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A Float Type Liquid Level Measuring System Using a Modified Inductive Transducer

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Abstract: Float type liquid level sensor is generally used as a very simple technique for local level indication and level switching. In the present paper a technique has been proposed to transmit the measured liquid level signal of a float type sensor at remote terminal using a modified differential inductance type electromechanical transducer. The theoretical characteristic equation of this transducer has been derived. A prototype unit of the transducer has been developed and fabricated and its performance characteristic has been experimentally determined. The experimental results are reported in the paper. From experimental data, a very good linear characteristic of the proposed level transducer has been observed. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Float type liquid level measurement, Inductance coil, Modified differential inductance measurement, Magnetic reluctance, Operational amplifier.

1. Introduction

The liquid level in a storage tank should be measured for different applications in process industry. There are various well recognized techniques for level measurement [1] which are broadly classified in two groups, such as direct method and indirect method. In direct method the techniques like dip stick, gauge glass, float, displacer etc. are used. In indirect method, the techniques like capacitance type, pressure sensing type, ultrasonic type, radiation absorption type, electrical conductivity type etc. are used. Liquid properties [1] like buoyancy, relative electrical permittivity, electrical conductivity, thermal conductivity, pressure at a depth, absorption of radiation by liquid level, liquid surface reflection of sound or light waves etc. are generally utilized for liquid level measurement. With the change in liquid level, a particular parameter of a sensor such as position, capacitance, inductance, resistance etc. changes and that change is converted into mechanical or electrical signal with the aid of a suitable transducer [1-2] to drive a controller or an indicator calibrated in terms of level. In float and displacer type level sensor, the position of sensing element changes with the change in liquid level, and this change is converted into electrical signal by using a suitable transducer. The capacitance between a level probe and a metallic storage tank or between two level probes changes with the change in level in capacitance type level sensor. The pressure at a particular point of the liquid level column changes with the change in level in case of pressure sensing type level sensor. In ultrasonic type sensor, the time of flight between the transmitted and received signals from the liquid level changes with the liquid level. In radiation absorption type sensor, the intensity of the transmitted signal to a receiver through a liquid storage tank changes with the change in level. Various works are still being reported to measure liquid level with more accuracy reliability and simpler design. Capacitance type liquid level measurement techniques [4-10] have been proposed by different workers. Bera, *et al.* [4] have designed a modified capacitance type liquid level transducer which eliminates the effect of self inductance of the metallic sensing probe and found a good linearity. A microcontroller based self calibrating water level measuring system using inter-digital capacitive sensor consisting of a printed circuit board with configuration of two interpenetrating finger electrodes has been proposed by Chetpattananondh, *et al.* [5]. Terzic, *et al.* [6] have introduced an artificial neural network approach to eliminate the effects of liquid slosh on fluid level measurement in an automotive fuel tank under dynamic condition using a single tube capacitive sensor. Canbolat [7] has used three parallel plate capacitive sensors among which two are used as reference sensors, to develop a novel liquid level measurement technique which is independent of the liquid type, air, and fluid dielectric constants in the tank. A liquid level measurement system of a conductive liquid (tap water), based on a remote grounded capacitive sensor has been presented by Reverter, *et al.* [8]. A non-contact capacitance type level transducer for a conductive liquid has been developed by Bera, *et al.* [9]. They have used the conducting liquid column as one electrode and a non-inductively wound short circuited coil around a level sensing cylinder made of insulating material as the other electrode and have found good linearity, resolution and accuracy comparable with those of conventional contact type sensors. A finite element simulation program has been developed to predict the impedance behavior of a capacitive type level sensor due to double layer polarizable liquid medium by Biswas, *et al.* [10]. Terzic, *et al.* [11] have used a single ultrasonic sensor coupled with Support Vector Machines based signal processing and classification approach for accurate determination of the fuel level in an automotive fuel tank under dynamic conditions and have minimized the effects of slosh and temperature on the acoustic sensor. Nakagawa, *et al.* [12] have utilized the absorption principle of a millimeter wave passing through an opaque container to develop a noncontact liquid level measurement system using a piezoelectric vibrator coupled with a millimeter wave Doppler sensor. Paul, *et al.* [13] have used discrete wavelet transform and discrete wavelet packet transform based noise removal technique to remove measurement noise from differential pressure transmitter output measuring the level of a liquid level system and have achieved better signal to noise ratio and minimum square error. An image based non contact type liquid level measurement system has been proposed by Wang, *et al.* [14] using a single digital camera and a circular float hovering on the liquid surface. Zheng, *et al.* [15] have presented a wide range water level gauge by measuring the distance of the water surface from a benchmark which can be applicable for the measurement of water levels of dam or river where levels can vary slowly and only a very few data in a day is required. Yin, *et al.* [16] have designed a new inductive sensor consisting of two circular coils of different radii for simultaneous measurement of conductivity and level for low conductive liquids based on a simplified model to describe the imaginary part of the inductance. A micron order liquid level sensing technique has been reported by Campbell and Mutharasan [17] using a lead zirconate titanate (PZT) actuated millimeter-sized cantilever where the PZT layer acts both as an actuating and a sensing element.

