Sensors & Transducers

http://www.sensorsportal.com

Design and Development of a Pressure Transmitter Using Modified Inductance Measuring Network and Bellow Sensor

[1] Venkata Lakshmi Narayana K. and [2] Bhujanga Rao A.
[1] School of Electrical Engineering, VIT University, Vellore-632 014, Tamilnadu, India
[2] Department of Instrument Technology, Andhra University, Visakhapatnam -530 003, India
E-mail: kvl007in@yahoo.co.in, dr_abrao@yahoo.co.in

Received: 6 January 2013 /Accepted: 19 March 2013 /Published: 29 March 2013

Abstract: In this paper, a pressure transmitter using a modified op-amp based network for inductance measurement using a bellow as sensor has been proposed to measure the pressure and to convert pressure changes in to an electrical current which can be transmitted to a remote indicator. The change in inductance due to change in pressure is measured by an improved modified operational amplifier based network. The proposed network permits offset inductance compensation of sensing coil and also minimizes the stray capacitance between sensing coil and ground using dummy inductor whose value equal to zero level inductance of sensing coil and op-amps with high input impedance. In the first part of experiment, a modified op-amp based inductance measuring circuit has been simulated using LabVIEW (Laboratory Virtual Instrument Engineering Workbench) and studied with test inductance, and in the second part, the experimentation was done by replacing the test inductance with a sensing coil fitted to bellow by means of ferromagnetic wire for the measurement of pressure. It has been observed that the variation in gauge pressure from 0 to 70 psi having linear relationship with output ac voltage in the range of 0 to 85.0 mV. Corresponding to pressure variations, the ac output voltage further converted into an electric current of 4 to 20 mA for remote indication and control purpose. The investigations have been performed to sense air pressure of pressure tank fitted with pump piston. The experimental results are found to have good linearity of about ± 0.1 % and resolution. *Copyright © 2013 IFSA.*

Keywords: Bellow, LabVIEW, Inductance measurement, Differential amplifier, Virtual Instrument, Pressure Transmitter, Linearization.

1. Introduction

In any process industry, the pressure is one of the most important process variables which are required to be measured and controlled. The absolute pressure at a point inside a fluid is the force exerted normally per unit area surrounding that point, and the gauge pressure is the difference between the absolute pressure and the local atmospheric pressure. The absolute pressure can be measured in terms of the height of a liquid column in a manometer, where as the gauge pressure is measured by different types of sensors [1-4] where one or more parameters vary due to the difference between the absolute pressure of a fluid and the atmospheric pressure.

The pressure transducers, such as the Bourdon tube, diaphragm, capsule, bellow element, etc., are usually operate as primary sensing elements while the sensors like the strain gauge, piezoelectric transducers, linear variable differential transformer,

Article number P_1153

capacitive element, inductive element, etc. all act as secondary sensors to measure the positive or negative gauge pressure. The negative gauge pressure or vacuum pressure can also be measured by many other sensors like the Pirani gauge, ionization gauge, McLeod gauge, etc. In industrial application, usually the pressure measured at one location is required at another location and is hence to be transmitted to a remote distance for control of whole pressure monitoring system. Different groups of authors are still being reported many works on the development of a reliable and accurate pressure transmitter.

