

Liquid Level Measurement through Capacitive Pressure Sensor

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Abstract— Property of fluid and material compatibility limit the level sensor's fabrication, dynamic range and accuracy. Piezoresistive pressure sensing elements with media compatible diaphragm are limited in low pressure dynamic. In contrast, capacitive pressure sensing elements provide better solution in terms of dynamic range. In this paper, liquid level measurement is realized through a capacitive differential pressure sensor. A custom digital synchronous detection is implemented in order to optimize the measurement performances, gaining a sensitivity of 40 ppm/mm. Different operating frequencies have been defined and a DFT based feedback loop is proposed in addition to eliminate the impact of interferences at predefined frequency. The sensor characterization indicates linear response. The maximum error is limited to 0.3 mm in range of 0- 200 mm as level displacement.

Keywords— liquid level measurement, phase sensitive detection, differential capacitive pressure, Digital Lock-in amplifier, single-tone DFT.

I. INTRODUCTION

Liquid level measurement is a common task for a number of industrial applications. Various commercial instruments are available, based on different measurement principles. The comparison between such approaches is indicated briefly in table I in terms of their dedicated techniques, advantages and disadvantages. As shown in this table, they are classified mainly as contact or non-contact method, with direct or indirect measurement technique. Floating-based level sensors are the most diffused but are limited in precision and accuracy. Other commonly used contact systems are based on capacitive measurements. These approaches eliminate the requirement of moving part as in conventional techniques. However, the capacitive probes suffer from miss-reading not only due to parasitic capacitance but also to fluctuations [1][2]. Despite of stray or parasitic capacitance effect, the performance of proposed contact based capacitive level sensors will be affected more due to effect of change of property of insulating coating material due to direct contact with the liquid and consequently limited life period. As an alternative solution, non-contact capacitive probe has been proposed where the effect of direct contact with the liquid is avoided [3][4]. However, some installation problems in non-contact capacitive probes have been reported which limits their application. Another possibility is the time domain reflectometry (TDR), but pulse-duration measurements with high resolution requires high bandwidth and consequently high costs for the acquisition electronics. In addition, the sensitivity depends on liquid under the test where it reduces in case fluid with lower dielectric constant [5]-[7]. Considering

non-contact indirect methods, different approaches have been proposed to measure liquid level: ultrasonic [8], vision [9], optical sensors [10]-[12]. In techniques based on Time of Flight (TOF) principle, the accuracy is limited when they are subjected to measure the quantity of liquid with low dielectric constant due to weak back reflection. Under dynamic operating condition such as temperature variation or the presence of the foam on the surface of the liquid during acceleration, ToF based approaches are subjected to inaccurate level detection. In [13], a low-cost and indirect contact-based level detection instrument is proposed using piezo-resistive pressure sensor. The pressure-measurement approach has been demonstrated robust against sloshing conditions and could be a good alternative to capacitive sensors.

TABLE I. COMPARISON BETWEEN DIFFERENT TECHNIQUES FOR LIQUID LEVEL MEASUREMENT

Method	Type	Advantages	Disadvantages
Floating-Based	Direct Contact	Simple Low cost	Mechanical moving part
Capacitive probes	Indirect Contact & non-contact	Rigid design Low cost Easy to implement	Parasitic capacitance; Probe contamination; Temperature variation
TDR	Indirect Contact	High accuracy	High costs; Probe contamination; Dependency on property of liquid
ToF	Indirect non-Contact	Suitable for different type of fluids	Multireflection due to presence of foam; Dependency on property of liquid; Temperature variation

Translating a pressure into a mechanical deformation or displacement is the operating principle of all pressure transducers. Resulted deformation of the sensing element is then converted into an electrical signal. Commercially available pressure transducer, by either individually or in combination, are mechanical, capacitance, piezoresistive, piezoelectric, thin- film and quartz gauge. In this work, we propose and characterize a different pressure sensor, based on capacitive sensing. The structure of this paper is as follows. Section II describes the working principle of proposed differential pressure sensor and level detection approach which is implemented in this paper. The performances as liquid level measurement system has been evaluated experimentally under steady state condition in section III. However, presence of the interferences at selected operating frequency affects the performance. To avoid this, a Discrete

Fourier Transform (DFT) based feedback loop is proposed here in evaluating operating frequency and detect the level accurately in addition, as represented in section IV. The results are presented in section V where the experimental characterization curve is determined under steady state condition. Finally, section VI presents the conclusion.

