

Fluidic Capacitive Sensor for Detection of Air Bubble Inside Engine Lubricating Oil

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Abstract: In this paper, a capacitive sensor based on printed circuit board was designed and fabricated to detect air bubbles that appear in the engine lubricating oil. A three-electrode capacitive sensor structure is designed and simulated for monitoring and estimating amount and size of air bubbles in oil. The capacitive sensor consists of three electrodes that are structured by the PCB, copper sheets and vias. The oil pipe as a fluidic channel is threaded through the hole of capacitive sensor. By using that structure, air bubble inside fluidic channel can be detected in real-time monitoring. Simulations showing the change of signal in correspondence to the volume of air bubble inside oil channels are compared to the measurement to give a good idea of fabrication structure. In this measurement, this capacitive sensor can monitor an air bubble with a small size of 0.1 mm^3 to 3.83 mm^3 . The occurring of multi air bubbles is also monitored by this capacitive sensor for distinguishing each bubble when the bubbles have a small distance among them.

Keywords: Capacitive sensor, Fluidic sensor, Air bubble detection.

1. Introduction

The air bubbles appear in the lubricating oil in some cases of using machine during reaction with environment and sweep inside machine. This type of air pollution is the most dangerous, since many air bubbles in the lubricant oil can increase the rate of oxidation and thermal degradation, degrade additives, as reduce heat transfer coefficient and reduce its lubrication.

This problem is exacerbated when the air bubbles move into the high-pressure environment where changes in volume caused a drastic increase in temperature. In machine environments where dramatic pressure changes occur, such as a hydraulic pump, the dramatic and instantaneous volumetric change causes bubbles to implode violently, which leads to erosion of machine surfaces. In hydraulics, entrained air can create other problems as well, such as spongy operations, loss of controls and increased likelihood of surface deposits in valves.

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Moreover, if droplets appear in the lubricating oil, water droplets will cause the engine to rust corrosion, increased oxidation of the oil, resulting in a precipitation of additives. Contamination droplets also increase the oil's ability to attract air, thereby increasing air entrainment [1].

In applications in petrochemical industry people need to detect and control the appearance of air bubbles in pipes. In an oil well, the presence of air bubbles may be an early indicator of pockets of natural gas in oil wells, from which one can prevent and stop the danger from these large gas pockets.

In this paper, the research team introduced a method to detect and estimate the amount of air bubbles and the volume velocity of air bubbles appeared in the lubricating oil. To detect the presence of very small air bubble size in oil, three capacitive sensors are used placed extremely tightly outside the pipeline. Types of the capacitive sensors have more advantages in comparison with other methods to detect air bubbles with a size as small as millimeters and lubricants like detected in x-rays - rays or ultrasound [2-4] or metal particles detected by the sensor inductance method. The method capacitive sensors use three electrodes giving achievements as high accuracy and low cost, and easy fabrication.

2. Designs and Simulations

A. Mathematical background

Capacitive sensors convert a change in location, distance, or dielectrics to electrical signals. Capacitive sensors detect any changes in the three parameters of a capacitor: the distance (d), the area of the electrode plate (S) and dielectric constant (ϵ_r) [5].

$$C = f(d, S, \epsilon_r) \quad (1)$$

A schematic for measuring a small capacitance to the appearance of an object inserted between the electrodes of the sensor is shown in Figure 1.

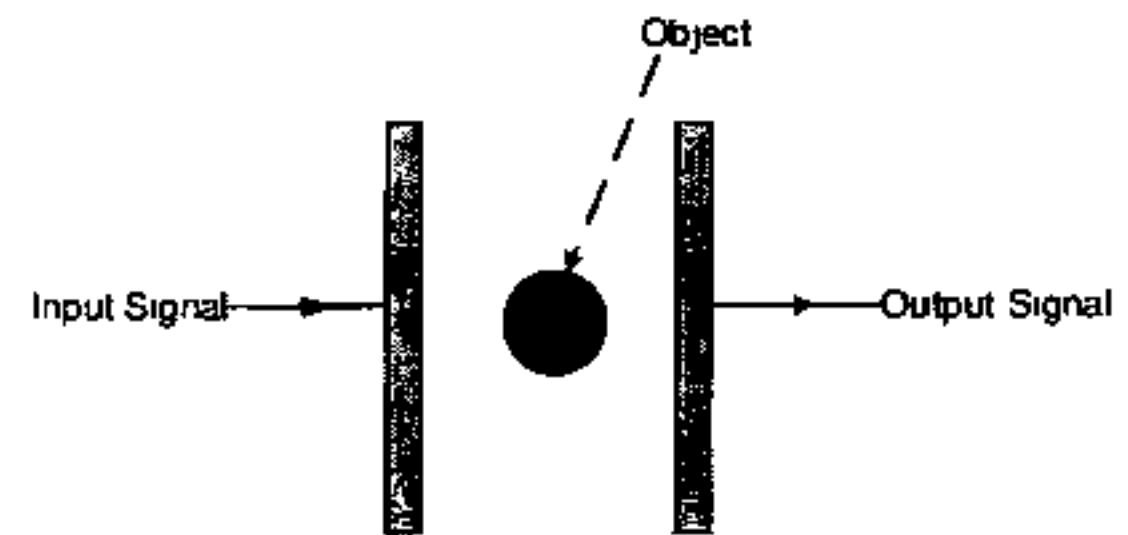


Figure 1. Capacitance change during the impurities enters space between the electrodes of the sensor [5].

B. Sensor structure

Figure 2 shows a design of the proposed fluidic capacitive sensor system. Two fluidic channels are perpendicular to a PCB board as sensing and reference channels. Three-electrode capacitors on PCB surround the fluidic tubes. The two capacitive sensors are fabricated on the same PCB board with the electronic circuits. This design structure allows reducing the parasitic capacitance and noise by ignoring connected wires.

The capacitor consists of 3 copper electrode plates with cross area of 1.96 mm^2 . The capacitor has inner diameter about millimeter larger than 1.6 mm outside diameter of microfluidic channels.

Figure 3 shows an electrical diagram of the three electrodes sensor. The dielectric inside capacitors is a shell and tube from the capacitor dielectric liquid in the pipe. Equivalent capacitance between two adjacent electrodes is $C_d/4$. C_d can be calculated by the following formula (1)[6]:

$$C_d = \frac{\epsilon_0 \epsilon_r wh}{d} \quad (2)$$

where ϵ_0 is the dielectric constant of space, ϵ_r is the relative permittivity of the dielectric layer on the electrodes, w is the width of the each electrode inside the tube, d is the thickness of the dielectric layer, and h is the vertical length of the electrode contacting with liquid.

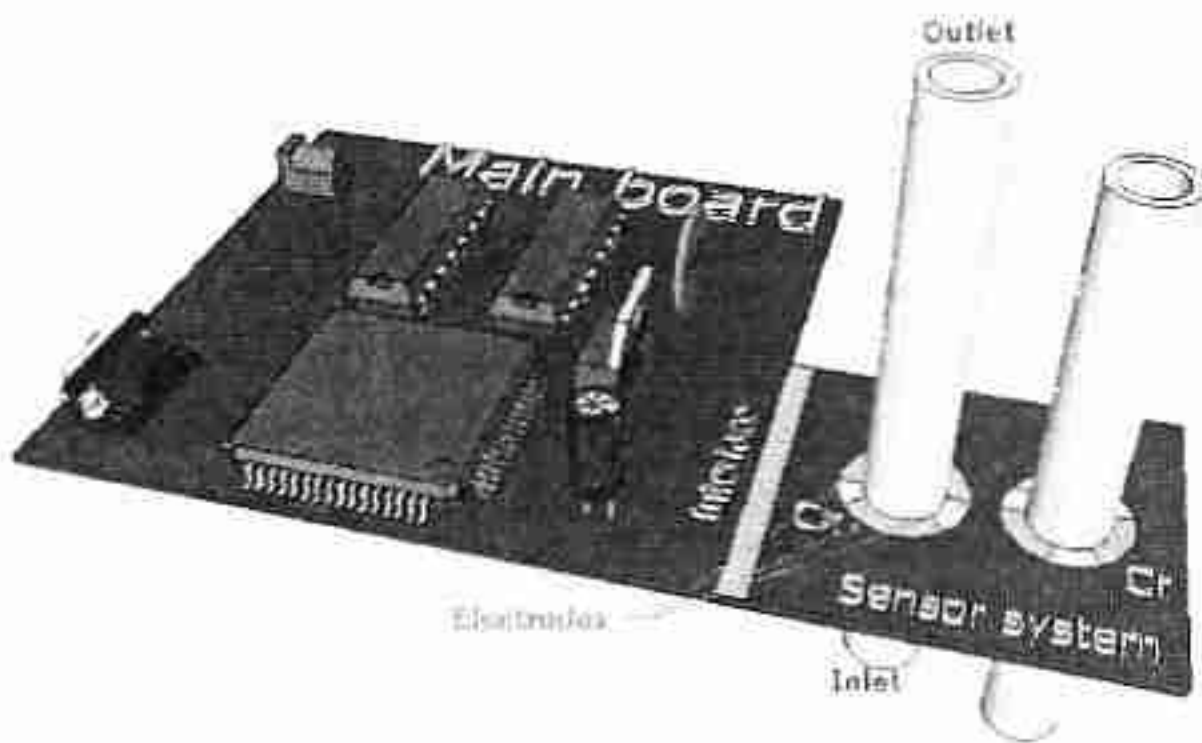


Figure 2. Design of fluidic sensor, there are two micro-fluidic channels for sensing and reference.

