

# Differential pressure based densitometer in dynamic condition

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**Abstract**— *Change in density will cause error in measurement for indirect based level sensing approaches such as capacitive sensors. In addition, there is growing attention in measuring density accurately not only in laboratory conditions but also in a real-time dynamic environment. To address the mentioned above issues, an independent instrument based on differential pressure sensors is proposed in this paper. Synchronous detection is used to detect the desired signal by calculating the coefficients of the digital Fourier transform. The characterization of the sensor is experimentally determined under a steady-state condition where a linear response is observed. The thermal behavior of the proposed sensor is studied and compensated using the polynomial fitting technique. Evaluating the uncertainty due to reference values, linearity and repeatability, the obtained results show a combined uncertainty lower than  $7.5 \frac{\text{mg}}{\text{cm}^3}$ , mainly limited by observed asymmetric hysteresis at higher temperatures.*

**Keywords**— density measurement, differential pressure, phase-sensitive detection, DFT, uncertainty, temperature variation

## I. INTRODUCTION

Mass of a substance per unit of volume is expressed as density which represents the compactness of matter within that substance. Fluid density measurement is regularly required in numerous industrial and research applications such as food, biomedical, and petrochemical industries. For example, the variation of density due to the temperature causes inaccuracy in the majority of contact-based indirect level sensors such as capacitive sensors. Since the majority of the densitometers are limited by their laboratory-based working principle and high cost, typically lookup tables are utilized to provide correction in this manner. In case of accessing the lookup tables where shows the density as function of temperature, the error caused by the density can be addressed. However, in case of working with different type of liquids, the solution based on such database is limited or costly. This drives industries to seek a precise, reliable, and cost-effective solution to measure density of liquid in dynamic environment.

Generally, the density measurement of different liquids is performed in laboratory conditions, with different environmental demands, depending on the working principles. For this reason, pycnometers, aerometers or hydrometers are well-known density measurement instruments [1]. However, standard laboratory assessments are not applicable in manufacturing processes due to the time delay between collecting the samples and obtaining the desired results [2-3]. In addition, they are subjected to the

measurement errors in case of changing the features of the liquid during the test [4].

Several advanced approaches have been proposed and developed which are suitable for in-site measurements such as near-infra-red, spectroscopic, and X-ray absorption [5]. Such spectroscopic techniques are accurate and reliable, but they are expensive.

In Coriolis meters, the vibrating tube is interacting with flowing fluid and therefore generates the Coriolis forces. In [6], the effect of density on flow measurement by the Coriolis flow sensor is outlined. The tube is stimulated via an electromagnetic driver and oscillates in its first eigenfrequency. A digital signal processor (DSP) unit controls the oscillation as well as the analysis of the velocity signals measured by two electromagnetic sensors. When there is no mass flow, all parts of the measuring tube will vibrate synchronously. In the case of entering mass flow to the measuring tube, the Coriolis forces are caused by two orthogonal velocities, one addressing the velocity of the fluid and the other the velocity of the measuring tube. These Coriolis forces behaving on the wall of the tube go in opposite directions in the upstream and downstream sides of the tube when the flow enters the tube. In other words, the oscillation of the upstream and downstream parts will no longer be synchronous. This is the reason that the Coriolis meter is known as an instrument that measures some kind of “nonsymmetric”. In addition to application limitation, the accuracy of this method to measure the density is limited due to applied static pressure.

In [7], a thermal expansion-based approach is proposed to measure the volumetric change as a function of temperature. To perform this, densities were calculated from a sequence of images. However, such an approach is suitable for combustion able liquid only. Density measurement is also investigated using optical-based techniques. Due to total internal reflection, light is guided through the optic fiber from one end to the other. In [8], density measurement is carried out using a plastic fiber optic sensor. The light refracted to the external medium depending on the refraction index of the medium as a function of density. Consequently, fiber losses are proportional to the density of the external medium. At the end of a fiber, the light reaches a photodetector and the output current is proportional to this light. It is an expensive solution, and temperature variation strongly affects its accuracy.

Electrodynamically driven based techniques and therefore mechanical oscillators read-out is another approach to measure the density of the liquid. In [9], the proposed sensor is developed by adding a piezoelectric bimorph into a metallic chamber, where the quantity of liquid is fixed. The

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mass of the liquid causes a variation in the resonance frequency of the piezoelectric bimorph; the volume is fixed and therefore the frequency variations can be related to the liquid density. However, the frequency values monotonically reduce by increasing the height  $h$  where the height dependency of resonance frequency is not linear. Therefore, the slopes are not constant and are higher for low  $h$  values. Later, the optimized model is proposed and evaluated in [10]. The characterization of the sensor is performed only considering the different values for  $h$  and simulation results show improved sensitivity in density measurement. However, temperature variation strongly affects the electrical impedance of the piezoelectric sensors. This should be considered to evaluate the performance of the proposed sensor to measure real density variation.

