Can low frequency accelerometry replace pressure measurements for monitoring gas-solid fluidized beds?

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A B S T R A C T

This paper is addressed to introduce a methodology based on low frequency accelerometry that can be used for gas solid fluidized bed monitoring, and for dynamic diagnosis purposes. The proposed methodology consists on extracting the low frequency information encoded within an accelerometry signal, by means of the Hilbert transform method. The time and the frequency domain analysis show how this low frequency information is directly related to the conventional pressure fluctuation measurements, providing useful information on bulk and bubble dynamics. The cross correlation and the coherence function analysis between the pressure and the envelope process of the measured accelerometer signals “E”, exhibit values approaching unity for frequencies ranging between 2 and 4 Hz. This reveals that pressure signals and accelerometry envelope are related processes. The results from the Coherent Output Power, COP, and the Incoherent Output Power, IOP, analysis confirms that both pressure and envelope time series exhibit the same global and local features open the possibility of using low frequency accelerometers instead of conventional pressure transducers for monitoring and for dynamic diagnosis purposes.

1. Introduction

The monitoring of gas solid fluidized beds (FB) has been an important issue since they were first used in industry. As the dynamical behaviour characterizing those systems is complex, it is necessary to monitor different bed properties continuously. As an example of that dynamical complexity, it has been shown that, depending on the operational condition, FB can exhibit dynamical chaotic features (Daw et al., 1990; Schouten and van den Bleek, 1992), which can be used, for instance, to predict malfunctioning (van Ommen et al., 2000, 2004).

During the past, a large research effort has been directed towards developing measurement techniques aimed to get knowledge on the dynamic phenomena that take place within the bed (Werther, 1999; Yates and Simons, 1994); some examples are the capacity and the inductance measurements (Brereton and Grace, 1993; Louge and Opie, 1990), techniques based on optic fiber probes (Amos et al., 1996; Zhang et al., 1998), and laser based measurements (Briongos and Guardiola, 2003; Solimene et al., 2007). However, among those techniques, the pressure fluctuations measurements remain as the most used technique (Johnsson et al., 2000; Sasic et al., 2007). The success of the

pressure monitoring is explained by its low cost and the direct relation that exists between the property measured and the bed dynamics. Moreover, from pressure measurements sampled at relatively low frequency it is possible to extract useful information about the bulk, bubble and wave dynamics (van der Schaaf et al., 2002). Therefore, both the quality and the quantity of the low frequency information contained in the pressure signal make this technique the most used to monitor the bed dynamics. Nevertheless, it has several great disadvantages that compromise its applicability to industrial installations: on one hand, the measurement of pressure fluctuation is a local technique, thus it has been reported that the dynamic measured can be affected by different factors such as the pressure probe itself or by the probe length (van Ommen et al., 1999), moreover, some other additional measurement problems might appear such as solid probe blockage. On the other hand, invasive features should be considered, since it is necessary to perforate the vessel in order to introduce the pressure probes inside the bed, limiting applications under severe, corrosive and high pressure/temperature conditions, and pressure probes can represent an obstacle for the free development of bubbles and solid motion.

According to that, the need for non invasive measurement methods is clear, which in principle will offer several advantages with respect to the invasive methods. Thus, because they are located outside the vessel, they neither suffer the harsh operating conditions inside the bed nor do they interfere with the bed

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dynamics. Nevertheless, the application of these methods in industrial fluidized beds is still an unresolved matter; some factors such as the large size of industrial facilities becomes a big challenge for reported non invasive measurement techniques such as tomography, ECT.

During the last decade, the need for non invasive techniques led to the development of acoustic monitoring methods, which are based on microphone/hydrophone and accelerometer measurements (Boyd and Varley, 2001). Those acoustic techniques are later applied as active or as passive methods (Cents et al., 2004; Herrera et al., 2002; Boyd and Varley, 2002). With regard to the passive acoustic emission in which the signal collected is created by the fluidizing process itself, acoustics measurements have been reported by either placing the sensor inside (Zukowski, 2001) or outside the vessel (Briongos et al., 2006b; Cody et al., 1996; Finney et al., 1998). In spite of the initial advantages of the external acoustic measurements (non invasive and low implementation cost), they present some problems. Thus, the measured signal is very complex, and it can be strongly influenced by factors such as the background noise, secondary mechanical vibrations and the vessel response. Moreover, working at ultrasonic measurement ranges is frequently used to avoid noise. Nevertheless, this would lead to high computational costs due to the great number of data in each sample. For this reason, most of the published papers have used data analysis based on averaged properties, which have been mainly attributed to particle dynamics (Cody et al., 1996; Tsujimoto et al., 2000).