The change in inductance of an inductive transducer due to a change in process variable is generally very small. Hence, various attempts have been made by different investigators to accurately measure this change in inductance. In the conventional inductance bridge network like Maxwell's bridge, Anderson's bridge, Hay's bridge, etc., a very small change of inductance in a large value inductor becomes insignificant, and so, the bridge output is almost insensitive to measure such a small inductance change of a large-inductance coil. Many conventional and modified bridge methods have been reported in literature to measure the changes in inductance effectively, but these methods are tedious and time consuming, as convergence toward balance requires several iterative steps. A modified self-inductance measurement technique has been proposed in [5]. In this technique, the measurement errors due to stray capacitance and stray electromagnetic field have been minimized and the percentage deviation from linearity has been found within the tolerable limit of ±2 %. A modified differential inductance measurement circuit has been proposed in [6] to sense the position of piston in the power cylinder. The major disadvantage of this circuit is that the direct connection of inductance in the feedback path of op-amp provides derivative action to the input signal, which may damage the op-amp if proper precautions are not taken. A pressure transmitter using an improved inductance bridge network has been developed in [7] for the measurement of pressure ranging from 0 to 45psig with the resolution of 5 psig. Subramanian *et al.* [8] have developed a MEMS-type capacitive pressure sensor with sensitivity in the order of a few femtofarads per kilopascal. A universal frequency-to-digital converter technique has been used by Yurish [9] to develop an intelligent digital pressure transducer. A multiplexed frequency transmitter technique has been used by Vrba *et al.* [10] to design a reliable pressure transducer using a ceramic diaphragm. Vlassis and Siskos [11] have developed a CMOS operational amplifier-based interfacing circuit converting a signal from a piezoelectric pressure transducer into an output frequency signal which is independent of temperature effects. Another temperature-compensated pressure sensor designed by Taslakov [12] operates on the principle of converting pressure change into an oscillator frequency shift.

The bellow is most commonly used pressure sensor in the industry because of its simple and rugged construction with an almost linear scale, capability of providing large force and wide pressure range. The major drawback of this sensor is that it is unsuitable for dynamic measurements because of their great mass and long relative movement. It can only be used as a local indicator and hence an additional circuitry needs to be made, thus converting and processing the bellow movement into an electric signal, so that its reading can be transmitted into a remote location.

This paper proposes a very simple inductive pickup-type technique to convert the bellow movement in to an equivalent 4–20 mA dc current signal. The designed instrument consists of modified operational amplifier based inductance measuring network-type pressure transmitter using a bellow as a sensing element. A ferromagnetic wire attached to the rod of the bellow acts as the sensing element. With the change of pressure, the rod of the bellow, along with the wire, moves. The movement of the wire inside a pickup coil changes the self-inductance of the coil. An improved and modified op-amp based inductance measuring network has been designed to measure the self-inductance of this coil. The designed instrument compensates the offset inductance of the sensor and also minimizes the stray capacitance between sensing coil and ground since the inverting terminals of op-amps are connected to circuit common and the selected op-amps have high input impedance. In this instrument, resolution and linearity have been improved. The output current has been found to be linearly related with the pressure changes. The inductance changes have been measured by *LCR* meter (MIC-4070D) of ±0.5 % accuracy and converted in to voltage by inductance measuring circuit. The ac output voltage is interfaced to PC-LABVIEW through DAQ card. The designed virtual instrument system is easy to implement and convenient for various applications.

2. Method of Approach

2.1. Theory and Design of Bellow Element

The bellow element is a one-piece expansible, collapsible and axially flexible elastic member, which can expand axially on air pressure and not appreciably in any other direction. It is a serviceable elastic deformation element mostly suitable for measurement of slightly high pressures in the range of 0 to 100 kPa. The bellows may be considered to be made up of cascaded capsules as shown in Fig. 1. The most commonly used materials are brass, phosphor bronze, hardenable stainless steel, nickel alloy and beryllium copper. The pressure-deflection relationship [4] for a bellow element in common design is given by the following equation:

$$\Delta x = 2NA(P - P_0).\frac{R_b^{\,2}}{E.t^3} \qquad (1)$$

where Δx is the deflection of the tip of bellows element, E is the Young's modulus of elasticity of material of bellows element, N is the number of convolutions in the bellow, P is the applied pressure, P_0 is initial pressure or atmospheric pressure, R_b is the mean radius of the bellow, t is the thickness of the bellows material and A is effective area of the bellow.

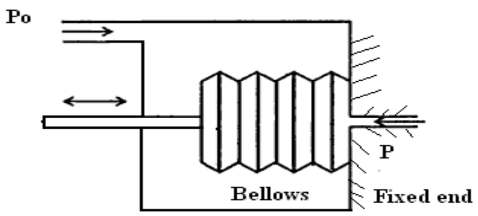

Fig. 1. Schematic of bellow element.

For a particular bellows element, E, A, N, t, and R_b parameters are fixed by the manufacturer and the movement Δx of the tip of bellows element is linearly related with a pressure. The sensitivity parameter of the bellows element can be increased sufficiently by increasing number of capsules and the effective diameter. The equation (1) can be written as

$$\Delta x = k(P - P_0) \qquad (2)$$

where $k = 2NA\frac{R_b^{\,2}}{E.t^3}$ is the spring constant of the bellows element.