Along with piezoelectric bimorph, the liquid density is sensed by the resonant tuning fork. The natural frequency of the tuning fork has an essential role in sensor performance. This frequency relies on the dimension and material used in tuning fork. A piezoelectric drive element is used to stimulate the tuning fork. When an alternating voltage is applied to piezoelectric material it contracts and expands. This alternating voltage is transmitted by actuator to make tuning fork vibrate at its resonance frequency. The vibration only depends upon the properties of the material, added mass due to temperature of liquid, and pressure [11]. In [12], a small quartz tuning fork is presented for viscosity and mass density measurements yielding repeatability of better than 1%. However, these quartz tuning forks are very fragile and thus might be easily destroyed during cleaning or the standard measurement process. To achieve improvements of mechanical solidity, steel tuning forks were investigated for viscosity and mass density measurement application showing their fundamental resonance frequency at nominally 440 Hz in air. In [13] a setup based on ferromagnetic tuning forks is used for viscosity and mass density sensing. An electromagnet is placed close to the end of the commercially available steel tuning fork which is welded to a solid stainless-steel stand. At the end of the second prong, an electrodynamic pick-up consisting of a permanent magnet in the middle of a copper coil is placed. Typically, higher viscosities yield higher damping and higher mass densities yield lower resonance frequencies. They demonstrated that viscosity and mass density showed a weak but non-negligible influence on resonance frequency and damping, respectively. Due to thermal dependency, sensitivity of natural frequency should be characterized, determined, and modeled otherwise it limits the sensor accuracy. In addition to low sensitivity and thermal dependency, effect of applied static pressure should be studied in such density measurement techniques.

Ultrasound based density measurement sensors also have been proposed by researches where density of the liquid is found from the measured transmission or reflection coefficients. Generally, these techniques are divided into the transmission method [14] and the pulse-echo method [15-16]. The principle of the first method is based on the measurement of the ultrasonic wave transmitted through the solid/liquid and

liquid/solid interfaces under test, and calculation of the transmission coefficient  $T$ . While in the second approach, it is based on the measurement of the reflected ultrasonic wave from the interface solid/liquid medium under test, and calculation of the reflection coefficient  $R$ . Majority of the in-line ultrasound measurements are based on the pulse-echo method. This is mainly due to the specific geometry of the measurement system and the difficulty in accessing the liquid under measurement. In [17], a Multi Reflection Method (MRM) based techniques is proposed where the Time-of-Flight (TOF) and the amplitudes of three echo pulses are evaluated to measure the density. However, they concluded that some parameters should be considered such as signal resolution, temperature variation, and noise. As shown by the results, the poor signal-to-noise ratio of the second reflector echo was found to be the main accuracy limitation. Although noise can be reduced by improvements of the electronic circuits, signal averaging, or filtering, considering non-constant process conditions or low signal acquisition rates, echo averaging results into undesirable amplitude errors. Furthermore, unstable material properties temperature gradients across the signal path might be added as an application-related concern. Nevertheless, the ultrasonic measurement methods are accurate but, in most cases, they can be applied for density measurements of different liquids only at thermal steady-state conditions [18].

As mentioned earlier, commercially available high precision instruments to measure density are mainly laboratory-based instruments. Therefore, the accuracy of the available instruments which can measure density out of laboratory activities is lower. In this paper, a Differential Pressure (DP) based densitometer is proposed to measure the density of a liquid in real-time. The sensor can work as a stand-alone instrument or in parallel with any contact-based level sensor where density measurement is required.

The principle of the proposed densitometer is based on simple modification on differential pressure based level sensor which is proposed in [19] for detecting the level of liquid inside a tank where the high-pressure side is in direct contact with liquid while low pressure is in contact with the air. In the proposed level sensor, differential pressure sensing results in eliminating the uncertainty due to compressed gases on the surface of the liquid. Here, the working principle of the proposed densitometer is based on submerging both high- and low-pressure sides into the liquid instead of the only high-pressure side. Considering the previous solution having the reference point in air to measure the density instead of level, the level should be known accurately. It can be used to measure the density in full tank condition since the level is known. While the proposed densitometer eliminates the dependency on the level measuring density locally. For the proposed technique, it is required that the liquid is not shaken or subjected to acceleration, to avoid unwanted forces acting on the sensors. Concerning the temperature, the thermal drift of silicon-based pressure transducers should be considered. In this work, the thermal characterization is performed to reduce such systematic error where the accuracy of

temperature measurement plays an important role. Measuring circuit and detection algorithm are presented in section III. Section IV demonstrates the experimental results where the static characterization curve is determined. In Section V thermal behavior of the proposed densitometer is evaluated to compensate for the thermal drift of the sensor while the result of dynamic density measurement for different fluids is presented in section VI. The conclusion and references are shown in sections VII and VIII respectively.

