Characterization of pressure sensor for liquid level measurement in sloshing condition

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***Abstract*—To achieve a reliable and accurate liquid level detection, a differential pressure-based instrument is proposed in this paper. The phase-sensitive demodulation of the signal is performed by discrete Fourier transform through microcontroller. Good linearity in both AC and DC measurements has been observed. AC-based level sensing demonstrated reliable and robust level detection compared with DC, in both steady state condition and experiencing turbulence on the surface. In addition, thermal behavior of the proposed instrument is characterized and compensated, in order to evaluate its uncertainty as liquid level sensor. The obtained results show a combined uncertainty lower than 1 mm, mainly limited by sloshing conditions.**

Keywords— Level measurement; pressure sensors; pressure measurement; uncertainty; discrete fourier transforms.

I. INTRODUCTION

Precise level measurement of liquid in a tank is essential for the efficient operating of a process plant in any process industry. There are various methods widely used in industry for the measurement of liquid level. They can be categorized into either direct/indirect or contact/ non-contact methods. To compare with conventional float-operated level measurement system, as a contact type indirect measurement, capacitive based reading systems require no moving part. This leads to increase the reliability of such liquid quantity indicators [1]. In contact-type capacitive sensor, the capacitance changes almost linearly with liquid level. They have simple, rugged construction and high sensitivity in water level measurement due to high dielectric constant. However, their accuracy is influenced by stray or parasitic capacitance. Based on Time Domain Reflectometry (TDR) principle, guided wave radar based are frequently employed for measuring the level of liquids in storage tanks [2-5]. These approaches are very accurate measurement solutions, but pulse-duration measurements with high resolution requires high costs for the overall data-acquisition system. Pressure based level sensing technique has been proposed for the analysis and monitoring of a ship’s stability [6]. These sensing approaches can operate reliably under rough environmental conditions. However, to provide a better accuracy, calibration must be performed frequently [7]. In [8], a leak detection methodology was developed based on the use of pressure sensor measurements and proper calibration of the sensors was reported to be important for improving the accuracy of the results produced by the algorithm. Later, a technique based on Wavelet transform is presented in [9] for removing such a noise from the measurements of a differential pressure sensor. An accurate liquid level measurement system using six absolute pressure sensors has been proposed [10] with the sensitivity of 1.48 mV/mm and nonlinearity within ±0.5 %. Besides contact type indirect methods, several non-contact direct sensing approaches have been proposed for level measurement such as ultrasonic [11,12], vision [13], optical techniques [14,15].

Depending on the application, precise level detection may encounter with some abnormal conditions such as temperature variation or experiencing fluctuations, especially in non-stationary tanks. Such conditions become more critical when evaluating the instrument reliability and accuracy while dealing with small dynamic range. In all mentioned above approaches, the performance evaluation was made at room temperature and in steady state condition. The disadvantage of the capacitive-type sensing approach is not only miss-reading due to parasitic capacitance [16,17], but also inaccuracy when it is subjected to fluctuations [18]. Such accelerations will induce slosh waves in the tank. This phenomenon of fluid fluctuation is called sloshing. In capacitive based sensing approach, the value of the capacitance increases or decreases due to the presence of sloshing which results into miss-readings. Direct optical techniques suffer for weak back reflection when they measure the quantity of liquid with low dielectric, that may experience further reduction due to the presence of foam on the liquid surface, as result of sloshing. In [19], a level instrument based on the self-mixing effect induced in the laser diode by modulating the laser wavelength is proposed to measure the level during industrial filling process. The measurement is performed by focusing the laser beam shortly after the free surface due to optical behavior of water rippled surface at high frequency which is like diffusive surface. The resolution of 1 mm is achieved when level is increasing slowly without high frequency stirring. Similarly, the creation of the foam is evaluated for radar level instrument at 6 GHz and 26GHz [20]. In both radar and guided-wave radar level instrument, the surface covered with foam or, in more general, surface contaminated as result of acceleration affects the reflection and transmission of the microwave pulse. Consequently, this effect compromises the measurement accuracy. In addition to sloshing, temperature variation is another major source of uncertainty. Recently, a low-cost ultrasonic-based sensor system for the marine environment was characterized in [21] and changes of climatic conditions, such as temperature and humidity, were monitored in a climatic chamber. Time of Flight (TOF) values detected at fixed 30% humidity value and different temperatures. As results shown, the temperature has

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a remarkable effect on the measured TOF values and limits the functional range of the ultrasonic sensor.