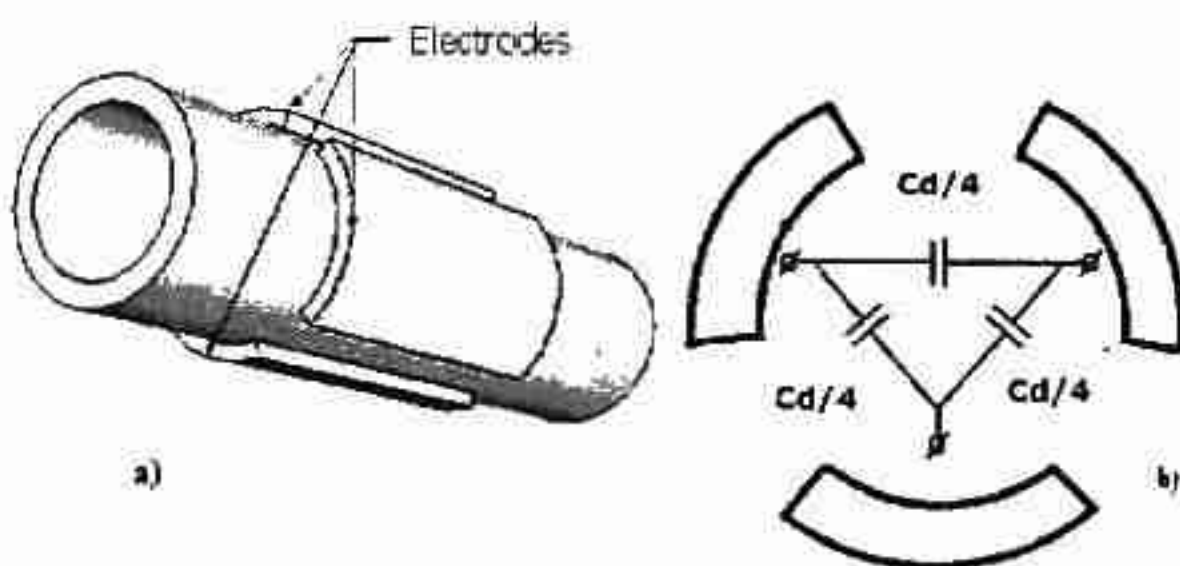


Figure 3. Design of the proposed capacitive sensor:
 a) electrodes placed outside the tube;
 b) top view of the sensor and equivalent circuit.

Geometrical dimensions of the device with three electrodes placed symmetrically are shown in Figure 4 and listed in Table 1.

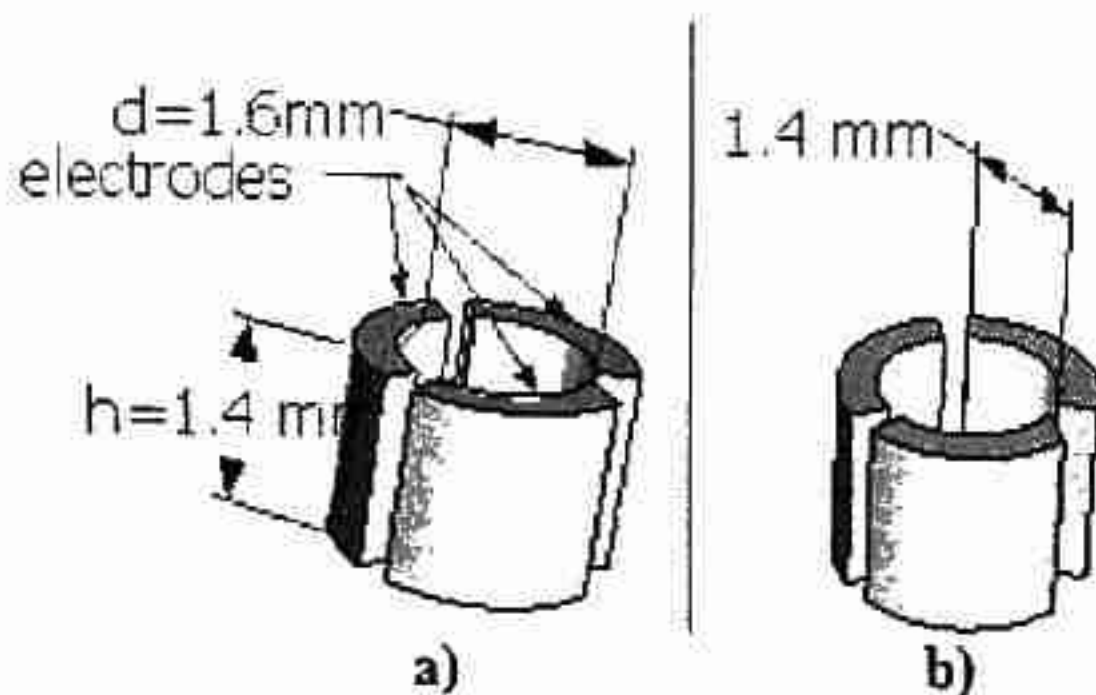


Figure 4. Schematic and geometrical parameters of the proposed capacitive sensor.

Table 1. Main geometric sizes of the designed sensor

Parameter	Value (mm)
Tube outside diameter (d)	1.6
Electrodes width (w)	1.4
Electrodes height (h)	1.4

C. Simulating the effects of air bubbles to capacitive sensors

To analyze this design structure, a simulation is implemented by FEM method on COMSOL software (COMSOL Inc., USA). The diameters are entered, and changes of environment inside the fluidic are made such as different sizes of air bubbles in the channel to see the corresponding value of capacitance. Table 2 shows dielectric constants of materials of the PCB and oil inside the fluidic channel. The dielectric constant of the PCB material is 4.5.

Table 2: dielectric of materials in this simulation

Material	Epsilon
Air	1
Engine oil	3
PCB	4.5

During the measurement, some cases of the unwanted position of air bubbles may make the worst sensing. To investigate errors in this measurement, the position of object inside fluidic channel such as air bubble is changed as seeing in Figure 5, the bubble moves from center of sensor to the electrodes. For each case, size of the air bubble is unchanged. The capacitance value is changed for each position, such as the air bubble is nearby the active electrode, sensing electrode, ground electrode and the center of capacitive sensor. The simulation is made on various sizes of air bubble for the positions which may happen during the measurement. The simulation results

are in Figure 6. The capacitance between two electrodes is changed for different positions. The air bubble position is farer to the input and output electrodes, the sensor is less sensing.