The bellow element with its rod is fitted to a wire made of ferromagnetic wire as shown in Fig. 2. The diameter of the wire is to be selected as very small so that its weight does not affect the free movement of the bellow rod. Let the deflection of wire in sensing coil at zero gauge pressure be l_1 which changes to $l_1+\Delta x$ when the bellow is subjected to a gauge pressure of (P-P_0). Since the ferromagnetic wire is rigidly attached to the rod of the bellow element, the linear movement of the ferromagnetic wire may be assumed to be equal to the movement Δx. Therefore, if the ferromagnetic wire is allowed to move through a sensing coil as shown in Fig. 2, then the effective inductance of the coil will increase with the raise in gauge pressure.

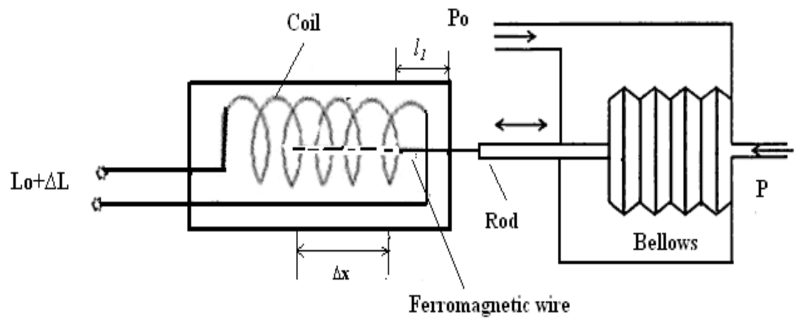

Fig. 2. Bellow element with inductive type transducer.

The resulting inductance variation as a result of the pressure variation is generally too small, so an additional circuitry of a modified op-amp based circuit is used to make it as a measurable representative of the variation in pressure.

A ferromagnetic commercially available galvanized iron (GI) wire of 2 mm diameter and 30 mm length was used as a sensing element. One end of the wire was fixed to the rod of the bellow element by a brazing technique, while the other end was inserted as a core of the inductance coil. The inductance coil is made from 1230 turns of a 46 standard-wire-gauge super enamel copper wire which was uniformly wound on an insulating shaped cylindrical structure and placed inside an aluminum cover tube so that the coil was protected from mechanical damage as well as from an external time-varying magnetic field. The aluminum cover tube with the coil was fixed by brazing it onto the backside of the bellow, while the ferromagnetic wire was brought out through a small hole of the cover plate as shown in Fig. 2 so that it can move freely with the movement of the bellow.

The total length and the length of the ferromagnetic wire inserted into the sensing coil at zero gauge pressure are l and l_1, respectively. Hence the self inductance of the coil is given by,

$$L = \mu A_1 N^2 l_1 + \mu_0 (A - A_1) N^2 l_1 + \mu_0 A N^2 (l - l_1), \qquad (3)$$

where μ is the permeability of the ferromagnetic wire, A_1 is the cross-sectional area of the ferromagnetic wire, N is the number of turns of sensing coil, A is the cross-sectional area of the sensing coil and μ_0 is the permeability of the material of coil.

The equation (4) becomes

$$L = (\mu - \mu_0) A_1 N^2 l_1 + \mu_0 A N^2 l$$

$$L = k_1 l_1 + L_0 , \quad (4)$$

where

$$k_1 = (\mu - \mu_0) A_1 N^2; \text{ and } L_0 = \mu_0 A N^2 l \quad (5)$$

Let the deflection of wire in sensing coil at zero gauge pressure be l_1 which changes to $l_1+\Delta x$ when the bellow is subjected to a gauge pressure of (P-P_0). As a result the self inductance of the sensing coil changes from L to L_x. The expression for L_x is given by:

