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Accurate Level Measurement Based on Capacitive Differential Pressure Sensing

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Abstract: In this paper, a capacitive differential pressure sensor is characterized as a liquid level measurement system. The sensor is configured as a first-order low pass filter. Different operating frequencies have been defined and a DFT based feedback loop is proposed in addition to eliminate the impact of interferences at predefined operating frequency. The phase-sensitive demodulation of the signal is performed using a single-tone DFT algorithm, acquiring both excitation and output signals. Each signal is acquired at 10 MSPS and the DFT is computed on 8000 samples. The sensitivity of the proposed instrument is 40ppm/mm with very good linearity and error as low as ± 0.3 mm. The measurement characterization of the sensor indicates good performances as low-cost level measurement system.

Keywords: Liquid level measurement, Differential capacitive pressure, Phase sensitive detection, Digital Lock-in amplifier, Single-tone DFT.

1. Introduction

In a wide range of scientific and industrial applications, precise liquid level measurement plays a crucial role. To achieve accurate level detection, request for dedicated techniques that are working to tighter accuracy limits become more severe while production costs are limited due to economic issues.

As a result, the requirement for designing an instrument, to be both accurate and cost-effective, becomes ever harder to satisfy. Various techniques have been proposed in this manner. These approaches can be categorized into either direct/indirect or contact/non-contact methods. Typically, direct methods such as floating based level measurement systems are limited by the lack of precision and accuracy. Several approaches in the field of contact-based indirect level measurement such as time domain reflectometry (TDR), capacitive and pressure-based

reading systems have been proposed. 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]. Although TDR based approaches are very accurate solutions, but pulse-duration measurements with high resolution requires high costs for the overall data-acquisition system. In addition to contact-based methods, different non-contact indirect methods such as ultrasonic [3-4], vision [5], optical [6-8], microwave [9-12] have been proposed to measure the level. In techniques based on Time of Flight (TOF) principle, the performance becomes poor when they are subjected to measure the quantity of liquid with low dielectric constant due to weak back reflection. In addition, the presence of the foam on the surface of the liquid results into inaccurate level detection during acceleration. In [13], a low-cost and indirect contact-

based level detection instrument is proposed based on differential pressure sensing approach.

A Capacitive differential pressure sensor is used as a sensing element in the configuration of first-order low pass filter where a sinusoidal signal generated by Digital-to-Analog Converter (DAC) of multi-function instrument to drive it. In order to eliminate any non-linearity, induced by distortion of the driving signal, the output signal of the proposed instrument is expressed as the ratio between the signal at the output of the operational amplifier and input signal. Then, single-bin DFT (Discrete Fourier Transform) is performed based on evaluating the phase and quadrature component with a digital synchronous receiver, which performs the multiplication of the sampled signal for two quadrature signals to then evaluate the Fourier coefficients. The performance of the proposed instrument has been evaluated experimentally under steady state condition. However, presence of the interferences at selected operating frequency affects the performance. To avoid this, a DFT based feedback loop is proposed here in evaluating operating frequency and detect the level accurately in addition.

2. Liquid Level Measurement Based on Differential Pressure Sensing Principle

Pressure based level sensing technique has been proposed for the analysis and monitoring of a ship's stability [14]. The Pressure transmitter measures level based on the principle that pressure (P) is proportional to the level h of the liquid multiplied by its specific gravity given by (1).

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

where ρ and g are the density and gravitational acceleration respectively. Depending on the technology, different types of pressure transducers are commercially available such as piezoresistive, piezoelectric and capacitive pressure transducers. Fig.1 represents the working principle of the capacitive differential pressure sensor for measuring liquid level, used in the proposed level instrument. The output of the transducer is an equivalent capacitance which changes its value as a function of the applied pressure. In the frequency-shift-based implementation, the capacitive sensor is used in an RC low pass filter, such that a change in capacitance causes a change in frequency response. The transfer function of a low pass filter is represented in (2) as a function of frequency where f_c is its cut-off frequency. While working at cut-off frequency provides maximum sensitivity in the phase, working close to this frequency maximum sensitivity in gain and linearity can be achieved. This is where the excitation signal is generated to derive transducer and measure accurately the level of the liquid.

