALPSO) was employed to avoid multiple local optima and the optimal solution was further verified with the SNOPT local optimization software. The ultimate maneuver condition was considered as the structurally sizing one, whereas the objective function to maximize was the range (through Breguet's formula). Four wing segments having six parameters each (dihedral, twist, taper, span, area, sweep) were considered. The structural optimization was concurrent with the aerodynamic one, forming an aero-structural optimization. The sizing was always performed on the jig shape.

Aerodynamic modeling was based on vortex lattice method, compressibility and viscous drags were taken into account through section airfoil data and approximated methods; a stall condition was also employed to avoid unrealistic predictions of lift. Structural modeling relied on an equivalent finite element beam; the thickness of the beam section was a parameter, and maximum stress was a constraint of the optimization process. Neither structural stability nor ad hoc distribution of material in the wingbox were pursued (this is indeed a very relevant design strategy for efficient joined-wing structures).

With a pure aerodynamic analysis (drag minimization) considering only induced drag, the box-wing shape was recovered. When compressibility effects were added, again the box-wing solution was found (in these preliminary assessments the chord and the wingspan were externally limited). If also viscous drag was considered, the C-shape was the optimal one. Finally, when the aero-structural analysis was performed (range maximization), classical wings with racks were found as optimal. Flight mechanics, i.e., trim and stability constraints, was not considered in the design.

Effort [169] explored effects of mission requirements on the design of nonplanar configurations. Similar framework of that presented above was employed. In the short-range mission a box-wing layout (having rear wing considerably smaller than front wing) was the "best" performer (smaller MTOW). It had smaller aerodynamic efficiency, but it was lighter than the reference conventional configuration. For a longer mission different layouts were chosen as optimal.

32.2.2. MDO and aircraft synthesis

Conference paper [7] augmented similar investigations (as those above) with flight mechanics constraints (stability and trim) evaluated both with analytical and computational (vortex lattice) means, but, on the other hand, used lower-fidelity methods (statistical formulae) to assess structural weight. Given the reference mission and a typical regional-jet size aircraft (Bombardier CRJ-200), the MTOW was chosen as cost function, various constraints set, and the optimization (based on same tools showed above) launched. The solution featured a box-wing configuration with smaller wingspan (see Figure 82), structural weight, and MTOW. The configuration was slightly less efficient in cruise than the reference monoplane. However, given the short mission, this had a small relative impact. It was noted how the lower induced drag of the layout could offer more substantial benefits during low-speed operations (higher lift coefficients). For this reason, spending large fractions in climb/descent phases (which were not considered in the optimization process) could be the ideal situation for Box Wings. In the same work it was stressed that wing weight prediction model has a prominent role in this kind of MDO efforts.

32.2.3. Higher-fidelity aerodynamics with flight mechanics constraints

Following a previous study on the aerodynamic optimization using Euler code [162], paper [126] explored unconventional (and box-wing) layout potentials. The recent paper [127] exploited better the advantages of the Box Wing within an optimization process considering trim and stability (but not structures), see Figure 83. One of the most relevant results was that, in agreement with theoretical arguments, reallocation of lift was offering a suitable way to satisfy the constraints without any (or with negligible when compared to a traditional layout) induced and wave drag penalties. Although it was already demonstrated by previous studies that induced drag would not have increased as consequence of trim and stability constraints (at least in high-speed conditions), in this paper also negative compressibility effects were under control to the same

Figure 82: Optimal box-wing layout for regional jet, superimposed to the reference CRJ-200 aircraft. Taken from reference [7].

Figure 83: Box Wing, aerodynamic field for nonoptimized (left) and optimized (right) layouts. Taken and adapted from reference [127].

extent as for traditional configurations, even if the Box Wing features critical areas as lateral joints and fin-rear wing connection.

32.3. Work Performed in Germany

Different works have been performed in Germany in the last decade. Among the institutions and industries performing studies on Box Wings there are Airbus (Germany) and Bauhaus Luftfahrt e.V. However, most of their research efforts on the topic were not published on scientific journals, and were distributed in form of internal documents, and thus, not available. Some efforts carried out by Hamburg University of Applied Sciences were presented at renowned aeronautical conferences, and are available in the relative proceedings.

32.3.1. Preliminary aerodynamic investigations

In efforts [181, 182] a preliminary aerodynamic design of a box-wing configuration was attempted (see Figure 84). Among others, effects of dihedral (anhedral) and taper ratio on induced drag were preliminary studied (showing results in agreement with those of works [96, 98]).

Influence of the cant angle was also assessed, with the result that the most favorable situation had the joint departing externally from the wing: in fact, in such a situation wingspan was increasing (see results of [90, 96, 98]).

After this initial assessment, a genetic algorithm was employed to sort out the optimal (in a pure induced drag sense) configuration given a vertical aspect ratio, a wingspan, and a design lift. It was found that the absolute minimum was attained for a value of the parameters that guaranteed a minimum when being the only parameters in an associated optimization problem.

For a higher level of fidelity, an Euler code was then employed. In the low subsonic case the advantages were partially confirmed ($M = 0.3$). To have a complete exploitation a more refined twist description was needed in order to better reproduce the optimal lift-span distribution. In the transonic regime ($M = 0.78$) shock wave developed in the lateral joint areas. A need for a local optimized design was clear, as well as an appropriate selection of the airfoils.

Figure 84: Top: Box Wing studied in reference [182]. Bottom: family of Box Wings, as shown in effort [306].

A final very conceptual assessment of the potentials of Box Wing in three different scenarios, namely single aisle aircraft, long endurance aircraft and very large aircraft, was done suggesting that the latter case is where the configuration potentials may be better exploited.

32.3.2. Aircraft design perspective

In reference [306] the fundamental design perspectives of a medium-range Box Wing were discussed and its performances were compared to the ones of an Airbus A320. Very preliminary and low-fidelity methods (handbook) characterized the investigations. Low-speed design, not without reason, was assessed as a problematic one. Interesting studies about the fuel capacity, and the possibility of creating a family of airplanes (see Figure 84) were also taken into consideration. Finally, problems regarding engine integration, and landing gear positioning were noted. Overall, some prospective advantages over the traditional configuration were found.

Paper [48] continued the previous conceptual design effort investigating more in-depth the flight mechanic/dynamic properties. The configuration was preliminary designed with only the aft wing having trimming capabilities, whereas both the wings were equipped with high-lift devices (Fowler flaps). In the paper, moments of inertia were evaluated through handbook methods. During the investigation, difficulties were underlined about fine tuning parameters (for trim purposes) since modifications in one direction were not possible without affecting other disciplines to a nonnegligible extent. For the aerodynamic calculations

and part of the aerodynamic derivatives a vortex lattice method was used, whereas for the dot derivatives the *lag-of-downwash* method was considered. Moreover, the tool SDSA (Simulation and Dynamic Stability Analyser, part of the CEASIOM suite¹⁵) was employed for evaluation of the *flying qualities*. Stability of longitudinal and lateral flight dynamics was assessed according to MIL-F-8785C and the Cooper-Harper rating scale, showing a good behavior, especially for heights not exceeding 12000 meters. Among the dynamic modes, the ones more prone to problems were the *short period* (level 2) and *roll subsidence* (level 3).

As a final step, the *handling qualities* were assessed with the software JSBSim (engine of the flight simulator FlightGear) and Datcom+, on three typical nominal conditions: cruise, landing and take-off. The judgement of a pilot was always reported, in relation to the Cooper-Harper Rating scale. It was finally possible, following the pilot's inputs, to comply with regulations without changing the basics design, and acting only with small modifications. The investigations were carried out on the wing system without considering fuselage effects.

In effort [307] a study on the conflicting requirements for aerodynamic efficiency and longitudinal stability was presented. However, the underlying assumption was extrapolated from equations of reference [272] valid for biplanes only, and implying that the optimal condition was associated with an equal repartition of the lift between the wings. With this hypothesis a conceptual penalty was introduced, especially considering that for a Box Wing reallocation of lift between the wings (in an optimal way) does not change the induced drag [96, 98]. For this reason, it was found a 4% increase of the induced drag (for a vertical aspect ratio $V = 0.2$, see Figure 55 for the definition of V) when the lift ratio of the front-to-rear wing was 2. For stability and trim purposes maintaining an appropriate maneuverability, and considering also other constraints, the found lift ratio was 1.74. However even larger values were necessary if a larger CoG envelope was sought.

Alternative ways of attaining stability (appropriate twisting to have some unloaded parts, special airfoils) were considered impractical or not convenient, other (surface at the end of the fuselage) looked promising. The paper also underlined that a compact fuselage (typical of the design) helped in minimizing the CoG shift, and thus, relaxing trim and stability constraints.

32.4. Work Performed in England

Only few researches were conducted in England, the most relevant being carried out by Cranfield University. In paper [172] (based on the PhD thesis [171]), the authors introduced a wing mass estimation correction for Box Wings, studied effects of the lateral joint fixativity and its inclination. Moreover, they developed an ad hoc novel MDO methodology, investigated stability and control, and discussed economic aspects. Finally, they applied the design process to a medium-range (in the same class of a Boeing 767-200), 270 single-class passenger Box Wing, with the following design requirements: range of 4000 nm at Mach 0.8, cruise altitude of 36000 ft, maximum take-off distance 2500 meters (see Figure 85).

To evaluate the wingbox weight, a handbook formula was calibrated for Box Wings, using some FEM analyses (carried out considering a symmetric wingbox¹⁶), see also reference [173]. More in detail, the algorithm was based on an empirical formula valid for traditional configurations, and one parameter was calibrated in order to have a weight estimation of the front wing and aft wing, separately.

One section of the effort [171] was devoted to the study of the joint (called in the paper tip fin) fixativity, suggesting that rigid joints were the best ones to minimize the out-of-plane moment on the wings, at the price of creating larger stresses on the joint. Effects of joint inclination were also examined, especially in reference [174], see also Figure 85. Results showed significant changes in torsional dragwise bending moments and shear forces, whereas out-of-plane bending moments and shear forces were not significantly affected. Being torsion and shear forces not the sizing stresses, the mass of the torsion box was not significantly changing with the inclination of the joint.

Final comparisons were given against same traditional configurations within the MDO framework. Box Wing had smaller MTOW (for a fixed mission) and smaller direct operating costs (DOCs). The

¹⁵It is interesting to notice that the components of the suite were used outside the framework since the architecture of the Box Wing was not easily handled by the program.

¹⁶And thus, giving a penalizing estimate of the structural weight.

Figure 85: Top left: studies on the inclination of the joint, adapted from reference [174]. Center/bottom: final optimized version of a Box Wing, from reference [172].

advantages on DOCs would have been more significant with higher fuel prices. The wingspan was smaller, making the design suitable for large long-range applications. A further interesting point was that field performances were better than the ones of the reference traditional configuration (in terms of take-off and landing length). Aeroelastic studies were suggested, also considering the nonlinear regime.

32.5. Work Performed in Spain

In publication [10], carried out at Universidad Politcnica de Madrid, an experimental campaign was undertaken to assess the comparative performances of box-wing layouts (the paper did not provide indications on the vertical dimension of lateral joints; in the picture, they look relatively short) when sweep angle was changed. The baseline model was an UAV (*Dara Aviation D-1*, see Figure 86). Eleven different configurations were tested, global force and moment coefficients in the longitudinal plane measured for two different Reynolds numbers (both in the low region, $7 \cdot 10^4$ and $14 \cdot 10^4$, respectively). The test showed that the best configurations in terms of maximum C_L and higher efficiency had the classical low front-wing and high aft-wing solution, featuring the two wings opposite sweep angles. Thanks to visualization techniques, the flow was shown to stall later on both wings for this arrangement. This result is exactly the opposite to those found by numerical investigations in references [9, 219, 225].

In reference [225] a parametric study on the aerodynamic performances of Box Wings was carried out by means of a VLM code when different parameters (like wings gap, stagger, decalage, aspect ratio, and area ratio) were varied. Some discordant results were found when compared to the ones presented above [10]. Generally it was observed a positive stagger (lower wing being also the rear one) to give better performances.

In reference [11] further studies were carried out, focusing on two-dimensional aspects, and performing, again, a sensitivity analysis to some geometrical parameters.

32.6. Work Performed in Poland

In the nineties performances of a Joined Wing were assessed in a wind tunnel [128], and it was found that testing the same configuration upside down gave better results in terms of aerodynamic efficiency. Later, in

Figure 86: Left: experimental wind tunnel model of Dara Aviation D-1, from reference [10]. UAV box-wing model, adapted from work [11].

the engineering note [219], the above concept was recovered and applied to a small experimental Box Wing; stagger was changed and results investigated by means of a VLM code and method known in the literature (for an estimate of the total drag). Also different parameters were consequently changed, with fixed values of the previous ones, in the following order: sweep angle, vertical gap, wing aspect ratio, wing area ratio and dihedral.

