Displacer-Type Liquid Level Sensor with Liquid Density Auto-Compensation

Matheus Souza[1], Elyson Carvalho[2], Jânio Canuto[2], Raimundo Freire[3], Valner Brusamarello[1]

[1] PPGEE, Federal University of Rio Grande do Sul, Porto Alegre, RS, Brasil
[2] PROEE, Federal University of Sergipe, São Critóvão, SE, Brasil
[3] PPGEE, Federal University of Campina Grande, Campina Grande, PB, Brasil
e-mail: souza.matheus@ufrgs.br

Abstract— **In the classic displacer-type liquid level measuring method, liquid level is calculated via the buoyancy force exerted by the liquid on a displacer. This technology has high linearity, precision, accuracy, ease of installation and low cost. Nonetheless, displacer level sensors have significant sensitivity to variations in liquid density, which hinder its use in industrial applications that such quantity is not held constant. In this paper a novel displacer-type liquid level sensor is presented and analyzed. The innovation of the new sensor consists of adding another displacer and thus calculating the new measured value by the quotient of the buoyancy forces of both displacers. Therefore, the new measurement is ideally insensitive to the variations in liquid density. A prototype was built and prototype results presented high linearity, being able to mitigate the sensitivity to the liquid density, increasing accuracy in the measurements.**

Index Terms— **Displacer level sensor, liquid level measurement, density invariant, load cell.**

I. INTRODUCTION

Liquid level measurement plays an important role in various industrial processes [1]. It implies the need to measure level under different situations such as environmental conditions, vessels forms, liquid density, corrosiveness, temperature and viscosity [2, 3]. Thus, there are several kinds of level sensors available whereby capacitive, optical fiber, radar, ultrasound, time-domain reflectometry, hydrostatic, superconducting, displacer, laser, among others [4, 5, 6]. Level sensors can be classified according to the measurement principle, being divided into three categories: measurements using the effects of density, time-of-flight measurements and measurements by detecting physical properties [7]. Each measuring principle has its advantages, limitations, the most appropriate applications, and for some situations, involving the environment and people safety, more than one measurement principle is used to increase the system robustness. In order to expand these applications and qualities of sensors, works in this field are still developed.

Bera *et al.* [8] presented a novel capacitance-type liquid level sensor which eliminates the effect of self-inductance of the metallic rods improving the sensor linearity. Xu *et al.* [9] implemented a level sensor based on acoustic resonance by detecting a frequency range instead of the single fundamental frequency and increasing the measuring accuracy. Li *et al.* [10] proposed an alternative method to improve the measuring accuracy of ultrasonic level sensors. They developed a liquid level detection based on the multiple-input multiple-output ultrasonic transducer array. The experimental results showed the method proposed by Li *et al.* is superior to the conventional approach.

Some industrial processes such as oil, food and pharmaceutical industries suffer significant variations in liquid density [2, 6]. Also, several level sensors are sensitive to liquid density variations hindering such applications. Thus, the most appropriated level sensors for these activities are the time-of-flight measurement sensors, because they are insensitive to variations in liquid density [7]. However, those sensors are usually expensive (*e.g.*, laser sensor) or they are strongly sensitive to the wave propagation medium (*e.g.*, ultrasonic sensor) [4, 7]. Such applications require a level sensor insensitive to variations in liquid density, low cost and insensitive to the wave propagation medium.

A specific low cost level sensor is the displacer-type sensor. In addition, it has high linearity, accuracy and ease of installation [11, 12]. Nonetheless, this sensor has significant sensitivity to variations in liquid density [7, 11], because the level measurement is performed indirectly through the buoyancy force, also dependent of the liquid density. In this article we present the analysis and the results of a new displacer-type liquid level sensor [6, 13]. The innovation of the new sensor consists of doing measurements ideally insensitive to the liquid density by adding another displacer and thus calculating the new measured value by the quotient of the buoyancy forces of both displacers. This new approach was proposed in [6] and [13] validated only by simulation, in this paper we have built a prototype and validated the system through actual experiments. Several tests were performed in order to measure the sensor characteristics, such as linearity, hysteresis and liquid density dependence. The results showed a high linearity sensor that significantly mitigated the sensitivity to variations in liquid density.