In this paper a pressure sensor is described for detecting the level of liquid inside a tank by measuring applied pressure as a function of the level. The measurement is made through an AC technique, with enhanced sensitivity over DC methods achieved, by preventing preamplifier $1/f$ noise. Measuring the differential pressure instead of absolute one as in [7], provides less complex design and reduces the uncertainty due to unknown external pressure applied on the liquid surface. In addition, probe contamination due to sloshing is not an issue anymore since the sensing diaphragm is place at the bottom. A preliminary description of the system was published in [22]. The performance of the proposed transducer has been experimentally evaluated, under sloshing conditions and as a function of temperature. This paper is structured as follows. Section II briefly describes the differential pressure sensing based on phase sensitive detection approach. Then measuring circuit is presented in more detail in Section III. The characterization curve of the proposed instrument is determined under steady state condition in section IV, where very good linearity is observed. To evaluate the impact of turbulence on the performances, the level measurement under sloshing conditions is evaluated and presented in section V. Due to high temperature sensitivity in piezoresistive pressure sensors, the thermal behavior is studied and characterized in section VI. As results of applying suitable correction methods, new characterization curve of the proposed instrument is determined. Finally, the uncertainty evaluation for both sloshing and temperature variation as major sources of uncertainty is presented in section VII.

II. METHODOLOGY

Pressure sensor can directly measure liquid level: pressure P is proportional to liquid level h multiplied by its specific gravity.

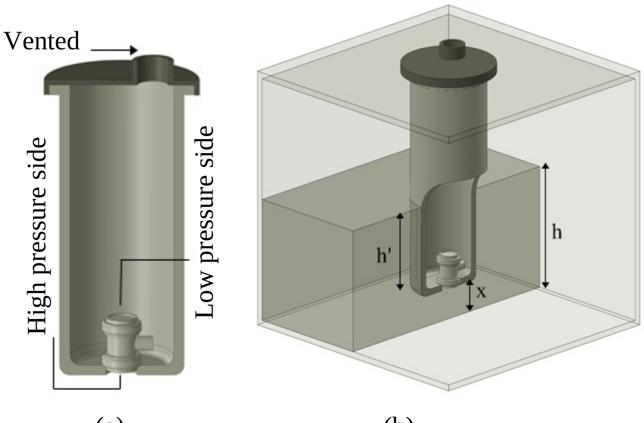
$$P = \rho g h \qquad (1)$$

Where ρ is density and g is gravitational acceleration. Considering the absolute pressure for measuring the level includes an uncertainty contribution in presence of external pressure applied on the surface. To improve the accuracy, the level is measured using differential pressure sensing approach. In case of differential pressure sensor, level can be determined as (2).

$$P_{high\ pressure} - P_{low\ pressure} =$$

$$\left(P_{liquid} + P_{air}\right) - P_{air} = \rho g h = \rho g(h' + x) \quad (2)$$

Where x is the distance from bottom of the tank to one of the sensing diaphragm of differential pressure sensor, and $h' = h - x$, as illustrated in figure 1. The pressure sensor together with electronics is mounted into a cylindrical body where one of the sensing diaphragms (high pressure side) is in direct contact with liquid while the other one (low pressure side) is surrounded by the cylindrical body only. High-pressure side can measure pressure proportional to level of the liquid in addition to air pressure on the surface of the liquid, since the tank is vented. While, only air pressure is measured on the other side due to vented gas cap of transducer. Since there is no liquid inside low pressure side, it cannot splash out in case of acceleration.



(a) (b)

Fig 1. Schematic of proposed differential pressure level transducer. (a) Body of the proposed transducer, (b) Transducer position inside the tank.

In piezoresistive pressure sensor, conversion of pressure into an electrical signal is achieved by the physical deformation of strain gages, which are bonded into the diaphragm of the pressure transducer and wired into a Wheatstone bridge configuration. Therefore, the output voltage V of the sensor is proportional to the pressure P with sensitivity S:

$$S \times P = V \qquad (3)$$

Due to different frequency dependence of various noise sources, measurement should move from low frequency for improving signal-to-noise ratio. However, working at higher frequencies requires a narrowband filter to recover the signal. Alternatively, phase-sensitive detection is a powerful technique to filter out signals that are not synchronized with the reference one [23]. In this work, sinusoidal signal at 10 kHz is used as excitation signal. Then, DFT (Discrete Fourier Transform) is performed based on evaluating the phase and quadrature component (Fourier coefficients) with a digital synchronous receiver, which performs the multiplication of the sampled signal for two quadrature signals. Increasing the acquisition time, i.e. performing longer DFT, implies that each bandpass filter becomes narrower, resulting in less noise contribution. Therefore, there is always a tradeoff between frequency and time resolution. Here, the DFT is performed on 1250 samples, a good compromise between measurement accuracy and speed.