In reference [129] a project of UAV box-wing flight demonstrator (see Figure 87) was presented. A ducted fan was placed at the extreme end, on the axis of the fuselage. Elevator were placed on the aft wing, flaps on the front one. Numerical aerodynamic investigations and wind tunnel tests were also carried out.

Figure 87: UAV Box Wing studied in reference [129].

Part VI

PrandtlPlane

33. Patents

Several US/EU (and also German and Italian) patents [109–112] were taken out by Frediani in the last years of the nineties and first decade of the 21th century. With the name *PrandtlPlane* he wanted to

honor the German aerodynamicist first proposing the *Best Wing System* (BWS) [272], on which the aircraft concept was relying. Although Box Wings have been studied in the seventies, Frediani strongly focused on the aerodynamic advantages trying first an application to a large dimension aircraft (MTOW larger than 400 tons). The novelty in respect to previous work was also in the different level of integration: a design to pursue the potential advantages needed to be different also in the fuselage layout (both inside - multideck arrangement - and outside - horizontally larger section). With latter patents, e.g. [112], the concept was extended to a wide range of aircraft, from very large to very light designs. The rear-wing connection with the fuselage was selected to be a double fin one (instead of the original direct fuselage-wing junction) in order not to deteriorate the aerodynamics in that region (which could have led to flight mechanics instabilities) and also to give a more robust design against aeroelastic problems. Work conducted by Frediani's group, at

Figure 88: Artistic representation of two possible PrandtlPlane configurations. Right picture is a rearrangement from patent [109], left one from patent [112].

the Aerospace Engineering Department of Università di Pisa, and partner universities on the PrandtlPlane is summarized in this part.

34. PrandtlPlane: General Concept and Vision

Article [117] represents a milestone as a review paper on the PrandtlPlane configuration, summarizing motivations, possible applications and experience gained in more than a decade of studies on the topic.

A need for a more sustainable aviation, enhanced by the expected increase in air traffic, was the driving reason for interest towards innovative aircraft. Documents as Vision 2020 and Vision 2050 (see reference [2]) set very ambitious goals concerning quality and affordability, safety, environment, efficiency of air transport system, and security. In particular, cut of 30% of DOCs while increasing safety level, a drastic cut (larger than 50%) of noxious emissions and perceived external noise are indicated among the objectives (defined in reference [2] as *Sustainable Growth* concept). These goals are even more challenging to be achieved if one considers that air traffic is expected to increase. An in-depth analysis of challenges introduced by the above documents is given in effort [113].

According to reference [117], the history of aviation shows a decrease of costs by a factor of three in the second part of the 20th century. One approach to reduce the operative costs is to increase size or capacity, strategy that has culminated with the Airbus A380 (capable of hosting 700-800 passengers) whose dimensions almost reach the 80×80-meter value, upper limit for compatibility with airport infrastructures.

Improvements in *aerodynamics* seem to be then the most impacting ones on fuel efficiency increase, pollution and noise emissions reduction. Total drag is dominated by friction and induced drag; whereas studies on reducing the first source (e.g., boundary layer ingestion, turbulent flow control) can approximately apply to every configuration, the induced drag is related to the lift distribution. Its share of the total drag (generally in the 40 – 45% range) can reach the 80 – 90% value during take-off. It is also true that on current configurations the induced drag is so optimized, that, without radical changes, significant gains are probably not possible.

34.1. Innovative Configurations

Within the above scenario, a different number of layouts have been proposed and studied. Concepts as Oblique Flying Wing, Blended Wing Body, C-Wing, Joined Wings (in its general meaning, including thus Diamond Wings, Strut- and Truss-Braced Wings, Box Wings/PrandtlPlane) are possible alternatives capable, in theory, to ameliorate current aircraft efficiency and take a step towards the goals set in the *Vision* documents [2]. Comparative general analyses of some of these configurations can be found in the open literature; in references [113, 117, 123] a discussion is briefly given in that sense, from the PrandtlPlane point of view.

It is straightforward to understand that, within space limitations, a concept like the BWS perfectly fits the needs: given a target lift and fixing the wingspan, a box-layout can be optimized to show the lowest possible level of induced drag.

Later, some authors [90, 96, 98, 195] demonstrated that the induced drag of a C-Wing could be almost as low as the one relative to a Box Wing. However, design of an aircraft needs to take into account different disciplines, and cannot be only based on aerodynamics. In this specific case, it might be intuitively stated that a closed system is, in comparison, much stiffer and, hopefully, less prone to structural and aeroelastic issues.

34.2. PrandtlPlane in Short: Advantages

This section briefly describes the possible advantages of a PrandtlPlane configuration. Some of them are inherited from its joined-wing nature, some are particular to the BWS, and others are just characteristic of the specific layout and concept. References [113, 117, 118, 123] give an overview of these advantages. The aim of this section is only to show them without talking about disadvantages, limitations and open questions: this will be pursued in part VII, in which an in-depth technical discussion is given based on literature results pertaining to box-wing layout, and also based on critical considerations by the authors. This automatically clarifies the extent to which some advantages can be exploited, underlines the “grey-areas” and fairly contributes to a better understanding of the validity of this aircraft concept.

34.2.1. Aerodynamics

BWS concept is the main driver, capable of reducing the induced drag up to 30% (in respect to the corresponding monoplane case) for vertical aspect ratios (ratio of the vertical gap to the wingspan) within “reasonable” values. Although Prandtl’s concepts was developed on a system without sweep angle, Munk’s theorem extended the validity of these results to general swept-wing cases, thanks to the so-called *Stagger Theorem*.

As discussed later, the above considerations hold for a rigid wake, whereas when its real shape is considered, the actual induced drag can even be lower.

34.2.2. Flight Mechanics/Dynamics

The characteristic architecture enables a wide variety of options for the control system. In particular, direct lift or pure pitch control can be achieved with an appropriate design. These options can increase safety, especially when operating close to the ground. Pitch damping is also large, eventually favoring an overdamped short period mode, providing a higher quality flight experience, especially in turbulent regimes. At the same time, pitch control is very efficient due to the long distance between front and rear elevator (in case elevators are present on both front and aft wings).

With an appropriate design of the fuel tank it is possible to reduce variations of the center of gravity, and thus design for a single flight condition.

On the lateral-directional plane, vertical (lateral) joints and, eventually, twin fins (which seem mandatory for solving or reducing flutter problems in large aircraft) offer to numerous options for fine-tuning the static and dynamic stability properties.

34.2.3. Structures

Fuselage can be thought as a beam, which is now doubly supported: with an appropriate longitudinal positioning of the wing the maximum bending moment can be reduced. When twin fins are required the fuselage needs to be horizontally enlarged. An appropriate design can turn this particular layout as more spacious and efficient.

The overconstrained nature of the system makes the structure stiffer, reducing structural and aeroelastic problems (when compared to a similar design without joints or a closure, as the C-Wing configuration). Moreover, it allows an easy exploitation of “Damage Tolerant” structures.

As far as aeroelasticity is concerned, the front wing counteracts the rear-wing unstable tendency (divergence), whereas flutter can be counteracted with double fin solutions.

34.2.4. Low-speed regime

With a smart design of high-lift devices, it is theoretically possible to achieve trimmed conditions with both wings producing lift, and having a considerable lower induced drag compared to the monoplane case. This could have direct impact on the weight, since engines are dimensioned mainly by low-speed constraints.

34.2.5. Operational aspects

In some designs, the front wing can cross the fuselage under the cargo bay, providing a continuous cargo compartment with enhanced capacity, and possible improvements in loading and unloading operations.

34.2.6. Engine integration

Engine integration is facilitated by several options provided by the architecture, which also favors the employment of different class of engines. Large open rotors can be ideally mounted on the upper wing (this is not possible on a conventional aircraft with a low wing), providing the necessary distance to the ground. Concepts like *distributed thrust*, using smaller and more efficient units, can naturally be applied to the present layout.

35. Different Applications of the PrandtlPlane Concept

The PrandtlPlane concept has been studied and applied to different configurations, demonstrating its versatility. Some of these applications are briefly summarized below, with reference to specific literature work.

35.1. Very Large Aircraft

Considering the infrastructural constraints, and the need to cut down direct operative costs increasing aircraft capacity, PrandtlPlane concept was originally conceived for very large aircraft [109].

35.1.1. Five Italian Universities project

In conference paper [118] results of a two year project (2000-2001) co-financed by the Italian Ministry of University were summarized. The research team composed of universities was led by the Aerospace Engineering Department of Università di Pisa. The joint effort continued officially until January 2003, although later further collaborative work was carried out. The most relevant results were manifold.

First, ad hoc tools for analyses were created: computer codes for the MDO, for parametric aerodynamic and structural design, and for grid generation (fine-tuned for the typical layout). In the conference paper [119] the importance of having a fast parametric tool for modeling the aerodynamic surface was stressed. This convinced the team to develop a solid modeling tool based on NURBS [125] (continued later in some master thesis works [55, 265, 295] and also published in [63]), capable of efficiently creating a surface grid, and of exporting the geometry in IGES format for easier integration with CFD analysis tools. Within the joint effort [118] paper [18] describes application of BEM (integrated with viscous boundary layer method) for aerodynamic design of the PrandtlPlane (results of paper [131] were reproduced). The assumption of flat vortical wake used for traditional configuration was stated not to be justified for the box-wing

layout. Results were indicating an increase in efficiency when wake roll-up was taken into consideration. An interesting discussion about mathematical issues regarding the multiconnected domain typical of the configuration was provided. Later, in work [234] an in-house MDO/CD (Multi Disciplinary Optimization for Conceptual Design) framework was applied to the PrandtlPlane concept.

An aerodynamic design with flight mechanic constraints was pursued on a very large configuration (600 passengers, 78-meter wingspan, $M = 0.85$), showing how the original layout with the rear/upper wing connected directly on the fuselage had serious problems related to the transonic aerodynamics, see Figure 89. Moreover, it was not possible to retain stability of flight having the wings equally sharing the overall lift,

Figure 89: Very large aircraft studied in the Five Italian Universities project. Top: initial design showing aerodynamic issues. Bottom: alternative configuration with twin fins. Pictures are taken from reference [119].

and locally refine the design to reduce interference problems. This led to an arrangement with two fins, not perfectly vertical but slightly pointing outward. This choice was also dictated by aeroelastic reasons, and was significantly increasing the aerodynamic efficiency of the rear wing (making it higher than the corresponding central section of the front wing). It was finally possible to achieve equal repartition and stability. It is worth noting that the fuselage was larger (no need of an high fuselage to provide a large height-to-width ratio of the wing system for reducing the induced drag), also with the aim of providing sufficient distance between the roots of the fins for a more efficient *bracing* action. Integration of a structural code was suggesting a reduction of the wingspan with large benefits on the weight, showing that a real design concurrently considering all the disciplines (something that was achieved in successive collaborations, see below) was needed.

Within the project, also an aircraft in the Ultra Light Machine (ULM) class was designed, wind tunnel tests were carried out on a scaled model and flying models were tested. The aircraft appeared suitable for an amphibious version. This activity will be described in the following sections.

35.1.2. Ultralarge application

An example of the PrandtlPlane applied to very large configurations is presented in effort [117], for an over 1000-seat aircraft. Such a concept well highlights the possibility of the PrandtlPlane in respect to the traditional architecture. Fuselage design in terms of layout and structural analysis was carried out in work [54], showing potential significant reductions of empty structural weight per passenger.

35.2. Very large Freighter

PrandtlPlane concept was applied to a Freighter in references [251, 253]. More in detail, decreasing the operative Mach number makes favorable the use of *large open rotor*, with milder impact on flight speed if also the cruise altitude is decreased. These engines have an higher efficiency (than the jet-engine counterpart), a first important step towards the economical competitiveness of airfreight. The PrandtlPlane architecture is particularly well suited to integrate such propulsion system, and, given also the theoretical higher aerodynamic efficiency, enhances the affordability of airfreight. The horizontally enlarged fuselage offers also noteworthy prospective advantages in terms of storage capability and structural efficiency of the design.