## II. METHODOLOGY

Following the simple rule of physics, pressure sensors can directly measure liquid level where pressure  $P$  is proportional to liquid level  $h$  multiplied by its specific gravity.

$$P = \rho gh \quad (1)$$

Where  $\rho$  is density and  $g$  is the gravitational acceleration. Figure 1 represents the prototype of level measurement sensor proposed in [19] and its position inside the test tank. Let's assume that high-pressure side is in direct contact with the fluid under test while low pressure side is surrounded by the air. In case of considering differential pressure, measured pressure is proportional to the level of the liquid as in (2).

$$\begin{aligned} P_{high\ pressure} - P_{low\ pressure} = \\ (P_{liquid} + P_{air}) - P_{air} = \rho gh = \rho g(h' + x) \end{aligned} \quad (2)$$

Where  $x$  is the distance from bottom of the tank to one of the sensing diaphragm of differential pressure sensor, and  $h' = h - x$ .

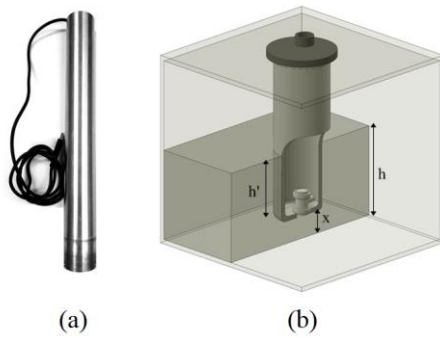


Fig 1. DP-level sensor proposed in [25]. (a)Prototype of the level sensor, (b) Sensor position inside the tank.

Assuming simple modification and submerging both low- and high-pressure sides into the liquid, differential pressure is a direct measurement of the density, considering that the distance  $h$  between upper and lower face of the sensor is known (26 mm for our sensor). This is the simple principle of proposed sensor to measure the liquid density as shown in (3).

$$\Delta P = P_{high\ pressure} - P_{low\ pressure} = hgp \quad (3)$$

It should be noted that the measurement of density is performed in flow free condition. The 3D model of the proposed instrument with designed suitable housing to place all the electronics inside is shown in figure 2. As shown in this figure, the electronics are placed into a box close to the sensing element.

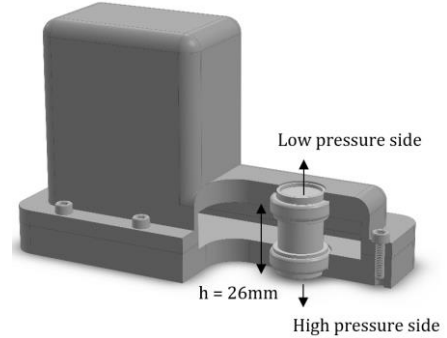


Fig 2. 3D model of proposed densitometer.

The employed sensor is a piezo-resistive differential one, with full scale range equal to 10 kPa.

## III. MEASURING CIRCUIT

Block diagram of the detection circuit is represented in figure 3 where piezo-resistive differential pressure sensor is in Wheatstone bridge configuration. A dedicated signal conditioning is required, involving both analog and digital processing due to the low voltage amplitude and the required measurement accuracy. The transducer's differential output is filtered and amplified through an Instrumentation Amplifier (INA) to fit the Analog to Digital Converter's (ADC) input voltage dynamic with 12-bit resolution. The DAC and the ADC are built-in inside the same microcontroller. The second ADC is used for monitoring the excitation signal. 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.

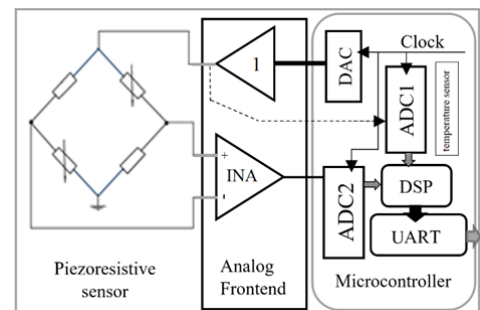


Fig 3. Measuring circuit block diagram of the proposed densitometer

The flowchart of the proposed instrument is shown in figure 4. DAC and ADCs work under the same clock domain. Using DAC of microcontroller, biased sinewave with amplitude of 0.5 V RMS is generated at 10 kHz to drive transducer. Using

two ADCs, both excitation signal and output of the INA are acquired simultaneously to have ratio metric output.