$$L_x = k_1 (l_1 + \Delta x) + L_0 \quad (6)$$

$$L_x = \Delta L + L_0 \quad (7)$$

where

$$\Delta L = k_1 (l_1 + \Delta x) \quad (8)$$

2.2. Modified Op-Amp Based Inductance Measuring Circuit

The modified operational amplifier based network using op-amps and dummy inductor has been designed as shown in Fig. 3 to measure the inductance of the sensing coil. The network consists of three low-noise, high input impedance operational amplifiers A_1, A_2, and A_3. A stabilized sinusoidal signal source of small RMS voltage V_{in} is connected at the common input of two op-amps A_1 and A_2 operating in the inverting modes. The circuit was mounted on a printed circuit board. A stabilized sinusoidal oscillator at 5 V and at 100 Hz was selected to excite the circuit as a supply source. The value of R_1 was selected to be a 10 kΩ standard resistance and the value of R was selected as 1 kΩ. The operational amplifier selected in this design was OP07 since it has high input impedance and a high signal-to-noise ratio. The pressure sensing coil fitted with ferromagnetic wire having self inductance of L is connected in the feedback path of op-amp A_1. Similarly, the dummy inductor, L_0 of having inductance equal to that of sensing coil at zero pressure is connected in the feedback path of op-amp A_2.

For the pressure of P, let the bellow be deflected by an amount of Δx .Corresponding to this deflection the change in self-inductance of the sensing coil be the L=L_0+ΔL, where L_0 corresponds to the zero pressure. The output voltages V_1 and V_2 of the two op-amps A_1 and A_2 are given by

$$V_1 = -V_{in} \frac{R}{R_1} \left[1 + \frac{2(L_0 + \Delta L) jw}{R} \right] \quad (9)$$

$$V_2 = -V_{in} \frac{R}{R_1} \left[1 + \frac{2(L_0) jw}{R} \right] \quad (10)$$

The difference (ΔV) of these two outputs is given by the differential amplifier consisting of A_3 and is given by

$$\Delta V = V_{in} .2 jw (\frac{\Delta L}{R_1}) \quad (11)$$

Combining equations (2), (8) and (11)

$$\Delta V = V_{in} .2 jw \frac{k_1 (l_1 + k(P - P_0))}{R_1} \quad (12)$$

$$\Delta V = a + b.\Delta P \quad (13)$$

where $a = k_2 .l_1$; $b = k_2 .k$; $k_2 = \frac{V_{in} .k_1 .2 jw}{R_1}$;

$$\Delta P = P - P_0 \text{ are constants} \quad (14)$$

Therefore, from equation (13) the output voltage of the inductance measuring circuit is linearly related with the gauge pressure.

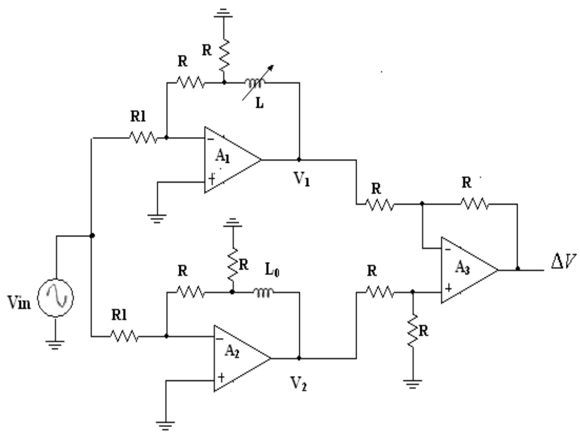

Fig. 3. Modified op-amp based circuit for inductance measurement.

2.3. Pressure Measurement Using Modified op- amp Based Inductance Measuring Circuit

The complete circuit assembly of instrument for the measurement of small pressure changes is shown in Fig. 4. The output voltage of inductance measuring circuit has been filtered and interfaced to PC-LabVIEW through NI-cDAQ as shown in Fig. 5 in order to transmit over remote location devices. The output voltage signal (ΔV) is amplified to a voltage signal, V^1 in the range of 1–5 V ac, which is finally converted into a current signal (I_0) in the range of 4–20 mA dc by a voltage to current converter. After calibration, the output of the pressure transmitter becomes 4 mA when V^1 is 1 V and pressure P is zero psig and becomes 20 mA when V^1 is 5 V and pressure P is at the maximum range (P_{max}). Hence, the pressure transmitter voltage output, V^1 in volts and the current output (I_0) in milliamperes may be written as