In a recent effort [254], based on PhD thesis [252], an optimization procedure was used in the preliminary design. The aircraft payload was increased as much as possible maintaining the maximum allowable dimensions (80×80 meters); the wing planform was designed in such a way to increase the aerodynamic efficiency under the constraints of trim, stability (flight mechanics) and low-speed requirements. Especially for concurrent high MTOWs and lower wing-loadings, the introduction of a third small wing (which the optimizer was placing as canard or tail, see Figure 90 and also reference [50, 51]) led to configurations better complying with stability requirements, and, most important, satisfying low-speed needs with traditional high-lift devices (double slotted on the front wing, single slotted on the rear one), with a negligible price in terms of aerodynamic efficiency. The introduction of a canard was also suggested by Wolkovitch on Diamond Wings [356].

Figure 90: Possible configuration featuring the typical box wing with a third small lifting surface, as deduced from references [50, 51].

35.3. Ultralight Aircraft

Beside the very first application of PrandtlPlane as very large aircraft, the concept was soon adopted also for smaller machines, as first explained in reference [118]; in particular for the Light Sport Aircraft (LSA) and ULM categories. The motivations were further elaborated in efforts [113, 117]. It was noted that the majority of accidents for this class of airplanes was consequence of human errors. Thirty percent of these events were related to stall, and became fatal for the fire provoked by contact of fuel with hot components (engines).

The design was discussed in works [74, 79]. A scaled model was realized, wind tunnel and also flight tests were then carried out [75, 118, 124]. Also a full-scale prototype was built, but was never flown. A picture

Figure 91: PrandtlPlane ULM prototype, built in years 2009-2010.

is given in Figure 91.

In the case of small aircraft, the potential advantages on induced drag are of minor impact since the wing loading is very small. However, design of such configurations represented a valid test case in which the fundamental knowledge gained during previous activity and the established design procedures were tested and put into practice.

The design [124] featured a classic layout with a lower front and a higher rear wing connected to the fuselage through a single fin. Focusing on safety, the position of the engine and propeller was accurately chosen (different options were possible), passenger cabin was separated from engine and fuel tank by an anti-fire protection. Since a large number of accidents is consequence of a lack of visibility causing impacts close to the runaway, the engine was positioned behind the cabin, enhancing safety. Moreover, fuel tank was located close to the center of gravity, inside the fuselage, in a protected position, to alleviate inertial variations and, thus, reduce excessive change of margin of stability during the flight.

Pitch control was achieved by two control surfaces (elevators), positioned in the inner part of the wings and working in opposition of phase, so to exploit the pure pitch control. Both wings also mounted flaps, whereas the aileron was located on the rear wing only (flaperon), as can be seen in Figure 92. An interesting point underlined in reference [124] is that differently than a traditional configuration, in which flaps produce a large pitch-down moment to be counteracted by a negative force of the tail, in the PrandtlPlane case an

Figure 92: PrandtlPlane ULM: mobile surfaces arrangements and scaled (1 to 5) flying model.

appropriate design aims to have positive lift on both wings. As it will be discussed later in section 38.3.2, this represents a departure from some previous designs, e.g., Diamond Wing of reference [134] having the rear wing producing a large down force, jeopardizing one of the theoretical advantages of this configuration¹⁷.

Stall quality represents one of the most interesting properties: wind tunnel tests [75, 118] showed a very flat stall and poststall curve, see Figure 93. This has a significant impact on safety, especially in the small aircraft category.

Figure 93: PrandtlPlane ULM wind tunnel model and results summary, reproduction from reference [75].

A final note was given about the typical high pitch damping, which increased the flight comfort especially

¹⁷Even though reallocation of lift between wings, when properly done, does not change the induced drag, it is clear that having one wing producing large down force is detrimental to the overall aerodynamic performances and to the efficiency of the whole design.

in the presence of turbulence. In particular, for an optimized model, short period eigenvalues were both negative and larger than one, indicating an overdamped nonoscillatory behavior.

35.3.1. Design procedure

The design relied strongly on an optimization tool described in references [296, 297]. However, parallel strategies were also pursued [74, 79]. The high-speed design was characterized by trim and stability constraints, in a process that led to successive modifications of the aerodynamic surfaces and structural inertial properties. Aerodynamic evaluation was carried out by means of a VLM, and results were corrected with some CFD runs and procedures suggested by the experience gained in the process (e.g., the way the fuselage is modeled from an aerodynamic point of view).

As far as low speed was concerned, pure pitch control was pursued (considering command saturation), whereas for stall verification a procedure studied in reference [167] for a mid-range commercial civil concept, was adopted. In the optimization process both high- and low-speed conditions were concurrently considered since this proved to be necessary for a feasible design.

35.3.2. Wind tunnel campaign

Wind tunnel tests were conducted as described in reference [75]. They referred to a configuration different than the final one because they were carried out earlier in time. Nevertheless, those campaigns were of great importance to have a confirmation of the aerodynamic behavior. In particular, examination of stall and poststall regimes successfully validated physical reasoning based on wing interference (downwash/upwash). Despite the strongly not optimized nature of the model, the aerodynamic efficiency was in line (or better) with expectations.

35.3.3. Scaled model and flight tests

A 1-to-5 scale model of the optimized design was manufactured in Italy and flight tests were carried out. All the main features inherent to PrandtlPlane configurations were demonstrated (high pitch damping, good longitudinal and lateral stability, smooth stall behavior). Moreover, all theoretical calculations and mathematical models were validated.

The same model was also presented at the *Aerodays2006* exhibition in Vienna. More recently, also a 1-to-3 scale model of a tandem ULM PrandtlPlane (the full-size prototype is depicted in Figure 91) has been built and flown.

35.4. Medium-size Civil Transport PrandtlPlane Aircraft

A consistent part of the scientific production on the PrandtlPlane configuration has been devoted to medium-size civil aircraft (200-300 passengers).

Efforts [113, 123] (based in part on work [41]) showed an application of the PrandtlPlane concept in this class, precisely a 250-seat with almost 50 meters wingspan. Detailed design of innovative fuselages was proposed in works [20, 41, 102, 271], with weight estimations based on analytical and numerical approaches, and not relying on inappropriate statistical data. In one solution the fuselage had reduced vertical dimension and two decks, one for the passengers and the other one for the goods and luggage, with a continuous cargo deck (lower wing under the cargo deck), favoring very efficient loading/unloading operations. Overall, smaller weights and wetted surface combined with better load and comfort indices were claimed.

A high-lift design method was studied and applied in reference [167], suggesting that not particularly sophisticated (for the aircraft class) low-speed architecture systems (flaps and slats) were capable of satisfying the relative requirements.

Structural design of wings was tackled with a multilevel multidisciplinary optimization process, taking into account also aeroelastic constraints [83, 84] in a collaborative effort with Politecnico di Milano. It was found that the ratio of lifting system weight to maximum take-off weight was close to typical values observed for traditional configurations. The design was further refined at the detailed structural level. An advanced solution employing full composite wing was also studied in references [122, 273].

Figure 94: Medium Size Civil Transport PrandtlPlane. Reproduction from reference [117].

Since flutter constraint was found to introduce a penalty in terms of weight, a more detailed study was devoted to this topic in works [104, 105]. Later, collaborative researches with a partner university extended the analysis considering also free-flying model and freeplay of control surfaces [30, 57, 58].

Flight mechanics and dynamics, control architecture and engine integration were tackled in collaborative studies with Delft University of Technology [143, 144, 352].

Most of the cited efforts gave very important design indications, and will be discussed in the dedicated technical section (part VII).

35.5. Other Proposed Applications

35.5.1. Aircraft propelled with liquid hydrogen

In references [15, 117, 338] a liquid hydrogen propelled PrandtlPlane concept was studied, see Figure 95. Investigations were driven by the environmental cause, in an effort of reducing pollution and CO₂ emissions;

Figure 95: Liquid hydrogen propelled PrandtlPlane. Reproduction from reference [15].

as already stated, noxious emission represented (and still do) a serious issue, especially considering the expected increase in transport aviation numbers. Moreover, availability of conventional fuel (kerosene) was identified as a possible issue.

The liquid hydrogen was stored in tanks placed at the tip of the front wing for keeping it far from the passengers and also for exploiting the positive effect against flutter of inertial elements placed in such location, see effort [105].

An economic analysis was given showing how, regardless of other issues, the proposed solution was judged not marketable due to high costs of the liquid hydrogen production.

35.5.2. UAV

As described in reference [117], an application of the PrandtlPlane concept was pursued for an UAV, with enhancements in range and maneuverability, see Figure 96. A very relevant advantage was stated to

Figure 96: UAV PrandtlPlane. Reproduction from reference [117].

be the increased stability (due to the high aerodynamic damping) favoring the installation of sensors and observation devices. In the study, the model had a *vertical take-off and landing* (VTOL) capability: the vertical take-off propulsion system (ducted fans or one helicopter-like rotor) was perfectly integrated into the PrandtlPlane layout, maintaining a position close to the center of gravity.

35.5.3. Convertiplane

In a very recent patent [116] a PrandtlPlane convertiplane was presented, see Figure 97. Good maneuverability, stability properties, and aerodynamic performances were claimed.

35.5.4. Executive Aircraft

In reference [117] an application to an executive aircraft is shown. Reference layout was the *Piaggio P180*. In respect of the original architecture, employing the Prandtl lifting system would lead to an increase in internal volume, a reduction of induced drag for fixed span, possibility of enhancing MTOW, decreasing landing/take-off speed with a careful design of high-lift devices, and increase of pitch maneuverability.

36. IDINTOS - Amphibious Aircraft

IDINTOS (in Italian, acronyms of Tuscan Innovative Seaplane) has been a research project co-financed by the regional government of Tuscany (Italy) in which an amphibious light PrandtlPlane aircraft was designed (see also references [115, 163, 164]). The project started in 2011 and ended in 2013 with the manufacturing of a prototype (shown in Figure 98). The consortium was coordinated by the Aerospace section of Department of Civil and Industrial Engineering (DICI) of Università di Pisa (Italy) and it included both public and private firms.

The efforts in the engineering design of IDINTOS are collected in several works. A complete overview is given in references [78, 114, 115].

36.1. Early Stage MDO

Conceptual/preliminary design was carried out with the aid of an MDO software (see reference [297]). Aerodynamic efficiency was maximized, and among others, flight mechanics (stability and trim) and low-speed constraints were considered. For aerodynamic analyses VLM tools augmented with corrections based on know-how gained during previous experimental and numerical investigations, were mainly employed. This activity led to a suitable preliminary configuration, a good starting point for further higher-fidelity analyses.

Figure 97: Convertiplane featuring the box-shape. Reproduction from patent [116].

Figure 98: A picture of the IDINTOS prototype, taken on May 2014 at *Airport Capannori*.

36.2. Detailed Design Stage

The complexity of the innovative design was enhanced by the amphibious nature of the plane. For this reason, besides common testing procedures, also very particular ones were carried out.

36.2.1. High-speed conditions: aerodynamics

Performances and fine tuning of the aerodynamic capabilities in nominal cruise (or analogous) conditions were assessed both with computational means and wind tunnel tests. Regarding CFD analyses, in references [213, 350] pitching equilibrium, longitudinal stability (considering also the presence of ducted fan propellers) and drag reduction in cruise conditions were studied. As far as pitching equilibrium was concerned, the twist angles of both front and rear wings were modified, while a proper positive stability margin was verified (in any case, the preliminary tools enhanced with corrections proved to give reliable indications). In addition, the adoption of an air blowing system acting on the hull step was investigated to reduce drag.

Figure 99: IDINTOS wind tunnel model (top), and lift/moment coefficient vs angle of attack curves (bottom); reproduction from [77].

Wind tunnel test campaign was conducted on a 1 to 4 scale model, as reported in reference [77] (see Figure 99 for a picture of the model). Among the most noticeable results, the smooth stall behavior was confirmed. Moreover, the moment-slope curve showed two quasi-linear regions (the second one being connected with the stall of the front wing). In the same experimental test, the pitching moment vs elevator deflection curve showed a linear dependence for a wide range of angles of attack.

Drag comparisons were carried out when the lateral joints were removed; the advantages were more evident for higher Reynolds numbers and higher lift coefficients, showing a decrease of the total drag in the 6 – 10% range. Observing the polar, a pretty high aerodynamic efficiency was observed, especially in comparison with the efficiency of other aircraft of the same class.

36.2.2. Low-speed conditions: aerodynamics

Low-speed condition constraints were already taken into account in the early MDO, and the need for a high lift coefficient on the front wing led to the choice of a Fowler flap, as opposed to the plain flap architecture for the rear wing. In reference [350] a two-dimensional analysis of airfoils in landing conditions was first carried out to find the optimal position and deflection of the chosen (Fowler) flap. Based on these results, a three-dimensional model was created and the whole aircraft was analyzed in landing conditions;

particular attention was dedicated to verify that the front wing was not operating in stall conditions. Also longitudinal stability and trim of the aircraft were verified.