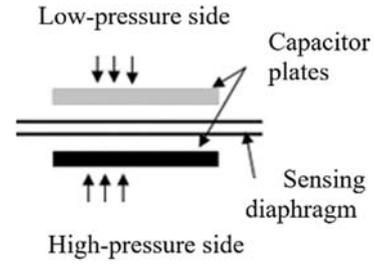


Fig. 1. Capacitance variation in capacitive differential pressure transducer due to applied pressure.

$$A_v = \frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1 + (\frac{f}{f_c})^2}} \quad (2)$$

Due to different frequency dependency of various noise sources, as in many electrical and physical systems, there is increasing in noise level as the frequency approaches DC. In case of having flexibility in the choice of the modulation frequency, part of the spectrum can be chosen as the operating zone where the noise level is the lowest. Working at higher frequencies requires a narrowband filter to recover the signal. Alternatively, phase sensitive detection technique is introduced to move the modulated signal back to dc while filtering out other signals that are not synchronized to the reference signal [15]. Here, the single-bin DFT is performed based on evaluating the phase and quadrature component with a digital synchronous receiver, which performs the multiplication of the sampled signal for two quadrature signals (sine and cosine at the same frequency), to then evaluate the Fourier coefficients. From the two-phase and quadrature signals, amplitude and phase measurements are easily obtained. The amplitude and phase measurements become the more accurate depending on how many points have been acquired. 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).

In Vandermonde matrix (3), introduced by Sylvester [16] in 1867, DFT is expressed as the DFT matrix assuming the unitary definition of the DFT.

$$F = \begin{bmatrix} \omega_N^{0,0} & \omega_N^{0,1} & \dots & \omega_N^{0,(N-1)} \\ \omega_N^{1,0} & \omega_N^{1,1} & \dots & \omega_N^{1,(N-1)} \\ \vdots & \vdots & \ddots & \vdots \\ \omega_N^{(N-1),0} & \omega_N^{(N-1),1} & \dots & \omega_N^{(N-1),(N-1)} \end{bmatrix}, \quad (3)$$

where $\omega_N = e^{-\frac{2\pi j}{N}}$. As shown in (4), the DFT becomes a unitary transformation, defined by a unitary matrix with unitary normalization $\frac{1}{\sqrt{N}}$ constants.

$$X[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] e^{-\frac{2\pi jkn}{N}} \quad (4)$$

Parseval's theorem for DFT is represented by (5). According to this, the sum (or integral) of the square of a function is equal to the sum of the square of its transform [17].

$$\sum_{n=0}^{N-1} |x[n]|^2 = \sum_{k=0}^{N-1} |X[k]|^2 \quad (5)$$

Let's assume that $x[n]$ represents a zero-mean white noise process with variance σ^2 . Applying the expectation of both sides results into (6) and (7).

$$\sum_{n=0}^{N-1} E(|x[n]|^2) = \sum_{k=0}^{N-1} E(|X[k]|^2), \quad (6)$$

$$N \delta^2 = NE(|X[k]|^2) \quad (7)$$

Finally, by simplifying N , it is concluded that expected value of the noise spectrum's squared magnitude does not change by increasing DFT length under unitary definition of DFT.

$$\delta^2 = E(|X[k]|^2) \quad (8)$$

Now consider $x[n]$ is a sinusoidal tone of interest. For simplicity, assume $x[n]=1$ (considering tone of the interest is at zero frequency). Recalling (4):

$$X[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x[n] e^{-\frac{j2\pi kn}{N}}, \quad (9)$$

$$X[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} e^{-\frac{j2\pi kn}{N}}, \quad (10)$$

$$X[k] = \frac{1}{\sqrt{N}} N \delta[k], \quad (11)$$

$$|X[k]|^2 = N \delta[k] \quad (12)$$

Nevertheless, the expected squared magnitude of the noise process in the frequency domain stays constant, the expected frequency-domain squared magnitude for a narrowband signal is proportional to N . This could be evaluated from filter point of view since The DFT implements a uniformly spaced bank N of critically sampled filters. The frequency response of each filter the shape of a Dirichlet kernel, whose width is inversely proportional to N . Therefore, the frequency-domain SNR can be effectively increased the by increasing the DFT length N . Increase the observation duration or in the other words performing longer DFT implies that each bandpass filter covers a smaller portion of the frequency band resulting less noise power passed by each bin's corresponding filter.

3. Measuring Circuit

In this paper, the instrument design is divided into three main parts: the capacitive differential pressure transducer, the analog frontend for signal condition and a digital part to provide sensor operating condition and making the elaboration as represented in Fig. 2.

The Excitation signal is generated by DAC. Using two ADCs working in parallel and triggered by the same clock signal, it is possible to acquire the DAC output used to drive the transducer and the output of analog frontend at the same time. In this case any non-linearity induced by distortion of the driving signal is eliminated. Then, Digital Signal Processing unit (DSP) processes the acquired signals using DFT and provides respective phase and quadrature.

