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Development of an Intelligent Capacitive Mass Sensor Based on Co-axial Cylindrical Capacitor

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Abstract: The paper presents a linear, robust and intelligent capacitive mass sensor made of a co-axial cylindrical capacitor. It is designed such that the mass under measurement is directly proportional to the capacitance of the sensor. The average value of the output voltage of a capacitance to voltage converter is proportional to the capacitance of the sensor. The output of the converter is measured and displayed, as mass, with the help of microcontroller. The results are free from the effect of stray capacitances which cause errors at low values of capacitances. Developed sensor is linear, free from errors due to temperature and highly flexible in design. The proto-type of the mass sensor can weigh up to 4 kilogram only. *Copyright © 2009 IFSA.*

Keywords: Intelligent sensor, Mass sensor, Accurate measurement of capacitance, Microcontroller based measurement, Capacitive sensors

1. Introduction

The measurement of mass plays very important role in the industrial processes. To fill the exact amount of materials, automatically, in the small or big containers, mass sensing and measuring systems are used. The automatic measurement of mass started with the help of systems based on strain gauge load cells and still it is prevailing in most of the automatic systems. However, strain gauge is temperature sensitive, linear in a limited range and over all deflection, in load cell, is very small [1].

The transduction of several physical quantities into electrical quantities is a very common but important requirement in control, industrial electronics and biomedical instrumentation engineering

[2]. The capacitive transducers are frequently encountered due to their small size, low power consumption and low temperature errors. However, their use always implies the choice of a suitable capacitance measuring technique, with good order of accuracy, precision and reliability. Thus different techniques, used for this purpose, begin from conventional bridges like Wien bridge, Schering bridge etc. However, for the accurate and precise measurement of small capacitances, Transformer ratio-arm (TRA) bridges were invariably employed [3, 4].

Smart or "intelligent" sensors are becoming a reality in process control systems which are employed in industrial production system [5].These sensors are more sophisticated than traditional sensors as they collect, analyze and transmit data [6].

The proposed sensor is based on concentric co-axial cylinders. The sensor element consists of two stationary concentric cylinders and the change in the capacitance takes place due to the movement of the grounded, co-axial cylindrical shield, between them. The change in capacitance is detected by analogue electronic circuit which is interfaced with the microcontroller for data processing and displaying.

2. Theory

In practice, the capacitive sensors have small capacitances and for their precise and accurate measurement, they are provided with a conducting shield. Hence a capacitive sensor may be represented by a three terminal device as shown in Fig. 1 (a) and its equivalent circuit is shown in Fig. 1 (b).The capacitance C'_{12} is the designed capacitance while C'_{13} and C'_{23} are undesirable capacitances. Moreover, to get a linear variation in C'_{12} , the shield may be extended between the main electrodes to shield the effective area of the main electrodes. In the development of a linear and accurate mass sensor this principle is successfully employed. However, C'_{12} measuring circuit should be designed such that its measured value should not be affected by C'_{13} and C'_{23} .A new circuit is developed which serves this purpose successfully. The developed mass sensor comprises of a capacitor made of stationary concentric cylinders and a movable conducting shield of concentric cylinder shape and placed between them.

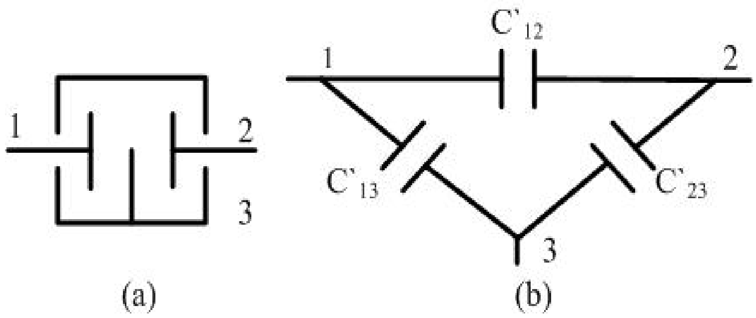

Fig. 1. (a) A three- terminal Capacitor, (b) Equivalent circuit of the Three-terminal capacitor.