Further research on the landing conditions and deflection of mobile surfaces, flap extraction motion, and effects of fences was presented in reference [213].

Wind tunnel tests focused also on configuration in its landing asset, with the flap deployed [77]. Figure 99 gives an eloquent picture in this regard. The campaign showed that lift coefficient requirements were met and trim of the aircraft was achieved for a wide range of angles of attack.

36.2.3. Hydrodynamics

The amphibian nature of IDINTOS made particularly relevant the assessment of the hydrodynamic properties [211]. In references [120, 210] the hull of the IDINTOS was studied by means of CFD codes employing biphasic fluid modeling. Forces and moments applied by both air and water were evaluated by CFD simulations, whereas external forces due to wing system and propellers were introduced by means of functions, depending on speed and pitch angle. Simulations were run considering the hull as a rigid body with the pitch rotation, vertical and horizontal displacements as degrees of freedom. Focus was on the dynamics of take-off manoeuvre, from rest to lift-off. Twelve hull variants were simulated leading to the selection of two hulls, chosen according to a compromise criterion between performances (short take-off run), pilot visibility (limited pitch angle values) and comfort (small pitch oscillations).

As described in detail in reference [76], towing tank tests were carried out on a 1 to 3 scale model at INSEAN-CNR facility in Rome (see Figure 100). The model was connected to the towing carriage through

Figure 100: A moment from the water tank tests conducted on IDINTOS hull at INSEAN-CNR facility [76].

a test rig, provided with actuators, springs and dampers to introduce forces and moments generated by the wing system. A shorter version of the forebody hull was chosen over a longer one, more efficient but less stable.

Different types of tests were carried out, focusing selectively on the different phases of the take-off run: “*low-speed tests*” studied the displacement phase up to the transition to planing phase (“hump”), “*high-speed tests*” measured water resistance in planing phase considering wing system effects, and “*stability tests*” examined the dynamic behavior of the hull in planing conditions, considering the wing system effects, in order to avoid *porpoising*, a typical instability phenomenon.

A very relevant result was the assessment of the influence of pitch damping coefficient (C_{m_q}) on the stability of hull dynamics. The test was carried out using a variable hydraulic damper, and a direct correlation between C_{m_q} and stability was noted. Considering that a PrandtlPlane configuration displays approximately

a three times larger value of C_{m_q} than a traditional wing-tail one does (this holds also for other class of vehicles), *porpoising* problems were overcome.

The data of the experimental tests were further analyzed in reference [44], in which the take-off run was simulated.

36.3. Scaled Flight Model

A scaled 1 to 4 radio controlled model was built with the purpose of investigating the dynamic behavior of the airplane, with emphasis on low-speed and stall conditions [114, 115]. Particular attention was devoted to dynamic scaling criteria in order to “transfer” results to the full-scale case. For example, measured stall speed was used to estimate the stall behavior of the full-scale airplane; in the specific case, it was suggested that stall requirements would have been met.

Similar flight tests were carried out to increase lateral-directional stability, with significant improvements. A video [323] of the flight tests is available online.

36.4. The Prototype

A propotype was finally manufactured, and presented at different international exhibitions (among others, *Aeroexpo* in Friedrichshafen in 2014). A picture of the prototype is given in Figure 98.

36.4.1. Structures

Preliminary structural studies were conducted in reference [305]. Different options were compared (e.g., number of spars, number of fins, number of carbon fibre layers on spars), and the most efficient one, also in terms of manufacturing simplicity, was selected. Further FEM analyses were carried out on fuselage and lifting system, leading to the final structural design of the prototype.

36.4.2. Propulsion

Propulsion system consisted in two three-bladed variable pitch ducted propellers, connected to a 100 hp engine by means of synchronous belts. The propellers were located forward of the step section and above the fuselage in order to have a protection from water sprays. Reference [230] provides some information about the preliminary design of the blades.

36.4.3. Undercarriage

The amphibian was provided with a retractable main landing gear and a nose wheel. The solution found for the main landing gear was an innovative one [237] and a patent request was submitted by Università di Pisa. The following advantages were claimed for the adopted solution: housing needed a small internal volume and did not interrupt the fuselage stringers, in retracted position the continuity of the fuselage surface could be maintained and hydrodynamic effects on step section were reduced, the system could be actuated both electrically and manually.

36.4.4. Interior design

A large effort was directed to the interior design of IDINTOS. Aspects like ergonomics and instrumentations were strongly improved and were enhanced relying on cutting-edge technologies. A more detailed description can be found in references [78, 115].

Part VII

Box Wing: Critical Discussion

This section critically discusses the results obtained by different groups on box-wing layouts.

37. Aerodynamics

37.1. Potential Aerodynamics

37.1.1. Optimal Aerodynamic Load Minimizing the Induced Drag

Although the theoretical foundation was introduced by Prandtl in 1918 (reproduced in [272]), it is only with recent works focusing on the optimal lift distribution that a clear picture has been drawn. In particular, in his original work, Prandtl did not mention which method was used to obtain the formula

$$\frac{D_{\text{ind}}^{\text{opt}}}{D_{\text{ind}}^{\text{ref}}} \approx \frac{1 + 0.45\mathbb{V}}{1.04 + 2.81\mathbb{V}} \quad (1)$$

relating the vertical aspect ratio $\mathbb{V} = \frac{2H}{2b_w}$ (see Figure 101) and the optimal induced drag $D_{\text{ind}}^{\text{opt}}$ over the optimal induced drag $D_{\text{ind}}^{\text{ref}}$ of a traditional wing having same span and lift¹⁸. Moreover, he never showed the

Figure 101: Definition of vertical aspect ratio for a Box Wing.

distribution of circulation in optimal conditions, nor did he talk about the lift shared by the two wings. The only available early work on the optimal load of a Box Wing was qualitatively presented in reference [351] (see Figure 54). The wings appeared to be equally loaded (this is not a requirement for achieving the minimum induced drag).

The shape of the distribution on the wings *resembled* a superposition of an elliptical-like and constant one. Moreover, it was stated that, when increasing vertical gap, the distribution was flattening. Several efforts referred, *incorrectly*, to this study as the one claiming the constant plus elliptical optimal distribution. For example, the investigation of Lockheed Martin [198], referring to work [283], was clearly carried out (in its initial phases) considering the biplane theory and thus, it was implicitly assumed that the optimal condition featured equally lifting wings.

Later, Frediani et al [121, 233, 260] studied the problem assuming that under optimal conditions the lift was equally shared by the two wings, and the circulation distribution was a superposition of an elliptical and a constant functions. They demonstrated that the distribution on the lateral joints could be described, within a Taylor approximation perspective, with a polynomial having only the linear term different than zero. Presence of higher than fifth order contributions was not studied. In the same efforts, as the vertical aspect ratio was approaching infinity, the optimal induced drag was exactly half of the corresponding optimal monoplane. This was only partially supported by other studies [296, 297], in which with an optimization algorithm the induced drag showed to approach a smaller value, whereas, considering the original Prandtl's work (see equation 1 and calculate the limit for $\mathbb{V} \rightarrow \infty$), a 0.16 value was expected (although Prandtl's approximated function was introduced for vertical aspect ratios of aeronautical interest and using the formula he provided to evaluate the asymptotic value was an extrapolation).

¹⁸Throughout this part the reference monoplane is thought as having the same wingspan and producing the same lift of the Box Wing.

Parallel works [195] pointed out that, being induced drag related to gradients of the circulation, a finite number of optimal conditions were possible having a target total lift and different lift repartition.

Recent efforts [90, 96–99] discussed these issues on a more rigorous mathematical perspective. As a distinctive approach, hyperellipse-based superformulae were used to reproduce the geometry. Mathematically, singularities like corners are difficult to be treated and solved. However, from an engineering point of view, perfect edges do not exist (and if they existed, the potential flow assumptions could not be locally satisfied). Results showed that the optimal sectional lift distribution was *not* an elliptical function superimposed to a constant value. For relatively small vertical aspect ratios, the assumption of elliptical function added to a constant was shown to be an acceptable approximation of the optimal distribution, whereas for large vertical aspect ratios this was no longer the case. Figure 102 presents the actual optimal load for a vertical aspect ratio of aeronautical interest when wings are equally loaded.

Figure 102: Aerodynamic load of minimum induced drag of a Box Wing with equally loaded wings. $\mathbb{V} = 0.2$.

When there is a large gap between the wings, one may be tempted to argue that the induced drag is negatively affected due to a lateral aerodynamic load perpendicular to the joints (see Figure 102) which does not have any component in the vertical direction of the lift. However, at the same time, increasing the vertical aspect ratio *reduces the circulation gradients* and this effect is the dominant one [95, 98]: in fact, as the vertical aspect ratio approaches infinity, the induced drag asymptotically goes to zero (similarly, the induced drag becomes increasingly smaller when the wingspan of a traditional wing is increased).

The actual optimal circulation on the upper wing of a Box Wing is graphically shown in Figure 103 where it is possible to observe the progressive decrease of lift distribution gradients, with consequent reduction of the induced drag.

Figure 103: Aerodynamic load of minimum induced drag on the upper wing of a Box Wing with equally loaded wings. Effect of the vertical aspect ratio.

37.1.2. Multiple Optimal Aerodynamic Loads but Uniqueness of the Minimum Induced Drag

The minimum value for the induced drag of a Box Wing is unique [98]. However, from a theoretical point of view there is an infinite number of aerodynamic loads achieving the optimum.

Although a formal mathematical proof has not been found yet, it has been verified [96, 98] that in the limit process in which two separated parts of the Box Wing approach each other, as to form the *primitive* box layout, multiple optimal circulation distributions are possible. In other words, adding a constant circulation (and thus, differently reallocating the lift between the two wings) to an optimal configuration would not change the induced drag, and thus, leads to another optimal situation with the same value of drag. This is graphically shown in Figure 104, note that the discontinuity of the gradients of circulation shown in some of the cases is only a convenient graphical representation (postprocessing) but is not a physical fact.

Figure 104: Examples of optimal aerodynamic loads on a Box Wing with the same minimum induced drag.

An intuitive explanation of the nonuniqueness of the optimal aerodynamic load for a Box Wing is given by the following theoretical experiment. With the aid of Figure 105, imagine to start from Biwing I. When the two wings are brought close to each other so that the box shape is essentially formed, the minimum induced drag exactly equates the optimal value for the corresponding Box Wing. This is also the case if another different biwing is selected, such as Biwing II. The optimal circulations of the Box Wings generated with this theoretical operation can be generated from the same circulation by adding an appropriate constant, as previously explained in Figure 104.

This property represents actually an important advantage of Box Wings (and, to some extent, Joined Wings) since the need to strictly have the front and rear wings carrying the same share of total load vanishes. Part of the literature efforts strictly adhering to the above equality condition led thus to penalizing results, e.g., reference [307]. On the contrary, aero-mechanical optimization [127, 297] showed that compliance with flight mechanics stability constraints did not induce appreciable penalties in terms of induced drag, even when the share of the total lift among the two wings was not the canonical 50/50 case. A similar flexibility in off-design conditions was also noted in reference [198].

37.1.3. Additional Minimum Induced Drag Properties

Box Wings have also other interesting properties regarding the minimum induced drag calculation. It is possible to verify [94] that a Box Wing under optimal conditions for the induced drag is asymptotically equivalent to a series of straight/nonplanar/closed systems whose wingtips are exactly on the Box Wing lifting line. An example is shown in Figure 106. The case of equivalence between Box Wing and a multiwing made of straight wings was first mentioned by Prandtl in his original work (see page 17 of reference [272]):

Figure 105: Conceptual experiment showing the nonuniqueness of optimal circulation of a Box Wing.

Figure 106: Asymptotic equivalence between a Box Wing and multiwing systems whose wingtips are on the perimeter of the Box Wing. The equivalence is true if all wings are under optimal conditions. Wings need not to be straight, can have dihedral and can be closed, see reference [94].

“If we consider the limiting case of an infinite number of wings within the outside dimensions $2b_w$ and $2H$, we obtain¹⁹, in the case of the multiplane, the same induced drag as for the wing system [Prandtl was referring to the Box Wing]”

¹⁹Prandtl indicated the wingspan and height of the Box Wing with symbols different than the ones used in this review paper, see Figure 101. The notation has been adapted for convenience and readability.