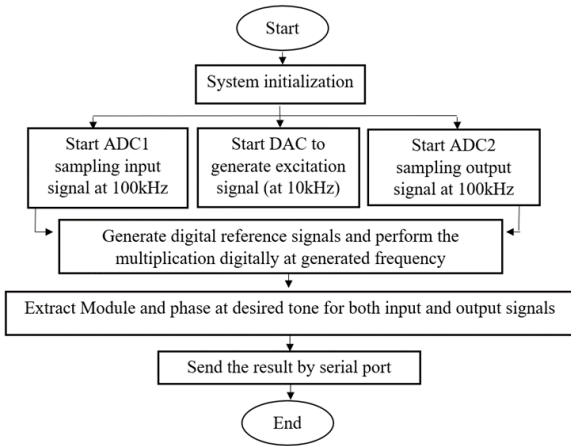


Fig 4. Flowchart of the signal acquisition and elaboration

Then, synchronous detection is used to detect desired signal by calculating the coefficients of the digital Fourier transform. Therefore, the microcontroller processes both signals using DFT and provides respective real and imaginary values. Here, the Analog signal at the output of instrumentation amplifier in addition to excitation signals are acquired at 100 kSPS and the DFT is computed on 3000 samples. This implies that there is 10 points per period which good enough to have accurate DFT. Here, the DFT is the mean of three performed DFT inside the microcontroller. Considering 3000 sample for DFT, exactly 300 period is acquired to avoid DFT leakage. It should be noted that there is a good compromise between measurement accuracy and speed considering the variation of the density as function of temperature. To measure the temperature of the piezo-resistive pressure sensor, a digital thermometer (DS18B20) protected by stainless steel housing with the accuracy of 0.5°C is used in direct contact with sensing diaphragms. Due to small size of the tank, we can assume that temperature is homogenous inside the tank. Since the sensing diaphragms are in direct contact with the liquid and, the measured temperature is a good approximation of the temperature of the liquid. The prototype of the sensor is illustrated in figure 5. As shown in figure 5 (a), the proposed instrument can work independently to measure the density as a standalone instrument. In addition, it can be used as an external instrument, see figure 5 (b), in parallel with commercial indirect level detection sensor, such as capacitive or pressure-based, or with any other process where the measurement of density is required.

### I. STATIC CHARACTERIZATION

In this section, the static characterization of the proposed densitometer is determined. To perform this, the prototype of the proposed DP-densitometer with associated test tank is shown in figure 6. The liquids under the test have carried on small and different containers. A small lab jack is used to move up and down the container and make it easy to repeat the measurement for different fluids. The steady-state

characterization has been performed using three sample liquids. The characterization curve is shown in figure7.

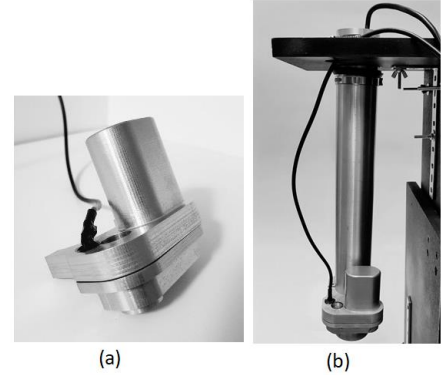


Fig 5. Prototype of proposed instrument: (a) as standalone densitometer (b) in parallel with any other level sensors (such as DP sensor).

Table 1 represents the absolute values for the density of liquids under the test provided by laboratory analysis with an accuracy of the 0.01%.

Table 1: list of test liquids to measure density

Sample	Density [ $\frac{g}{cm^3}$ ]
Test fluid 1	0.78516
Test fluid 2	0.75727
Test fluid 3	0.998

The sensor shows a linear response under steady-state conditions. Since density is a function of temperature, any thermal drift of the sensor should be addressed and compensated to reduce the measurement error. As mentioned earlier, the sensing element is a piezo-resistive pressure sensor. The major drawback of silicon-based piezo-resistive pressure sensors is its inherent temperature dependence that causes a remarkable thermal drift of characteristic. Consequently, the thermal characterization of the sensor is mandatory to define the parameters that cause the output drift. Numerous hardware, as well as software techniques, can be applied to compensate for the thermal drift. The most common approach is compensation resistors [20].