The sequence of this paper is structured as follows: Section II. briefly describes the classic displacer-type level sensor. Section III. presents the novel method. The sensor prototype is described in Section IV. Section V. details the prototype calibration. Results and discussion are presented in Section VI. Finally, Section VII. draws conclusions and future works.

II. CLASSIC DISPLACER-TYPE LEVEL MEASURING METHOD

The classic sensor proposed by Kulkarni, Karekar and Aiyer [11] is like the one illustrated in Fig. 1 only without the displacer D_2 and the load cell C_2. It is composed of the displacer D_1, which is a solid cylinder with weight W_1 connected to the load cell C_1. The liquid level is computed through the buoyancy force over the displacer D_1 measured

Digital Object Identifier 10.29292/jics.v15i3.179

by the load cell C_1. The buoyancy force over D_1, denoted by B_1, is given by

$$B_1(\rho_L, L_S) = \rho_L \cdot g \cdot A_1 \cdot L_S, \tag{1}$$

where ρ_L is the liquid density, g is the gravitational acceleration, A_1 is the area of the cross-section of D_1 and L_S is the length of the submersed part of D_1. Since ρ_L, g and A_1 are known, and the buoyancy force B_1 is measured by the sensor, the actual level can be calculated through L_S, described as

$$L_S(B_1) = \frac{B_1}{\rho_L \cdot g \cdot A_1}. \tag{2}$$

Analyzing (2) it is easy to infer the classic displacer-type level measuring method is sensitive to variations in liquid density ρ_L, because L_S is inversely proportional to ρ_L, hindering the application of this method in industrial activities under variations in liquid density. Kulkarni, Karekar and Aiyer [11] have implemented this classic method and results have shown sensitivity to variations in liquid density in spite of high linearity, precision, accuracy, low cost and easy implementation.

The sensitivity to variation in liquid density of the method is analyzed in [6] and in order to solve this problem we have proposed a novel approach described in the next section.

III. Novel Displacer-Type Level Measuring Method

The proposed method consists in adding a second displacer, D_2, connected to a second load cell, C_2, as illustrated in Fig. 1. The buoyancy force, B_2, applied in D_2 is given by

$$B_2 = g \cdot \rho_L \cdot V_2, \tag{3}$$

where g is the gravitational acceleration, ρ_L is the liquid density and V_2 is the volume of D_2.

Displacer D_2 is placed in such a way that it is always submerged, making the volume V_2 a constant. Thereby, the buoyancy force B_2 depends only on ρ_L. However, the load cell C_2 measures the resulting force on the displacer D_2, then, B_2 can be calculated by

$$B_2 = W_2 - F_2, \tag{4}$$

where W_2 is the weight of D_2 and F_2 is the resulting force on D_2. Note that the buoyancy force over the rod connecting D_2 to the load cell C_2 is disregarded in the ideal mathematical model and will be analyzed in Subsection A.

The sensitivity to the liquid density variations is eliminated dividing B_1 by B_2. This ratio, R, is given by

$$R = \frac{B_1}{B_2} = \frac{g \cdot \rho_L \cdot A_1 \cdot L_S}{g \cdot \rho_L \cdot V_2} = \frac{A_1 \cdot L_S}{V_2}, \tag{5}$$

thus, the liquid density can be eliminated making the level measurement ideally insensitive to variations in liquid density. Note that in order to eliminate ρ_L in (5), we have considered the liquid density throughout the reservoir constant. Thus, the sensor can be applied only in homogeneous liquids. When the liquid density is not constant a measurement error is added to the system, as presented in [13] by simulations.