In the present paper design of a low cost modified inductive pick-up type liquid level transducer using float as the primary sensing element has been described. The transducer consists of a level sensing cylinder connected with a main tank. The cylinder has uniform cross-section attached with a gauge glass. It has a spherical plastic float which rises with the increase of the liquid in the main tank. The diameter of the float is just slightly less than that of the cylinder, so that the cylinder itself almost acts as the guide to the float. A uniform rod of ferromagnetic material like carbon steel is attached with the float. The length of the rod is so selected that at datum level the rod is inside a non-metallic guide cylinder vertically fixed on the top cover plate of the sensing cylinder, so that with the increase of level, the rod moves upward inside the guide cylinder with diameter slightly greater than the diameter of the rod. Guide cylinder consists of two identical inductive pick-up coils over two equal lengths. With the increase of level the movement of sensing rod inside the pick-up coils increases and self inductances of these coils increases. A stopper inside the guide cylinder between two pick-up coils restrict the motion of the sensing rod, so that the rod does not move inside the second coil placed above the first coil. The difference in self inductances between these two coils is measured by a modified differential inductance bridge network working as proposed level transducer. The theoretical equations of the transducer are derived in the paper. Its operation is experimentally verified and the experimental results are reported in the paper. A very good linear variation of transducer output with level has been observed.

2. Method of Approach

The proposed level sensor is a spherical cistern float attached with a uniform solid rod made of ferromagnetic material placed inside a uniform cylinder made of PVC or metal as shown schematically in Fig. 1 (a) with its photographic view in Fig. 1 (b).

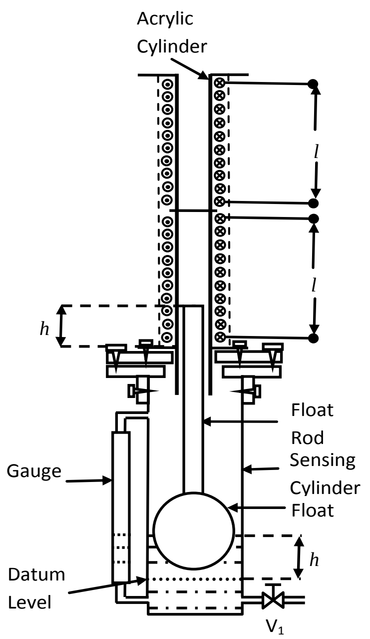

Fig. 1 (a). Schematic diagram of proposed level sensor.