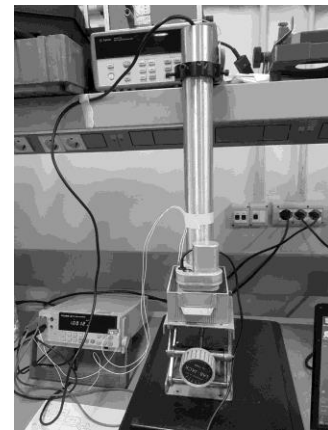


Fig 6. Experimental setup of proposed densitometer during steady-state characterization

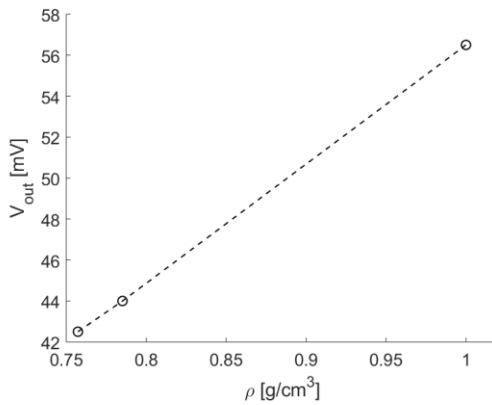


Fig. 7. Characterization curve for proposed DP-sensor to measure density

In such techniques, due to temperature coefficient of compensation resistors, the effectiveness and reliability are limited. Despite of hardware methods, simple digital compensation techniques, such as look up table [21], or polynomial-fitting methods [22] can be applied. In addition, approaches based on intelligent algorithms such as Artificial neural network (ANN) and hybrid thermal drift compensation [23] have been proposed. Although enough accuracy improvement can be achieved using such algorithms, complexity and requirement of large number of calibration data limit their application. In [24], a differential pressure-based level sensor is proposed where the performance is evaluated under temperature variation and presence of turbulences. 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. As result show, error without compensation is higher than 1 cm, while after the whole compensation it is limited to almost 0.15 mm under temperature variation. In other words, a good compensation of the deterministic error due to temperature is determined. Following the same approach, the thermal behavior of the proposed densitometer is studied and characterized, then applying a suitable correction method, associated errors during density measurement are evaluated. In this paper, instead of evaluating the temperature dependence of the offset and sensitivity separately as in [25], they are considered together to reduce characterization complexity and required time.

## II. THERMAL BEHAVIOR

Figure 8 shows an experimental setup to perform thermal characterization. As shown in this figure, the densitometer is attached to a cylindrical supportive body while placed inside a test tank and enclosed into the thermal chamber. The thermal characterization is evaluated ranging from 12 [°C] to 35 [°C]. The reason to work in such a small temperature range is to evaluate the performance of the sensor for small variations in density. Two test fluids, as indicated in Table 1 are used during the thermal characterization test.

Measurement includes temperature variation in a positive and negative direction.

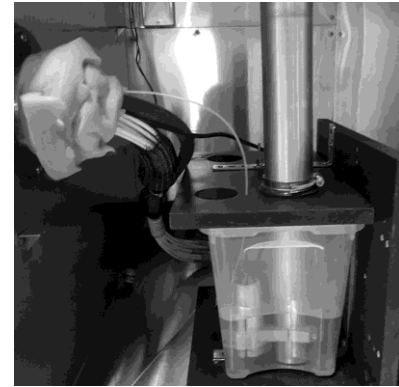


Fig. 8. Experimental setup to perform temperature characterization

Figure 9 demonstrates the total output voltage drift as a function of temperature which is about 34 mV. It should be noted the variation of the output due to density is factored out to characterize the drift only due to the instrument itself. As shown in this figure, a sort of asymmetric hysteresis behavior is observed. The correction for temperature drift is performed using a polynomial fitting approach in this paper. Figure 10 represents observed absolute measurement errors during each step of correction. After the compensation procedure, the maximum measurement error becomes limited to  $14 \frac{mg}{cm^3}$  under temperature variation. Generally, in polynomial based compensation approaches, different factors such as the size of the experimental dataset and coverage of measurement range influence the accuracy of the fitting formula. This implies lower compensation efficiency for different densities. By repeating the density measurements as a function of temperature, the measurement performance, and consequently the effectiveness of the compensation is evaluated. The measure densities in comparison with reference values for both test fluids are determined in figure 11 where the dashed lines indicate the maximum allowable error ( $\pm 1\%$ ).