III. MEASURING CIRCUIT

The proposed instrument design is composed by three main parts, as represented in figure 2: differential pressure transducer, analog frontend for signal conditioning and a digital part to provide sensor operating condition and making the elaboration. The pressure transducer is a piezoresistive differential pressure sensor in Wheatstone bridge configuration. The full-scale range is 10 kPa, nominally corresponding to 60 mV when supplied at 1.5 mA. Considering the low voltage amplitude and the required measurement accuracy, a careful signal conditioning is required, involving both analog and digital processing. To achieve pressure measurement in both DC and AC stimulation, Wheatstone bridge is driven by a buffered digital to analog converter (DAC). The voltage signal is the superimposition of a sinewave at 10 kHz (V_{rms} =0.5 V) on a DC bias value of 1.7 V. The transducer's differential output is filtered and amplified through a low-cost instrumentation amplifier (INA-331 from Texas Instruments) to fit the analog to digital converter's (ADC) input voltage dynamic.

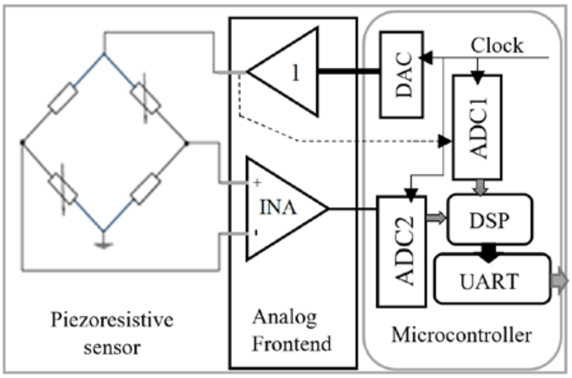


Fig 2. Measuring circuit block diagram of the proposed instrument

A single microcontroller (model STM32F3) includes both DAC and ADC's. Through two ADC's triggered by the same clock signal, it is possible to acquire at the same time the buffered DAC output, used to drive the transducer, and the output of the INA. Figure 3 represents a detailed flowchart, where biased sinewave with amplitude of 0.7 V is continuously generated by DAC using Direct Memory Access (DMA) and all ADCs are managed by the elaboration cycle. The microcontroller processes both signals using DFT and provides respective real and imaginary values. Since DAC and ADCs work under the same clock domain, the result of the DFT elaboration is very accurate. Each signal is acquired at 250 kSPS for 5 ms, consequently the DFT is computed on 1250 samples. Considering that the driving signal is at 10 kHz, the system acquires exactly 50 periods, avoiding problems of spectral leakage in the DFT elaboration. The ratio between complex numbers, representing the INA output and the driving signal, eliminates any non-linearity induced by driving signal distortion and errors due to lack of synchronization. After a calibration process, implemented by first order function, the system provides liquid level measurement in millimeters. A new measure is ready every 10 ms and it is available on the UART peripheral of the microcontroller. In the actual configuration, a PC reads the data through an UART-USB converter, to show and eventually save the results. A prototype of the proposed level instrument is illustrated in figure 4.

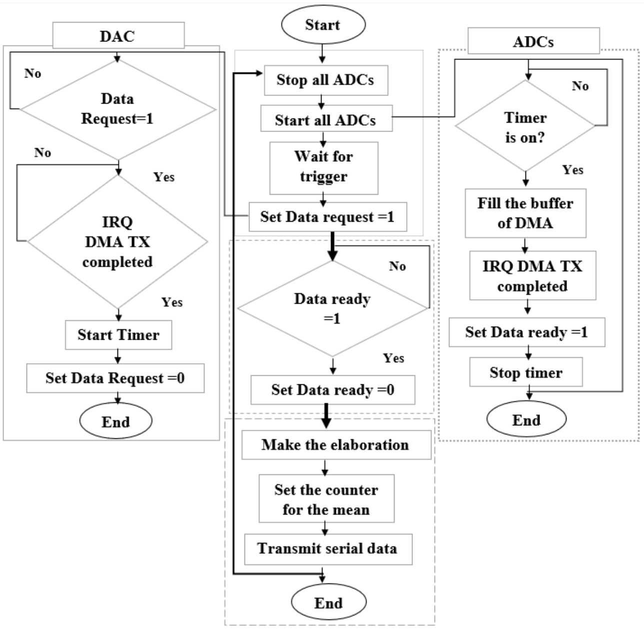


Fig 3. Flowchart of the signal aqusition and elaboration

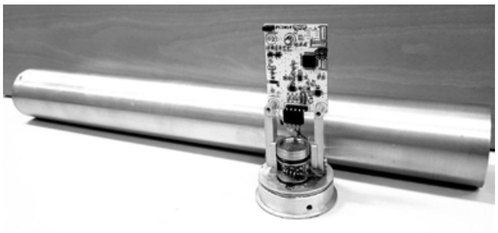


Fig 4. Prototype of proposed instrument

IV. STATIC CHARACTERIZATION

Figure 5 illustrates the prototype of proposed level instrument in the experimental setup inside a liquid tank. Since accurate level detection in small tanks is considered here, the tank has length of 50 cm, width of 20 cm and depth of 20 cm.