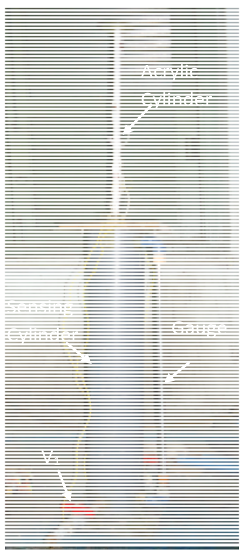

Fig. 1 (b). Photographic view of proposed level sensor

The diameter of the ferromagnetic rod is so selected that the net weight of the float with rod is almost equal to the weight of liquid two-third the volume of the float, so that float with rod is immersed up to two-third the volume of the float. Diameter of the float is slightly smaller than the inside diameter of the cylinder in which it is kept. Now the upper end of the cylinder is attached with a vertical uniform acrylic cylinder of inner diameter slightly larger than the diameter of the float rod with a certain length of lower part inserted into the main cylinder through proper attachment as shown in Fig. 1(a). The length of the float rod is so selected that at minimum liquid level, the rod is inside the acrylic cylinder up to a certain length placed inside the main cylinder. The acrylic cylinder is attached with two circular flanges made of acrylic sheets of which one is attached with the upper end and the other is attached at a location certain length above the lower end so that the acrylic cylinder can rest on the lower flange above the main cylinder attachment plate. It is rigidly attached with the attachment plate by fixing screws. The attachment plate is made of tic wood of 0.008 m thickness. The attachment plate again rest on another plate which is rigidly attached with the upper end of the main cylinder through fixing nut and bolt. Thus a rigid dismantle able system is formed with a certain portion of the vertical acrylic cylinder placed inside the main cylinder with a certain upper portion of float rod inserted inside the acrylic cylinder at minimum level of liquid inside the main cylinder. With the increase of liquid level the float rod moves freely inside the acrylic cylinder with lower part of the cylinder and the walls of the main cylinder acting as guide. The acrylic cylinder between its two flanges is provided with a stop pin just at the middle of the cylinder, so that float rod cannot move further from this middle point. The outside length of the acrylic cylinder above and below this middle point is uniformly wound with two identical coils of equal number of turns. With the increase of level the float rod moves inside the lower coil so that self inductance of the lower coil increases with the increase of level and that of the upper coil remains fixed as explained below. Thus the whole unit acts as a rugged level sensor using float as the primary sensing element. In order to measure the level of any type of liquid inside a tank the proposed level sensor is connected with the tank through suitable connecting tube with the sensing cylinder placed rigidly at a suitable location near the tank as schematically shown in Fig. 2. To physically observe the liquid level inside the tank a gauge glass is attached with tank or with the sensing cylinder as shown in Fig. 2.

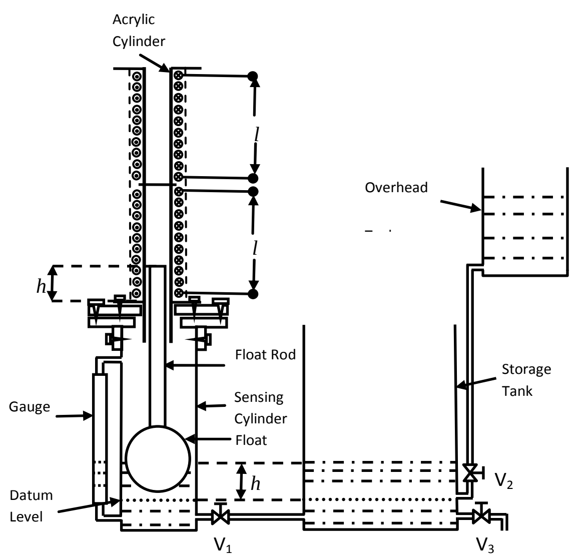

Fig. 2. Schematic diagram of experimental setup.

If the length of the float rod is so selected that its upper end is just at the location of lower end of the lower coil when liquid in the sensing cylinder and storage tank is at datum level, then for a liquid level h above the datum level of storage tank, the movement of the upper end of float rod from the lower end of the lower coil will also be h. Under this condition the reluctance of the magnetic circuit for the lower coil of length l is given by

$$R_{1h} = \frac{h}{\mu_0\left(A_c - A_{fr}\right) + \mu_{fr}A_{fr} + \mu_0' A_t} + \frac{l-h}{\mu_0 A_c + \mu_0' A_t} + R_0, \quad (1)$$

where μ_0 is the permeability of air or vacuum; μ_0' is the permeability of the material of the acrylic cylinder; μ_{fr} is the permeability of the material of the float rod; A_c is the inner cross sectional area of the acrylic cylinder; A_{fr} is the cross sectional area of the float rod; A_t is the cross sectional area of the material part of the acrylic cylinder; R_0 is the reluctance of the leakage path for the lower coil; or

$$R_{1h} = C_1 - C_2 h, \quad (2)$$

where

$$C_1 = \frac{l}{\mu_0 A_c + \mu_0' A_t} + R_0 \quad (3)$$

and

$$C_2 = \frac{1}{\mu_0 A_c + \mu_0' A_t} - \frac{1}{\mu_0 A_c + \mu_0' A_t + A_{fr}\left(\mu_{fr} - \mu_0\right)} \quad (4)$$