$$V^1 = \left(\frac{4}{P_{\max}}\right)\Delta P + 1 \tag{15}$$

$$I_0 = \beta V^1, \tag{16}$$

where β is constant. From equations (15) and (16)

$$I_0 = \beta + \left(\frac{4\beta}{P_{\max}}\right)\Delta P \tag{17}$$

Since from (13), $\Delta P \cong \frac{(\Delta V - a)}{b}$, the relative measurement error (E_1) expressed in percentage may be calculated by the following equation:

$$E_1 = \frac{(\frac{(\Delta V - a)}{b} - \Delta P)}{\Delta P} \times 100\%, \tag{18}$$

where ΔP is the measured pressure; ΔV is the measured output voltage.

In terms of percentage of the maximum range, it changes to (E_2); this may be defined as relative measurement error

$$E_2 = \frac{(\frac{(\Delta V - a)}{b} - \Delta P)}{\Delta P_{\max}} \times 100\%, \tag{19}$$

where ΔP_{max} is the maximum value of pressure change. Again, from the measured values of ΔV at different values of ΔP, the best-fit linear characteristic may be drawn using the LabVIEW. The linear least squares fitting technique which is the simplest and most commonly applied form of linear regression, has been used to find the best-fitting curve to a given set of points (measured values of ΔV at different values of ΔP by minimizing the sum of the squares of the residuals of the points from the curve. The actual values of ΔV are obtained from the best-fit linear characteristic at different values of ΔP, and the relative output voltage measurement error (E_3) from linearity may then be defined as:

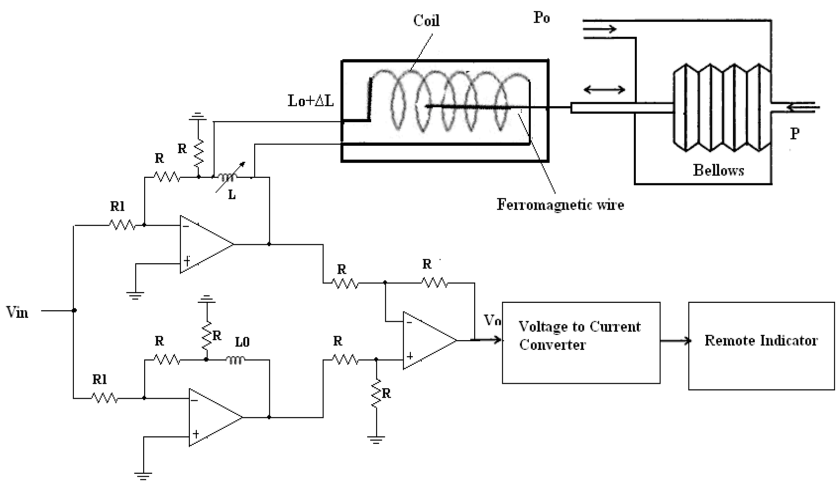

Fig. 4. The complete circuit assembly of pressure transmitter.

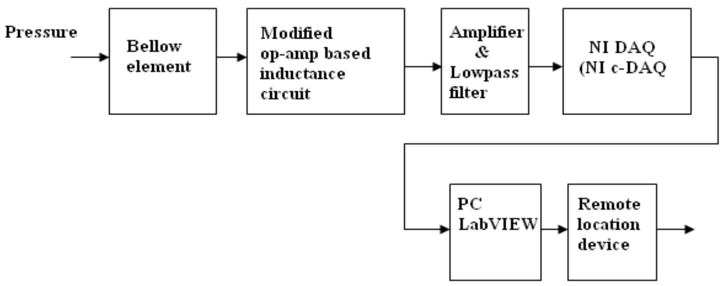

Fig. 5. Block diagram of virtual instrument system for level measurement.

$$E_3 = \frac{(\Delta V_{actual} - \Delta V)}{\Delta V_{actual}} \times 100\% , \quad (20)$$

where ΔV_{actual} are the actual values obtained from the best-fit linear curve for a given pressure change, *ΔP*.