To the best of the authors' knowledge, there are few works in literature that use advanced techniques over external passive acoustic signals for getting low frequency information (Briongos et al., 2006b; Finney et al., 1998). Besides, those previous works deal with the unwanted slugging regime. Consequently, the challenge of finding a low cost, non invasive methodology that can replace the conventional pressure measurements is still open.

This paper is addressed to introduce a methodology based on low frequency accelerometry that fulfils the challenge. The proposed methodology consists on extracting the low frequency information encoded within an accelerometry signal, by analyzing the envelope process of the measured accelerometer signal. This low frequency information is shown to be directly related with the conventional pressure fluctuation measurements and consequently, it provides useful information on bulk and bubble dynamics that can be used for monitoring and dynamic diagnosis purposes.

2. Accelerometry fundamentals

The mechanical vibration can be seen as an oscillation motion about a reference position. Moreover, it is well known that the oscillatory motion can originate waves and *viceversa*. In that way, the vibration measurement has information on the physical phenomena behind the oscillating motion. Thus, in order to understand how the information is encoded, let us consider as first approximation the simpler case, where a physical phenomena originates a wave that leads to a periodic oscillating motion, in that case the movement can be described by the harmonic motion as sinusoids. Moreover, the wave theory also establishes that different waves can couple to generate a phenomenon known as beats where the information of forming waves is encoded.

In order to characterize the mechanical vibration, it is necessary to measure such an oscillatory motion where both the amplitude and frequency information are encoded. In principle, it should not matter whether the displacement, velocity or acceleration parameters are measured when studying mechanical vibration, since all three quantities are related by integration or differentiation. However, the physical nature of vibrations sources

Fig. 1. Experimental accelerometry signal in a FB.

and the characteristics of the transducers used for measuring, make one parameter preferred over the others. Thus, it is well known that displacement measurements are suitable when a wide band signal is expected and the low frequency component has to be studied, whereas acceleration, which gives most weight to high frequency components is applied for high frequency studies (Gatti and Ferrari, 1999). However, the accelerometers are most commonly used in practice because of their versatility, small dimensions, wide frequency and dynamic operational ranges, availability and low price. Up to now, the limiting parameter for applying accelerometry to study low frequency phenomena has been the unfavourable signal to noise ratio that characterizes the low frequencies components of the conventional measured accelerometer signals, which used to have poor low frequency response characteristics.

In contrast to conventional accelerometers, in this work, the mechanical vibrations of a FB, are measured with accelerometers with high sensitivity (~ 995 mV/g), which allow to study the low frequency information encoded within the measured signal. An example of the measured accelerometry signal is shown in Fig. 1, where the beat phenomena characterizing narrow band signals can be observed.

As stated above, it is well known that, in order to extract the low frequency information of the phenomena behind the measured signal, it is not suitable to use the direct accelerometry signal (Harris and Piersol, 2002). According to that, for extracting the low frequency information, it is a common practice to integrate the power of the signal with a moving root mean square, rms (Norton, 1989). That operation returns the envelope process associated to the signal. Consequently, similar information can be obtained with other techniques such as the Hilbert transform method or the use of nonlinear energy operators (Huang et al., 2009).

Since most of the dynamical phenomena characterizing FB dynamics such as bubble, and bulk dynamics take place at relatively low frequency (generally below 20 Hz), this paper focuses on the low frequency information stored within the acceleration signals by using the Hilbert transform method to extract the low frequency information. Furthermore, the time and frequency domain analysis are applied to compare the similarity between the pressure and the envelope acceleration, "E", signals recovered through the Hilbert transform methodology,

3. Analysis methods

3.1. Frequency domain

The frequency domain analysis has been widely applied to characterize fluidization regimes (Satija and Fan, 1985; Zijerveld

et al., 1998) and to gain knowledge on the physical phenomena that take place inside a fluidized bed (Kage et al., 1991; Sun et al., 1994). Among the different spectral properties, the power spectrum density (PSD) provides a picture of the characteristic frequencies appearing within a signal. There are different methods to estimate the spectra; here, Welch's method is used for the PSD estimation by averaging 29 periodograms, achieving a good trade off between resolution and error (Brown and Brue, 2001).