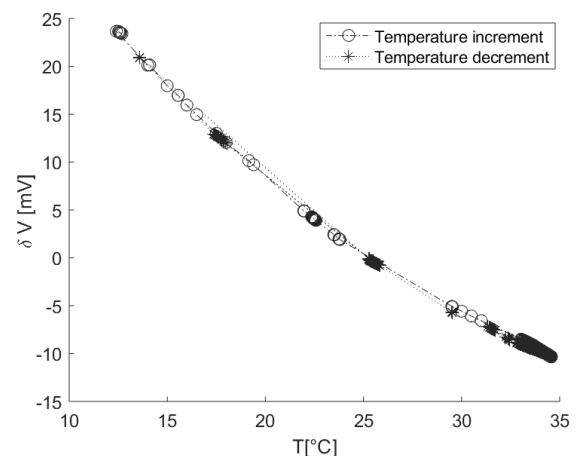


Fig. 9. Total drift of output voltage for fluid2 due to temperature variation

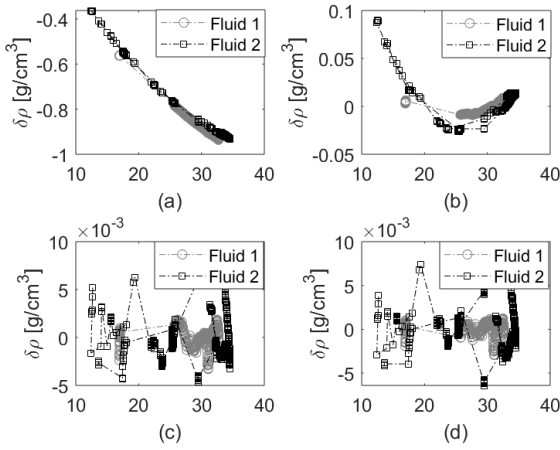


Fig.10. Observed absolute error versus temperature during continuous density measurement: (a). without compensation. (b) the 1<sup>th</sup> order approximation. (c) the 2<sup>th</sup> order approximation. (d) the 4<sup>th</sup> order approximation.

Due to the size of experimental dataset, the nonlinearity error is observed. As mentioned earlier, asymmetric hysteresis is determined for temperature starting from 32 °C during characterization for second fluid with lower density. Therefore, as it is expected, higher nonlinearity error is observed while measuring the density of second fluid in temperature around 32 °C. In order to evaluate the accuracy of the proposed densitometer, the uncertainty evaluation should be considered which is discussed in following section.

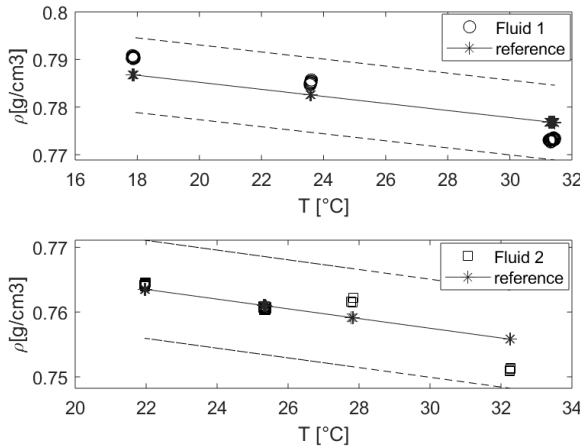


Fig. 11. Measured densities for different fluids V.S reference values

### III. UNCERTAINTY EVALUATION

All measurements are performed with a goal, ranging from the assessment of the compliance of a product with a specification to the characterization of new material. Therefore, the first step is to set target uncertainty which is the maximum admissible uncertainty defined for a specific measurement goal. In this paper, the desired maximum

allowable error in density measurement is defined as  $\pm 7.5 \frac{mg}{cm^3}$ . Measurement uncertainty is defined as the dispersion of the values attributed to a measured quantity [25]. In this paper, reference density values during calibration are laboratory analysis-based database with accuracy of lower than 0.01%. Therefore, the uncertainty related to calibration instrument is negligible. In figure 12, the nonlinearity error is represented. As shown in this figure, the uncertainty due to temperature dependence induces an error limited to almost about  $10 \frac{mg}{cm^3}$ . Considering observed asymmetric hysteresis, the uncertainty due to linearity is about  $5.5 \frac{mg}{cm^3}$ .

The standard deviation curve is shown in figure 13 which is based on 100 repeated measurement. Therefore, the uncertainty due to repeatability is about  $0.6 \frac{mg}{cm^3}$ . Evaluating the uncertainty due to reference values, linearity, repeatability and considering the quadratic sum of all uncertainty sources, 90% of measurement results using proposed instrument falls into the  $\pm 7.5 \frac{mg}{cm^3}$  confidence interval.