3. Experimental Results and Discussion

The experiment was conducted in two phases. In the first phase of the experiment, performance of modified op-amp based network for inductance measurement has been studied with a known variable inductor and ac test signal of sinusoidal voltage ($V_{in}=V_m \sin(\omega t)$), with an amplitude V_m of 5 V and a frequency of 100 Hz. The values of components used in the measuring circuit (as shown in Fig. 3) are R_1=10 kΩ, R=1 kΩ. The amplifiers, A_1, A_2 and A_3 are OP 07 operational amplifiers. The three-and-one-half digit ac millivoltmeter was used for inductance measuring circuit output voltage. The change in inductance, *ΔL* in both increasing and decreasing modes has been varied in steps of 1 mH over 100 mH range and at each step, the output voltage was measured. Experimental characteristic graphs were then drawn by plotting the output voltage against the known variable inductance, *ΔL* as shown in Fig. 9. In the second phase of experiment, the modified op-amp based circuit for inductance measurement has been used for measuring pressure, replacing the variable inductor by an inductive coil with the ferromagnetic wire which was fitted to the bellow element. The ferromagnetic wire, the inductive coil and the bellow element of the developed virtual instrument system is the laboratory standard equipment with the following specification.

<u>Ferromagnetic wire</u>
Material: galvanized iron (GI)
Diameter: 2 mm
Length: 30 mm
Cross sectional area: 3.141 mm^2
<u>Inductive coil</u>
Material: 46-standard-wire-gauge super enamel copper wire
Number of turns: 1230
The length of the coil: 75 mm
<u>Bellow</u>
Material: SS316 stainless steel
Young's modulus of bellow material: 28 ×10^6 *psi*
Thickness: 0.889 mm
Outer diameter, D: 31.75 mm
Inner diameter, d: 15.875mm
Mean effective area, A: 445.35 mm^2
Number of convolutions: 10

The pressure tank was fitted with a pressure gauge so that gauge pressure can be measured. The offset inductance of the sensing coil with zero pressure is L_0 = 50 mH. Hence, the base inductance of pressure sensing coil with zero pressure is approximately 50 mH. The dummy inductor was connected in the feedback of op-amp, A_2 of the measuring circuit is set to 50 mH to get zero output voltage and then, the pressure tank was filled by an air having a resolution of 5 psi. The output voltages for different values of the air pressure are measured in both increasing and decreasing modes. The variation of the output voltage with the change in air pressure and coil inductance with the change in air pressure are found to be linear as shown in Fig. 8 and Fig. 9, respectively. The static characteristic graph of the pressure transmitter was drawn by plotting transmitter output current of 4 to 20 mA against pressure variation from 0 to 70 psig. as shown in Fig. 11. The linear characteristics over a wide range of pressure with good linearity, and resolution have been described.

In a pressure measuring technique based on piezoresistance or strain-gauge-type, the sensing element is mounted on a diaphragm or Bourdon tube acting as a primary sensor, and the change in the resistance of the sensing element is measured by a Wheatstone bridge circuit having a fixed sensitivity value for a fixed bridge supply voltage. Moreover, the sensing element mounted on the diaphragm is in direct contact with the process fluid. Hence, a special technique is required to compensate the effect of the fluid temperature. This makes the whole sensing circuitry much more costly than the proposed technique. In the designed instrument, the major part of the bellow element with the sensing ferromagnetic wire is kept at atmospheric temperature. Therefore, the effect of the fluid temperature is negligible, which can be further reduced by using an identical pressure insensitive dummy tube with a dummy ferromagnetic wire with its identical length inserted into the dummy coil. This technique is much simpler than the conventional piezoresistance or strain-gauge-type technique. The proposed ferromagnetic wire sensor has a higher operating temperature range with a longer life period when compared to the piezoresistive pressure sensor.