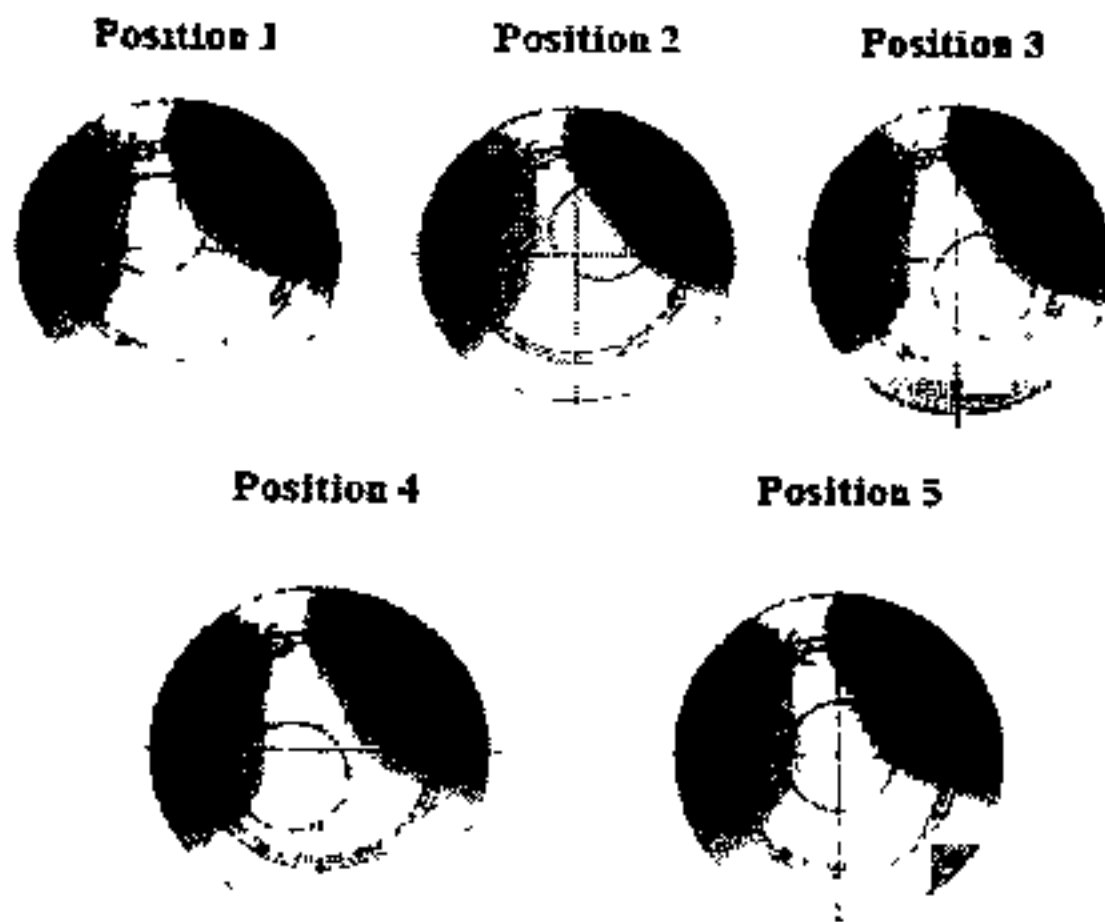


Figure 5. Electrical fields for different positions of air bubble inside the capacitive sensor.

In case of position 1 and position 2, the air bubbles are nearby the input and output electrodes. The Figure 6 shows that the position 1 is the most sensitive position, the maximum value of capacitance can be reach to 10 fF for biggest bubble at volum of 1.2 mm³. The position 2, where the air bubble is nearby the output electrode, gives a good sensing while the value can reach to 8 fF of capacitance. The position 3, where the air bubble is far from the input electrode and output electrode, give a worst sensing. The position 4, where bubble is nearby the input electrode and far away from the output electrode, gives a less sensitivity than the position 5. The position 5, where the air bubble is center of capacitive sensor, both position 4 and 5 have almost the same sensitive detection and the sensing is less sensitive than case of position 1 and position 2 [7].

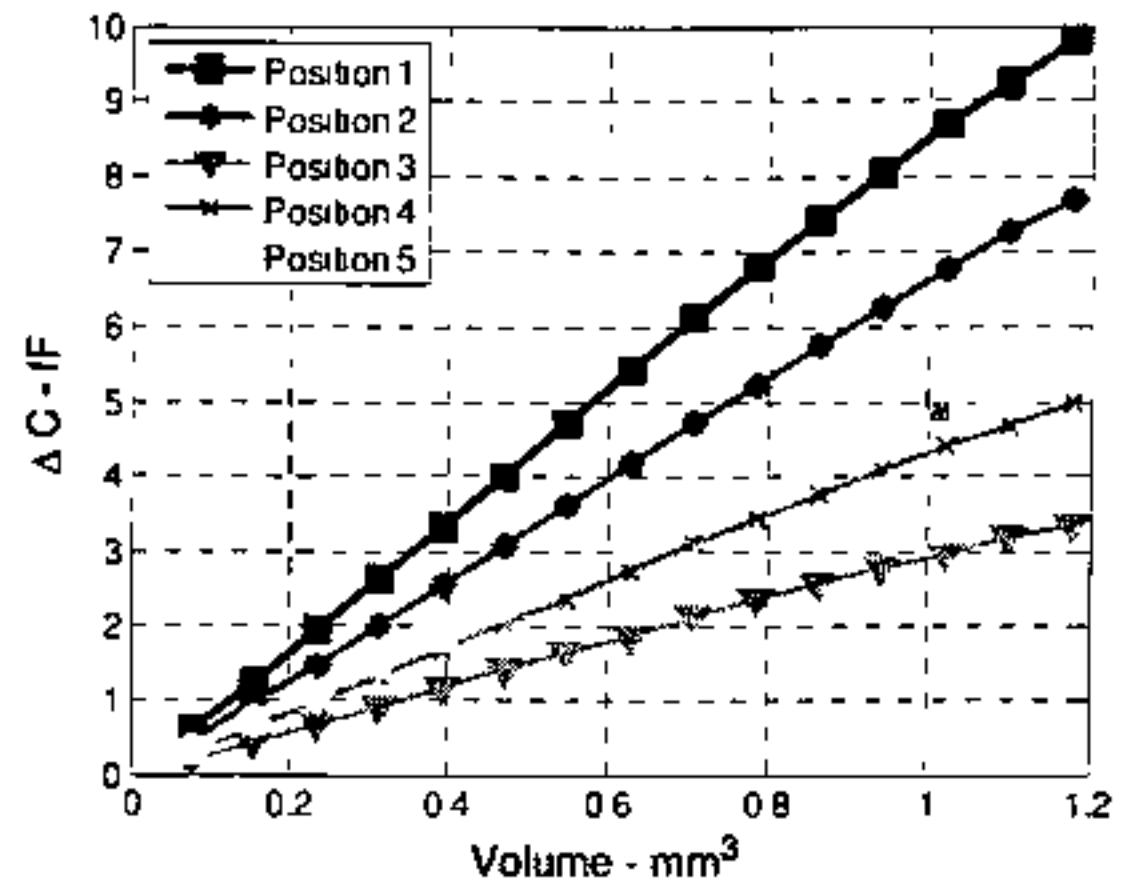


Figure 6. Capacitance change corresponding to the positions of bubble as shown in Figure 5 [8].

3. Fabrication and Measurement Setup

Capacitive sensors are small in size therefore output signal is small. Moreover, the output signal of the capacitive sensor is sensitive to parasitic components [8]. To accurately detect the presence and motion of air bubbles inside the oil pipeline, a low noise readout circuit is required.

To detect air bubbles, an electronic circuit is used to switch capacitance to voltage. The charge in the electrodes of the sensor is converted into a voltage using amplified activities [9-11].

Fig. 7 shows block diagram of electronic circuit of the sensor systems [12]. In this work, the capacitance of sensor is in the range of about fF, the impedance of the device ranges 100 Ω with a modulated frequency of 100 KHz. Then the parasitic capacitor as a resistor with a low impedance ground connection can cause significant attenuation of the signal.

The output of the sensor circuit is employed to ensure detection of the sensor capacitance change with the required accuracy. Prior to

these requests, the output circuit includes a power amplifier with a built-in lock-in amplifier. The lock-in amplifier is used to measure very small AC signals (of a few nano-volt) [13]. It uses a technique called phase-sensitive detection, where only one of the components of a signal at a particular frequency is amplified, while the noise signals of any other frequencies are rejected. In this way, even if the signal at a known frequency, which is much smaller than the scale over all the noise, can be detected in the noise source.