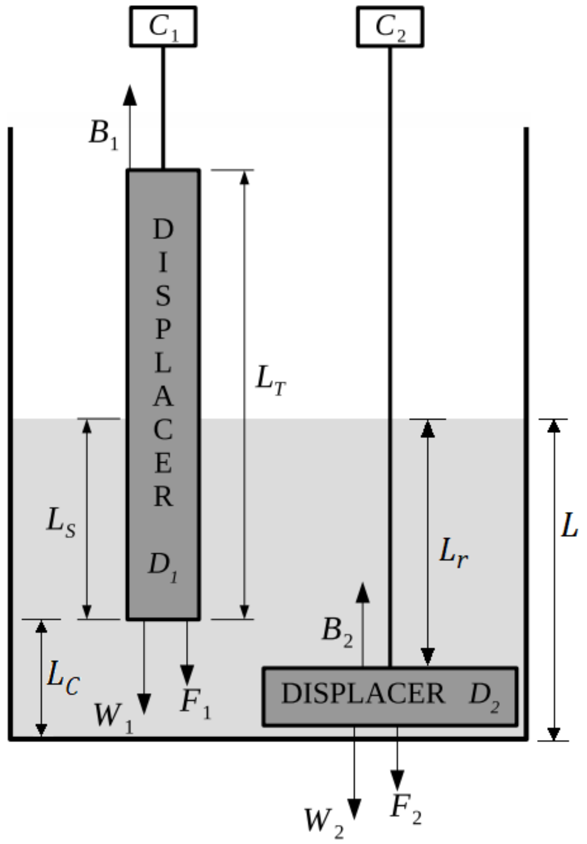

Fig. 1: Novel displacer-type level measuring method. Level estimation is calculated dividing B_1 by B_2, described by (7).

Rearranging (5) we have

$$L_S = R \cdot \frac{V_2}{A_1}, \tag{6}$$

thereby, the level L can be calculated by

$$L = L_S + L_C, \tag{7}$$

where L_C is the distance between the bottom of the reservoir and the beginning of the displacer D_1, see Fig. 1.

A. *Prototype Model*

Equation (5) demonstrates the presented displacer-type level measuring method is ideally insensitive to variations in liquid density. Nevertheless, the prototype model has a non-ideality that should be considered: the buoyancy force over the rod connecting D_2 to the load cell C_2, described by

$$B_r = L_r \cdot A_r \cdot \rho_L \cdot g, \tag{8}$$

where L_r is the length of the submersed part of the rod and A_r is the cross-section area of the rod.

The mathematical model is obtained by dividing B_1 by B_2. In order to build the prototype model we need to include B_r:

$$\begin{aligned} \frac{B_1}{B_2 + B_r} &= \frac{g \cdot \rho_L \cdot A_1 \cdot L_S}{g \cdot \rho_L \cdot V_2 + L_r \cdot A_r \cdot \rho_L \cdot g} = \\ &= \frac{A_1 \cdot L_S}{V_2 + L_r \cdot A_r}. \end{aligned} \tag{9}$$

By knowing that A_1, V_2 and A_r are constants, (9) depends on L_S and L_r. The non-linearity introduced by L_r

to the model is analyzed in [13]. In order to make the prototype feasible, that non-linearity was disregarded by making $B_2 >> B_r$, and using the ideal mathematical model described in (7). The prototype was built with a large V_2 and a small A_r to make $B_2 >> B_r$.

Considering the values of V_2 and A_r of the prototype and for the conditions of the experiments carried out in this work, the maximum measurement error as a result of disregarding Br is 0.023%, calculated by (5) and (9) using the prototype parameters. When level increases the error also rises. Thus, in order to maintain this error negligible in measurements for large level values, it is mandatory to choose suitable values for V_2 and A_r. The prototype parts and parameters will be detailed in the next section.

IV. PROTOTYPE

Fig. 2 shows the sensor prototype, which consists of two displacers, D_1 and D_2, two load cells, C_1 and C_2, and a signal conditioning circuit for each load cell. D_1 was made using a cemented PVC pipe. The bottom was sealed with silicone and the upper part was fixed to the load cell C_1. Mass, height and diameter of D_1 are 1.820 kg, 1.040 m and 0.025 m, respectively. In this setup, the weight is always greater than buoyancy force making the resulting force acting on D_1 always in the same orientation.

Displacer D_2 was built using PVC pipe filled with lead in order to guarantee the weight is always greater than the buoyancy force. D_2 is fixed to the load cell C_2 by an enameled wire with a diameter of 0.39 mm. Mass, width, depth and height of D_2 are 0.365 kg, 0.064 m, 0.045 m and 0.040 m, respectively.