4. Conclusions

The experimental characteristics of the designed pressure transmitter shown in Figs. 8 and 10 for pressure and inductance measurement, respectively, have been found to be quite linear about ±0.1 % within a resolution of about 5 psi. The percentage deviation of inductance measurement from the best fit linear graph, as shown in Fig. 7 has found to be within the tolerable limit. The small percentage deviation of inductance measurement may results if the measured circuit and sensing coil is operated up to few 100 hours and may be due to the calibration error of the components of measuring circuit, as well as due to the aging effect of the components. The human error in taking the reading of the pressure may also contribute to a small percentage error as the pressure has been measured by a pressure gauge. The modified op-amp based network permits offset inductance compensation of pressure sensing coil. As the non inverting terminals of op-amps *A*1 and *A*2 are connected to circuit common, the inverting terminals are at virtual ground. The stray capacitance between terminals of the sensing coils is negligible, since the sensing coil is connected between ground and output. Again, the same excitation signal is input to op-amps *A*1 and *A*2 through identical input resistance (R_1). Hence, the other two terminals of the inductance coils are almost at the same potential, and the stray capacitance between these terminals is also negligible. Thus, the measurement may be considered to be free from error due to the stray capacitance effect.

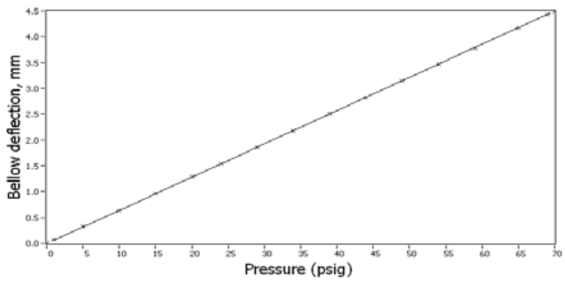

Fig. 6. Change in deflection of bellow versus variation in pressure.

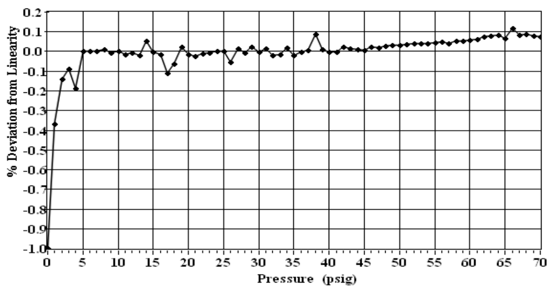

Fig. 7. Percentage deviation of the pressure from straight line characteristic.

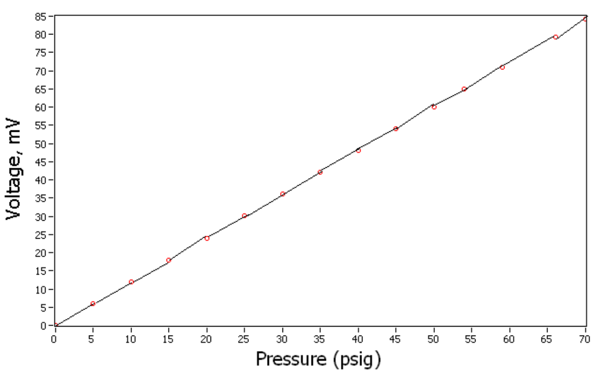

Fig. 8. Variation in output voltage with change in pressure.

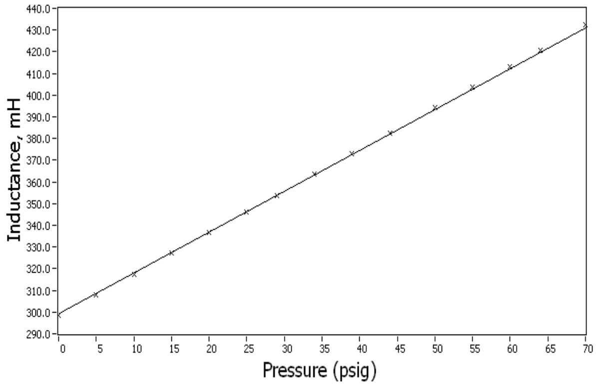

Fig. 9. Variation in inductance of coil with change in pressure.