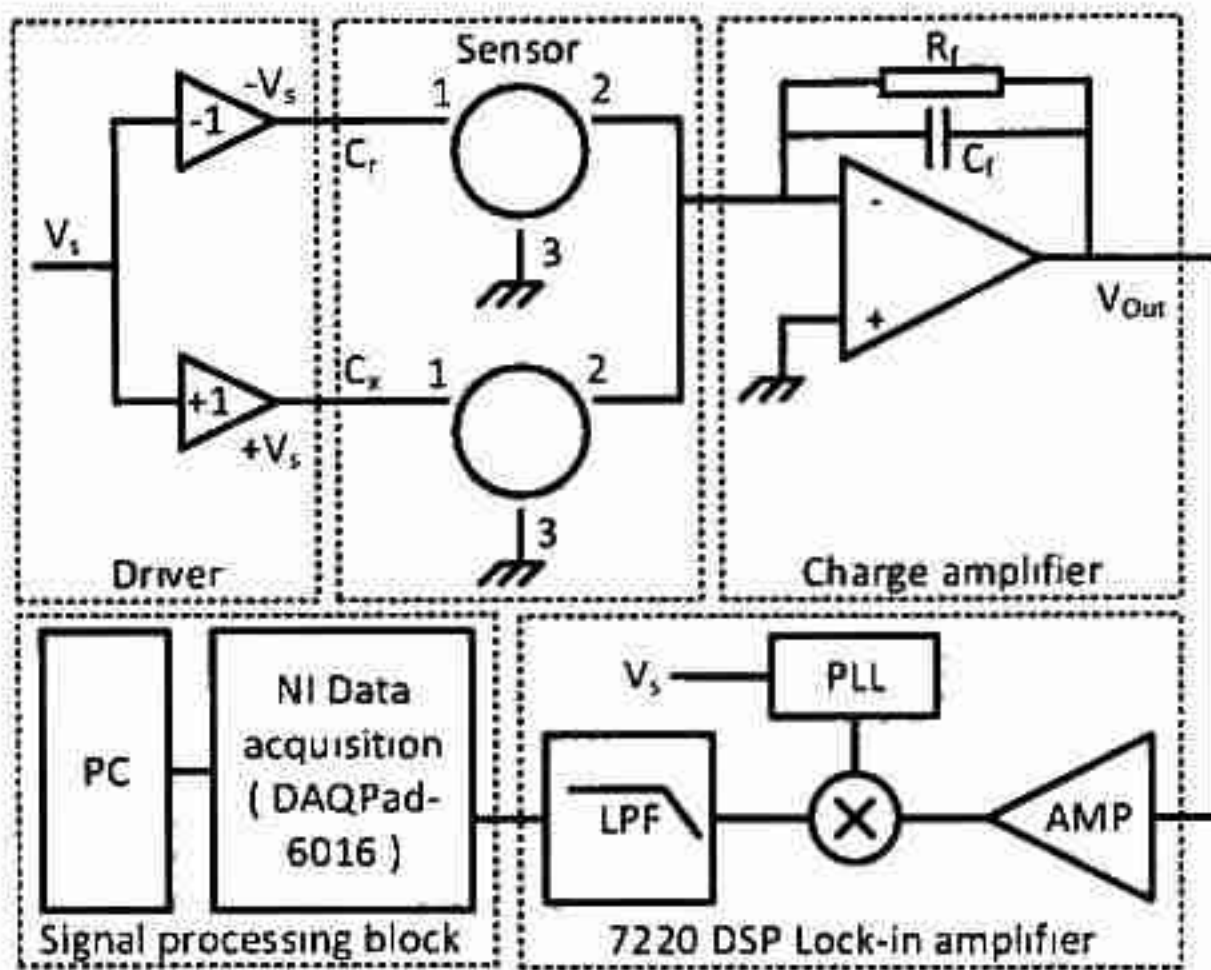


Figure 7. Capacitive amplifier circuit schematic design [7].

To solve the noise and parasitic components, differential circuit is employed based on sensing capacitor C_x and referencing capacitor C_r (see Fig. 7). The common noise is compensated in this differential circuit. In this work, sensing capacitor and referencing capacitor have similar design. Oil pipes are threaded through both capacitors. Therefore, the C_r and C_x have same capacitance value. The unbalance between the two capacitors is occurred when there is an air bubble and is defected with the sensing capacitor.

In this work, Lock-in amplifier 7220 (National Instruments, USA) is used. The lock-

in output signal is then applied to the input of an NI data acquisition NI with Labview software to analyze the obtained data.

Fig. 8 shows two cylinders with a palmer for air bubble injection in to an oil channel. By using the palmer, an air bubble volume in the range of $0.1-3.83 \text{ mm}^3$ can be created for investigation. Fig. 9 shows a picture of the measurement setup.

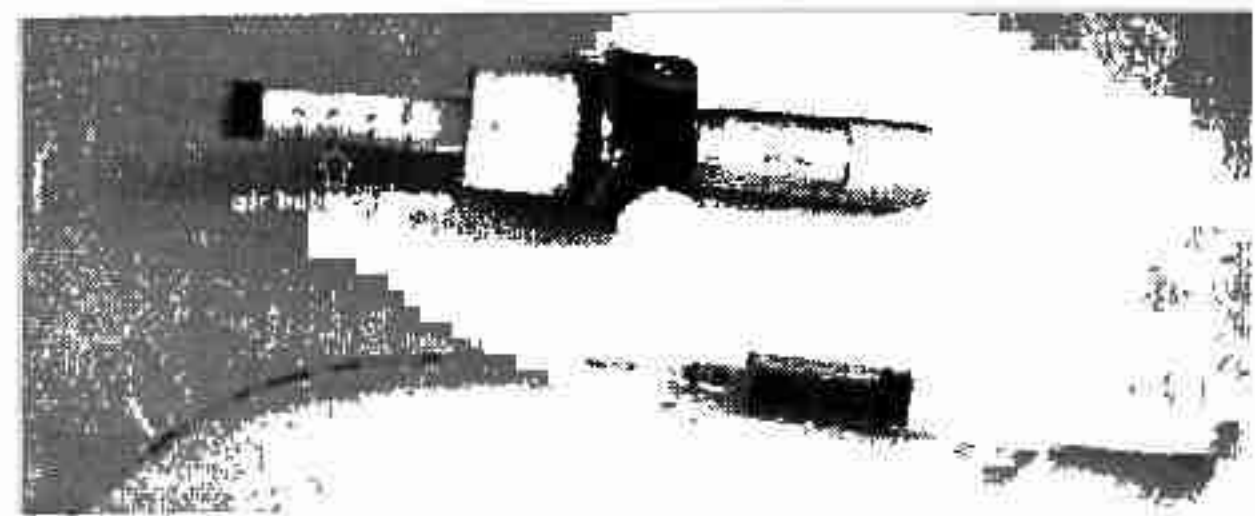


Figure 8. The pump to create liquid flow inside the pipe with two cylinders to control the liquid channel flow.



Figure 9. The measurement setup of the capacitive sensor.

4. Results and Discussions

A sine signal of frequency 100 KHz, with peak to peak amplitude voltage of 3.0 V from a pulse generator HM8030 (HAMEG Ins., Germany) output is applied to the input of the circuit (see Fig. 7).

Reverse-phase pulse $+V_s$ and $-V_s$ is applied to the capacitive sensor and reference capacitor.

Fig. 10 clearly shows sensor system response when an air bubble crosses the investigated oil channel. The output voltage is about 93 mV when there is no air bubble inside sensing capacitor. This output voltage decreases to about 60.57 mV when as air bubble crosses the sensor. The output signal get maximum value when air bubble in middle position of the sensor (see Fig. 10(b)).

Output voltage amplitude is depended on the volume of the investigated air bubble. Fig. 11 shows response signal when three air bubble with different volumes passing through the sensor. Fig. 11(a) and (b) are picture and sketch of the air bubbles in oil channel. The maximum output voltage is corresponded to the largest air bubble volume.