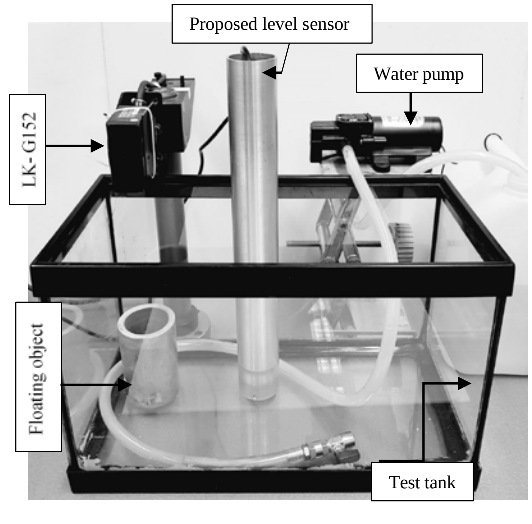


Fig 5. Experimental setup of proposed level measurement instrument in test tank equipped with laser range finder

The water level in tank was increased in steps by adding the test liquid. The reported results are obtained with pure water. During characterization and calibration processes, the reference for level measurement is a Keyence laser range finder (LK- G152). Since water is transparent for laser range finder, a floating object is included on the water surface. According to the experimental results shown in [22], very good linear response in both DC and AC measurements have been observed. Due to 1/*f* noise and offset fluctuations, AC measurement provides more reliable and robust performances with a standard deviation improvement of about one order of magnitude (Figure 6).

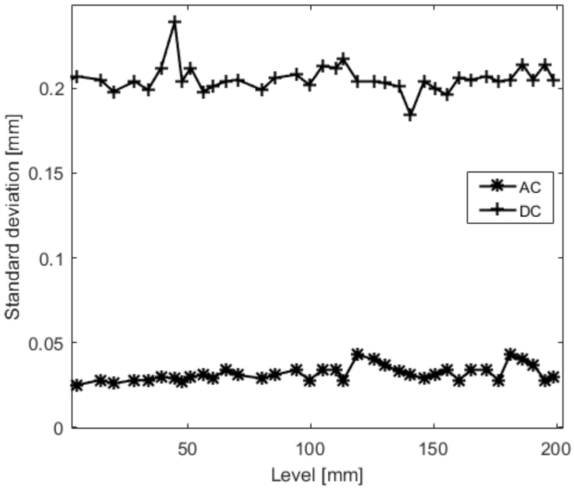


Fig 6. Standard deviation curve for both AC and DC based level sensing

V. TURBULANCE ON THE SURFACE

As mentioned earlier, conventional contact-based direct level measurement techniques suffer from miss-reading due to experiencing turbulence on the surface of liquid. Different approaches such as mechanical or electrical damping methods have been proposed to compensate the effect of sloshing. Not only such approaches lead to higher production cost but also the accuracy is not satisfactory. In [24], a capacitive type liquid level sensing system is proposed that uses three capacitors to detect the liquid surface plane angle. The fourth capacitor is used as reference capacitor to compensate for the variations in the dielectric constant. The high cost and complexity make this approach infeasible. In addition, they assumed the liquid surface as a plane, whereas, even under steady state condition, the surface of the liquid experiences slosh waves that fluctuate at varying rate. In this paper, instead of external compensation system, robustness of differential pressure sensing is utilized to evaluate the overall performance under sloshing condition. To do this, a dc motor equipped with a blade is utilized to simulate sloshing by providing waves on the surface of liquid. Figure 7 shows the corresponding experimental.

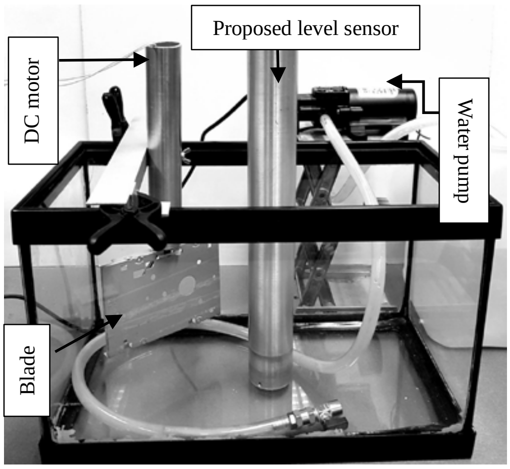


Fig. 7. Experimental setup up for simulating sloshing condition.

To perform this test, turbulence amplitude was controlled by increasing and decreasing the motor speed. Figure 8 reports the motor speed in round per minute (rpm) during time, for seven sloshing levels (phases a, b, c, d, e, f, and g). Phase a and g are steady state conditions when there is no fluctuation on the surface. In phase d, the speed reaches to its maximum while it is minimum during phase b.

