A Plastic Fiber-Optic Liquid Level Sensor

S. Vargas, C. Vázquez, A. B. Gonzalo, and J. M. S. Pena

Dpto. Tecnología Electrónica, Escuela Politécnica Superior, Universidad Carlos III Madrid

Avenida Universidad 30, 28911 Leganés, Madrid, SPAIN, email: sevargas@ing.uc3m.es

ABSTRACT

A system for measuring liquid level in multiple tanks using optical fiber technology has been developed. Oil field service industry or any sector requiring liquid level measurements in inflammable atmospheres can be benefited from this intrinsically safe technology. Three different models considering various effects have been derived and tested on two prototypes. The first model use punctual emitters and divergence, the second model use finite emitters with paraxial approach, and the third model use a constant power rays distribution in the emitters using with each one of the rays the Snell's law, to take in count the optical aberrations. A Monte-Carlo method is used to fit the experimental data and obtain the models parameters. The simplest model is demonstrated to be accurate enough for a proper correlation between the experimental data and the fitted curve in a range of 2 m.

Fiber-optic sensor, liquid level measurement, plastic optical fibers.

1. INTRODUCTION

There are several methods for measuring and remote monitoring liquid levels. Mechanical float-type level indicating devices have been used to measure fluid levels by placing a float in the vessel itself. This method provides accurate readings but requires frequent calibration and maintenance because it is an intrusive method so the liquid can deteriorate the hardware. Other disadvantage is that the electronics must be kept close to the measuring point. Ultrasonic level detectors avoid direct contact with the fluid, using a transmitter/receiver but suffers from inaccuracies caused by varying temperatures and densities in the area above the fluid level and from potential confusion of echoes [1]. Microwave and radar indicators also avoid contact with the fluid but in some designs inaccurate measurements are obtained in fluids with poor dielectric constants. Depending on the operation frequency, the antenna dimensions can limit the minimal distance to the liquid surface to be measured. Even more, all previous methods are electronic in nature so they suffer from intrinsic safety concerns. As with any electronic device, there are necessarily, heat generating components that create, no matter how remote, the possibility of hazardous situations when used in areas where flammable materials are present. So an extra cost must be considered to make these techniques suitable for inflammable atmospheres with no risk.

Optical technologies with optical fibers are intrinsically safe in nature, with no risk of explosion even under malfunction operation, because inside the tank and the surroundings there is only inert materials such as optical fibers. Different laser and optical instrumentation devices have been already used in level measurement systems, Clark R. [2] disclosed one and referenced others but in any of them the laser, so the electronic driver, is in the sensor head. Optical fibers have been used in the sensor heads but for measuring short distances or just as simple control level devices [3 – 6]. A remote sensor head based on optical fibers for long distance is disclosed by Clifford B. and Harrison J. [7], but using different lenses for the fibers in the transmitter and the receiver and the level in the vessel is measured as a function of the time required for a laser signal to be transmitted from the sensor, reflected off the liquid surface and returned to the receiver lens located in the sensor.

In this paper, we discuss three models for a fiber-optic liquid level sensor that use the received modulated power to detect the level of the vessel with only one lens by sensor head. Optimization of the models is made using data from a liquid level sensor system developed in our laboratories. This sensor system consist of electronics that modules 650 nm

lasers diodes which are housed in ST connectors to obtain compact and rough prototypes. The laser light excites the sensor heads through a polymer optical fibers. The received light on the sensor heads is transmitted with another polymer optical fiber, to the opto-electronics circuits of detection, for properly conditioning the light reflected off the liquid surface. The sensor head consist of one collimation lens, and two polymer optical fibers one for the modulated laser light sent and the other one to recovery the reflected light off the liquid surface. Control and Data acquisition in the system is developed using a micro-controller which is connected via RS-232 port to the PC.

1. MODELS

The models presented here, approach the data acquired using two different sensor heads (as a function of the liquid level), to the best fit curve using the Monte Carlo method. In figure 1, we can see a picture of the two sensor heads (SH1 and SH2) used in the system to acquire data, in both can be seen the emitter and reception fibers and the lens. The SH1 use a Fresnell lens with 60 mm of diameter and a focal of 75 mm, and the SH2 use a lens with 25.4 mm of diameter and a focal of 75 mm.

Figure 1. Sensor heads 1 (SH1) and 2 (SH2).

The three models presented are, punctual emitter and divergence, finite emitters with paraxial approach, and rays count with Snell's law.

1.1. Punctual Emitter and Divergence

In this model the emitter and reception fibers of the sensor heads are placed on the focal plane of the lenses. Under this assumption the light will be perfectly collimated, but this beam must form a little angle with the optical axis of the lens which depends on the geometry of the fiber ends on the sensor heads. Also we assume that the absorption of light by the air is negligible, the power in the beam is uniform, and the numerical aperture of the fiber is enough to accept the incidence angle of the reflected beam. In figure 2 we can see the transmitted and reflected beam with the assumptions until now exposed.