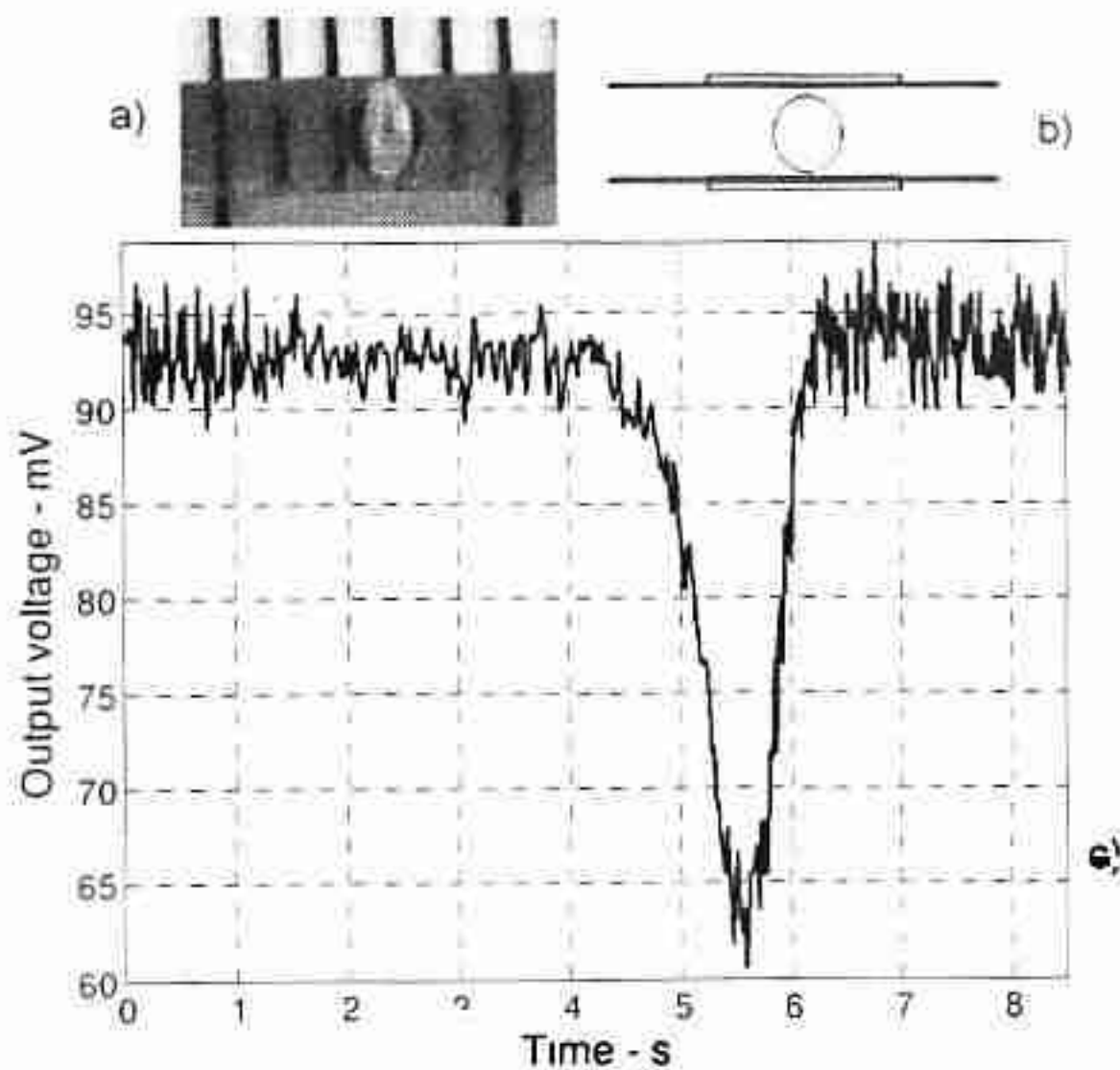


Figure 10. Detection of air bubbles in the oil: (a) captured image of a air bubble in the pipeline, (b) air bubble in the middle position of the sensor, (c) measured output voltage versus time.

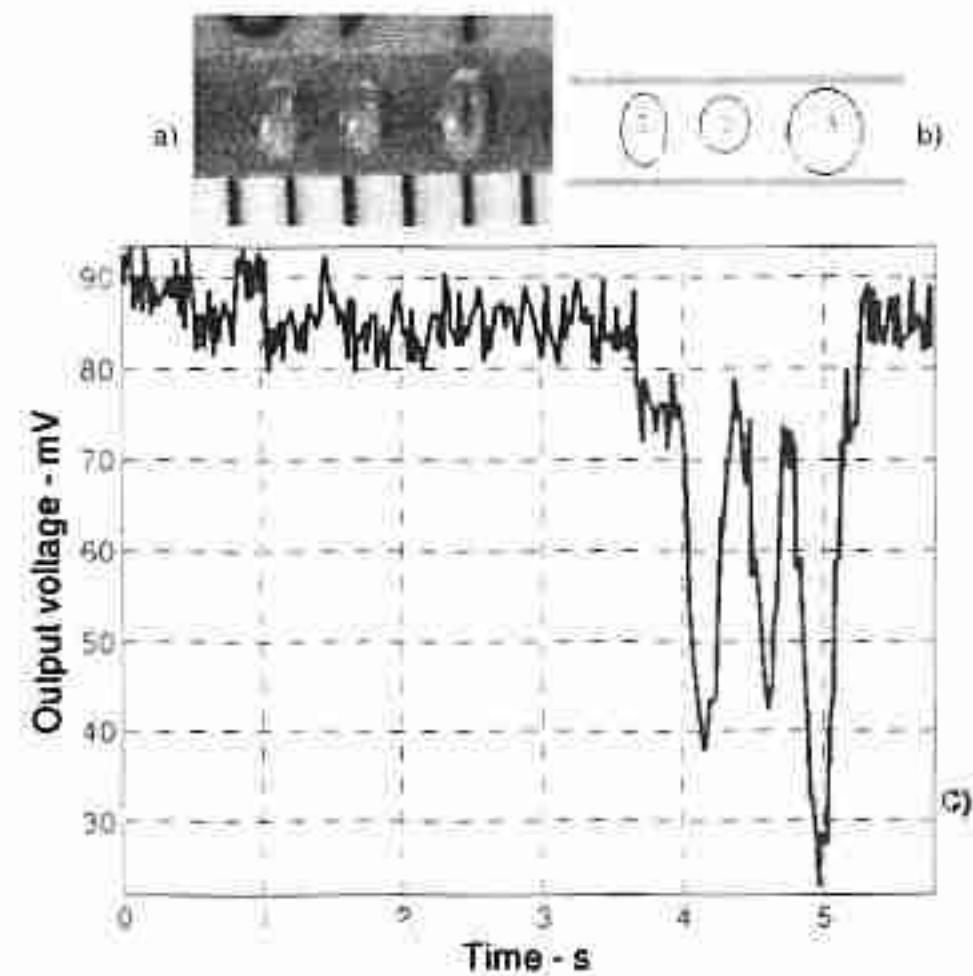


Figure 11. Detection of air bubbles with different volumes in oil channel:; (a) a picture of 3 air bubbles, (b) sketch of air bubbles inside oil channel; (c) measured output voltage versus time.

Fig. 12 also shows output signal when three air bubble cross the channel. The distance between air bubbles in this case longer than that of the case in Fig. 11. The output voltage dips are clearly separated in comparison with that in the Fig. 11. Figs. 11, 12 show that two air bubble can be detected when distance between them is large enough. This distance should be larger than the thickness of the used PCB.

The output voltages in Fig. 12 have almost similar amplitudes for the three similar volume air bubbles.

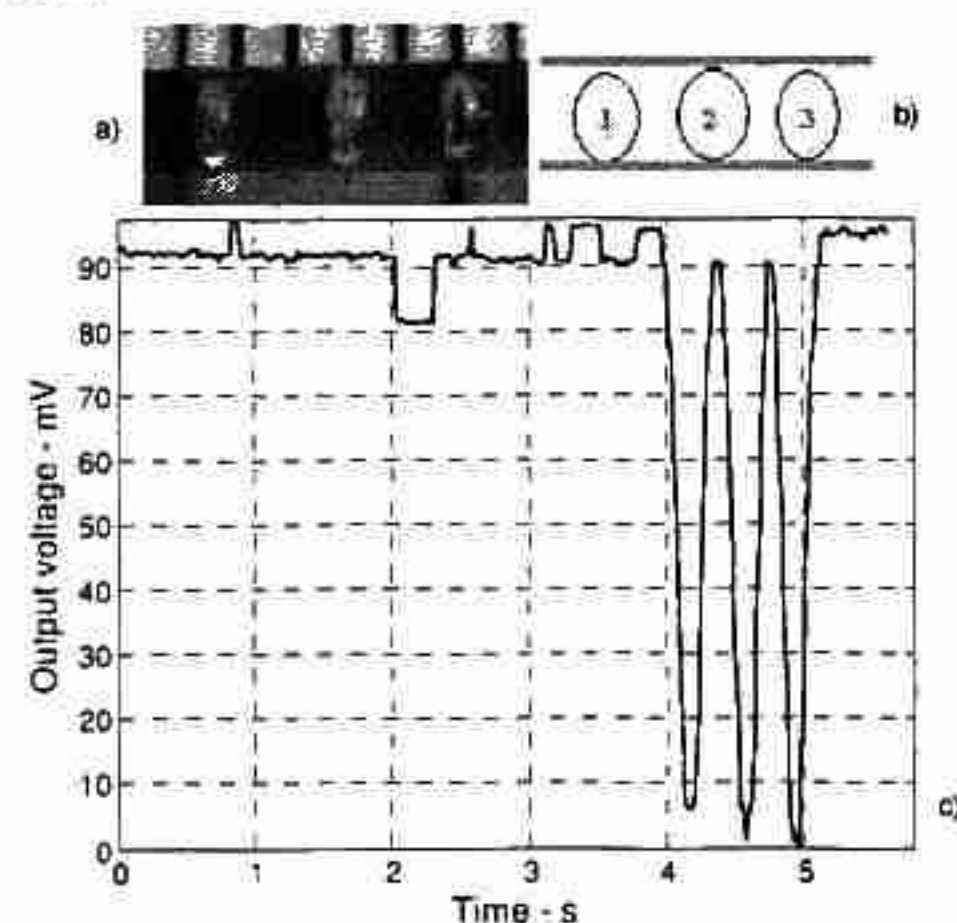


Figure 12. Detection of air bubbles with approximately equal volume in oil channel; (a) The picture 3 air bubbles. (b) Sketch of air bubble inside oil channel; (c) Measured output voltage versus time.

The measurements monitor the air bubbles from small to large volume (respectively 0.796 mm³, 1.185 mm³, 1.522 mm³, 2.834 mm³) shown in Fig. 13. The difference sizes give a various output signal. The output signals of bubbles give not only the information of bubble volume but also their velocities as shown in Fig. 13 that shows if the volume of an air bubble is larger, the amplitude of corresponding signal decreases. The relation between absolute value of the output amplitude and volume of air bubbles is shown in Fig. 14.