It has been reported in literature that pressure fluctuations within the bed can be due to local and global contributions (Bi et al., 1995; Sasic et al., 2007; Bi, 2007). That fact leads to the use of different techniques focused on identifying and distinguishing those contributions from the measured signal. Thus, the multi scale nature of fluidized bed dynamics has drawn considerable attention in the last years (Li and Kwauk, 2001; Lu and Li, 1999; Zhao and Yang, 2003; Briongos et al., 2006a, 2007; Abbasi et al., 2009). However, due that the causes and sources of accelerometer signals are not yet understood, the Coherent Output Power, COP, and the Incoherent Output Power, IOP, analysis used in van der Schaaf et al. (2002) is applied here as a first approach to analyze the different dynamical components appearing in the envelope process, comparing the local and global information stored in both pressure and envelope accelerometer signals. Consequently, the cross spectral properties measured by the normalized cross PSD function (coherence function), between two or more signals collected at different positions within the bed, have been used to study the joint behaviour of the compared signals, quantifying the linear causality existing between them. Thus, the more correlated the frequencies, the higher the coherence. According to that, the joint behaviour of plenum and in bed pressure signals is used to perform a preliminary distinction between local and global dynamics from a measured signal.

3.2. Envelope process and the Hilbert transform

As stated above, in order to extract the low frequency information contained in the signal measured by the accelerometers, $a(t)$, the Hilbert transform is used to recover the envelope process, $A(t)$, associated with $a(t)$. As Fig. 2 shows, the envelope process consists of a pair of smoothly varying curves around the measured signal. Considering $a(t)$ as a non stationary dynamical process having evolutionary spectral density, its envelope is given by (Nigam, 1983)

$$A(t) = \sqrt{a^2(t) + b^2(t)}, \quad (1)$$

where $a(t)$ and $b(t)$ are orthogonal non stationary dynamical processes and can be considered as the rectangular coordinates of a point in the (a,b) plane (Fig. 3), defined by an analytic signal of the form:

$$Y(t) = a(t) + b(t)i \quad (2)$$

Fig. 2. Time series and associated envelopes.

Fig. 3. Temporal evolution of an analytic signal in the complex plane.

Table 1

Fluid-dynamic characteristics of Ballotini glass beads (Group B of the Geldart classification).

d_p (m)	ρ_{mf} (kg/m ³)	Φ	ε_{mf}	ρ_p (kg/m ³)	u_{mf} (m/s)
$3.8 \cdot 10^{-4}$	1462	0.9	0.407	2464	0.107

Fig. 4. Frequency response of the used accelerometers. Reference sensitivity: 995 mV/g.

Fig. 5. Standard deviation of pressure and E signals vs. reduced air velocity.

According to that, in order to obtain the envelope from an experimental accelerometer signal, we need first an analytic function $Y(t)$. Consequently, though there are many ways of defining the imaginary part of a function, the Hilbert transform

provides a unique way to obtain such an imaginary component. Therefore, the result of applying the Hilbert transform to an experimental accelerometer signal is an analytic function. Analytic signals have been broadly applied in vibration studies despite the fact that this technique might induce some errors in the calculation of the envelope that could influence its nonlinear characteristics (Harris and Piersol, 2002; Cheng et al., 2007).

4. Experimental

Accelerometry and pressure fluctuation signals were recorded in a cylindrical poly methyl metacrylate (PMMA) vessel of 0.07 m diameter and 1 meter high. The air distributor consists of 7 tuyeres that provide a homogeneous air distribution. Each tuyere has 8 holes 0.5 mm diameter giving a distributor total pressure drop between 290 and 750 Pa in the operating conditions. The

Fig. 6. Autocorrelation and cross-correlation functions for pressure and E signals: (a) u_R 1.2; (b) u_R 2.6.

Fig. 7. Pressure spectra, f_s 200 Hz: (a) u_R 1.2; bubbling regime (b) u_R 1.6, bubbling regime; (c) u_R 2.1, churn regime; (d) u_R 2.6, churn regime.