The shield is firmly attached with the mass carrier and a co-axial spiral spring supports it. For varying the value of capacitance, with mass, grounded shield is extended axially between the active area of the main electrodes [4].The shielding effect of the conducting coaxial cylinder transducts the mass into change in capacitance. This type of variation has two major advantages. Firstly, the relationship between the mass and the change in capacitance, will be strictly linear and secondly the radial movement of shield, towards the electrodes, will not cause any variation in the value of the direct capacitance of the sensor. It is a very important aspect with respect to the fabrication of the sensor.

The cross sectional elevation of the proposed sensor is shown in Fig. 2. Two stationary co-axial cylinders (1 and 2) make the main capacitor which is designed for a capacitance of 18 pF. These are fixed on a base made of acrylic glass (Perspex). Shielding cylinder (3) is fixed on the mass carrying platform (4) and rests on the spring (5) which serves as a load carrier for the weight to be investigated. A Teflon guide (6) is provided to keep the movement of the shield vertical and in between the main cylinders (1) and (2). Spring is provided with a guide made of iron (7) so that spring may apply uniform force, against the weight, to be investigated. A screw (8), with fine threads, is provided to adjust the position of the shield as well as to replace the spring to cover different weighing ranges. Over all system is contained in a metallic container (9) which provides stable base as well as acts as a shield against the external fields. The guide of the shield is provided with a hole covered by a screw (10) which may help in the adjustment of the damping of the system. When hole is open, the air friction damping will be nearly negligible because air pressure will be quickly equalized on both sides. However when hole is partially blocked, trapped air will provide some order of damping.

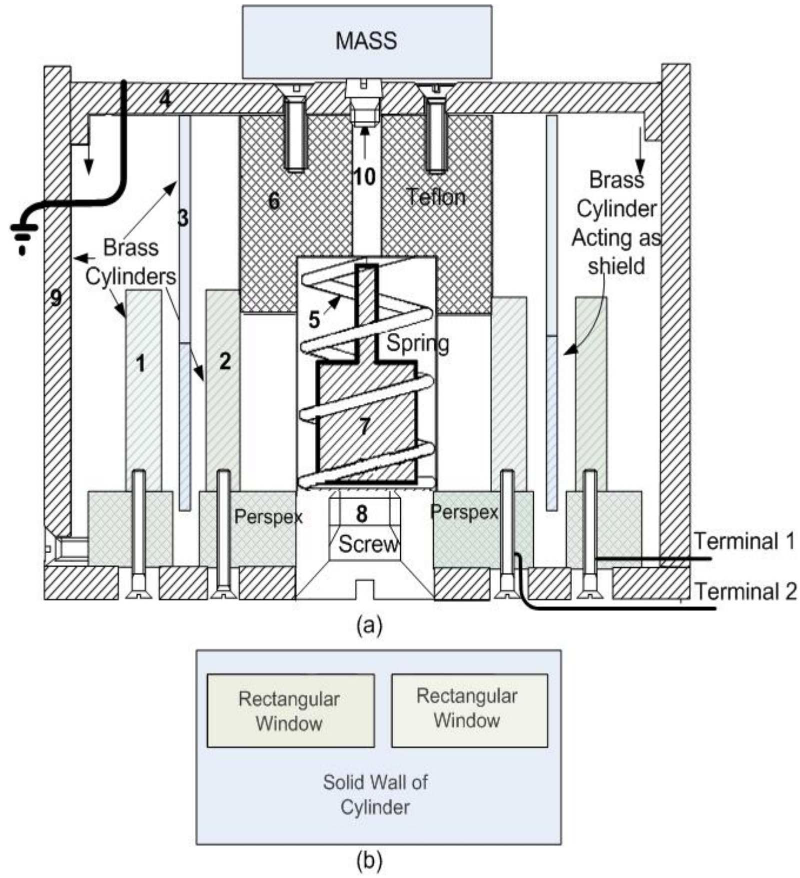

Fig. 2. Cross- sectional view of the proposed sensor.