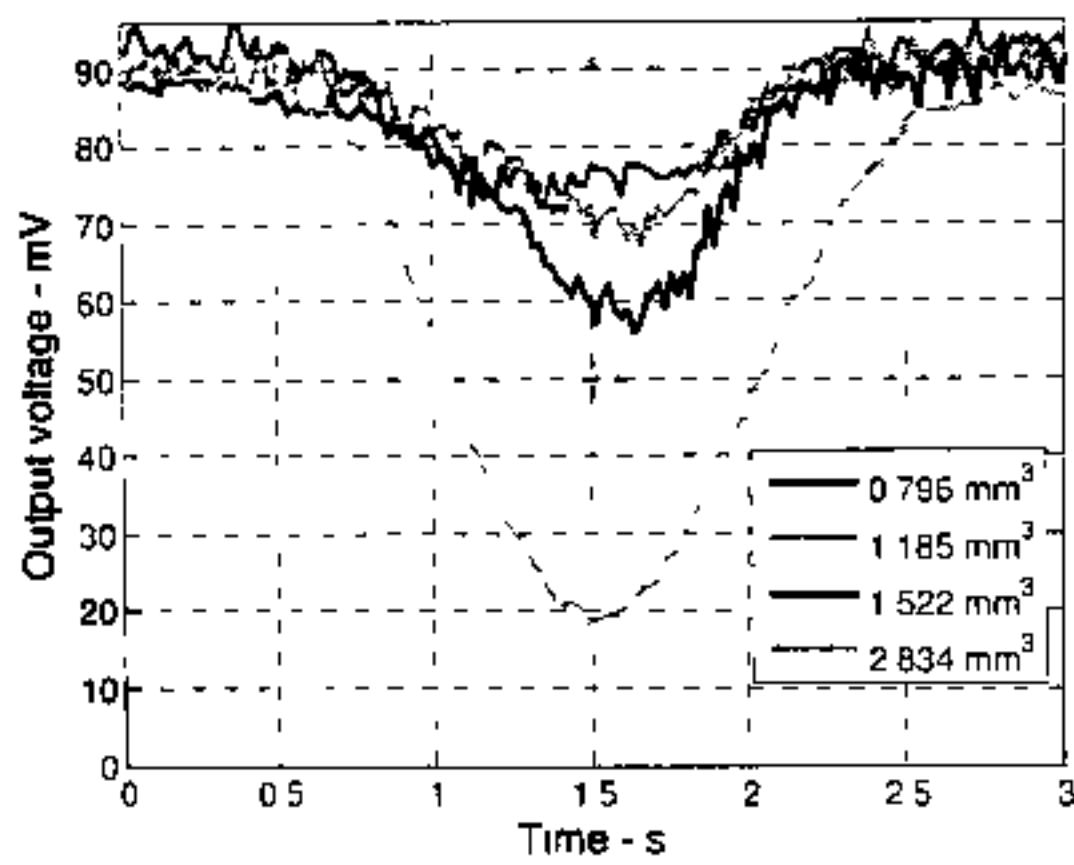


Figure 13. Output signals for different air bubbles with different volumes.

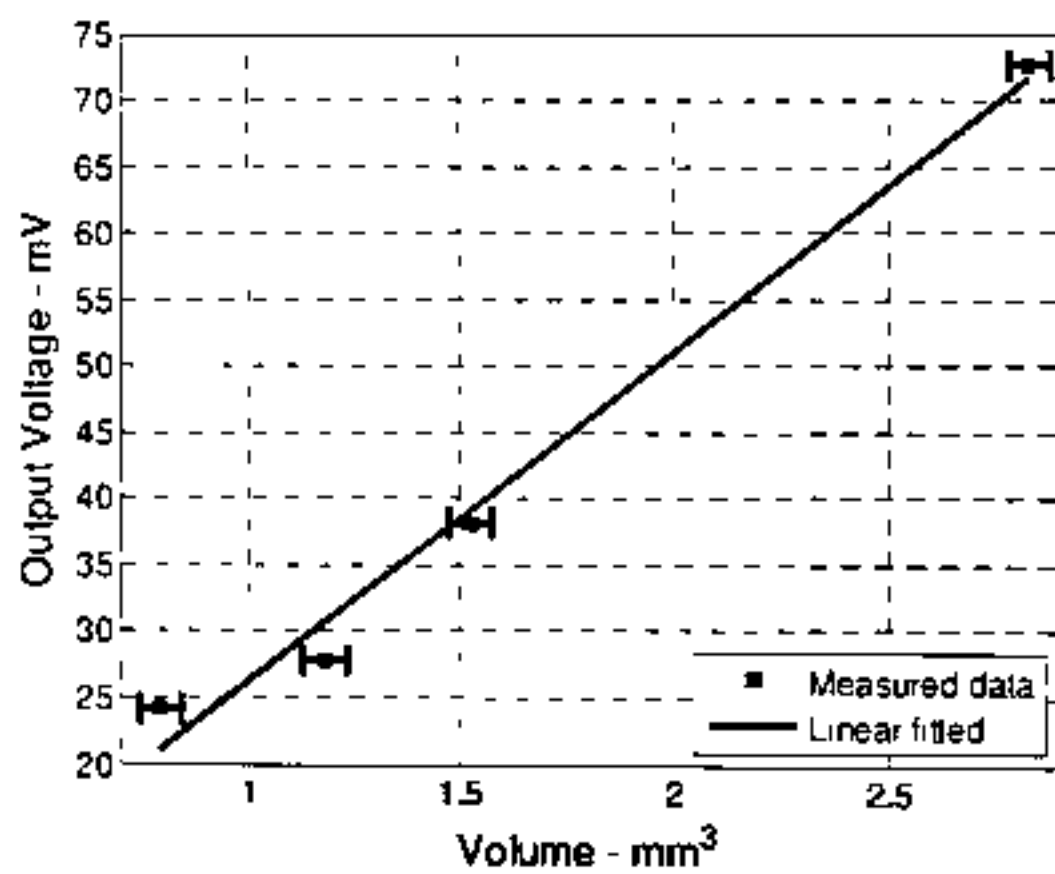


Figure 14. The plot of the amplitude change corresponding to the volume change of air bubbles.

Fig. 15 shows the simulated and measured capacitance changes versus air bubble volumes.

The simulated value is larger than the corresponded measured value. The different maybe came from the parasitic value, edge effect and several physic phenomena which are not considered in this simulation. The more accuracy model will be developed in our future work.

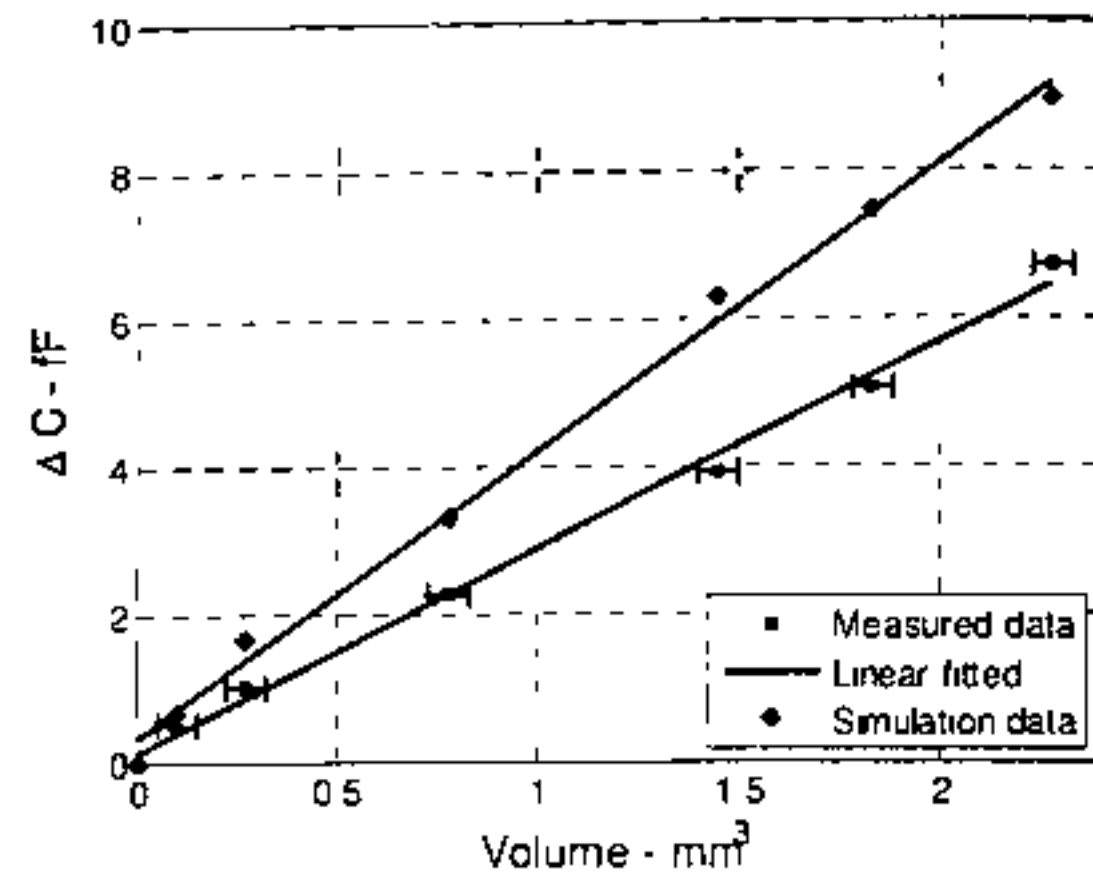


Figure 15. Simulation and measurement capacitance changes versus air bubble volumes.