Load cells C_1 and C_2 were designed for a maximum load of 5 kg. They were fixed to the reservoir top and each load cell has four strain gauges forming a full Wheatstone bridge, which allows compensation for environment temperature variations [14]. Each Wheatstone bridge is powered by a 5 V source and the differential output signal of each bridge is connected to an instrumentation amplifier INA126. Fig. 3 shows the complete circuit for each load cell. The RG, gain resistor, for the load cells C_1 and C_2 circuits are 47 Ω and 56 Ω, respectively, and the gain in each INA126 is given by

$$G = 5 + \frac{80k\Omega}{RG}. \tag{10}$$

The circuits output voltage were measured by two multimeters Minipa ET-1400.

V. CALIBRATION

In the prototype calibration process a millimeter scale arranged on the front wall of the reservoir was used as the standard reference. Calibration results allowed the system output to be adjusted through multiplicative and additive corrections [15]. This process was carried out in two stages, in the first stage the slope was corrected supposing the measurement is given by

$$L(x) = a_1 \cdot x + b_1, \tag{11}$$

where L is the measured level by the prototype and x is the actual level.

Ideally, L should be equal to x, for this, the intercept and slope of (11) should be equal to 0 and 1, respectively. Thus, the slope of the prototype measurement curve are corrected by R_A, given by

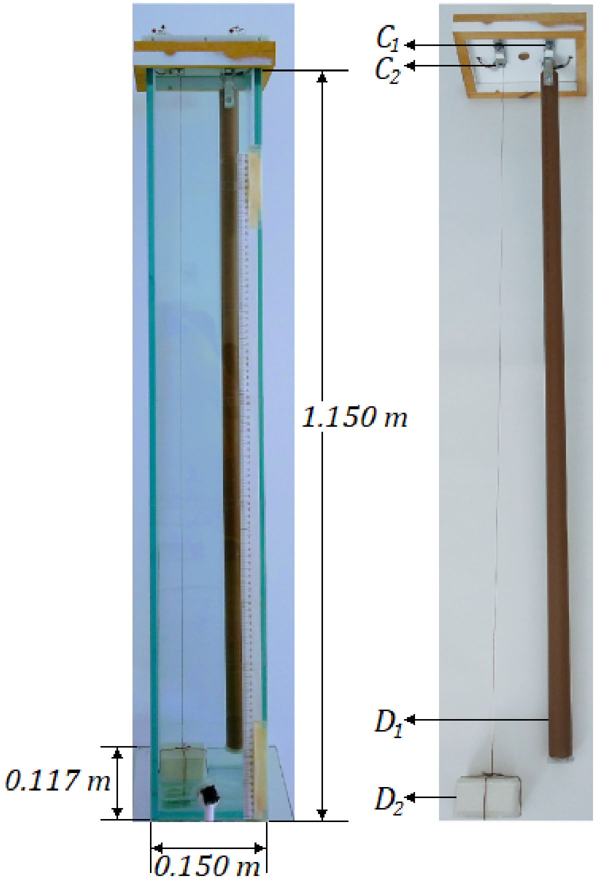

Fig. 2 Sensor prototype.

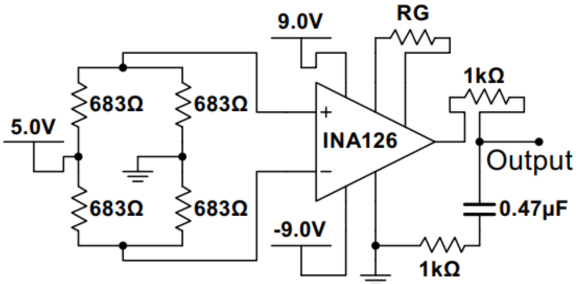

Fig. 3: Signal conditioning circuit. Composed by a Wheatstone bridge, formed by four strain gauges, and an instrumentation amplifier.

$$R_A = \frac{1}{a_1}. \tag{12}$$

The equation after correcting the slope is described as

$$L_A(x) = R_A \cdot L(x), \tag{13}$$

where L_A is the measured level after correcting the slope.