Electrical connections are taken from the main cylinders (1) and (2), and the outer metallic container (shield and container are kept at earth potential). As the mass is increased, depending upon its spring constant, some down ward movement of the shield will take place. Shield is designed and placed to provide zero capacitance at the condition of zero mass. When mass is added on the top of the sensor, shielding effect of the shield decreases linearly and hence capacitance increases linearly. Relationship between mass and capacitance, if Hooke's law holds, can be given by following expression:

$$C'_{12} = SM \ , \tag{1}$$

where $C`_{12}$ is the direct capacitance, M is the mass under measurement and S is the sensitivity of the system which depends upon the spring constant of the spiral spring used in the system. However, due to fringing effect, some error may be introduced which will remain same in all positions and hence proportionality constant will take care of it.

3. Estimation of Temperature Errors

The temperature rise will affect the main cylinders (1) and (2), shield (3) and the spring (5). The increase in length of active electrodes will not have any effect on the final results because length is defined by shield only. Increase in length of shield, made of brass, has been estimated and comes out to be 18.7×10-7 mK^{-1} which will change the effective capacitance by a factor of 2.95×10-4 pF K^{-1}. It will give rise to a full scale error of 0.0016% K^{-1} which is acceptable in the present design. However, it can be further reduced by making the shield of a material which has still lower value of the coefficient of linear expansion like invar36. Spiral spring will also be affected by the temperature and proper selection of the material for the spring, may reduce temperature errors. Phosphor bronze is one of the suitable materials for making spiral springs which are free of temperature errors.

3.1. Precise and Accurate Measurement of Small Capacitances Using Active Circuits

The electronic circuit shown in block 1 of the Fig. 3 can sense the direct capacitance C'_{12}, of the sensor without the effects of C'_{13} and C'_{23}. As shown in Fig. 3, C'_{13} will appear across supply voltage and will not affect the output voltage provided that output impedance of the supply is negligible in comparison of the reactance of C'_{13} . The capacitance C'_{23} appears across the input terminals of the operational amplifier (opamp) and hence will not affect the output as it appears between the ground and virtual ground terminals. In this way output of the circuit will be free from the effects of C'_{13} and C'_{23}.

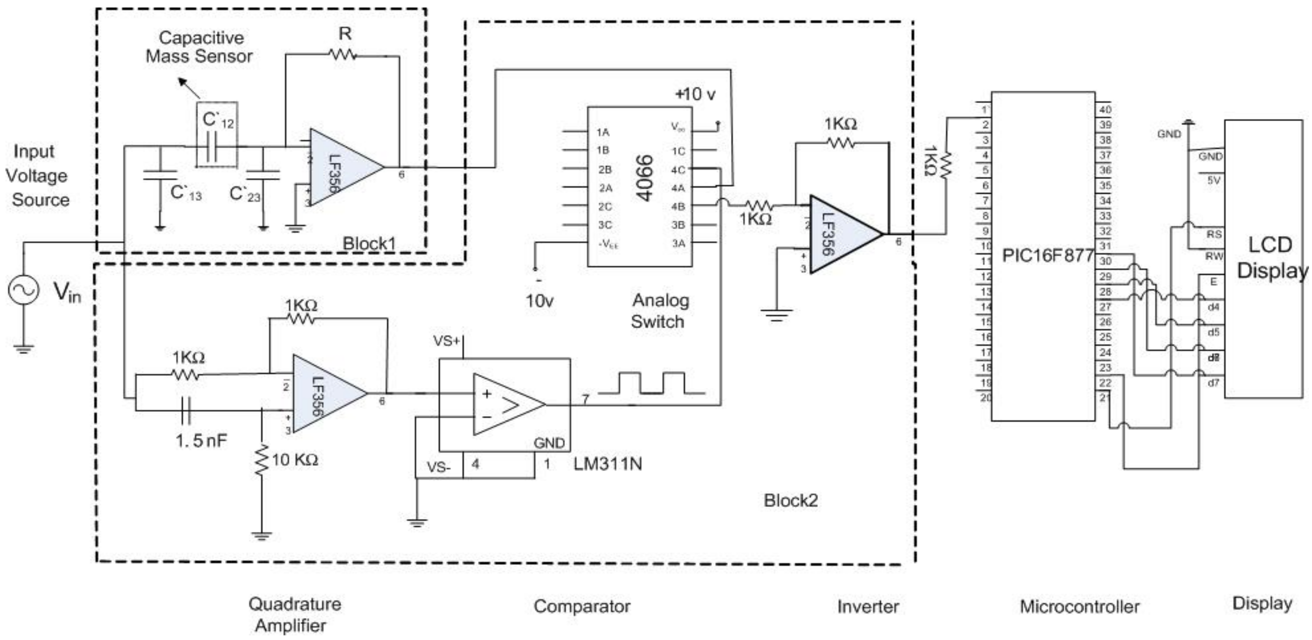

Fig. 3. Schematic circuit diagram of the capacitance measuring system.