To calculate the velocity of air bubble inside oil channel, measurement setup is shown in Fig. 16. Two sensor cover the investigated channel with distance of 10 mm.

Fig. 17 shows output signal when combining two sensor. By monitoring output signal, the velocity can be estimated. The velocity in the case of Fig. 17 is given by:

$$v = \frac{10\text{mm}}{(5.8 - 3.1)\text{s}} = 3.703 \left(\frac{\text{mm}}{\text{s}} \right) \quad (3)$$

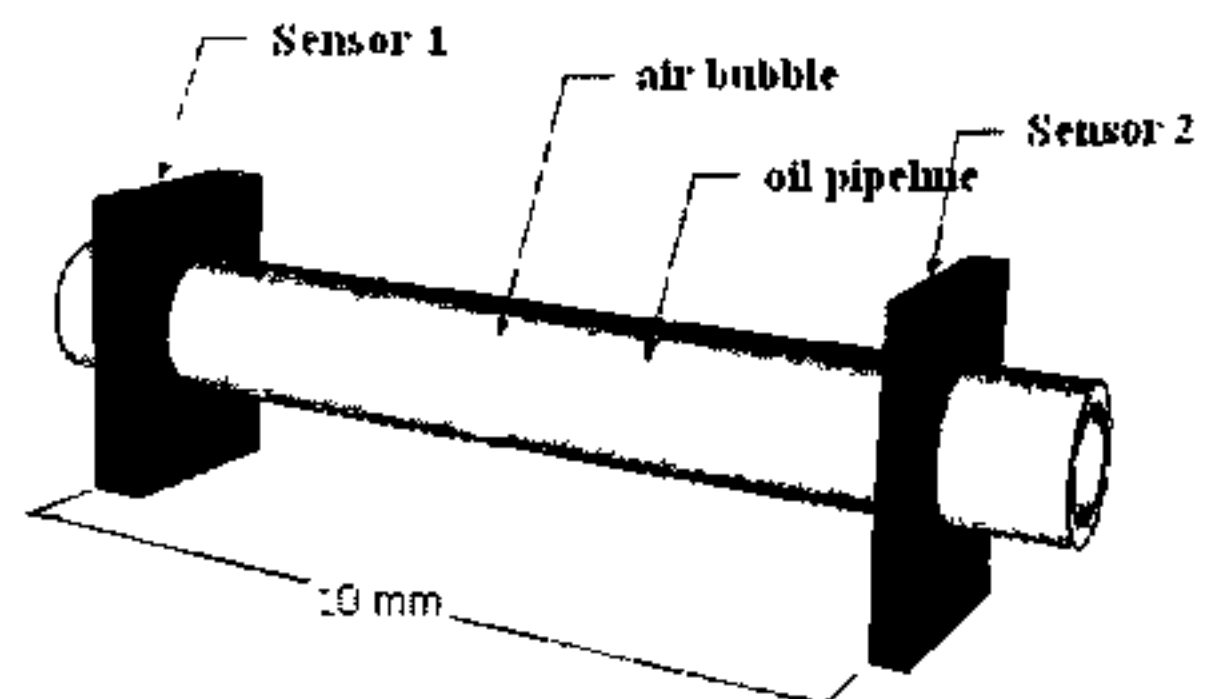


Figure 16. Velocity detection configuration using two sensing capacitor.

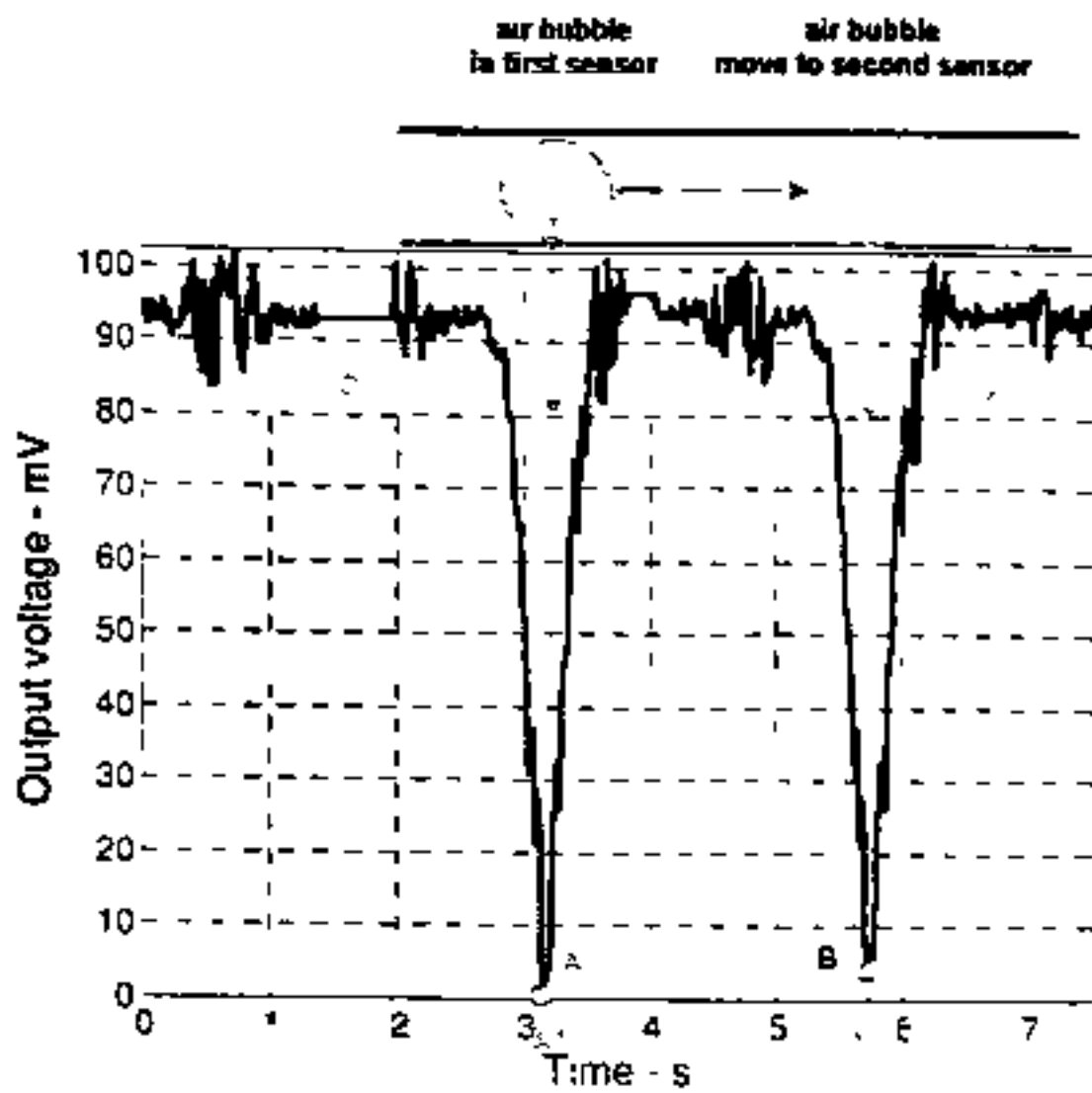


Figure 17. An air bubble passing through two sensors of the two measurement systems.

Velocity of the investigated air bubble can be measured by using configuration in Fig. 18. Sensing capacitor C_x and reference capacitor C_r are threaded through by one pipe. Velocity can be calculated by monitoring both C_x and C_r change and pipe distance between two capacitors.