Since $\mu_{fr} >> \mu_0$,

$$\frac{1}{\mu_0 A_c + \mu_0' A_t} > \frac{1}{\mu_0 A_c + \mu_0' A_t + A_{fr}\left(\mu_{fr} - \mu_0\right)} \text{ and } C_2 > 0$$

Therefore, for two identical coils each of N turns, the self inductance of the lower coil for level h above datum level is given by

$$L_{1h} = \frac{KN^2}{R_{1h}} = \frac{KN^2}{C_1 - C_2 h} = \frac{KN^2}{C_1}.\frac{1}{\left(1 - \frac{C_2 h}{C_1}\right)}, \quad (5)$$

where K is the Nagoaka's factor [3].

Since the reluctance R_0 in leakage path of the coil is very high, so $C_1 >> C_2 h$. Hence Equation (5) is reduced to

$$L_{1h} = \frac{KN^2}{C_1} + \frac{KN^2 C_2}{C_1^2} h \quad (6)$$

Again, the upper coil has the same number of turns (N) and same length (l) and is always without any core material. So the reluctance of the magnetic circuit for the upper coil is given by

$$R_{20} = \frac{l}{\mu_0 A_c + \mu_0' A_t} + R_0' = C_3, \quad (7)$$

where R_0' is the reluctance of the leakage path of the upper coil.

Hence, the self inductance of the upper coil is given by

$$L_{20} = \frac{KN^2}{R_{20}} = \frac{KN^2}{C_3} \quad (8)$$

Now neglecting the proximity effect of the float rod on the reluctance of upper coil, $R_0' \approx R_0$. Hence from Equations (3) and (7), we have

$$C_3 \approx C_1 \quad (9)$$

Thus, Equation (8) is reduced to

$$L_{20} = \frac{KN^2}{C_1} \quad (10)$$

Hence from Equations (6) and (10), we have

$$L_{1h} = L_{20} + \frac{KN^2 C_2}{C_1^2} h = L_{20} + C_4 h, \quad (11)$$

where

$$C_4 = \frac{KN^2 C_2}{C_1^2} \quad (12)$$

Hence at a level h above datum level the difference between the self inductances of lower and upper coils is given by

$$\Delta L = L_{1h} - L_{20} = C_4 h \quad (13)$$

So it is found that the difference in self inductances of the two coils varies linearly with the liquid level above the datum level of the tank.

Now to measure the difference in self inductances a modified operational amplifier based differential inductance measurement circuit is designed as shown in Fig. 3.

For the sinusoidal ac source of rms voltage V_S at angular frequency ω, the output of OPAMPs A_1 and A_2 are given by

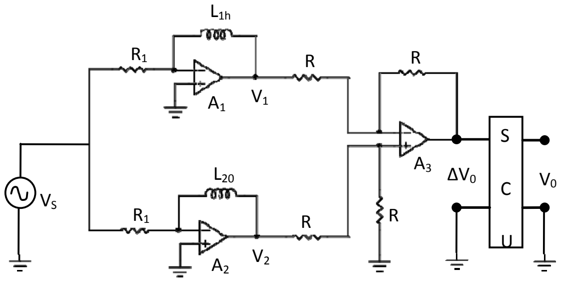

Fig. 3. Schematic diagram of the proposed level transducer.

$$V_1 = -V_S \times \frac{R_C + j\omega L_{1h}}{R_1} \quad (14)$$

and

$$V_2 = -V_S \times \frac{R_C + j\omega L_{20}}{R_1}, \quad (15)$$

where R_C is the resistance of each of the identical coils.