II. WORKING PRINCIPLE

Pressure based level sensing technique has already been proposed, for example for analysis and monitoring of stability of a ship [14]. It is well known that pressure P is proportional to the liquid level h .

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

where ρ and g are density and gravitational acceleration respectively (1). The working principle of the capacitive pressure sensor for measuring liquid level is explained in Figure 1. The transducer output is the value of a capacitance varying with the applied pressure.

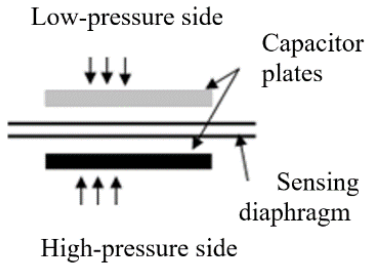


Fig 1. Working principle of capacitive differential pressure transducer.

The 3D model of proposed instrument, located inside the tank, is represented in figure 2.

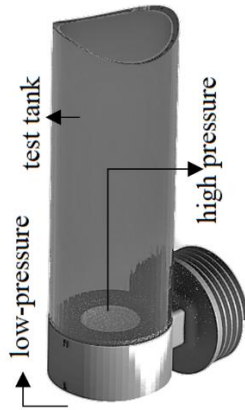


Fig 2. 3D model of implemented proposed level sensor inside the tank.

In Figure 2, x represents the distance from bottom of the tank to high pressure sensing diaphragm of differential pressure sensor. The level of the liquid is indicated by h . As shown in this figure, only one side of sensing diaphragm is in touch with the liquid (high pressure side). On the other hand, low pressure side is surrounding by the air and there is no contact with the liquid. In this configuration, applied pressure on the high-pressure side is the sum of total pressure due to the liquid and the air (surrounding environment) on the surface of the liquid. While, low-pressure side measures only the applied pressure due to the air only due to vented cap on the top. In case of acceleration, the liquid cannot splash out since

low pressure side is liquid free. Considering the absolute pressure for measuring the level, uncertainty due to external pressure applied on the surface of the liquid contributes in the measurement. 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).

$$\Delta P = (P_{liquid} + P_{air}) - P_{air} = \rho gh = \rho g(h' + x) \quad (2)$$

A possible implementation for reading the capacitance value is to include it in a single-pole low pass filter. In this way, the filter frequency response is a function of the capacitance value. The transfer function of a low pass filter at cut-off frequency provides maximum sensitivity in phase and good sensitivity in amplitude, with respect to parameter changes. Let's consider a single-pole low pass filter with $R=150 \text{ k}\Omega$, and $C_0=160 \text{ pF}$ where capacitance is increasing due to the applied different pressure. Since the variation of capacitance results in moving the position of the pole, the linearity error will arise in case of working at pole frequency ($f_{pole} = 6.64 \text{ kHz}$). Figure 3 represents the derivative of transfer function's magnitude respect to operating frequency. The range with minimum linearity error is indicated with an arrow. As shown in this figure, it is convenient to work close to pole frequency for a good tradeoff between linear response and good sensitivity. It should be noted that working close to the pole frequency should be guaranteed in case of considering different operating frequencies. Therefore, a digital potentiometer is included (R_{input}) to adjust the pole frequency while changing the excitation frequency. It has the same function of a normal potentiometer but instead of mechanical action, it is driven by digital signals.