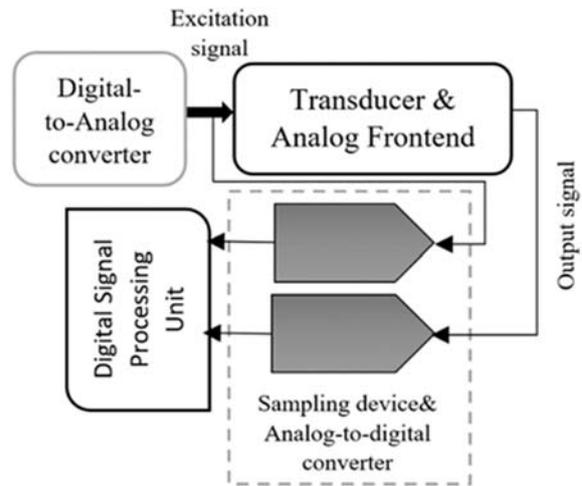


Fig. 2. Block diagram of the proposed instrument including capacitive differential pressure sensor, one DAC and two ADCs.

Fig. 3 shows the output defined as ratio between the output of operational amplifier and the excitation signal as function of frequency. As shown in this figure, linearity is guaranteed at lower than 200 kHz and higher than 400 kHz. Therefore, Optimum operating frequency can be selected based on sensitivity curve where it is defined in [ppm/Hz] unit, as shown in Fig. 4.

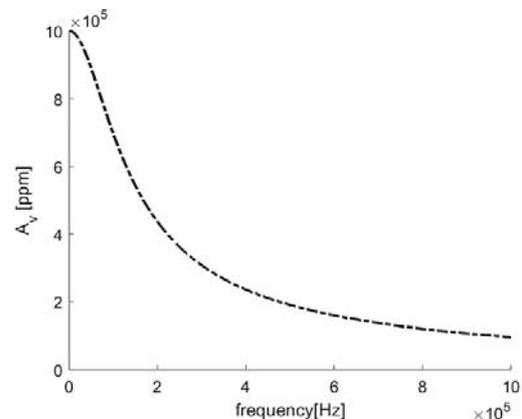


Fig. 3. Frequency response of DP based level sensor.

Following the Fig. 4, working at almost 68 kHz provides maximum sensitivity. The zoomed part of graph shows about 10 % reduction in sensitivity in

case of working at 100 kHz and it is acceptable in case of considering uncertainty while determining equivalent capacitance of DP at zero pressure (offset).

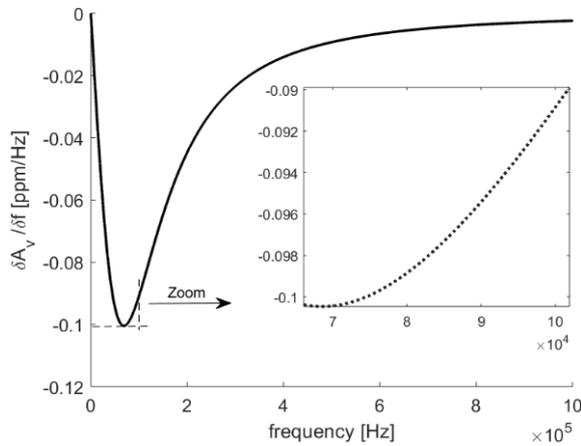


Fig. 4. Sensitivity defined in [ppm/Hz] V.S operating frequency.

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 can be used to adjust the pole frequency which has the same function as a normal potentiometer but instead of mechanical action it uses digital signals and switches.

4. Feedback Loop on Operating Frequency Selection

As mentioned earlier, part of the spectrum where the noise level is lowest can be selected if there is some freedom in the choice of modulation frequency. However, presence of unwanted and strong interference very close to selected operated frequency affects strongly the performance. One solution to discard the interference is to reduce main lobe width by increasing length of DFT. However, there is always tradeoff between time and frequency resolution. In addition, this solution is limited by hardware implementation and high cost. Alternatively, a feedback loop can be applied based on spectrum analysis to decide whether the operating frequency should be updated. Fig. 5 shows flowchart of the feed-back loop where 10 and 100 kHz have been considered as default operating frequencies.

As shown in this figure, first step is to stop the excitation signal to evaluate suitable operating frequency. After choosing the right pole frequency and changing filter configuration, DFT is performed. In this case, detected amplitude of the specified DFT bin shows the contribution of the noise on that bin since there is no excitation signal. It is expected to detect the amplitude of two tones in same range in case of interference free condition. However, higher detected amplitude at each predefined frequency results into

discarding associated frequency due to presence of interference.