Let *Vs* be the supply voltage to the system, V_0 be the output voltage of the circuit of block 1 which may be given by following well known expression:

$$V_0 = -V_S R / Z_X \,, \tag{2}$$

where, *R* is the feedback resistance and Z_X is the impedance of the sensor composed of the parallel combination of capacitance and resistance. Substituting the values of the components of impedance we get:

$$V_0 = -V_S .R[\frac{1}{R_X} + j\omega C_X \,] \,, \tag{3}$$

where, R_X and C_X are resistance and capacitance of the sensor, connected in parallel. However R_X is of very high value and it is not under consideration. In Eq.(2), V_0 is a phaser and may be represented in terms of its in-phase (V_{inph}) and quadrature (V_{quad}) components with respect to supply voltage V_s, and hence we can write:

$$V_0 = V_{inph} + jV_{quad} = -V_S .R[\frac{1}{R_X} + j\omega C_X \,] \tag{4}$$

Comparing the real and imaginary parts in Eq.(4) we get:

$$V_{inph} = -V_S \cdot \frac{R}{R_x} \tag{5}$$

$$V_{quad} = -V_S R.\omega C_X \tag{6}$$

However, considering the three-terminal structure of the sensor, C_X may be replaced by the direct capacitance of the sensor(C'_{12}) in Eq.(6).

$$V_{quad} = -V_S R.\omega C`_{12} \tag{7}$$

Substituting the value of $C`_{12}$ from Eq.(1) we get:

$$SM = \frac{|V_{quad}|}{V_S R\omega} \tag{8}$$

Eq.(8) shows that the quadrature component of the output voltage is directly proportional to the direct capacitance of the sensor.

3.2. Measurement of Quadrature Component of the Output Voltage

To measure the quadrature component of the output voltage, analog switch is employed. The output of the circuit is connected to the terminal 10 of the quad analog switch (4066) and corresponding control signal is obtained after passing the supply voltage V_S, through the quadrature amplifier (gain=1) and analog comparator and then connected to terminal 12 of the analog switch. The output signal is collected from the terminal 11 of the analog switch. Different waveforms of the input, output and control signals are shown in Fig. 4.