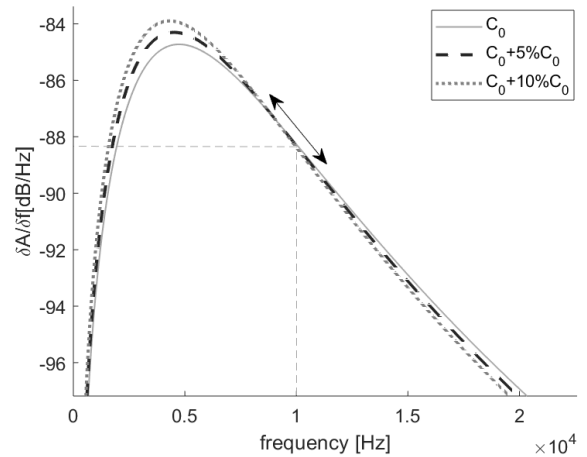


Fig 3. Operating frequency V.S linearity

As well known, DC and low-frequency measurements are affected by offset and $1/f$ noise, therefore precise measurement are often shifted at higher frequency. Synchronous detection is a good solution for realizing a strong filtering of noise and disturbances contributions, implementing a phase sensitive measurement, able to filter out signals not synchronized with the reference signal [15]. The implemented solution is a single-bin DFT, realized by the multiplication of the sampled signal for two quadrature signals (sine and cosine at the same frequency). From the two-phase and quadrature signals, amplitude and phase measurements are directly obtained. The

measurements become the more accurate depending on the number of acquired points. This is due to the contribution of white noise on every single bin which affects the measurement accuracy in case of dealing with low SNR (Signal to Noise Ratio). The DFT implements a uniformly spaced bank N of critically sampled filters. The frequency response of each filter has the shape of a Dirichlet kernel, and its width is inversely proportional to N [16][17]. Therefore, the frequency-domain SNR can be effectively improved by increasing the DFT length N . Increase the observation duration or in the other words performing longer DFT implies that each bandpass filter is narrower and integrates less noise and disturbances power.

III. REALIZED INSTRUMENT

In this paper, level sensor consists of three subsections. First subset includes capacitive pressure transducer as sensing element. The analog Front-end for signal conditioning and a digital signal processing unit for managing the measurement, sampling and elaborating signals are the second and third subsections respectively. A digital-to-analog converter (DAC) generates the excitation signal, and two synchronous ADCs (triggered by the same clock signal), acquire both the driving signal (DAC output) and the output of analog Front-end. In this way, any delay induced by the analog electronics is compensated. Finally, Digital Signal Processing unit (DSP) elaborates the acquired signals using DFT and provides gain in modulus and phase shift between input and output signals. Figure 4 shows the prototype of proposed level instrument, included in the experimental setup with the liquid tank. Low pressure side of the sensor is open to the air, while a graduated cylinder test tank is mounted on high pressure while.

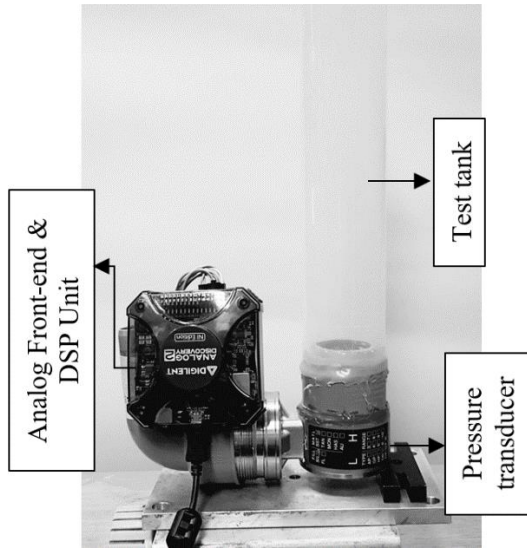


Fig. 4. Prototype of the proposed level instrument

As sensing element, a capacitive Differential Pressure (DP) sensor (range of 7.5 kPa) is connected to the input of operational amplifier in the configuration of first order low pass filter. Figure 5 shows the measuring circuit block diagram with signal generation, acquisition and processing block diagram. A multi-function instrument (DIGILENT-Analog Discovery 2) manages signal generation and acquisition. It is used to generate excitation sinusoidal signal at different frequencies with amplitude of $2 V_{p-p}$ provided by internal function generator ($\pm 5V$, 14-bit, 100MS/s). Using

Dual channel 14-bit, ADC form Analog Discovery 2, the excitation and output of the operational amplifier are acquired simultaneously. Both signals are processed using DFT for getting respective real and imaginary values. Each signal is acquired at 10 MSPS and the DFT is computed on 8000 samples. DFT algorithm and amplitude detection are performed on a personal computer by a program written in LabVIEW™ from National Instrument.