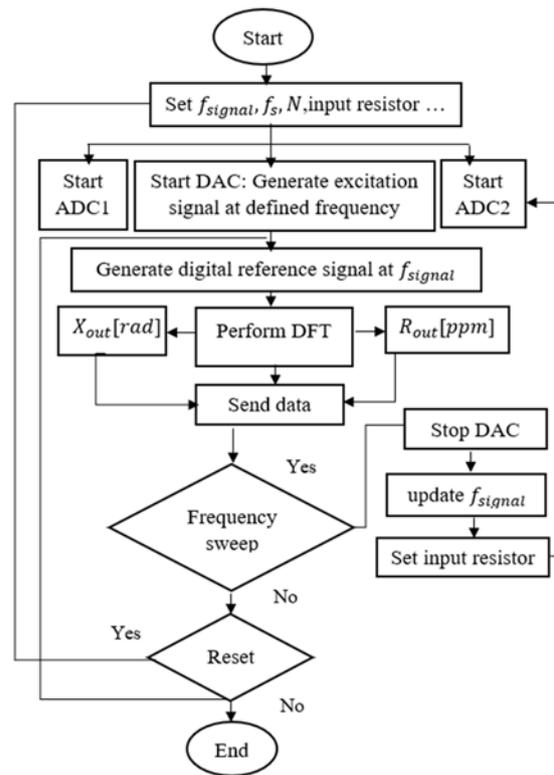


Fig. 5. Flowchart of DFT based feedback loop.

5. Experimental Setup

The prototype of proposed level instrument and experimental setup with the liquid tank have is illustrated in Fig. 6. Graduated cylinder test tank is mounted on high pressure while low pressure side is open to the air.



Fig. 6. Prototype of the proposed level instrument.

The Pressure sensing element is a differential capacitive pressure sensor in range of 0~7.5 kPa which is connect to the input operational amplifier in the configuration of first order low pass filter. A multi-function instrument (DIGILENT-Analog Discovery 2) is used to generate excitation sinusoidal signal at different frequencies with amplitude of $2 V_{p-p}$ provided by function generator (± 5 V, 14-bit, 100 MS/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 and provides respective real and imaginary values. Each signal is acquired at 10 MSPS and the DFT is computed on 8000 samples. Fig. 7 demonstrates measuring circuit with digital signal generator and two synchronous samplers. Further steps to perform DFT algorithm and amplitude detection is done in LabVIEW from National Instrument.

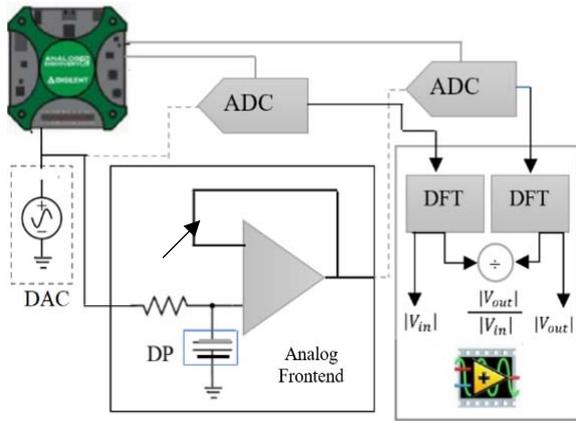


Fig. 7. Measuring circuit block diagram of the proposed instrument with signal generation, acquisition and processing block diagram.

Recalling the feedback loop, the detected amplitude in absence of excitation signal determines the presence of interference in selected frequency. After updating the value for resistor and performing DFT at 10 and 100 kHz, different amplitudes are detected at predefined frequencies. As shown in Fig. 8, the presence of a strong interference at 10 kHz is more evident due to its high amplitude. While working at 100 kHz is more convenient. Here, the frequency sweep is repeated every 10 ms.

To determine sensitivity curve, the water level in a test tank was increased in steps by adding water. Fig. 9 shows the sensitivity curve of the proposed instrument. As shown in this figure, the sensitivity is 40 ppm/mm.

To evaluate repeatability error, additional experiments have been performed. Fig. 10 shows the measured level increment and decrement using proposed instrument for repeated measurements to evaluated repeatability error of the instrument. Corresponding error is illustrated in Fig. 11. As result

shows, the repeatability error for the proposed instrument is about ± 0.3 mm.