The second stage of this process consists of the zero adjustment making the intercept of (13) equal to zero. This is done by adding the constant R_L, given by

$$R_L = -R_A \cdot b_1. \tag{14}$$

Finally, the measurement curve after calibration and corrections is given by

$$L_F(x) = L_A(x) + R_L, \tag{15}$$

where L_F is the value of the measured level after corrections.

VI. RESULTS AND DISCUSSION

Results and discussion are presented in three subsections: Subsection A. shows a prototype linearity analysis; a comparison between prototype and classic method measurements is described in Subsection B.; finally, a prototype hysteresis curve is shown in Subsection C.

A. Prototype Linearity

Prototype linearity was evaluated through tests performed with three different liquids: water, ethanol and chlorine. Their respective densities are 998.4 kg/m^3, 809.3 kg/m^3 and 1410 kg/m^3 at 20°C. The experiments were performed by emptying the reservoir from the level of 22 cm to 0 cm with resolution of 1 cm. In order to compute the linearity, a line was fitted to the data of each experiment by linear regression using the least square method [16]. Prototype linearity was computed by the mean squared error between the data of each test and the respective line fitted, given by

$$L_{(\%)} = (1 - MSE) \cdot 100, \tag{16}$$

where $L_{(\%)}$ is the linearity and MSE is the mean squared error between the data of each test and the respective line fitted.

Table I shows the experimental results from experiments. The linearity calculated was 99.99% for the experiments carried out with the three liquids. The liquids temperature in these tests were 25.5°C, 21.0°C and 21.0°C for water, ethanol and chlorine, respectively.

Table I.: Prototype linearity analysis. A comparison between each experiment data and a respective line fitted to them.

Liquid	Linearity (%)
Water	99.99
Ethanol	99.99
Chlorine	99.99

Results presented in this subsection show the prototype measurements have a high linearity maintaining the performance of the classic method [11].

B. Classic Method vs. Prototype Measurements

Prototype and classic method measurements are compared in this subsection. Experiments were performed using two liquids with different densities, ethanol and chlorine. It were performed by emptying the reservoir from the level of 22 cm to 0 cm with resolution of 1 cm and liquid temperature of 21°C for both liquids. Results for measurements with the classic method and the proposed method are presented in Fig. 4 and Fig. 5, respectively.

Fig. 4 shows a significant difference between the measurement curves of ethanol and chlorine, demonstrating the classic sensor is very sensitive to variations in liquid density, since there is a great difference between the ethanol and chlorine densities. In contrast, Fig. 5 shows the measurement curves for ethanol and chlorine tend to be the same, indicating the prototype is able to mitigate the sensitivity to variations in liquid density.

Fig. 5 shows a slight difference between the measurement curves obtained by the proposed method, ideally they should be the same. This can be explained by small changes in the initial conditions of the displacers D_1 and D_2 occurred when the liquid was changed. The error is best observed as the level increases, this statement is based on the results of [6], where it was observed that uncertainty associated with the level measurement grows linearly with the actual level by Monte Carlo simulation.

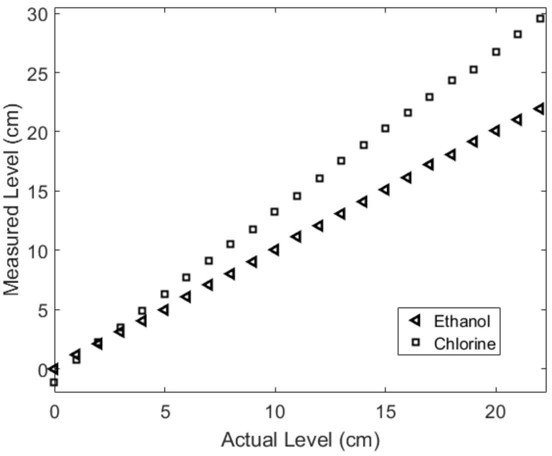

Fig. 4: Classic method measurement. Comparing the ethanol measurement curve and the chlorine measurement curve.