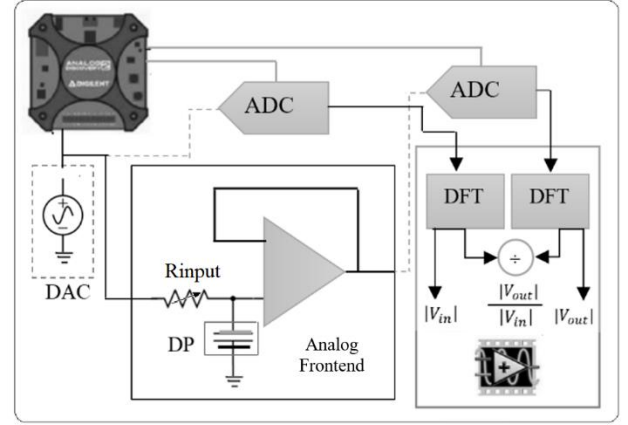


Fig. 5. Measuring circuit block diagram of the proposed instrument with signal generation, acquisition and processing block diagram. Capacitive pressure sensor is at the input of the analog Front-end.

IV. AUTOMATIC FREQUENCY CHOICE

As mentioned earlier, part of the spectrum where the noise level is lowest can be selected if there is freedom in the choice of excitation frequency. Indeed, presence of unwanted interference close to selected operated frequency affects strongly the performance, also of a synchronous detector. One solution to reduce the interference effects could be to improve the filtering by increasing DFT length N . However, there is always a tradeoff between measurement time and frequency resolution. In addition, this solution is limited by hardware implementation (memory and processing). Our solution includes a feedback loop based on spectrum analysis, to check in real time the best excitation frequency for the measurement. The block diagram of the proposed instrument including feedback loop is represented in figure 6. Figure 7 shows the flowchart including feed-back loop. As shown in this figure, first step is to initialize the system. Following default operating frequency (100 kHz), filter configuration is updated to have right pole frequency. The equivalent electrical model of capacitive pressure sensing element is a capacitance which is equals to 160 pF in absence of applied pressure. In this case, input resistance is 15 k Ω to have pole at 66.4 kHz. Then, the excitation signal is generated at 100 kHz. As mentioned earlier, each signal is acquired at 10 MSPS and the DFT is computed on 8000 samples to fit into sensor characterization curve. Once it is required, the frequency sweep cycle will be started. To do this, DAC is stopped and digital reference signals are generated in two predefined frequencies (10 kHz and 100 kHz) where DFT is performed. In this case, detected amplitude of the specified DFT bin includes only noise and disturbances contribution on that bin. The amplitude of two tones should be in same range in case of interference free condition. However, higher detected amplitude at each predefined frequency results in discarding associated frequency due to presence of interference. Following the

predefined threshold and comparing the detected amplitudes at both 10 kHz and 100 kHz, working at 100 kHz is more convenient due to its lower detected amplitude. Here, the frequency sweep is repeated every 10 ms.