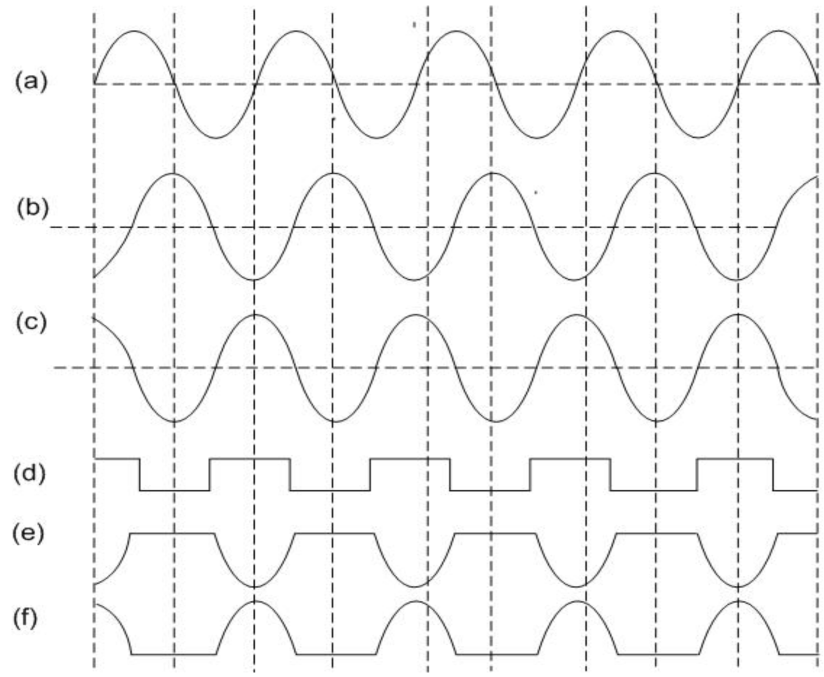

Fig. 4. Waveforms of different signals: (a) Waveform of supply voltage, Vs. (b) Waveform of the output voltage when *Zx =-j Xc.* (c) Waveform of the output voltage of the quadrature amplifier (gain=1) (d) Waveform of control signal to obtain quadrature component. (e) Waveform of the quadrature component when Z_X= =-*j Xc.* (f) Waveform of the voltage interfaced with the microcontroller.

The quadrature component of the output voltage is given in Eq. (7) which has negative sign. To interface it with the microcontroller, it will be necessary to pass the quadrature component through an inverter to change the polarity, as shown in Fig. 3. The microcontroller is embedded in the design to give the measurement system the properties of intelligence, low-cost, reliability, accuracy and adaptability. For all of these qualities, PIC16F877 is found most suitable and hence has been employed to develop an intelligent system. Initially, it samples the analog signal at the rate of 250 samples per half cycle and converts the values of the samples to digital form, through internal 10 bit- analog to digital converter (ADC).The average value of the output of the analog switch, which is proportional to the quadrature component of the output voltage of the converter are computed by the microcontroller and displayed in the liquid crystal display (LCD) in decimal form. Fig. 5 shows the flow chart of the functionality of the microcontroller.

4. Experimental Method and Results

To verify the developed theory, a proto-type of mass sensor was designed and fabricated with a total movement of the shield of the order of 2.7 cm. The maximum mass measured, with the device, is 4.0 kg in steps of 250 g (6.25 % of full scale). However, range can be changed by selecting a new spring with different spring constant. It has been calibrated with the help of active bridge at 1 kHz and it was found that it has sensitivity of the order of 0.002 pF g^{-1}. Complete calibration curve is shown in Fig. 6. Exact zero position is achieved by using the screw in the bottom of the sensor.