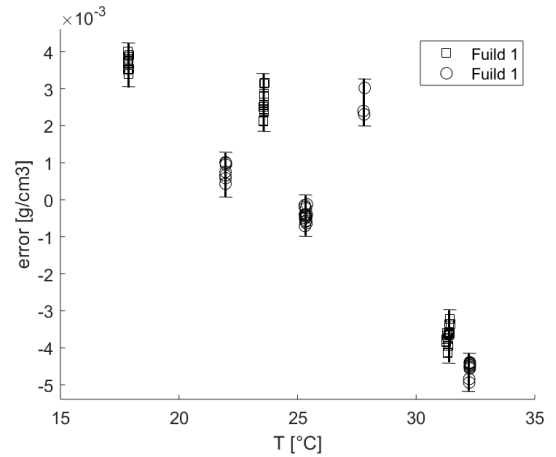


Fig. 12. Absolute error during density measurement for both test fluids.

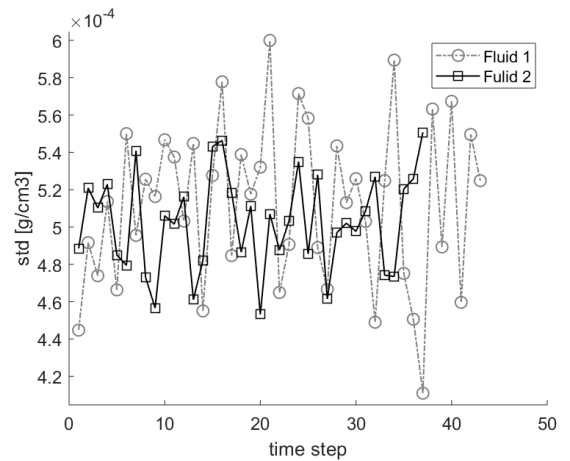


Fig. 13. Standard deviation curve while measuring density for two test fluids

#### IV. CONCLUSION

Currently available sensors to measure accurately the density are laboratory-based instruments. However, it is desired not only to measure absolute property of fluids but also tracking the variation of such properties in real time and dynamic environment. In this paper, a densitometer is proposed to measure density in dynamic environment. The proposed instrument is based on differential pressure sensing that can work either as a stand-alone or in parallel with any level measurement system where density measurement is required. The working principle is based on differential pressure sensing principle. The instrument is completely handled by a microcontroller. Here, both input and output signals are processed using DFT for getting respective real and imaginary values. The characterization of the sensor is experimentally determined under steady state condition where linear response is observed. In order to compensate for the thermal behavior of the pressure sensor, a temperature characterization was conducted. Temperature dependence is modeled through a fourth order polynomial, allowing a good compensation of the deterministic error due to temperature. Finally, an uncertainty evaluation of the proposed instrument is presented for measuring density of two different fluids under temperature variation. The contribution of uncertainty due to reference instrument and repeatability were negligible with respect to the linearity error mainly due to asymmetric hysteresis observed in higher temperature which are out of scope of this paper. the obtained results show a combined uncertainty lower than  $7.5 \frac{mg}{cm^3}$ .

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#### REFERENCES

- [1] Kazys, R.J.; Rekuviene, R. Viscosity and density measurement methods for polymer melts. *Ultrasonics* 2011, 66, 20–25.
- [2] Hauptmann, P.; Hoppe, N.; Püttmer, A. Application of ultrasonic sensors in the process industry. *Meas. Sci. Technol.* 2002, 13, 73–83.
- [3] Kontopoulou, M. *Applied Polymer Rheology. Polymeric Fluids with Industrial Application*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; pp. 3–28.
- [4] Thomas, S.; Shanks, R.; Chandrasekharakurup, S. *Nanostructured Polymer Blends*; William Andrew: Waltham, MA, USA, 2014; pp. 15–18.
- [5] Morard, G.; Garbarino, G.; Antonangeli, D.; Andrault, D.; Guignot, N.; Siebert, J.; Roberge, M.; Boulard, E.; Lincot, A.; Denoeud, A.; et al. Density measurements and structural properties of liquid and amorphous metals under high pressure. *High Press. Res. Int. J.* 2014, 34, 9–21.
- [6] Kolahi K, Schroder T, Rock H, “Model Based Density Measurement with Coriolis Flow meter”, *IEEE Transactions on Instrumentation and Measurement*, vol. 55, no. 4, pp. 1258-1262, August 2006.
- [7] Chung Snag K, Theissen David B, Won Kyu Rhim, “A Noncontact Measurement Technique For The Density And Thermal Expansion