The equivalence was also addressed by De Young in the NASA technical report [85]:

“...the prediction...for the multiwing [De Young was referring to the case of straight wings] of infinite wings is identical to that of the Box Wing by the outline of the infinite wings”

Another interesting induced drag property is that a Box Wing under optimal conditions is always more efficient than *any* wing system (even if under optimal conditions) virtually included in the region identified by the perimeter of the Box Wing [94].

Finally, any wing system fully included in a Box Wing or in an even more general closed system with dihedral (see Figure 107) must be completely unloaded to avoid penalties in terms of optimal induced drag. In other words, a closed system with a loaded wing (for example a canard) contained²⁰ inside its perimeter will always have higher optimal induced drag if compared against the optimal conditions of the stand-alone closed system.

Figure 107: Optimal induced drag property of a closed system with an inner wing (a canard in this example).

37.1.4. Wake shape

The use of potential theory requires an estimate of the wake shape. If the common assumption of wake aligned with the freestream velocity is considered, the well known *Munk's Stagger Theorem* [236] holds: induced drag does not change when lifting surfaces are moved up/down stream. Some efforts also demonstrated that numerically [182]). The above assumption has always been used in the preliminary stages of aircraft design, being effects of the wake shape of the second order (at least for isolated and planar wings).

For the typical joined-wing architecture, the situation is complicated by the particular arrangement: wake shed by the front wing passes relatively close to the aft one, thus, reproduction of its actual shape may become relevant in order to have a reliable prediction of the aerodynamic performances of the system. Quantitative comparisons of effects of wake modeling were first investigated in references [17, 18]. The induced drag was observed to be smaller when free-wake²¹ modeling was pursued. The difference was about 6% in the range of the vertical aspect ratio of engineering interest ($0.1 \div 0.2$, although some designs have been proposed in the literature having values up to 0.3). This reduced induced drag trend has been confirmed also in references [127, 308]. It is interesting to note that similar conclusions, applied to a tandem-wing layout, were stated in effort [354]: the downward drift of the vortex sheet shed by the front wing was thought to reduce the downwash that the front wing induced on the rear wing to give lower induced drag levels.

Different works [8] suggested a layout with positive stagger (high front wing and low rear wing) to have lower drag level. According to Munk's stagger theorem [236] it would not make any difference if the front or rear wings are in upper/lower position, as far as the induced drag is concerned. This apparent “discrepancy”

²⁰The inclusion has to be intended considering the projection of the wings in the plane perpendicular to the asymptotic speed.

²¹Differently than a rigid wake, a free wake is a wake free to deform and to be convected accordingly with the local stream.

may have been due to a free-wake modeling (in Munk's formulation the wake was assumed rigid) other than the fact that also viscous drag was considered. Similar results were observed in wind tunnel experiments, although not exactly on a box-wing layout, see effort [128]. However, since the total drag was measured, it is possible that the advantages of positive stagger were not directly related to lower levels of induced drag.

Redistribution of aerodynamic loads and shape of the wake for the PrandtlPlane amphibious aircraft IDINTOS and for a generic box-wing layout are shown in references [65, 66] and depicted in Figures 108 and 109. As can be appreciated in the graph, the total lift coefficient does not appreciably change. However, for

Figure 108: Wake shape for IDINTOS. Comparison of sectional lift coefficient when wake is modeled as deformable or rigid. Reproduction from references [66].

Figure 109: Wake shape for a Box Wing. Comparison of sectional lift coefficient, evolution of total lift coefficient (center) when wake is modeled as deformable or rigid. Reproductions from references [64, 65].

a swept-back front wing swept-forward rear wing, considering a more accurate wake shape led to a smaller lift on the tip region of the rear wing. A correct modeling of the wake shape, however, does not only impact aerodynamics, but also flight mechanics and aeroelasticity: reference [66] shows how trim of the aircraft is affected, whereas in effort [65] the higher flutter speed was thought by the investigators to be consequence of the different load distribution.

Some numerical difficulties were observed in work [66] when simulating high angle-of-attack conditions in ground effect: presence of wake-on-body impingement (on the lateral joint's area) issues had to be solved with an alternative formulation [19] of the BEM.

37.2. Compressibility Effects

Among the many original claims [232], the one concerning the reduction of transonic wave drag due to smoother volume and lift distributions (compared to a monoplane layout) was never thoroughly investigated. The transonic *area rule* was generally only qualitatively discussed, suggesting that, with the typical layout of the lifting system, a smoother area distribution was naturally possible. In this regard, the technical report [198] showed the cross-sectional area distribution, deducing that requirements of fuselage indentation were substantially reduced. Some old wind tunnel tests [47] studied the transonic regime, however, results were not conclusive.

For the PrandtlPlane, some analyses were carried out using Euler codes [41, 123, 124]. Specifically, in work [41] transonic simulations showed that an ad hoc design could minimize shock-wave problems. Moreover, *sponson* area (enlargement of the lower fuselage in correspondence of the landing gears) and the vertical joints were shock-wave free. What was considered critical was the rear wing-to-rear fin junction area.

Independent analyses [182] confirmed shock-wave issues in the lateral joints area, whereas in the paper [126] they were not observed. In a very recent effort [127] the external shape was optimized considering also flight mechanics constraints: compressibility issues were completely overcome, see Figure 83.

Transonic aerodynamic design is definitely one of the most complicated parts of the overall design process. In the case of Box Wings, other than the usual issues that need to be considered also for traditional layouts (e.g., area rule, supercritical airfoils), there are additional difficulties. Overall, it seems that compressible effects can be dominated with a local refined design, even in critical areas as wing-wing and wing-fin junctions. This is probably the most important result achieved in this regard, so far.

37.3. Experimental Investigations

Despite the several wind tunnel tests carried out on the configuration, contradictory results were observed. Early works, such as [47] (see Figure 75) were nonconclusive because of the rough model and also the nonnegligible aeroelastic effects. However, it was interestingly noticed that the rear-wing tip region featured attached flows till very high angles of attack.

Further aerodynamic investigations were conducted, as pointed out in reference [232]. Induced drag advantages were claimed to be confirmed by a wind tunnel campaign, although details were never given nor directly referenced. Probably, the above campaign is the one cited in effort [198], carried out by the same company (Lockheed) and described in the internal report²² [231]. Results closely reproduced the predicted advantages in induced drag, being a small deviation observed at higher lift coefficients due to flow separation at the wing-fuselage junction. In the same reference, it was stated that no reliable wind tunnel analyses were pursued for low-speed regimes, leaving the assessment of maximum lift coefficient of the box-wing configuration a relatively unexplored field.

In successive years, further experiments were carried out, as described in reference [161] (see Figure 80). The cited effort featured mostly a biplane, and extended investigations to the box-wing configuration joining the tip of the wings with rough plates. Thus, quantitative results could not be confidently extrapolated. However, from a qualitative point of view, interesting confirmation of the nose pitch-down tendency at stall was found. Moreover, it was observed a destabilizing contribution of the lateral joints to the $C_{n\beta}$ aerodynamic derivative.

Almost a decade later, new wind tunnel investigations were carried out, as described in reference [130]. Although the main flavor of this work was to compare biplane and Box Wing (as obtained by joining the wings) performances, the study showed higher lift-curve slope and maximum lift, other than lower induced drag (up to a certain angle of attack). The same smooth stall behavior was reproduced, due to a non simultaneous (unless specifically designed) loss of lifting capability of the two wings. It has to be remarked that just joining the tip of the wings *does not* lead to an optimal box-wing design, even if the starting biplane is in such conditions. For this reason, the advantages may have been underestimated.

²²Unavailable to the authors.

After a relatively long time of experimental (published) inactivity regarding Box Wings, within a joint effort for design of a PrandtlPlane configuration [118], an ultralight vehicle was studied [75]. The stall behavior showed an extreme flat response (see Figure 93), up to very high angles of attack ($\sim 32^\circ$). The drag coefficient had almost the same (minimum) value for a large range of angles of attack. Although the configuration was not optimized, encouraging values of aerodynamic efficiencies were registered. Moreover, the shape of the polar was very different than the one usually observed for traditional layouts. Asymmetric flow conditions were investigated too, showing a linear response for a large portion of sideslip angle range.

In the same year a further aerodynamic investigation was pursued [235] with the spirit of comparing biplane and associated box-wing configuration. Results did not confirm the expected theoretical advantages. However, as already stressed out, this should not surprise, considering that a fair comparison would take into account the relative different optimal layouts.

Last wind tunnel investigations have been carried out on the amphibious PrandtlPlane configuration [77], see Figure 99. The experimental campaign was not only devoted to the evaluation of performances (and aerodynamic derivatives) in nominal cruise conditions, but tackled also low-speed (flap deployed) and stall regimes. Regarding induced drag, a comparison between the biplane and box-wing layout was carried, showing that the theoretical advantages (referring to the induced drag, whereas wind tunnel results consider the total drag) were almost recovered (when an appropriate Reynolds number was used). Other than not comparing optimal configurations, small discrepancies could have been caused by effects of Reynolds number or aeroelastic issues (disconnecting the wings leads to an increase of the deformation).

Overall, it seems reasonable to expect the potential advantages of the layout to carry over a real aircraft, if an appropriate design is pursued.

37.4. Aerodynamics: Final Conclusions

A constructive review of the above results leads to the following considerations. It seems that induced drag potential advantages can be confirmed with an appropriate design. Of course, for achieving an overall lower drag, the design should be fine-tuned. In fact, compared to the pure biplane, the presence of the lateral joints has benefit on the induced drag part, but also increases the wetted area so that the zero-lift drag is higher. Areas as the joints and the vertical fin-rear wing connections need to be carefully designed to avoid compressibility or viscous effects penalties. Although it has been demonstrated that different minimum induced drag conditions exist, and optimization algorithm found the efficiency to be not too sensitive to small off-design situations, it may be interesting to assess to what extent this is valid when considering compressibility and viscous effects, especially in the above critical regions. In this regard, concepts like *active aeroelastic wing* would eventually enhance the performances of Box Wings.

Other areas that might be critical from an aerodynamic point of view as the sponson (necessary in some designs to carry the main landing gear) were found not as such.

38. Flight Mechanics/Dynamics

This section critically evaluates the results obtained by different groups on flight mechanics/dynamics, low-speed conditions and stall.

Dynamical properties of the box-wing layout are tightly connected with aerodynamic derivatives of the aircraft, which, in turn, are characterized by the peculiar arrangement. Aircraft control depends also on the allocation of mobile surfaces: the same layout gives a wide spectrum of options in this regard.

38.1. Aerodynamic Derivatives

Experimental investigation [47] found that the roll moment induced by sideslip angles did not change with the lift coefficient (dihedral fine-tuning would be enough to achieve a wanted behaviour). Positive dihedral effect, as well as a destabilizing contribution of the lateral joints to the $C_{n\beta}$, were observed in reference [161]. Moreover, pitching moment slope $C_{m\alpha}$ had a linear behavior far from the stall conditions (see also section 38.3.1).

As for pitch damping C_{mq} , different papers claim (based on numerical evaluations) that a higher damping value is expected (however, this has never been practically verified). This derivative is of particular importance not only for flying qualities, but, in case of amphibious configurations, also for the take-off run from water: investigation carried out in reference [76] show how higher values of this derivative eliminate a typical pitching instability called *porpoising*.

Some derivatives in respect of mobile surfaces deflections were experimentally studied in paper [77] for an amphibious Box Wing, whereas numerical evaluation was performed with CFD (and also VLM) in Master theses [213, 350, 357]. Other numerical evaluations (mainly with potential codes) have been performed in different reported efforts.

References [255, 357] analyze the values of some derivatives and associate them to the typical layout. Effects of lateral joints and also of the particular position of the wings are critically discussed, showing some coupling which are not observed for traditional layout.

38.2. Trim and Static Stability

Assuming that automatic controls could not be accepted, the aircraft need to be inherently stable. Considering the longitudinal static stability, $C_{m\alpha}$ needs to be enough negative in order to ensure an adequate margin of stability. The down/upwash induction between the wings has the effect of requiring, for the rear wing, a larger distance between its aerodynamic center and the CoG, or a larger wing surface, or a larger $C_{L\alpha}$. This design constraint is usually respected with a combination of the first two options, which in turn means that trim can be achieved with a larger lift allocation on the front wing. With such a choice, the front wing experiences higher wing loading than the rear one, with consequences on the low-speed design (conflicting requirements can be immediately perceived). Of course, there are different ways to satisfy the stability constraint. More on the topic can be found in references [7, 50, 198, 255, 307, 357].