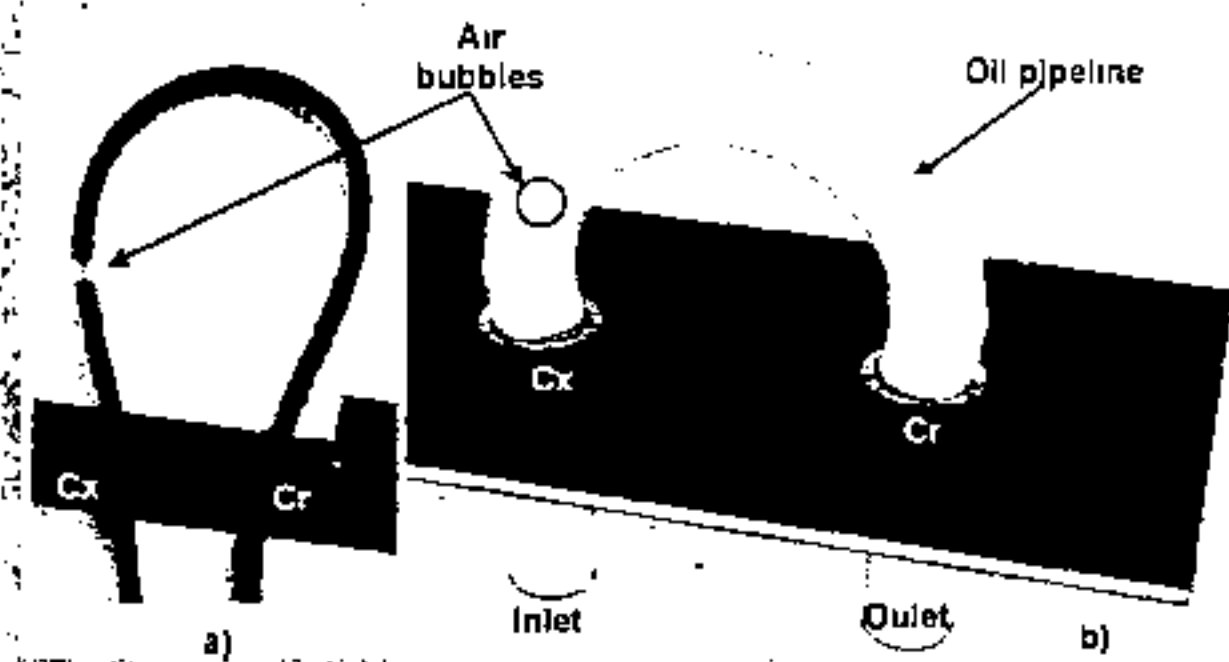


Figure 18. Velocity detection configuration uses sensing and reference capacitors.

Fig. 19 shows output signal when using velocity configuration in Fig. 18. There are two inverted voltage corresponded to the air bubble in sensing and reference capacitors, respectively. This configuration can be used when distance between two air bubble larger than the pipe distance between sensing and reference capacitor.

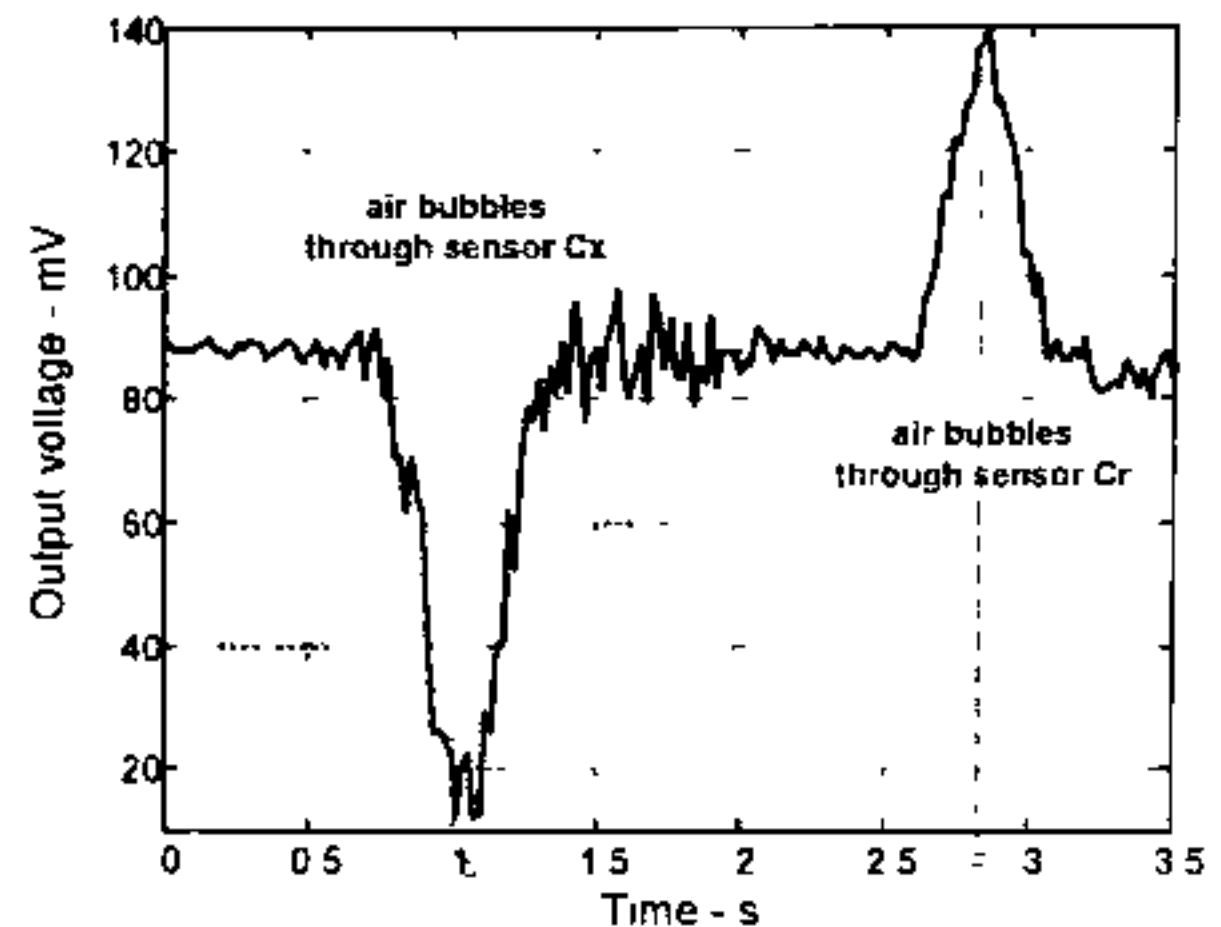


Figure 19. Received signal when an air bubble passing through sensors C_x and sensor C_r .

5. Conclusion

A capacitor type flow sensor is designed and fabricated with simple techniques. This sensor can detect air bubble inside an engine lubricating oil channel. This paper introduces design, fabrication and operation characterization of a proposed air bubble detection based on capacitive sensors. Volume of air bubble can be estimated using maximum response output voltage. Paper also shows two configurations for air bubble velocity monitoring. This capacitive sensor can monitor the air bubbles with a small size from 0.1 mm^3 to 3.83 mm^3 . This fluidic sensor could be used in void fraction detection in medical devices and systems, fluidic characterization, and water-gas, oil-water and oil-water-gas multiphase flows in petroleum technology. This structure also can be developed in micro-size scale to monitor and control changes in microfluidic channels.

Acknowledgment

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Cảm biến kênh dẫn lỏng phát hiện bọt không khí trong dầu bôi trơn động cơ

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Tóm tắt: Bài báo này trình bày thiết kế và chế tạo của một cảm biến kiểu tụ điện trên một tấm mạch in PCB dùng để phát hiện bọt khí trong dầu bôi trơn. Cảm biến này được thiết kế để theo dõi và phát hiện số lượng và kích thước của các bọt khí trong dầu. Cảm biến điện dung bao gồm ba điện cực được chế tạo trên bản mạch in trên cơ sở các mạch đồng và các xuyên lỗ. Cấu trúc này cho phép phát hiện thời gian thực bọt khí trong kênh lỏng. Các kết quả mô phỏng cho thấy sự thay đổi của tín hiệu tương ứng với thể tích của bọt khí trong kênh dầu. Các kết quả mô phỏng này được so sánh và kiểm nghiệm bằng kết quả đo đạc thực nghiệm để điều chỉnh thiết kế cấu trúc phù hợp. Các kết quả đo đạc thực nghiệm cho thấy cảm biến tụ điện này có thể phát hiện bọt khí với kích thước nhỏ cỡ 0,1 mm³ tới 3,83 mm³. Cảm biến này cũng có thể phát hiện được sự xuất hiện của nhiều bọt khí và có thể phân biệt từng bọt khí.

Từ khóa: Cảm biến kiểu tụ, cảm biến chất lỏng, phát hiện bọt khí.