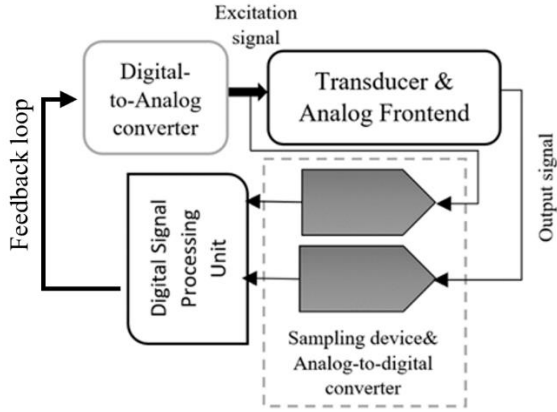


Fig. 6. Block diagram of the proposed instrument including feedback loop

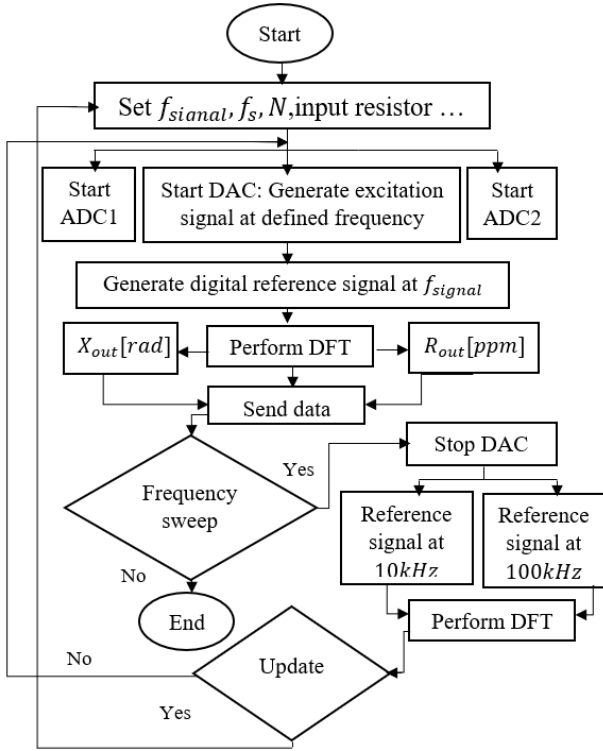


Fig. 7. Flowchart of DFT based feedback loop

V. SENSOR CHARACTERIZATION

To characterize the liquid level sensor, the water level in the tank (Fig. 4) was changes step-by-step adding water. Here, the minimum level of the liquid in the tank is 50 mm and it is required to measure up to 250 mm as maximum. The reference values are measured using laser range finder (Keyence -LK-G512) with accuracy in range of nm and a floating object on the surface of the liquid. Figure 8 shows the sensitivity curve of the proposed sensor, where the output is defined as ratio between output of operational amplifier and excitation signal ($A = |\frac{V_{out}}{V_{in}}|$). As shown in this figure, the sensitivity is 40 ppm/mm.

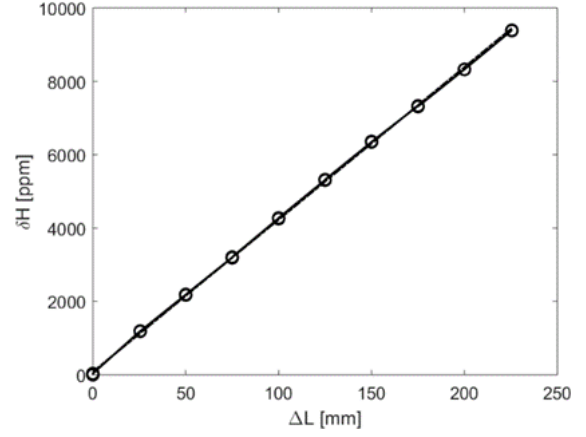


Fig. 8. Sensitivity curve of the proposed level sensor

Applying the gain and sensitivity coefficients determined by characterization curve, figure 9 represents measured variation in level of liquid versus the reference values taken by graduated cylinder test tank. The absolute error is then shown in figure 10.