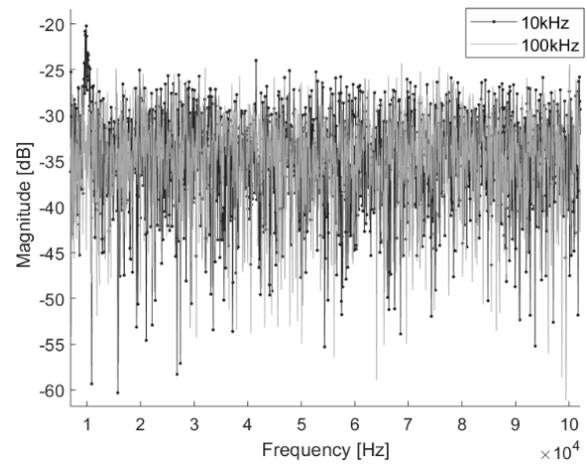


Fig. 8. Magnitude (in dB) of DFT spectrum of 8000 sample of without excitation signal at 10 kHz and 100 kHz.

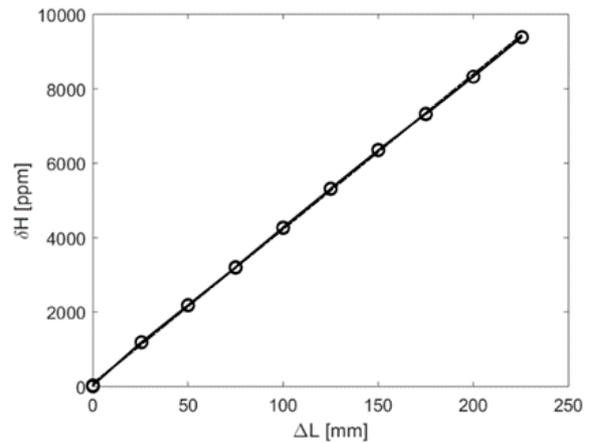


Fig. 9. Sensitivity curve of the proposed instrument defined as [ppm/mm].

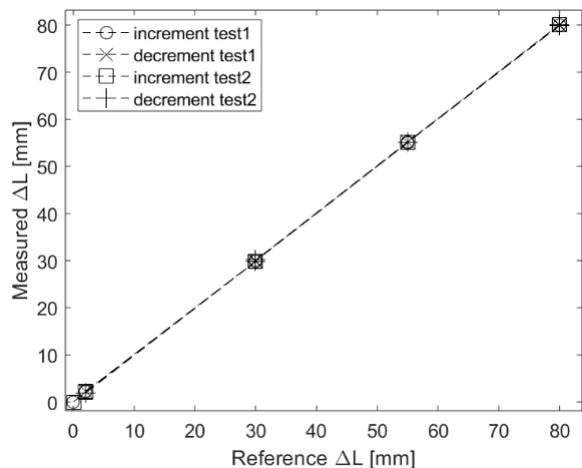


Fig. 10. Measured relative value of the level V.S reference values during repeatability test.

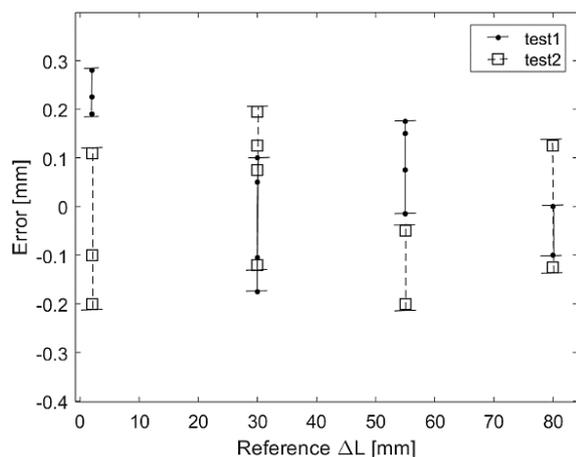


Fig. 11. Absolute values for repeatability error of the proposed instrument.

7. Conclusions

As low-cost level measurement system, a digital lock in amplifier based liquid level instrument is proposed in this paper, using differential pressure sensing approach. Different operating frequencies have been defined and a DFT based feedback loop is proposed in addition to eliminate the impact of interferences at predefined operating frequency. The output signal of the proposed instrument is defined as the ratio between the signal at the output of the operational amplifier and input signal to eliminate any non-linearity, induced by distortion of the driving signal. Dual channel ADC form DIGILENT is used to acquire the excitation and output of the operational amplifier simultaneously. Both signals are processed using DFT and provide respective real and imaginary values. Each signal is acquired at 10 MSPS and the DFT is computed on 8000 samples. The sensitivity of the proposed instrument reported here is 40 ppm/mm, with good linearity. In addition, the repeatability test is performed, and the error is determined as ± 0.3 mm.

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