Fig. 2. Operation principle, incident — and reflected ---- beams.

Fig. 3. Intersection area between the lens area and beam reflected area.

Under this assumptions and allowing a beam divergence (α) the power detected is proportional to the rate between, the intersection area of the reflected beam in the lens plane with the lens area, to the lens area, as we can see in figure 3. Since the power detected is given by:

$$P(k, \alpha) = k \frac{a_1^2(\theta_1 - \sin\theta_1) + a_2^2(\theta_2 - \sin\theta_2)}{2\pi a_2^2} \quad (1)$$

where k is a parameter used to take in count the liquid reflectance and the fiber attenuation, θ_1 and θ_2 are parameters which depends on the sensor head geometry, and a_1 is the lens radius and a_2 is the beam radius in the lens plane which is given by:

$$a_2 = a_1 + 2D \times \tan(\alpha) \quad (2)$$

where D is the lens to liquid length, and α is the divergence angle.

The experimental data is then fitted to $P(k, \alpha)$, using the Monte-Carlo method adjusting the parameters k and α that minimize the average length between the experimental data and $P(k, \alpha)$. Which is defined as:

$$d_m = \sqrt{\frac{\sum_i (Exp(i) - P(k, \alpha)(i))^2}{N}} \quad (3)$$

where d_m is the average length $Exp(i)$ are the experimental data, and $P(k, \alpha)(i)$, are the points of the fitted curve, and N the number of points.

Figure 3: Fitted curve of SH1 and SH2, with the first model.

In figure 3 we can see the data and the fitted curve for the SH1 and SH2 for this model. Where the average length for the SH1 was 3.9 mm and for the SH2 was 9.5 mm.

1.2. Finite Emitter with Paraxial Approach

This model is different to the previous because the fiber cores are considered as objects, the emitter fiber is placed out of the focus of the lens (not being needed the α parameter), and the power detected is derived using paraxial approach. With this model the power detected now is given by:

$$P(k, ef) = k \cdot \frac{A}{B} \cdot \frac{C}{D} \quad (4)$$

where k is a parameter to take in count the reflectance and attenuation of the fiber, ef is the length from the emitter fiber to the lens plane, A is the intersection area between the reflected beam and the lens, B is the beam area in the lens plane, C is the intersection area between the beam and the core of the reception fiber, and D is the beam area in the plane of the reception fiber. The ratio between the A/B , and C/D are calculated in the same manner of the previous model. The experimental data is fitted to the Eq. (4) adjusting the k and ef . In figure 4, we can see the experimental data and the fitted curve, being now the average length (d_m) for SH1 and SH2 of 4.2 mm, 10.4 mm respectively.

1.3. Rays Count with Snell's Law

In this model we divide the power emitted in N_l rays ($N_l > 400000$) and used the Snell's law with each one to take in

count the optical aberrations. The optical path of each ray is determined and the power detected in this model is proportional to the number of rays that impact in the core of the reception fiber (N_2). In this model we adjust the same parameters of the previous model k and ef . The resulting fitted curves for the SH1 and SH2 are shown in figure 5.

Fig. 4. Fitted curve of SH1 and SH2, with the second model.

Fig. 5. Fitted curve of SH1 and SH2, with the third model.

Whit this model the average length for SH1 and SH2 are 5.3 mm and 10.4 mm, respectively.

2. COMPARATIVE

The figures 3, 4, and 5, shown the data and fitted curves for the three models. At first can't be detected which of them is the best for the data acquired with the sensor heads SH1 and SH2, nevertheless, the average length given in Eq. (3) for each one of the models, can give us a real appreciation of which of them is the best model. In table 1, we can see the average length of each model and sensor head, showing that the first (and simplest) model is the model that best fits a curve to each one of the data acquired, because it have the minimum average length for the two sensor heads.

	Punctual Emitter and Divergence	Finite Emitter with Paraxial Approach	Rays Count with Snell's Law
SH1	3.9 mm	4.2 mm	5.3 mm
SH2	9.5 mm	10 mm	10.4 mm

Table 1. Average length for each one of the models, using two different sets of data acquired.

3. CONCLUSIONS

We have shown a fiber-optic liquid level sensor, which use polymer optical fiber to transmit and collect the modulated optical power of a laser diode, to a sensor head in a vessel. This sensor head is composed of only one lens, and two fiber ends, one for emit and other for receipt the power reflected in the interface liquid-air. The system is not intrusive and reliably, allowing the measure of inflammable liquids because separate physically the electronics from the liquid to measure. Also we have presented three models that have been used to fit the experimental data (obtained using two sensor heads), to parametric curves given for the models, using the Monte-Carlo method. We have found that the model of punctual emitter and divergence gives the best results, because give the minimum average length for SH1 and SH2.

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