38.3. High Angle-of attack Conditions

High angle of-attack conditions are quite unexplored for Box Wings. Claims about intrinsic safety of stall have been abundantly made. Indeed, nose pitch-down has been experimentally demonstrated. However, there is a lack of research about design of low-speed devices [77] such that control surfaces have the authority to trim and safely maneuver the aircraft.

38.3.1. Stall at high speeds

The mutual interference of the wings promotes a “premature” stall of the front wing and postpones the rear-wing one, with consequent nose pitch-down tendency. This has been demonstrated both numerically and experimentally. Early effort [47] assessed this tendency, and moreover, observed completely unseparated flows on the rear-wing tip region up to an angle of attack of 28° . Later, research conducted by Henderson et al [161] and Gall [130] found the same nose-down pitch moment at stall. Recent wind tunnel experiments on the ULM PrandtlPlane [75] and IDINTOS [77] also confirm this behavior.

The particular interaction of the wings also promotes a very smooth stall, and lift coefficient does not drop abruptly in the poststall regime. Eloquent examples are shown in references [10, 75, 77, 161], and Figures 93 and 99.

It is true that a thorough analysis should also consider trimmed conditions. However, based on those evidences, it seems that claims about a safer and smoother stall have been substantiated.

38.3.2. Low-speed conditions

In low-speed conditions, analyses need to take into account flaps and slats. Thus, experimental investigations cannot prescind from a thorough design of high-lift devices. One of the difficulties is given by the contrasting requirements of high- and low-speed conditions: the planform layout outcome of the high-speed sizing restrains the design possibilities for the low-speed regime. For Box Wings this is enhanced by the mutual interference between the wings, which changes at different angles of attack. For this reason, to recover trim and achieve a desired maximum lift coefficient, a different high-lift system design may be needed between the front and rear wings.

In the early work [198] it was predicted the need for sophisticated devices (double-slotted trailing edge flap and leading edge slat of advanced design, for a medium-range transport aircraft). They redesigned several times the system (based on numerical and in-house correction tools) increasing flapped area on the front and rear wing, and considering also trim issues (front and aft elevators power).

Recent efforts presented in paper [77] and Master Theses [213, 256, 350] showed numerical (CFD) and experimental (and also manufacturing) studies for the low-speed design of IDINTOS. Analyses assessed the necessity of having a Fowler flap on the front wing, whereas plain flap was sufficient for the rear one. Wind tunnel testing [77] verified the performances of the design and compliance with regulations. In the same investigation, with the high-lift system deployed for landing, it was shown that trim could have been achieved (elevators were located on both wings). Moreover, it was noted an abrupt stall followed by a plateau (probably consequence of a “leading edge” kind of stall).

The impact of low-speed conditions on Box Wings design has been also observed in different aeromechanical optimizations [50, 254, 296] carried out with lower order models, e.g., the one developed in [167], and is still an open issue currently under investigation [50, 254].

A further interesting observation comes from reference [47], in which it was observed that the tip region of the rear wing had unseparated flow until an angle of attack of 28° , suggesting that ailerons effectiveness would be maintained to very-high lift coefficients.

Summarizing, low-speed conditions and high-lift systems need a very thorough analysis and a very careful design. They strongly influence the design of the layout since the early stages. Postponing this design to later stages may induce strong weight penalties or even lead to review and change of the initial configuration. This is a relevant issue with Box Wings, which should be well clear when approaching their design.

Low speed and induced drag. At higher lift coefficient induced drag represents the largest contribution to the overall drag. For this reason, theoretically, low-speed design (especially take-off and early climb) can be fine-tuned to achieve particularly efficient configurations when compared to a traditional layout. A small advantage in such parts of the mission would indirectly impact also other segments. Think, for example, about the possibility of installing lighter power units. For all above mentioned reasons, it is not straightforward to comply with all the requirements and design a configuration enhancing the lower (induced) drag level in low-speed conditions. There is definitely a lack of studies on this specific topic.

38.4. Inherent Flying Qualities

Different efforts specifically studied the inherent flying qualities. In some investigations [143, 352] issues were found on the lateral-directional plane: roll (level 3) and Dutch roll (unstable) modes were unsatisfactory. Longitudinal phugoid mode was found to be in the level 2 (based on MIL-F-8785C specifications).

Other investigations assessed different scenarios [48], in which short period mode was level 2 and roll subsidence level 3.

All these analyses were based on common procedures and approximations. References [255, 357] discussed some fundamental issues related to flight dynamics of Box Wings, in relation to conventional layouts. Among others, it was numerically verified that longitudinal and lateral-directional derivatives were decoupled to a reasonable extent, justifying thus the common assumptions used for flight mechanics analysis. Considering that in some cases pitch damping for Box Wings has three to four times the value that a reference traditional layout has (see IDINTOS [76]), effects of the common approximation for the equation of the short period motion need to be better understood. In this regard, the cited efforts noted that a relevant stabilizing contribution to this mode was always guaranteed by the derivative C_{mq} (pitch damping). Thus, it was suggested that to comply with regulations on flying qualities, the static margin of stability needed to be smaller.

38.5. Controls Surfaces and Handling Qualities

One of the main prospective advantages of the box-wing layout is the possibility of having pure pitch and direct lift control. The first property favors an increase in angle of attack without changing altitude, promoting safer close-to-the-ground maneuvering. The second one regards not only the better precision

in flight path control during approach or landing (studies have shown error improvements of 15%), but also improved response to atmospheric turbulence (gust load alleviation) and preciseness during critical operations like refuelling. Both options are naturally possible when elevators are positioned on both wings, and are deflected in a synergic way.

Most detailed work in this regard is offered in references [143, 352], in which the control system (both longitudinal and lateral-directional) is dimensioned in order to comply with regulations. Some of the requirements like trim, take-off rotation, push-pull manoeuvre, minimum time to bank, one engine in-operative and steady turn at different conditions were verified. Inboard (elevators) and outboard (ailerons) mobile surfaces

Figure 110: Mobile surfaces of a PrandtlPlane, as designed in reference [143].

were located on both wings (specifically used for pitching and rolling, respectively), as shown in Figure 110. Conventional rudders were located on the vertical fins.

Handling qualities were studied also in reference [48] for three typical conditions, although the proposed design had elevators and aileron on the rear wing only.

38.6. Methodological and Conceptual Errors

A very important note on a common suboptimal approach when tackling aero-mechanical design of Box Wings follows: it would be a methodological error to consider the rear wing as the analogous of the tail of a traditional configuration. Some designs seen in small aircraft featuring a box-wing shape can be visually identified having rear wing unloaded when aircraft is trimmed. If, from a purely theoretically point of view, optimal induced drag condition can be achieved also with a down-lifting wing (recall the discussion about the multi-optima conditions and the possibilities of adding a constant circulation without penalty on the induced drag [96, 98] (as discussed in details in section 37.1), it is indeed questionable that such a design would give any benefit when all other aspects are considered.

39. Structures

Box-wing layout has the lifting system as real innovative element. However, also fuselage needs to be redesigned in order to exploit the potential advantages of the configuration. Probably, in the literature, the most controversial results regard structures and weight estimation of Box Wing lifting system. In fact, very often, handbook methods, traditional wingbox design procedures, and adjustment of equations born for classical wings have been used for the preliminary design and evaluation of the weight. This approach hides two errors; the weight estimates found in handbook are calibrated on wings which are inherently loaded differently (externally and, foremost, internally due to the overconstrained nature) than those of a Box Wing. Thus, similar external geometrical parameters (sweep angle, taper ratio, etc) lead to completely different thicknesses of the internal structures, and thus, weights. Moreover, to minimize the weight (fixing the topology of the wingbox) material needs to be redistributed differently than what

usually seen in common layouts. In other words, the secondary bending moment tilts the neutral axis, and thus, material is more efficiently employed when distributed far apart, on the two opposite corners. This concept was well underlined in the review [356], stating that it is necessary to change the traditional wingbox design to not incur in weight penalties. For these reasons, approaches which base the weight estimates on traditional structural architectures should be generally avoided. The extent to which a nonadequate design can affect the weight of the lifting system has been shown and quantified, see for example reference [84].

A very critical point regards the overconstrained nature of the system. Other than contributing in discouraging traditional weight estimation means (handbook), it has generated confusion among researches. Claims about a larger stiffness due to the hyperstaticity of the system have never been contextualized. It is obvious that, on the one hand, having two wings connected or not gives a large difference in terms of stiffness (and this should immediately warn against C-wing design suggested from a purely aerodynamic point of view). However, it is also true that considering the Box Wing built from splitting the wing surface of a monoplane configuration (and maintaining the same wingspan) leads to two contrasting trends: the hyperstatic nature and the fact that, being the chord half of the reference one, the height of the wingbox would also be approximately half, with strong consequences on the primary bending inertia (although as stated above, the load state is more complicated, and the most efficient distribution of material is different than for the monoplane case).

39.1. *Lifting System Design*

As the use of handbook is absolutely to avoid for Box Wings, results obtained with this (or similarly inadequate) methods are not considered in this discussion.

One of the first works to tackle the structural design was performed by Lockheed [198], using nonconventional weight-estimating techniques (based on FEM analysis with beam elements). Different configurations, different flight envelope conditions (with an extra 1.5 safety factor coefficient and load relief) were considered. The design also included details on some parts (flap mechanisms, etc). A slightly lower weight was found in respect to the reference monoplane case (having, however, larger wingspan, in order to match the same aerodynamic efficiency), although some results were claimed to be suspicious. However, the wingbox was not designed exploiting the nonsymmetric thickness distribution²³. For this reason, the weight was probably largely overestimated.

A careful structural design (including static aeroelastic constraints) was carried out in reference [84] for a 230 tons MTOW and 250-passenger layout, considering one nominal load condition ($n_z = 2.5$), metallic (aluminium alloy) structures (the equivalent acceptable stress was dropped to 233 Mpa to account for local stress concentrations and fatigue strength). Different constraints were considered: the maximum allowable stress, the stability of equilibrium in compression, aileron roll effectiveness, static aeroelasticity and flutter. Results were obtained for both the symmetric (no spar flanges) and the nonsymmetric wingbox cases see Figure 111; large weight penalties occurred in the first case. The final design had the wing system representing 15.8% of the MTOW, a value similar to those extrapolated for the wing and tail system of similar aircraft (Airbus A330, Boeing 767 and 777). This is a relevant result, considering that the studied configuration was designed focusing on a breakthrough in aerodynamics (efficiency).

Regarding effects of the different constraints [84], stability under compression was inducing most of the weight penalties, suggesting that a more accurate and technologically advanced design of the stiffeners could lead to large weight savings. More in-depth stress analyses were carried out on a higher-fidelity detailed model (describing stiffeners, spars, ribs of the wingbox instead of considering their effect in the inertial property of the beam cross section) [122]. Structural weight estimate was in good agreement with the one obtained on the previous lower-fidelity model [84].

A design of the same wing system employing composite materials was pursued in reference [122]. An additional 1.5 safety factor for the limit load condition was considered, and overall, a 40% reduction in weight was found compared to the aluminium alloy version. Interesting manufacturing decisions were introduced

²³In the report there is no direct mention to this aspect, thus, the authors speculate that a standard symmetric wingbox was considered.

Figure 111: Structural beam model (top left) [84], details of wingbox section (symmetric and nonsymmetric cases) [84], structural analysis on the detailed (higher-fidelity description of the wingbox) FEM model (top right) [122].

to exploit the possibilities of the configuration. For example, due to the large skin thickness, the wingbox was designed without stringer inside, increasing the number of ribs to avoid instability. This solution is well suited for a standard manufacturing procedure, e.g., the spar can be laminated first, connected together with the ribs, and at the end, upper and lower laminated skins can be bonded in a vacuum bag.

The overconstrained nature of the system manifested itself in several occasions, e.g., it was observed that fin-to-upper wing connection needed to be carefully designed since the chosen local solution affected the overall stress distribution.

Many of these theoretical aspects have been observed in the practical structural design of a PrandtlPlane (section 36).

39.2. Fuselage Structural Design

Not many efforts have been devoted to the design and weight estimation of the fuselage of a Box Wing. Here too, contrasting methodological approaches have been observed: the temptation of considering Box Wings only as a lifting system to be integrated to common fuselages has characterized many of the investigations presented in the literature. However, concepts like PrandtlPlane overcome this point of view, underlining the importance of an integrated project. For these reasons, the design needs to be approached as a whole in order to enhance the prospective potentials. This is also relevant when the fuselage is considered.