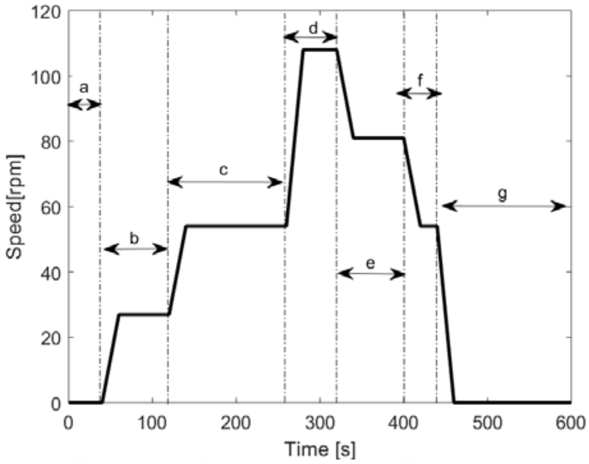


Fig. 8. Different speed of dc motor to create different waves on the liquid surface.

Due to the introduction of an external uncertainty source, as expected the system degrades both for AC and DC measurements, as confirmed by the standard deviation measurements represented in figure 9. Figure 10 shows the liquid level measurements during the sloshing simulation. For this test, the water level inside the tank is 84 mm. By introducing sloshing waves (b-c), fast growing error in DC level reading has been observed, while the AC measurements are still stable. For higher sloshing level (phase d), a level variation lower than 1 mm is measured in AC and confirmed by the DC measurement. It could be a real effect of the induced whirlpool. Phase f is a repetition of sloshing condition introduced in phase c but with less time duration.

Therefore, it is expected to observe same error in level reading as shown in figure 9. Once the turbulence is stopped (phase g), fast response of AC level reading to go back to steady state condition is also observed. As expected, also in this case level reading based on AC measurement shows better accuracy and robustness, in comparison with DC measurements.

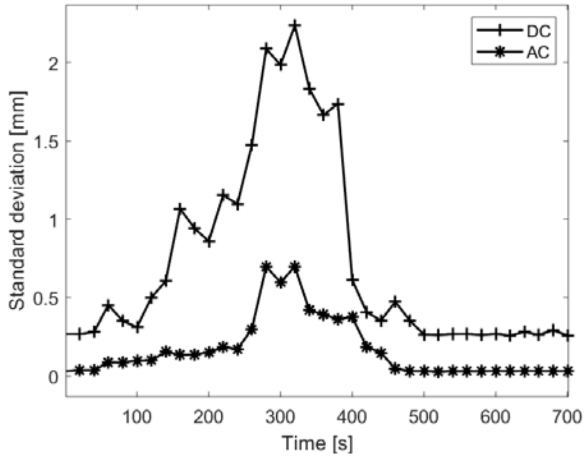


Fig. 9. The standard deviation curve during sloshing condition for AC and DC based level sensing

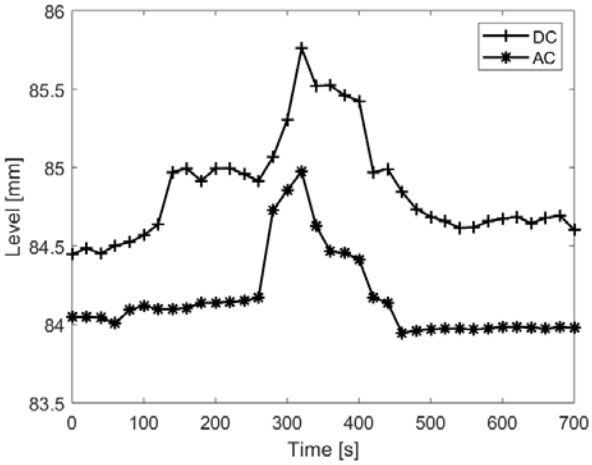


Fig 10. The level of the liquid inside the tank during sloshing condition for both AC and DC based level reading

VI. THERMAL BEHAVIOUR OF THE PROPOSED INSTRUMENT

Inherent temperature dependence of the piezoresistive pressure sensors based on silicon, causes a remarkable thermal drift of their characteristics. Therefore, thermal characterization of the sensor is mandatory to define the parameters that cause the output drift. The performance of the proposed instrument under steady state condition was evaluated in section IV. However, thermal dependence of piezoresistive sensors negatively affects level measurement stability. As result, the measurement may exhibit large systematic errors [25]. Therefore, correction methods are necessary to improve the measurement performance. In following sections, thermal behavior of proposed instrument is characterized, a suitable correction method is applied and associated errors during level measurement are evaluated. We first characterized the offset dependence on temperature (no pressure applied), and then measured the sensitivity as a function of temperature.