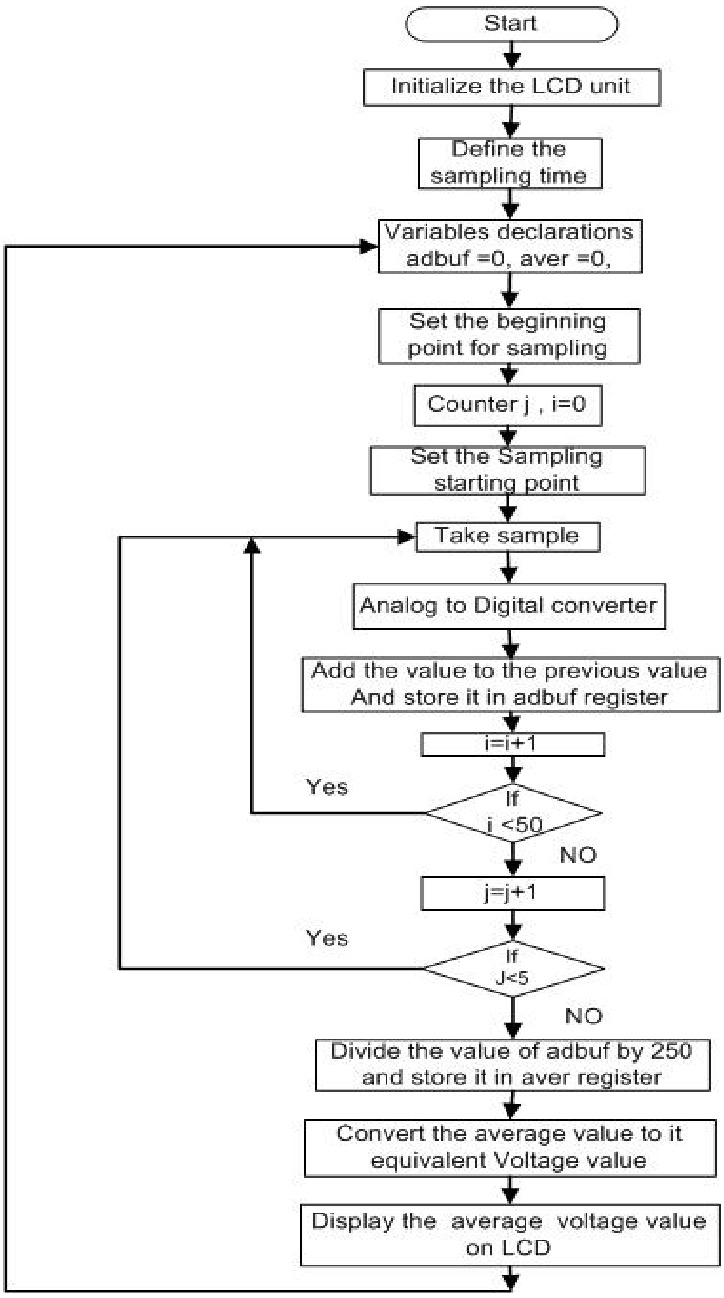

Fig. 5. Flow chart of the capacitance measuring system.

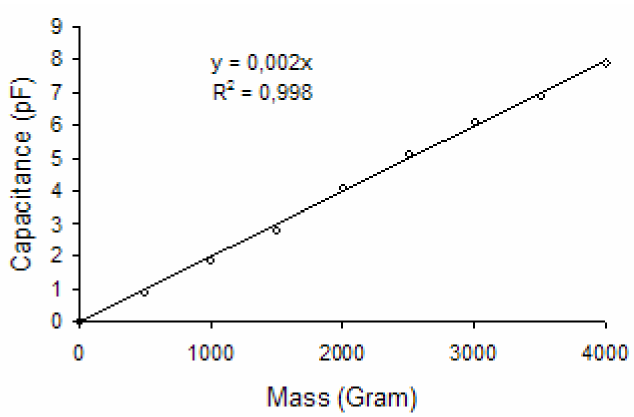

Fig. 2. Calibration curve.

The graph is appreciably linear and non-linearity may be attributed to random effects only. Afterwards the circuit shown in Fig. 3 is assembled and average value of output voltage is measured with the help of microcontroller and results are plotted in Fig. 7. The results are conforming to the theoretical derivations as well as to the experimentally obtained calibration curve of the mass sensor. The results are appreciably linear with R^2 (correlation coefficient) equal to 0.999. The pooled standard deviation for the results is 5.25 mV and the least square fitting curve is giving by:

$$y = 0.26x \tag{9}$$

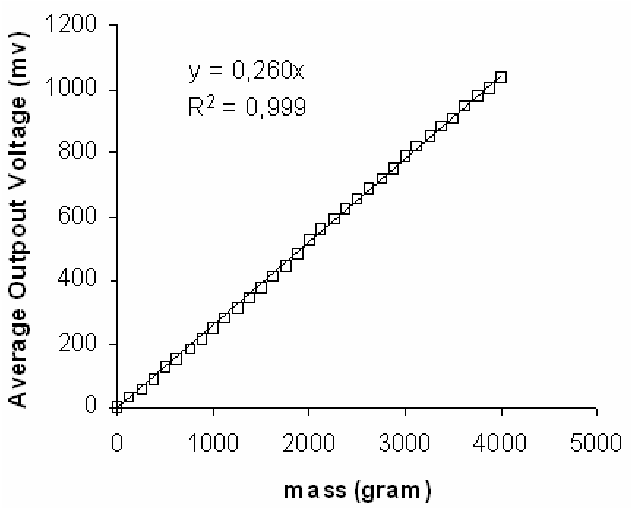

Fig. 3. Calibration curve of the sensor as obtained with the help of microcontroller.

5. Conclusion

An intelligent mass measuring system, with high degree of flexibility in the design, is presented in this paper. It has appreciably linear scale (R^2=0.999) and the same basic sensor can cover a large range of masses, by changing the spiral spring, in a very simple manner. It is robust, low cost, and simple in operation and trouble shooting and repair can be done easily. Temperature errors are negligible and can be further decreased by selecting suitable materials (invar) for the fabrication of main cylinders and shield. It can be easily used with systems involved with the accurate filling of materials in packets of small or big sizes. It can also be employed, with some modifications, for the measurement of force, pressure and level of liquids in big tanks.

Acknowledgment

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Aims and Scope

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