Considering the double supported nature of the fuselage, a careful study is needed. Different investigations, employing also FEM, were carried out in several efforts [20, 54, 102, 271] on different aircraft, different operative conditions, at different level of detail, and considering various structural parts. Work performed in reference [20] dimensioned (employing also FEM analyses of the detailed structural solution) the interface section between main landing gear and fuselage, for a 250-seat PrandtlPlane; the most critical load condition of the flight envelope (increased by appropriate safety factors) was selected for the design. As a relevant technical result, due to the horizontally enlarged fuselage section, introduction of vertical struts underneath the passenger floor and cargo floor keel beam proved to be beneficial.

Other areas such as the engine-fuselage and fin-fuselage connections, and bulkhead were examined in reference [271], considering ultimate loads as specified by regulations, and also incorporating (indirectly) fatigue issues. For the fin-fuselage connection an hybrid solution similar to the one employed on the B747 was chosen. In both works [20, 271] weight estimates were given, with much lighter results compared to those obtained with *NASAWEIGHT*: this was attributed to the completely different nature of the loading state of a PrandtlPlane, and on the unconventional solutions necessary to avoid weight penalties.

Figure 112: Structural design of PrandtlPlane fuselage. Details of the FEM analysis of the central area (top left) and section connecting main landing gear and fuselage (top right)(from reference [20]). Central section with vertical beam (bottom left), and excerpt from the FEM analysis carried out in effort [102] (bottom right).

With the aid of previous experience, more in-depth structural analyses were performed in reference [102] on a typical (critical) fuselage section undergoing combined maneuvering, inertial and pressure limit loads, and ultimate pressure loads (as prescribed by regulations). Lift repartition between the wings (55/45%) was confidently extrapolated from parallel work focusing on different aspects (aero-mechanical design). The central part of the fuselage was studied through FEM analysis, and the sizing conditions for the various structural elements were assessed. It was noted the importance of the vertical tie-beam connecting the upper part of the fuselage and passenger floor (see Figure 112). An estimate of the overall fuselage weight was then given, in relation to an aircraft of the same class (Airbus A330-200): it was found a similar incidence of the fuselage structure to the total empty weight (about 30%), even if some structural components (stringers and skin) were oversized. The relative bay-weight-to-volume-limited-payload ratio highlighted an unexpected operative flexibility, both in terms of passengers and cargo capacity.

The above investigations, carried out on a medium-size aircraft, were useful also for the design of the fuselage of an ultralarge aircraft (80×80 meters) [54]. In particular, under the loading conditions imposed by the regulations, similar architectural solutions proved to be successful from a structural point of view:

importance of the vertical strut was restated for a weight-efficient design solution. The typical section weight normalized by the number of passengers was used as a measure of the structural efficiency of the solution. Values of the above parameter were compared for the studied PrandtlPlane and A330-220 fuselages, and the novel architecture was found to be 2 times more efficient.

39.2.1. Final observations

Fuselage design of Box Wings has not been widely studied. The hyperstatic arrangement of the lifting system, as well as the “double supported-like” constraint on the fuselage call for an original design approach. Moreover, several configurations present an external shape enlarged in the horizontal direction. As for most of novel solutions, confidence given to weight estimates needs to be carefully assessed. Considering the solutions proposed in the above cited works, margins for efficient fuselage structures seem to be in place, especially when ad hoc strategies are pursued.

40. Aeroelasticity

There have been only a few studies on aeroelasticity of box-wing planes. Early works showed low-frequency flutter (both symmetric and antisymmetric analyses), involving rigid-body modes [198]. For the antisymmetric case, similarities with the classic T-tail flutter motion were observed. On the contrary, for the symmetric case, flutter resembled a

“highly modified, flexible, short-period mode”.

Although several structural and inertial modifications were later made, it was not possible to comply with regulations. However, it was suggested that this flutter could have been “dominated” with active controls.

Later studies [200, 353] showed the difference between two main flutter mechanisms associated to the constrained configuration (no rigid-body modes considered) and the free-flying one. It was noted that a constrained optimization of the structure to enhance performances led to configurations changing the flutter mechanism from body-freedom to cantilever.

Within a multidisciplinary effort [84], aeroelastic static and dynamic analyses (considering only constrained configurations) were carried out. Having assessed that flutter constraint was responsible of a weight penalty (localized on the front wing and the lateral joints), a more in-depth investigation was pursued in reference [105]. In this effort, flutter constraint was taken into account in a more sophisticated way, better taking into account the regulations (15% enlargement of the flight envelope, different altitudes, etc.), considering a conservative approach on the structural damping and taking into account the Mach number. For a flutter-free design, the most efficient solution was the addition of wingtip tanks on the front wing.

Very low frequencies of the first elastic natural modes were registered (first mode had a frequency smaller than 1 Hz, fifth mode had a 3 Hz frequency). Flutter was characterized by a coalescence of first two modes, being first natural mode associated with an in-phase vertical deflection of the two wings, and the second one mainly showing a tilting of the joint in the longitudinal plane. Antisymmetric analyses were not considered, however, the particular design of the rear wing-fin connection (featuring laterally tilted double fins to “embrace” the rear wing as far as possible from the symmetry plane) suggested the associated flutter instability to be fixed.

A more recent effort [57] studied several of the above points on an aeroelastically “similar” baseline, finding a large number of similarities. Moreover, postcritical analyses showed the associated limit cycle oscillation, and energy exchanged with the fluid was suggesting front-wing tip region to have an absorption role, see Figure 113.

References [56, 57] also studied effects of mobile surface freeplay, considering the control architecture presented in work [143, 352]. Some high-frequency-mode instabilities occurring for small windows of lower speeds were observed, however, in most cases, modeling a “reasonable” amount of damping (for example, considering structural damping or adding some source of damping related to the actuation system) was sufficient to overcome these issues. The main flutter mechanism (interaction of the first two elastic modes, observed on the baseline without considering the mobile surfaces) was always present; however, taking into

Figure 113: Aeroelasticity of a PrandtlPlane. Fluid-to-structure power transfer (left), limit cycle oscillation (right) [56, 57].

Figure 114: Aeroelasticity of a PrandtlPlane. Mobile surfaces layout (left) and coalescence of first and second frequencies (right) [56, 57].

account freeplay of the front aileron led to a higher instability speed. A possible interpretation relied on the previous energy analysis, showing how the aileron area was characterized by extraction of energy from the fluid, see Figure 114.

In the same effort [56], rigid-body modes were then considered. For the particular fuselage inertia (extrapolated from previous work on a similar configuration [143, 144]), flutter was not observed within the considered speed range. However, a sensitivity analysis showed that, smaller fuselage moment of inertia (or larger fuselage weight) led to body-freedom flutter, characterized by a coalescence of pitching and first elastic modes (in agreement with results found in the paper [353]). As shown in Figure 115, superposition

of the frequency-speed diagrams of flutter analyses carried out for different pitching inertia helps in giving an interpretation of the flutter-free condition of the reference case. As said, coalescence of first elastic mode and one between the second elastic or pitching modes characterized the cantilever or body-freedom flutter, occurring for “large” or “small” values of the fuselage moment of inertia, respectively. For an intermediate value (as the one chosen for the reference fuselage) a transition between the two characteristic limit behaviors is in place, thus, either coalescence(s) (and flutter) is (are) largely postponed or no coalescence is observed within the operative speeds. If, in a design, fuselage moment of inertia happens to have such kind of intermediate value, flutter constraint may be satisfied without (or with negligible) weight penalties.

Figure 115: Flutter properties of PrandtlPlane when pitching inertia of the fuselage is varied: passage from body-freedom to cantilever flutter when inertia increases.

Very recent efforts [58, 318] carried out similar investigations on a detailed wing model (taken from references [122, 273]) and confirmed the above trends. A version of the same layout made of composite materials was also considered: that solution was found not to have aeroelastic issues.

A current research [30] is focusing on the lateral-directional aeroelastic properties of the same PrandtlPlane layout studied in reference [57]. Antisymmetric analyses have been carried out considering the constrained configuration, excluding instabilities (contrary to the classic “T-tail-like” flutter observed in reference [198]). However, the same analysis on the unconstrained model gives a different scenario, with flutter occurring at relatively low speed. Further investigations are in progress.

40.1. Aeroelasticity: Final Conclusions

Box Wings present natural modes with low frequencies. In view of the results presented in the literature, aeroelastic properties of Box Wings seem to be strongly correlated with rigid (flight mechanics) modes. Whereas studies considering constrained models (cantilever cases) suggested that, even for structurally optimized configurations, flutter problems can be solved with reasonable or minimal redesign, occurrence of the body-freedom flutter opened a more complex scenario. With a fixed margin of longitudinal stability (guaranteeing a stable configuration), inertial properties of the fuselage seem to have a relevant impact on the aeroelastic behavior of the aircraft. In particular cases, also positive effects can be expected (when interaction of rigid and elastic modes postpones coalescence and flutter, or prevents it in the considered speed range).

Aeroelastic properties considering also antisymmetric modes need to be studied in more depth. A recent effort in this direction is given in reference [30].

For a more exhaustive review of aeroelasticity of Box Wings, the reader is referred to work [30].

So far, no studies have been conducted considering transonic effects on the aeroelastic response. Such investigations represent one of the last steps in the design of a (unconventional) configuration, as they require first a local detailed description of the optimized aerodynamic surface, which, in turn, is mainly driven by aerodynamic performances. However, it should be noted that an understanding of such phenomena is crucial for the development of Box Wings that can compete with conventional transonic transport aircraft. Given the few aerodynamic investigations in the transonic regime (see section 37.2) the feeling of the authors is that with a locally refined design this issues may be overcome without incurring significant penalties.

41. Aircraft Design

It is in the crucial phase of aircraft synthesis that all prospective advantages need to be translated into practical benefits. In the literature, several analyses used questionable approaches for the design or assessment of performances; such investigations often led to disappointing results for Box Wings, and consequent negative claims about the advantages of the configuration.

Other than the necessity of more sophisticated design methods and capabilities early in the vehicle conceptual development (as noticed in reference [70] for Joined Wings), probably one of the major barriers is the level of intrinsic high interdependence between the various disciplines. For example, consider the aerodynamics and the flight mechanics properties of an airplane: if these two disciplines are not taken simultaneously into account, an optimal design in terms of drag may, for example, be not even trimmable or stable. On the other hand, designing in order to reach stability and trim, without considering aerodynamic efficiency, may lead to far-from-optimal performances. If this is true for every configuration, it is definitely enhanced on Box Wings (and Joined Wings in general).

The above considerations may suggest that an MDO is then necessary since the early design stages. MDO, however, often does not provide a complete scenario: some parameters need to be preliminary set, and several choices have to be made, restricting the design space. These preliminary choices may have a large impact on the design, and require insight, specific experience gained by successive iterations in the design process, and a profound understanding of the results: these are definitely skills needed for the design of Box Wings. As a further note, some practical constraints are difficult to be translated into mathematical formulae and can't be easily incorporated in the MDO.

However, the most crucial factor is probably the level of confidence that should be given to the low-fidelity tools needed for a feasible MDO. Nowadays, after decades of experience on traditional aircraft design, handbook methods and relative corrections have been widely validated and are confidently used. The same cannot be stated for Box Wings. This represents a further barrier to the “early MDO without insight” approach.

An ideal synthesis (when talking about early design stages) would be the use of MDO with sensitivity analyses to preliminary fixed parameters, to the cost functional, to constraints, to level of fidelity of the tools within a global optimization. Why a certain “configuration” is “preferred” by the optimizer? Which “properties” are “emphasized” at the different local optima? These and similar questions need to be answered for a deeper understanding of the “DNA” of Box Wings.

41.1. Design

Classic design (without employing MDO algorithms) was pursued in different efforts. The first one [198] concerned a transonic Box Wing with the following operative requirements: 5500 nm range, 400 passenger payload, 0.95 Mach cruise speed, 10000 ft runaway length. The following very significant passages are quoted from the work:

“Because of the complexity of the transonic biplane²⁴ configuration, proper assessment of airplane characteristics utilizing this concept can only be accomplished by use of rather elaborate analytical procedures for aerodynamic, structural loading and aeroelastic characteristics.”

and

“Weights of the biplane wing structure could not be estimated with conventional weight-estimating techniques because of the redundant load paths and the unknown stiffness requirements for flutter prevention.”

For this reason, the researchers pursued (when possible) calibration of results with in-house procedures and experimental investigations. The design was characterized by a parametric study. Box-wing configuration was slightly more compact and lighter than the reference monoplane with same aerodynamic efficiency. Weight breakdown showed an heavier fuselage, “suspiciously low” wing weight and propulsion system of the same weight of the monoplane. Studies on sensitivity of induced drag to lift repartition highlighted the fact that off-design conditions led to small penalties.