A. *Thermal Drift of the Offset Voltage*

In perfect steady state or equilibrium, the output voltage of piezoresistive sensors in a Wheatstone bridge configuration should be equal to zero. However, due to temperature variation, the values of its four resistances will change, and an offset signal comes out at the bridge output. In [26], two different models of the mobility of holes in Silicon, the Arora mobility model [27] and the Dorckel mobility model [28], have been adopted to determine how the temperature affects piezoresistive pressure sensor's gauges values. They concluded that the variations of output voltages of the two half-bridges as a function of temperature should have a parabolic behavior. Therefore, the relative variation of the output voltage of the complete bridge at rest should have a parabolic form too.

To perform a thermal characterization, the proposed instrument is enclosed into a thermal chamber. The offset voltage drift as a function of temperature is characterized for temperature ranging from 5°C to 48 °C. Figure 11 represents the measured offset voltage during temperature variation. As shown in this figure, it follows a parabolic form. In this case, the implemented regression curve is a second order polynomial and its parameters were determined using the least squares method.

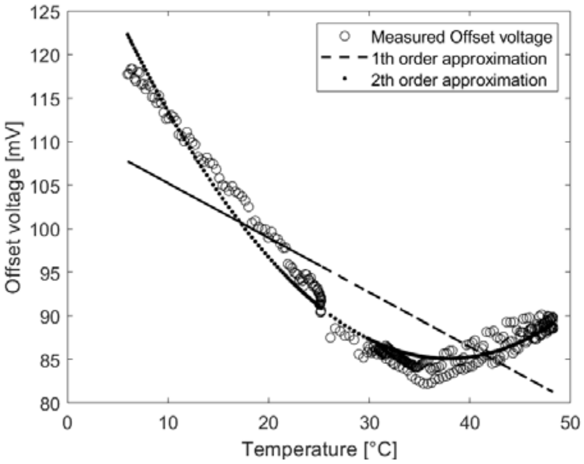


Fig.11. Measured offset voltage of the proposed instrument as a function of temperature

B. *Temperature effect on the sensitivity*

In order to cancel the systematic error due to temperature, after the measurement of the offset behavior, we have to compensate for the gain coefficient as function of temperature. Then, performance of the proposed level instrument while measuring 26 mm of liquid is analyzed under thermal variation. Figure 12 shows the continuous measurement results as a function of temperature, with only offset compensation.

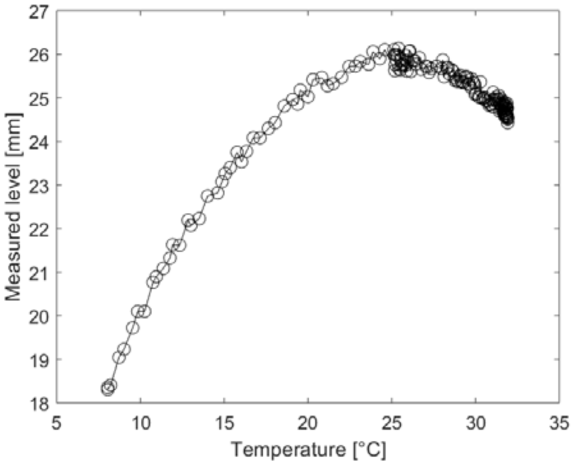


Fig. 12. Level measurement using the proposed instrument under temperature variation in case of having 26 mm of liquid inside the tank.

In this case, the measurement error is higher than 20% while approaching to the lower temperatures. Despite of the offset voltage's thermal dependency, another factor that greatly affects the level measurement performance is the thermal dependence of sensitivity of piezoresistive pressure sensors. To evaluate the thermal behavior of sensitivity coefficient for the proposed instrument correctly it is necessary to consider the liquid density variation due to change of temperature. Various databases are available in this manner. Figure 13 shows the absolute value of water density as function of temperature using database in [29].

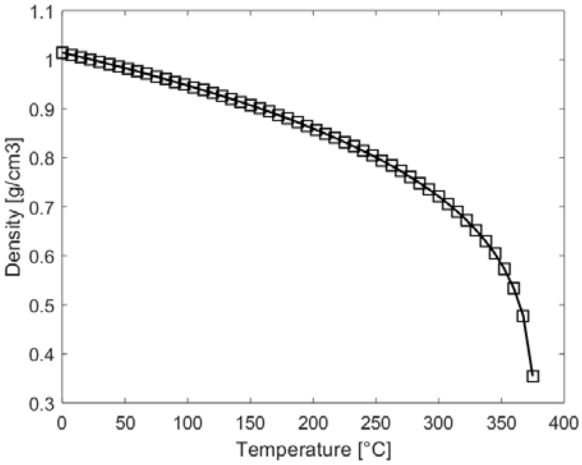


Fig. 13. Variation of the density of water as function of temperature

After considering the variation of density, the sensitivity dependence on temperature have been determined. Figure 14 shows the measured variation of the sensitivity, with respect to the reference value at 25°. As confirmed by the experimental results, the sensitivity variation with temperature still follows a parabolic form. Also, in this case, a second order polynomial has been chosen as regression curve and its parameters were determined using the least squares method.