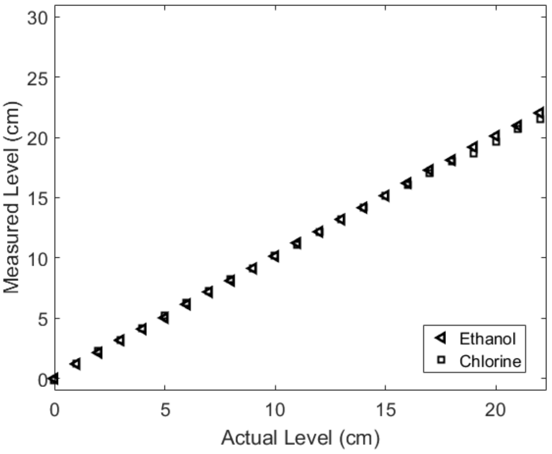

Fig. 5: Prototype measurement. Comparing the ethanol measurement curve and the chlorine measurement curve.

In order to calculate the difference between the two measurement curves for each method, the average error between them was computed and expressed as a measuring range percentage. The difference between the measurement curves for the classic method, presented in Fig. 4, was 19.54%. Whereas for the proposed method, shown in Fig. 5, the difference has decreased to 1%.

C. Hysteresis Curve

Prototype hysteresis curve was built in order to show the dependence of the system state, or the difference in value of the measured level as a function of the direction of the variations. The hysteresis curve was constructed by emptying the reservoir from 22 cm to 0 cm and then filling it from 0 cm to 22 cm, with a resolution of 1 cm and the liquid used for this experiment was water at 25.5°C.

Fig. 6 shows the prototype hysteresis curve with the difference between the ascending and descending curve is 2.4%. This value is the average error between the two curves, ex-

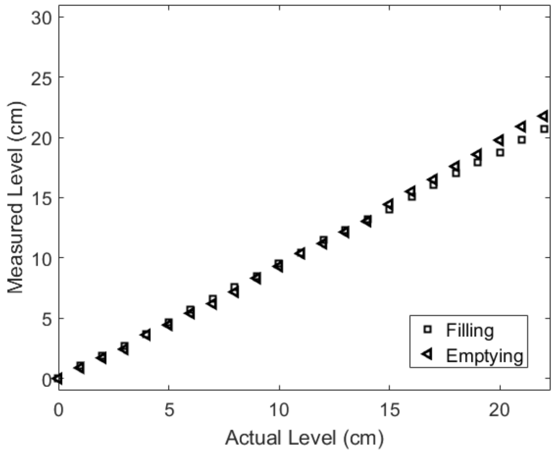

Fig. 6: Prototype hysteresis curve. This graph was constructed by emptying the reservoir from 22 cm to 0 cm and then filling it from 0 cm to 22 cm with a resolution of 1 cm.

pressed as a measuring range percentage. New experiments need to be done in order to better analyze the hysteresis curve with liquids of different viscosities, in this work we use only low viscosity liquids.

VII. CONCLUSION

This paper presents a novel displacer-type level sensor, insensitive to variations in liquid density. Several experimental procedures were performed in this work, in order to compare the performance of the proposed system with a classical displacer-type liquid level measurement system, and the results showed the proposed method can mitigate the sensitivity to variations in liquid density. The experiments were performed with two liquids with different densities. The classic method presented a deviation of 19.54%, while the proposed method presented a deviation up to 1%. Results also show the proposed system has high linearity and it has potential to make precise measurements, which indicates the prototype maintain qualities of the classic method.

Finally, the relationship between the diameter of the rod connecting the displacer D_2 to the load cell C_2 and the volume of D_2 is an important parameter for designing in order to maximize the performance of the measurements, which if not considered, can accumulate a significant error.

As future works will be investigated the influence of the liquid viscosity in the system by analyzing the hysteresis curve for liquids with different viscosities, it will be studied the feasibility of building a prototype without the rod connecting the displacer D_2 to the load cell C_2, some modifications to the prototype will be made to study the measurement response as a function of the temperature and investigating the system behavior for measurements in turbulent fluids.

ACKNOWLEDGMENT

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.

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