Fig. 8. E spectra. f_s 200 Hz: (a) u_R 1.2; bubbling regime (b) u_R 1.6, bubbling regime; (c) u_R 2.1, churn regime; (d) u_R 2.6, churn regime.

characteristics of the fluidized bed and particles are shown in Table 1.

Pressure and acceleration signals were measured during 5 min with a sampling frequency of, respectively, 200 Hz and 10 kHz (to avoid resonant amplification in the accelerometers). Later, the envelope of the accelerometer signals was estimated with the Hilbert transform and subsequently resampled at 200 Hz in order to have the same size as the pressure signals. Simultaneously, pressure fluctuations were recorded with a frequency of 200 Hz. Four runs at reduced air velocities u_0/u_{mf} of 1.2, 1.6, 2.1 and 2.6 were performed to explore different operational conditions. The minimum fluidization high, h_{mf} , was 0.165 m. The pressure probes P1, P2 and P4 are located at 0.125 and 0.055 m from the distributor and inside the plenum, respectively. The accelerometers E1 and E2 are placed at 0.125 and 0.055 m from the distributor, as close as possible to the pressure probes, respectively.

4.1. Acceleration measurement system

The horizontal vibrations of the vessel wall were collected by means of commercial accelerometers (Brüel and Kjaer Type 4507 B 005) located in the external face of the wall by means of mounting slots supported with glue. The accelerometers are fitted to a NI 9233 (National Instruments) acquisition module inserted in a chassis NI cDAQ 9172 connected to a PC. The software used to acquire the signals is Labview 8.5. The sensors have a sensitivity of 995 mV/g and a resonant frequency of 16.3 kHz.

Special care was taken with the wire that connects each accelerometer with the data acquisition device to avoid

triboelectric noise in the signal. The frequency response of the accelerometers is shown in Fig. 4.

4.2. Pressure measurement system

Pressure fluctuations were recorded by a probe 6 cm length and 4 mm i.d. connected to a pressure transducer PR3110 (Ellison Sensors) fitted to a NI 9205 data acquisition module. This module was also mounted in the chassis NI cDAQ 9172. The distance between the probe and the transducer is less than 0.2 m. These sizes led to ensure that damping effects are negligible (van Ommen et al., 1999).

5. Results

5.1. Information from visual observation

The visual inspection of the fluidization state has revealed two types of fluidization regimes within the operating conditions explored: bubbling regime was observed for reduced air velocities $1.2 \leq u_R \leq 1.6$ and churn type regime was observed for $u_R > 1.6$. The appearance of both states is qualitatively described below.

Bubbling regime: As described previously in literature, several bubbles simultaneously present within the bed that increase their size quickly with the distance from the distributor; as a result, the lower part of the vessel has a bubble distribution (bubble number and size) quite different from the upper part. Moreover, it has been observed that the bed geometry (narrow bed) strongly influences the resulting PSD, the narrow bed feature of the facility makes the natural bed frequency dominate the spectra.

Fig. 9. Cross coherence coefficient, $f_s = 200$ Hz: (a) $u_R = 1.2$; bubbling regime (b) $u_R = 1.6$, bubbling regime; (c) $u_R = 2.1$, churn regime; (d) $u_R = 2.6$, churn regime.

Churn type regime: Controversy exists about the existence of this regime in gas solid FB (Hewitt and Jayanti, 1993). In this work, we refer to a form of developing slug flow in short pipes with the appearance of a churning motion. Consequently, that region of churn like flow is characterized by large bubbles with a diameter similar to the vessel size, which result in a vigorous fluidization process.

5.2. Time domain comparison

The time domain analysis is frequently used to gain knowledge of the temporal scale of the dynamical processes (fast or slow processes) underlying the time series under study. The probability structure of the time series is used to be characterized by means of its moments. Thus, the standard deviation σ is a frequently used parameter for monitoring and diagnosis purposes of gas solid FB. In spite of the well known limitations of σ (Johnsson et al., 2000), it can be used, for instance, either to detect the transition velocity, u_c , towards turbulent fluidization or as an indicator to detect malfunctioning (van Ommen et al., 2004). The standard deviation of experimental pressure and E signals is shown in Fig. 5. It is observed that σ behaves similarly for both the pressure and the accelerometer signals, increasing with the air velocity. The fact that the standard deviation presents the same trend for both signals points out the similarity between the amplitude information stored in both the accelerometer and the pressure signals. Consequently, it can be argued that the standard deviation estimated from accelerometer signals could replace the standard deviation of the pressure signal in some reported

applications such as to determine malfunctioning and for estimating the minimum fluidization velocity.