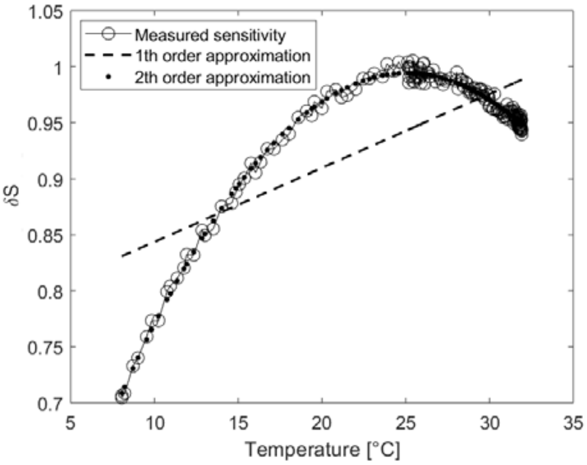


Fig. 14. Variation of the sensitivity of the proposed instrument as a function of temperature

The evaluation of thermal behavior and applying correction methods lead to deep understanding of the true characterization function of proposed instrument. Equation (4) represents the linear characterization function as result of characterization process under steady state condition. As confirmed by the experimental results, the sensitivity variation with temperature still follows a parabolic form. Also, in this case a second order polynomial has been chosen as regression curve and its parameters were determined using the least squares method. The evaluation of thermal behavior and applying correction methods lead to deep understanding of the true characterization function of proposed instrument. Equation (4) represents the linear characterization function as result of characterization process under steady state condition.

$$h(V_{in}) = A \cdot V_{in} + B \qquad (4)$$

where A and B being the sensitivity and gain coefficients respectively. Despite of random errors in a measurement process which are studied in section V, systematic errors are caused by imperfect calibration of measurement instruments or imperfect methods of observation, or interference of the environment with the measurement process. Evaluating thermal behavior result into a new characterization function, with the two coefficients A and B becoming functions of temperature. Correction for the temperature drift can be realized by either hardware or software techniques. Compensation resistors are most commonly used approach this manner [30]. However, effectiveness and reliability of such approaches are limited by temperature coefficient of compensation resistors. On the other hand, enough accuracy improvement can be achieved using simple digital compensation techniques, such as look up table [31], polynomial-fitting methods [32] or more complicated approaches based on intelligent algorithms such as Artificial neural network (ANN)-based signal conditioning. A hybrid thermal drift compensation, in which hardware and software compensation methods are mixed together [33], makes compensation more effective. However, complexity and requirement of large number of calibration data limit such methods implementation in practical application. In this paper, correction for temperature drift is performed using polynomial fitting approach. Observed measurement errors during each step of correction are presented in figure 15. After the compensation procedure, the maximum measurement error becomes limited to 0.11 mm under temperature variation, with standard deviation equal to about 0.04 mm, almost the same value obtained in the static characterization (see Figure 6). It indicates that the temperature dependence is well compensated for this liquid level, because the residual error is lower than the variability of the sensor itself. It should be noted that the different factors such as size of experimental dataset and coverage of measurement range influence accuracy of fitting formula in polynomial based compensation. This results into lower compensation efficiency for different liquid levels. To evaluate the effectiveness of the compensation, the measurement performances were evaluated by repeating the level measurements as a function of temperature for different liquid levels, ranging between 2 cm and 12 cm. Figure 16 shows absolute error in level measurement as a function of temperature, for liquid level equal to 12 cm. To better appreciate the contribution of offset and sensitivity variation, they are plotted separately. Figure 16a shows the effect of the offset compensation only. Figure 16b shows the final compensated measurement, against the measurement with offset compensation but just first-order compensation for the sensitivity. The error without compensation is higher than 1 cm, while after the whole compensation it is limited to almost 0.15 mm under temperature variation, with standard deviation still limited to about 0.05 mm. Similar results have been obtained for each liquid level considered.