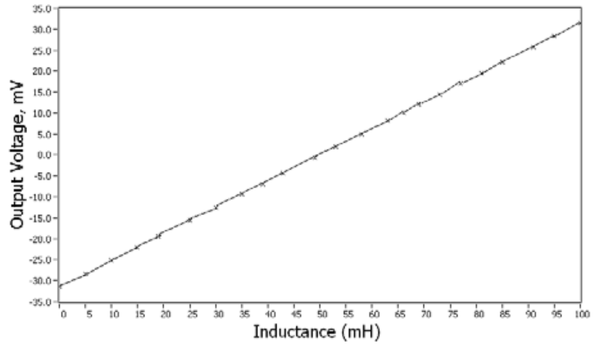

Fig. 10. Variation in output voltage with change in inductance.

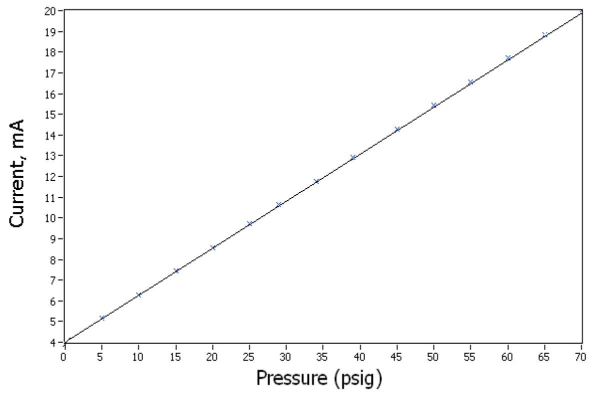

Fig. 11. Variation in output current with change in pressure of pressure transmitter.

The effect of derivative action to the input signal which is due to direct connection of inductive coil in feedback path of op-amp is minimized by using proposed technique. The proposed virtual instrument of pressure measurement has very good accuracy and resolution compared to the conventional measurements available in literature.

References

[1]. E. O. Doeblin, Measurement System Application and Design, 4th ed., *McGraw-Hill,* New York, 1990.

[2]. J. P. Bentley, Principles of Measurement Systems, 3rd ed., *Longman Singapore Publishers Ltd.,* Singapore, 1995.

[3]. B. G. Liptak, Process Measurement and Analysis, 3rd ed., *Butterworth Heinman*, Oxford, U. K., 1999.

[4]. D. M. Considine, Process Instruments and Control Hand Book, 2nd edition, *McGraw-Hill,* New York, 1974.

[5]. S. C. Bera and S. Chattopadhyay, Modification of the Maxwell–Wien bridge for accurate measurement of a process variable by an inductive transducer, *IEEE Trans. Instrum. Meas.,* Vol. 59, No. 9, Sep. 2010, pp. 2445–2449.

[6]. Satish Chandra Bera, Ranjan Sarkar and Madan Bhowmick, Study of modified differential inductance measurement circuit as position transducer of a power cylinder, *IEEE Trans. Instrum. Meas.,* Vol. 61, No. 2, February 2012, pp. 530–538.

[7]. Satish Chandra Bera, Nirupama Mandal and Ranjan Sarkar, Study of Pressure transmitter using an improved inductance bridge network and Bourdon tube as transducer, *IEEE Trans. Instrum. Meas.,* Vol. 60, No. 4, April. 2011, pp. 1453–1460.

[8]. K. Subramanian, J. B. Fortin, and K. Kishore, Scalable vertical diaphragm pressure sensors: Device and process design, design for packaging, *IEEE Sensors J.,* Vol. 6, No. 3, June 2006, pp. 618–622.

[9]. S. Y. Yurish, Intelligent digital pressure sensors and transducers based on universal frequency-to-digital converters (UFDC-1), *Sensors & Transducers,* Vol. 60, No. 10, October 2005, pp. 432–438.

[10]. R. Vrba, M. Sveda, and K. Marecek, Pressure transducer with multiplexed frequency transmitter, in *Proc. Sensors Ind. Conf. —SIcon*, New Orleans, LA, 27–29 January, 2004, pp. 7–10.

[11]. S. Vlassis and S. Siskos, An interfacing circuit for piezoresistive pressure sensors with frequency output, *Int. J. Electron.,* Vol. 87, No. 1, January 2000, pp. 119–127.

[12]. M. A. Taslakov, Temperature compensated pressure sensor, in *Proc. IEEE Int. Freq. Control Symp.,* Honolulu, HI, Jun. 5–7, 1996, pp. 563–566.