Since the probability structure of a time series is usually described in terms of second order statistics, the correlation function is frequently used as a measurement of the temporal structure of the time series. It is well known that the autocorrelation function assumes a linear relationship between the data. Nevertheless, it provides useful information about dynamical correlations existing within time series. Thus, the autocorrelation and the cross correlation functions for P1 and E1 signals estimated for $u_R = 1.2$ and $u_R = 2.6$, are shown in Fig. 6. The results from the autocorrelation analysis reveal that both P1 and E1 measurements exhibit a similar temporal structure. Moreover, the computed cross correlation function, between P1 and E1 time series, shows clearly that both phenomena, the pressure fluctuations and the mechanical vibrations, are related.

5.3. Frequency domain analysis

In order to study the characteristic frequencies of all the measured signals, let us focus the attention on studying the spectral properties of the correlation functions. Thus, as stated above, Welch's method is used for the PSD estimation and the coherence function, γ^2 , is subsequently computed to quantify the degree of linear coupling between pressure and E signals at a given frequency. According to that, from the characteristic frequencies of the measured pressure fluctuation signals shown in Fig. 7, it can be observed that the energy of the spectra is distributed mainly below 10 Hz with a dominant frequency at

Fig. 10. Normalized coherent (COP) spectra of pressure and E signals. $f_s = 200$ Hz: (a) $u_R = 1.2$; bubbling regime (b) $u_R = 1.6$, bubbling regime; (c) $u_R = 2.1$, churn regime; (d) $u_R = 2.6$, churn regime.

2.5 Hz, which correspond to the natural bed frequency ($f_{\text{bulk}} = 2.5$ Hz (Baskakov et al., 1986)), for all operational conditions covered. Moreover, the dynamical features of the two flow conditions qualitatively described previously, from visual observation, are now explained by the spectra shown on Fig. 7. Thus, during the bubbling regime, it is observed how the different bubble distribution along the bed give rise to pressure spectra whose energy is quite dependent on the probe position (Fig. 7a,b). In contrast, during the churn like behaviour (Fig. 7c,d) the promoted vigorous fluidization equalizes the energy of the spectra estimated from the different position.

The E signals shown in Fig. 8 provide a spectra characterized by an energy content distributed below 10 Hz as was observed for the pressure fluctuation signal. Moreover, the dominant frequency at 2.5 Hz is also distinguishable and, the different dynamical features characterizing the observed bubbling and churn like flow are clearly reflected on the envelope spectra. However, in contrast to pressure signals, which during the churn like behaviour (Fig. 7c,d) equalize the energy of the spectra estimated from the different position, the accelerometer power seems not to be influenced for that churning flow, in the sense that the energy relation between signals taken at different position remains unchanged. Nevertheless, as shown by the previous spectra (Figs. 7 and 8) there is a clear relation between the measured pressure and E signals. Accordingly, Fig. 9 shows the coherence function between pressure and E signals, which were collected simultaneously at the same bed height. As expected, a

high coherence is observed for frequencies ranging between 2 and 4 Hz, especially for measurements collected at P1 and E1 positions, with a coherence function, $\gamma^2 > 0.8$, which reveals the existence of a high degree of coupling between the processes occurring at that frequency interval. This is in agreement with the previous results reached in the time series analysis, concluding that both phenomena, the pressure fluctuations and the mechanical vibrations, are related.

5.4. COP/IOP analysis

It has been reported (van der Schaaf et al., 2002) that some dynamic phenomena such as bubble coalescence, gas flow fluctuation, bubble eruption and bed mass oscillation generate fast pressure waves that propagate in such a way that they can be measured almost instantaneously through the entire bed. Consequently, pressure measurements taken at different bed positions will show coherence due to those fast travelling waves. In contrast, other phenomena such as gas bubbles and turbulence only generate a local fluctuation in pressure corresponding to low coherence phenomena. Thus, in order to distinguish the different components in the E signals, the normalized coherent (COP) and incoherent (IOP) output power were calculated for the pressure signals collected at the plenum and at some in bed positions, and for accelerometry signals taken at two different positions within the bed (Figs. 10 and 11).