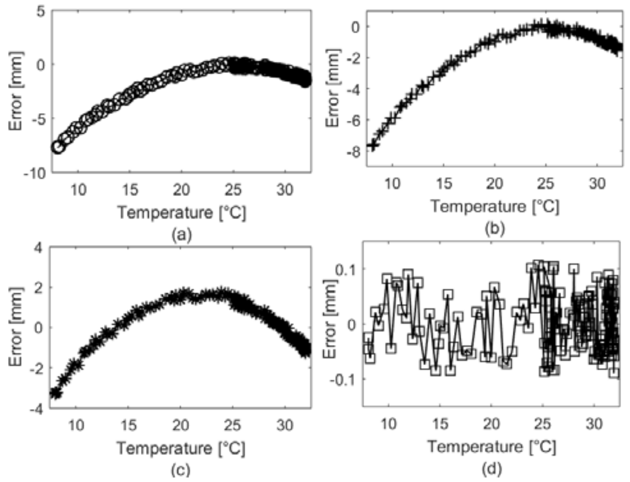


Fig. 15. Observed error during continuous liquid level measurement for both sensitivity and gain coefficients: (a). Constant A and the 1th order approximation of B. (b) Constant A and the 2th order approximation of B. (c) The 1th order approximation of A and 2th order approximation of B. (d) The 2th order approximation of A and B.

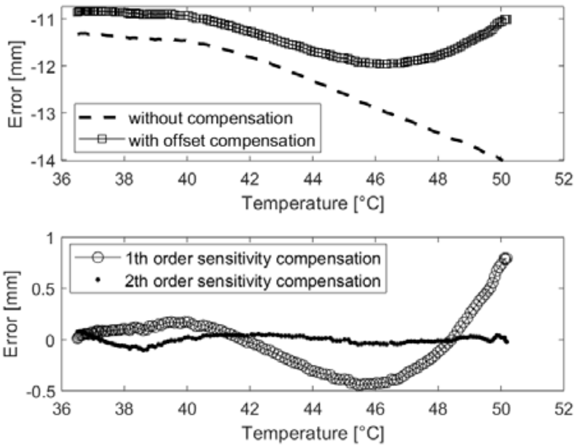


Fig. 16. Absolute error comparison for liquid level equal to 120 mm: (a) uncompensated V.S. offset compensation only; (b) offset and 1st order sensitivity compensation V.S. complete compensation.

VII. UNCERTAINTY EVALUATION

The expression of the statistical dispersion of the values attributed to a measured quantity in metrology is expressed as measurement uncertainty [34]. In case of dealing with more than one identifiable source of measurement uncertainty such as equipment calibration or environmental factors, it is necessary to calculate combined uncertainty, given by the quadratic sum of all uncertainty sources, when they are not correlated. In this paper, reference instrument during calibration is a laser range finder with micrometer resolution, therefore, the uncertainty related to calibration instrument is negligible. As two major sources of uncertainty, temperature and sloshing are evaluated, and the associated standard uncertainties have been calculated to assess the performance of the proposed instrument.

Due to high sensitivity to temperature of the piezoresistive pressure sensor, temperature could be one of the major uncertainty sources for any instrument based on such sensors. In section VI, after a deep characterization and correction procedure, such systematic errors were drastically reduced. The uncertainty due to temperature dependence induces an error limited to almost 0.15 mm.

Experiencing fluctuation on the surface of the liquid is another source of uncertainty. In section V, the performance of the proposed instrument is evaluated under sloshing condition. The standard deviation reached 0.63 mm only for very-high sloshing level, while system experiencing phase d sloshing as represented in figure 9. However, the level is also increasing in this phase and its variation is real, induced by the creation of vortex wave.

In conclusion, standard uncertainty is mainly dependent on sloshing conditions. For strong sloshing conditions, the uncertainty value results 0.63 mm. In [35], a neural network-based compensation approach is proposed for capacitive level sensor under dynamic environment. The accuracy for the statistical methods such as moving mean and median are

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reported in the order of magnitude of 3.5% and 3% respectively. They demonstrated the final accuracy about 1% using Backpropagation neural network with Moving Median filter. Considering the worst sloshing conditions, the proposed sensor in this paper shows a normal distribution with 0.63 mm of standard deviation, and 90% of the measurement results falls into the ± 1 mm confidence interval. It should be noted that for lower sloshing level the error would decrease considerably, and the maximum error becomes lower than 1 mm. As future step, the research will be focused to evaluate and improve the accuracy, by applying embedded artificial intelligent compensation algorithms.

VIII. CONCLUSION

In this paper, a reliable level measuring instrument based on differential pressure sensor is proposed to measure level of liquid. The instrument is completely handled by a microcontroller: it generates a driving signal and processes the sensor output evaluating the DC and AC values using synchronous detection. As expected, the AC measurement provides better performances with respect to the DC one, in terms of sensitivity and accuracy. The performance of the proposed transducer has been evaluated in sloshing condition, and in this case the AC measurement demonstrated higher robustness and reliability. In order to compensate for the thermal behavior of the pressure sensor, a temperature characterization was conducted for the offset voltage and the sensitivity. The behavior of offset and sensitivity both were modeled through a second order polynomial, allowing a good compensation of the deterministic error due to temperature. Finally, an uncertainty evaluation of the proposed instrument for water level measurements, under both sloshing condition and temperature variation, leads to a value lower than 1 mm. This kind of accuracy in level measurement is adequate for several industrial applications.

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