In effort [306] the fundamental design perspectives of a medium-range Box Wing were discussed and its performances were compared to the ones of an Airbus A320. However, investigations were characterized by very preliminary and low-fidelity methods (handbook). Interesting studies about the fuel capacity, and the possibility of creating a family of aircraft were also carried out. Finally, problems regarding engine integration, and landing gear positioning were noticed. Overall some prospective advantages over the traditional configuration were found.

Another conceptual design was proposed in reference [172], featuring a partial MDO (they considered symmetric wingbox structure) showing the box-wing configuration to be slightly more convenient, and highlighting that the DOC advantage would have risen with higher fuel prices.

Conceptual design of a PrantlPlane was carried out in references [41, 123]. One of the major contributions of these efforts was the study of the innovative aspects of the PrandtlPlane in terms of airport integration and customer requirements. A procedure for conceptual design was also discussed in reference [124].

41.1.1. Application of MDO

A few efforts applied an MDO approach to some aspects of aircraft design. An aero-structural optimization was presented in reference [170], in which the minimization problem was formulated as a single-level one. The ultimate maneuver condition was considered as the structurally sizing state, whereas the objective

²⁴Biplane was used in reference [198] to indicate a Box Wing and not an actual biplane understood in classical sense.

function to maximize was the range (through Breguet's formula). Viscous drag was also considered (by using airfoil data). The optimizer chose a monoplane (with winglet or raked wingtip) layout. The structural model relied on a beam description, using some coefficients to correlate it to the weight of the wing. Moreover, flight mechanics and low-speed constraints were not taken into consideration. Of course, for some conclusive results, an higher-fidelity model was strongly suggested.

Effort [7] augmented similar investigations with flight mechanics constraints (stability and trim) but, on the other hand, used lower-fidelity methods (statistical formulae) to assess structural weight. For the reference mission (typical regional-jet) the solution featured a box-wing configuration with smaller wingspan compared to traditional layout (see Figure 82), smaller structural weight, and overall smaller MTOW. The configuration was slightly less efficient in cruise than the reference monoplane. However, because of the short mission, this had a smaller relative impact.

Trim and stability (but neither structures nor low-speed conditions) were considered in reference [127], in which an aero-mechanical optimization was performed considering higher-fidelity aerodynamic codes and advanced optimization framework for designing shock-free configurations.

Aero-mechanical optimization was also pursued in reference [296, 297]. Constraint on low-speed regime (with a preliminary approach) was incorporated. This approach was used for designing flying models and full-scale prototypes of ULM machines. Optimization employed in reference [84], although mainly structural, showed some inherent multidisciplinary in the constraints.

41.1.2. Box Wing and its ideal application

In the literature, contrasting results have been found or proposed regarding the natural application of the box-wing layout. For example, according to reference [7] and therein cited works, the natural application of the concept is for short-range missions, typical regional jets. Effort [182] recommended very large aircraft applications, whereas in reference [172] large long-range designs were suggested. It is very difficult and, at the moment, premature, to have a conclusive answer to this question. Regarding very large aircraft, Box Wings have a natural application in that direction because of the infrastructural limitation on the maximum dimensions. However, one of the main issues could regard the structural designs of the lateral joints. MDO and design performed in reference [50, 254] suggested, for limited horizontal separation of the wings (needed also to reduced the length of the lateral joints), the introduction of a third small surface (canard or tail) to satisfy the trim and stability constraints (see also thesis [51]).

A further issue may be the limited amount of fuel that can be embarked, which could exclude long-range applications. On the other end of the spectrum, small-range aircraft may have the advantage of spending long time in the climb/descent phase (as stated in reference [7]), which enhances the importance of smaller induced drag generated by Box Wings.

An application of the PrandtlPlane for large freighter was studied in references [252, 254], see Figure 116. Besides the technological improvement, represented by the innovative layout, also the integration of the concept into a more efficient transport system was taken into account. An optimum network of freight airports was designed to optimize the traffic flows and to reduce costs (the problem belongs to the branch of mass transportation theories), increasing the competitiveness of the airfreight. This study represents a first step towards the integration of potentials of the typical architecture into ad-hoc missions.

It appears clear that aircraft synthesis, usually performed with lower order methods especially on the structural side, needs to be evaluated in terms of sensitivity to the modeling tool. Overall, the design process is strongly nonlinear, and, small variations in the "initial conditions" may lead to completely different optimal solutions.

41.1.3. Landing gear

In several investigations the main landing gear was located inside the fuselage. Examples can be found in references [117, 174, 198, 306]. Landing gear design is shown in effort [198]. The sponson (undercarriage structure) needed to accommodate them has been studied both in terms of aerodynamic [41] and structural [20] properties. The latter work also critically analyzed the landing gear exact positioning (complying with requirements of stability during ground operations) and design (kinematics of the extraction system was verified).

Figure 116: PrandtlPlane freighter, and studies of the optimum network of freight airports, as shown in reference [252].

41.1.4. Fuselage design

Design of the external shape and internal layout of the fuselage has been carried out in several studies. In effort [41] an innovative fuselage was proposed being shorter, horizontally enlarged and featuring a single deck for passengers and a constant width up to the end. An ergonomic analysis showed a larger volume per passenger, as well as a larger flexibility in respect of a typical mission. The cockpit was designed in order to comply with visibility constraints. A very noteworthy property was the very large (compared to similar aircraft) continuous cargo deck, possible because of the small height of the front wingbox (half the one of a conventional aircraft) which crossed the fuselage under the same cargo floor and, also, thanks to the larger width of the fuselage section. This last point enabled reduced ground operation times (to embark and disembark containers) due to a continuous flux (embarking and disembarking could be simultaneous pursued). Both aerodynamic efficiency (based on induced drag) and stability drove a design in which the last portion of the fuselage was tapered without losing height, so that fin root was high, with an increased wing-to-front aspect ratio. The result was a wedge-shaped tapering of the fuselage stern, rather than the conical shape observed in conventional aircraft.

For ultralarge aircraft, fuselage design was pursued in thesis [54]. In such large layout, featuring a double-deck economy class version with three aisle each, evacuation requirements were assessed as potentially critical.

41.1.5. Engine integration

Surely one of the claimed advantages of the Box Wing consists in the wide possibility given to engine integration. Different options have been chosen. In reference [198], the engines have been placed under the wings. Alternative design also located them in different areas, just in order to relieve flutter issues.

In reference [352] an in-depth investigation for the choice of propulsive system and its integration in a mid-range aircraft was carried out. Several propulsion systems and technology were initially considered, then, with a trade-off study the more electric conventional turbofan was selected. A further trade-off was pursued for the choice of the number of engines, indicating the best configuration to have two engines, mainly due to fuel efficiency reasons. A final trade-off study for the location of the engines was then performed. The followed criteria were several, e.g., the required landing gear length, structural weight, position of the center of gravity, one-engine out situation. Optimal location of the propulsive system was the rear fuselage. After these preliminary choices, also sizing and thermodynamic cycle optimization were performed. A typical mission was considered in this study. The fuel had to be embarked into the fuselage due to the insufficient wing volume. The fuel allocated into the wing had a large distance from the CoG, and importance of

reducing as much as possible its shift was underlined.

Theoretically, the options given by a box-wing layout are countless, not only in regard to the engine location, but, also, to their architecture: clearance from the ground of the upper wing is ideal to mount large open rotors, or turbofan with high bypass ratio without flattened intake.

An application employing large open rotors has been pursued in references [251, 252, 254].

Part VIII

Conclusions

42. A Concept from the Past and an Opportunity for the Future of Aviation

This review presented and critically examined the research carried out in the last decades on Sensor-Craft, Strut- and Truss-Braced Wings, Box Wings, and PrandtlPlane. Efforts conducted in research labs, universities, and industries have been organized and discussed.

These configurations, classified in the group of *Joined Wings*, significantly depart from traditional mono-plane wing design and, thus, present relevant research challenges. These difficulties are exacerbated by an enhanced intrinsic interaction between the different disciplines and by the overconstrained nature of the layout. However, this complexity also represents an opportunity since the *design space* available to the engineers is far larger than the one offered by traditional systems.

The review addressed the major technical points/innovations and achievements made worldwide. However, the general understanding of Joined Wings is still an open question, and research is in progress. A quantification and exploitation of the real advantages of the joined-wing configuration is still the final missing point. As already suggested, only a very “careful” MDO can give more definitive information about the practical technical advantages that can be achieved. In this regard, it is important to use higher-fidelity capabilities, or calibrate the less accurate ones relying on the more sophisticated (but costly) analyses and on experience. More than that, it is crucial to predict the sensitivity of the solution to the used analysis tools. This gives a reliable information and helps understanding the underlying physics, the “DNA” of the configuration.

With the word “careful” the authors refer not only to the use of higher-fidelity means for an assessment of the performances with an higher level of confidence, but also and foremost to a design that goes beyond dogmatism to overcome and bypass penalization that traditional or blind approaches may introduce. For example, an application of such nonconstructive approach is to take the fuselage of an existing aircraft and thinking that substituting the lifting system with a joined-wing one (especially Diamond Wing or Box Wing) would give a realistic or reasonable evaluation of the performance advantages. The approach should rather be a *radical redesign* of the different parts constituting the aircraft.

Among the technical open questions, role played by nonlinearities need to be further investigated. For some very-flexible designs, the structural geometrical nonlinearity can be a formidable obstacle to the project, for two main reasons. First, the aeroelastic response could show some extremely complex phenomena, difficult also to be predicted a priori. In the second place, higher-fidelity analysis tools, needed to correctly describe such nonlinearities, would be too expensive to be extensively used in an MDO effort. Abandoning an approach based on simplistic corrections, which really appears inappropriate for such cases, a partial solution to this issue could be the employment of reduced order models. So far, despite some studies in that direction, results have not been satisfying: a reliable and significant reproduction of the nonlinear response has been achieved with computational costs in the same order of the full analysis.

A relevant difficulty is also the definition of the class of aircraft for which the design can carry most of the advantages; in some cases it could be very interesting also to redesign some sectors of the aviation, according to the possibility given by the particular layout (as proposed with the new cargo system described in some cited references, or as implicitly assumed with the flying antenna usage in the SensorCraft case).

Among the different Joined Wings considered in this review, the authors noticed that funding has been directed to Box Wings in significantly smaller shares when compared to Diamond Wings or Strut- and

Truss-Braced Wings, especially in the last decades. If it is true that Box Wings did not recently attract military agencies, it may appear perplexing that other configurations have been preferred without clear evidence of superiority (at least in the published literature). The authors speculate that the higher level of intrinsic connection between the disciplines, the fact that the two wings have to be thought as two lifting surfaces (instead of a lifting front wing and a trimming rear one, or, as in the case of Strut-Braced Wings, instead of a strut supporting the main wing, with also the presence of the tail as in the traditional layouts) and the difficulty of efficiently design for both high- and low-speed conditions make more cumbersome to analyze, evaluate and enhance the prospective advantages of this configuration. The complicated scenario is reflected by the fact that research conducted on Box Wings has been, with only few relevant exceptions, carried out for a too short amount of time and starting from scratch, often ignoring results achieved by other groups. There is a strong feeling that some efforts were just published as an inorganic contribution, with a lack of vision in respect to the topic. This approach is indeed very questionable, especially if partial conclusions are drawn too easily and *presented as proven claims*. Nevertheless, review of previous efforts and critical discussion suggest that box-wing design is enough mature to deserve more attention by agencies and aircraft constructors.

As for every new configuration, also infrastructural issues, advanced economic analyses and certification process need to be carefully considered. For classical configurations industry can rely on more than a century of experience and this is not trivial to overcome to achieve the great potential advantages offered by Joined Wings, unless there is a political willingness and an investment/effort that can last for decades. On this regard, several studies have been put on hold in the past because of lack of funding and probably absence of a long-term view for the future. This approach needs to change to meet the ambitious goals of a sustainable aviation.

A further delicate point regards the certification process. With all the inherent characteristics of Joined Wings, certification may be cumbersome not just to be conducted, but also to be thought by the national safety agencies. This would be eventually reflected on the development/research costs.

The necessity of significant investments and the associated risks seem then to be the major barriers to Joined Wings. Regarding risks and technical difficulties, literature efforts and previous studies suggest that open issues can be overcome brilliantly without significant penalties. Thus, Joined Wings with their enhanced design freedom (intrinsic to the concept) represent a unique opportunity for the future of aviation.

43. Availability of Scientific Material

If an interested reader has difficulties in obtaining or finding some of the cited works he/she is welcome to contact the authors of this review. They will be immensely glad to help, and also to promote a scientific discussion and interaction.

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