- Coefficient Of Solid And Liquid Materials”, *Journal Review of Scientific Instruments*, pp. 3175-3181, September, 1996.
- [8] A M C Paz, J M Acevedo, Gandoy J D, A d del Vazquez, Freire CMP, “Plastic Optical Fiber Sensor for Real Time Density Measurement in Wine Fermentation”, *Proc. Instrumentation and Measurement Technology Conference*, May, 2007.
- [9] N. A. Lamberti et al., “A resonant sensor for liquid density measurement based on a piezoelectric bimorph,” *Proc. - 2015 6th IEEE Int. Work. Adv. Sensors Interfaces, IWASI 2015* Lamberti, N. A., Mura, M. La, Apuzzo, V., Casella, A., D’Uva, P., Caliano, G., Savoia, A. S. (2015). *A Reson. Sens. Liq. density Meas. bas*, pp. 293–296, 2015.
- [10] N. A. Lamberti, M. La Mura, V. Apuzzo, N. Greco, and P. D’Uva, “Optimization of a piezoelectric resonant sensor for liquids density measurement,” *IEEE Int. Ultrason. Symp. IUS*, vol. 2016-Novem, pp. 16–19, 2016.
- [11] L. Matsiev, J. Bennett, O. Kolosov, High precision tuning fork sensor for liquid property measurements, *IEEE Ultrasonics Symposium* (2005) 1492–1495.
- [12] Heinisch, M.; Voglhuber-Brunnmaier, T.; Reichel, E.K.; Dufour, J.; Jakoby, B. Application of resonant steel tuning forks with circular and rectangular cross sections for precise mass density and viscosity measurements. *Sens. Actuators A Phys.* 2015, 226, 163–174.
- [13] Kontopoulou, M. *Applied Polymer Rheology. Polymeric Fluids with Industrial Application*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; pp. 3–28.
- [14] Mathieu, J.; Schweitzer, P. Measurement of liquid density by ultrasound backscattering analysis. *Meas. Sci. Technol.* 2004, 15, 869–876.
- [15] Ruiz, M.; Junquera, E.; Lopez, S.; Aicart, E. A technique and a method for the continuous, simultaneous, and automatic measurement of density and speed of sound in pure liquids and solutions. *Rev. Sci. Instrum.* 2002, 73, 416–421.
- [16] Hoche, S.; Hussein, M.A.; Becker, T. Density, ultrasound velocity, acoustic impedance, reflection and absorption coefficient determination of liquids via multiple reflection method. *Ultrasonics* 2015, 57, 65–71.
- [17] Kielczyński, P.; Szalewski, M.; Balcerzak, A. Effect of a viscous liquid loading on Love wave propagation. *Int. J. Solids Struct.* 2012, 49, 2314–2319.
- [18] Jakoby, B.; Beigelbeck, R.; Keplinger, F.; Lucklum, F.; Niedermayer, A.; Reichel, E.K.; Riesch, C.; Voglhuber-Brunnmaier, T.; Weiss, B. Miniaturized sensors for the viscosity and density of liquids-performance and issues. *IEEE Trans. UFFC* 2010, 57, 111–120.
- [19] P. Esmaili, F. Cavedo, M. Norgia, “Differential pressure based liquid level measurement in sloshing condition,” *Proc. of IEEE Instrumentation and Measurements Technical Conference 2018 (I2MTC2018)*, pp. 2030-2035, Houston, USA, May 14-17, 2018.
- [20] Bao, M. (2000). *Micro Mechanical Transducers, Pressure Sensors, Accelerometers and Gyroscopes*. 1st ed. Shanghai: Elsevier Science.
- [21] Brignell, J. and Dorey, A. (1983). Sensors for microprocessor-based applications. *Journal of Physics E: Scientific Instruments*, 16(10), pp.952-958.
- [22] Šaponjić, D. and Žigic, A. (2001). Correction of a Piezoresistive Pressure Sensor Using a Microcontroller. *Instruments and Experimental Techniques*, 44(1), pp.38-44.
- [23] Chen, G., Sun, T., Wang, P. and Sun, B. (2006). Design of Temperature Compensation System of Pressure Sensors. In: *Proceedings of the 2006 IEEE International Conference on Information Acquisition*. Shandong: IEEE, pp.1042-1046.
- [24] P. Esmaili, F. Cavedo, M. Norgia. “Characterization of pressure sensor for liquid level measurement in sloshing condition,” *IEEE Trans. on Instr. and Meas.*, early access, DOI 10.1109/TIM.2019.2945414.
- [25] JCGM 100:2008. Evaluation of measurement data – Guide to the expression of uncertainty in measurement, Joint Committee for Guides in Metrology.