Fig. 11. Normalized incoherent (IOP) spectra of pressure and E signals. $f_s = 200$ Hz: (a) $u_r = 1.2$; bubbling regime (b) $u_r = 1.6$, bubbling regime; (c) $u_r = 2.1$, churn regime; (d) $u_r = 2.6$, churn regime.

The resulting normalized COP function of pressure and E signals are shown in Fig. 10, where the contribution due to the bed mass oscillation, $f_{bulk} = 2.5$ Hz (Baskakov et al., 1986) is clearly distinguishable on the COP spectra for both pressure and E time series. Moreover, it is observed that for bubble regime, the second maximum detected by the COP estimated from the pressure fluctuation signals does not appear on the COP computed from E signals that shows a low coherence for the frequencies above 4 Hz. That fact might be attributed to either vessel response or wave propagation mechanism. In contrast the COP for both the pressure and the E signal for churn like flow exhibit similar characteristics.

With regard to the normalized IOP analysis (Fig. 11), the high similarity between the pressure and the E spectra is remarkable, which points out that the local information due to gas bubble and turbulence is barely affected by the measurement technique. Consequently, from a frequency domain point of view there is no difference in using E or pressure signal to study local phenomena.

6. Conclusions

The low frequency information encoded within an accelerometer signal measured by low cost commercial accelerometers provides useful information on bulk and bubble dynamics that can be used for gas solid fluidized bed monitoring, and dynamic diagnosis purposes.

The proposed methodology, consisting on extracting the low frequency information carried within an accelerometer signal by means of the Hilbert transform method, succeeds in recovering the dynamical information below 20 Hz, which has been shown to be directly related to the conventional fluidized bed pressure fluctuation measurements.

The time domain analysis, in terms of standard deviation and autocorrelation function, reveals that both the pressure fluctuation and the mechanical vibration have a similar probability structure. Furthermore, from the cross correlation analysis between the pressure and E signals, it is concluded that they are related processes.

The frequency domain analysis confirms the previous results drawn from the time series analysis, pointing out the existing relation between pressure fluctuation and vibration phenomena. Thus, the PSD of both pressure and E signals reflect the different dynamical features characterizing the observed bubbling and churning like flow at the operational condition covered. Moreover, the coherence function computed between pressure and E signal exhibits values approaching unity for frequencies ranging between 2 and 4 Hz.

Finally, the COP/IOP analysis of the E signals exhibits similar characteristics as the COP/IOP analysis of pressure fluctuation signals, opening the possibility of using low frequency accelerometer instead of conventional pressure transducer for monitoring and dynamic diagnosis purposes. However, despite the fact that the results at lab scale level are very promising, more

research on low frequency accelerometry is needed before replacing pressure measurements for the monitoring of industrial gas solid fluidized beds. Other aspects such as insulation thickness and vessel material can influence the quality and quantity of the accelerometer data. Besides, multi resolution and state space analysis should be complementarily applied with frequency and time domain analysis to get further knowledge on the origin and characteristics of the E signals.

Notation

Uppercase letters

- $A(t)$ instant amplitude of the signal
 N_s number of averaged periodograms
 $Y(t)$ analytic signal

Lowercase letters

- $a(t)$ real part of the Hilbert transform
 $b(t)$ imaginary part of the Hilbert transform
 d_p mean particle size, m
 f frequency, Hz
 f_{bulk} frequency of the bulk oscillations, Hz
 f_s sample frequency, Hz
 h_{mf} minimum fluidization high, m
 u_0 air velocity, m/s
 u_{mf} minimum fluidization velocity, m/s
 u_R reduced velocity, u_0/u_{mf}

Greek letters

- ε_{mf} minimum fluidization voidage
 σ amplitude, mbarg, g
 Φ Sphericity
 ρ_{mf} minimum fluidization density, kg/m³
 ρ_p particle density, kg/m³

Abbreviations

- COP coherent part of the power spectrum, mbarg²/Hz, g²/Hz
IOP incoherent part of the power spectrum, mbarg²/Hz, g²/Hz
PSD power spectral density, mbarg²/Hz, g²/Hz

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