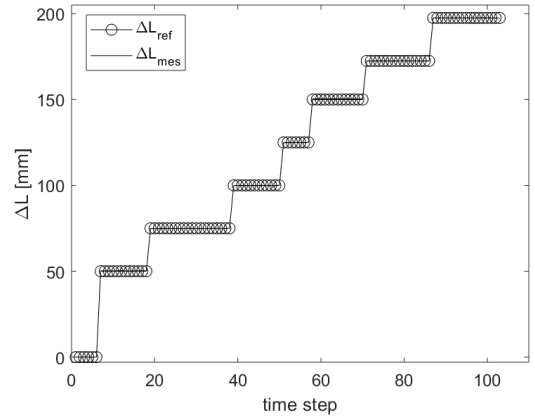


Fig. 9. Measured level values V.S reference level values

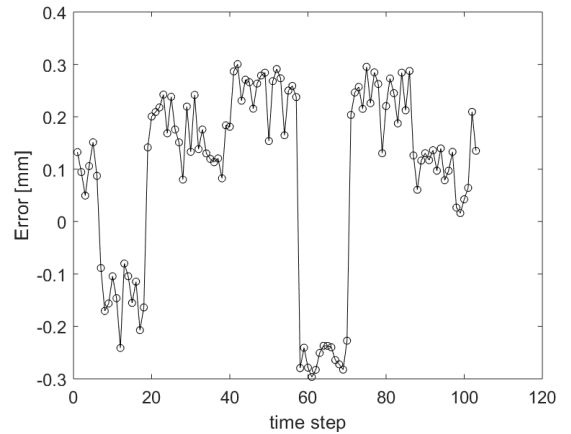


Fig. 10. Absolute error in level measurement in mm.

To evaluate repeatability error, additional experiments have been performed. It should be noted here the hysteresis effects have been included. Figure 11 shows the measured level

increment and decrement using proposed instrument for repeated measurements. Figure 12 shows the absolute error due to repeatability and hysteresis contributions. As result shows, the error for the proposed instrument is about ± 0.3 mm.

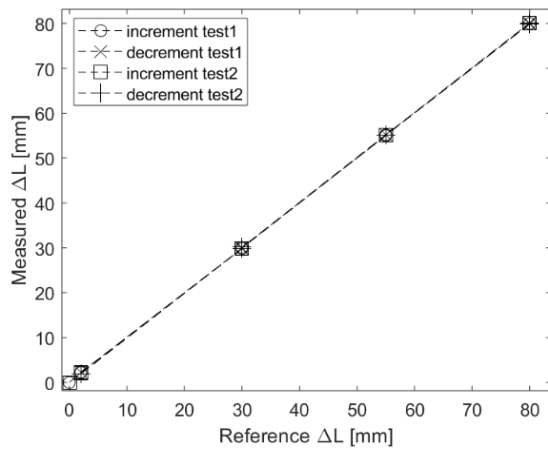


Fig. 11. Measured level values V.S reference values, during repeatability test

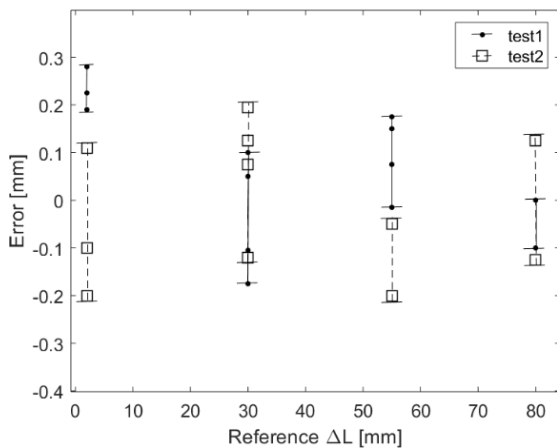


Fig. 12. Absolute values for repeatability error of the proposed instrument

VI. CONCLUSION

A differential capacitive pressure sensor has been characterized as liquid level measurement system. In order to optimize the performances, a dedicated digital acquisition system performs a synchronous detection, with the possibility of changing the excitation frequency as a function of the measured disturbances and interferences. A DFT based feedback loop is included to eliminate the impact of interferences at predefined operating frequency. The frequency sweep is performed every 10ms. A measurement campaign was conducted to evaluate the sensitivity, repeatability and absolute error of the sensor, as a function of the liquid level. The sensor shows a linear response, with sensitivity of 40 ppm/mm, and absolute errors limited to 0.3 mm. This kind of performances are adequate for a number of industrial applications.

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