Hence, the output of the differential amplifier circuit consisting of OPAMP A_3 is given by

$$\Delta V_0 = \frac{j\omega V_S}{R_1}\left[L_{1h} - L_{20}\right] = \frac{j\omega V_S}{R_1} C_4 h = C_5 h \quad (16)$$

where

$$C_5 = \frac{j\omega V_S}{R_1} C_4 \quad (17)$$

In practice there may be deviations from exactly identical conditions of the two coils at datum level as well as exactly identical circuit elements like OPAMPs (A_1, A_2 and A_3) and resistors (R_1 and R) may not be available, so at datum level, transducer output is modified as

$$\Delta V_0 = C_5 h + C_6, \quad (18)$$

where C_6 is the offset voltage.

Now, the signal conditioner unit (SCU) consisting of pre-amplifier, rectifier, filter and amplifier with zero, span and gain adjustments has a linear characteristic. This circuit is adjusted to obtain 1 Volt output at datum level and 5 Volt output at maximum level. Hence, if the gain of signal conditioner is C_7, then its output becomes

$$V_0 = C_7.\Delta V_0 + C_8, \quad (19)$$

where C_8 is the additional offset voltage introduced by the zero adjustment circuit to obtain 1 Volt output at datum level.

Therefore, signal conditioner output for level h above datum level is given by

$$V_0 = C_9 h + C_{10}, \quad (20)$$

where

$$C_9 = C_5 C_7 \text{ and } C_{10} = C_6 C_7 + C_8 \quad (21)$$

Thus the output of the signal conditioner unit is linearly related with the level h above datum level.

3. Design

The proposed level sensor consists of a spherical plastic cistern float of 0.095 m outer diameter placed inside a uniform cylinder of 0.8 m in length and 0.098 m internal diameter made of PVC as shown schematically in Fig. 1(a). The float is attached with a uniform solid rod of 0.009 m diameter and 0.72 m in length made of ferromagnetic material like carbon steel. The upper end of the PVC cylinder is attached with a vertical uniform acrylic cylinder of 0.01 m inner diameter, 0.001 m thickness and of 0.6 m in length, with 0.1 m length of lower part inserted into the main cylinder through proper attachment as shown. Two identical coils each of 3000 turns and of length 0.25 m are wound on the outer surface of the acrylic cylinder above and below the middle point separated by a stop pin. The super-enameled copper wire of 40 SWG is used as the winding wire.

The modified differential inductive transducer, shown schematically in Fig. 3, is designed with OP-07 as low noise OPAMPs (A_1, A_2, and A_3) and 10 kΩ and 1 kΩ registers of ½ Watt with 1 % tolerance as R_1 and R respectively. The transducer circuit is supplied from a stabilized sinusoidal ac supply source at 5 V, 1000 Hz. The signal conditioner unit (SCU) as shown by block diagram in Fig. 3 is used to obtain 1-5 V dc signal to drive a meter calibrated in terms of level. The signal conditioner unit consists of instrumentation amplifier INA101KP, rectifier, filter, and amplifier with zero, span and gain adjustments.

4. Experiment

The experiment is carried out with the experimental setup as shown in Fig. 2 using tap water as the process liquid. The proposed level sensor is connected with a storage tank placed at the same ground level through valve V_1 and suitable connecting tube as shown schematically in Fig. 2. The level of the storage tank is increased in steps by opening the valve V_2 and closing the valve V_3 whereas it is decreased by opening the valve V_3 and closing the valve V_2. At each step, level of the tank is measured from the gauge glass attached with the sensing cylinder and the corresponding transducer output is measured by a 3½ digit digital multi-meter in both increasing and decreasing modes. The static characteristic graph of the level transducer is drawn by plotting the transducer output ΔV_0 against level h . The experiment was repeated in both increasing and decreasing modes and experimental data were observed and recorded for three days. The static characteristic graphs in three increasing and three decreasing modes along with the ideal best fit graph are shown in Fig. 4 and the corresponding short term standard deviation graph is shown in Fig. 6. The percentage deviation from linearity of the measured data from ideal best fit linear graph is calculated and plotted against level as shown in Fig. 5.

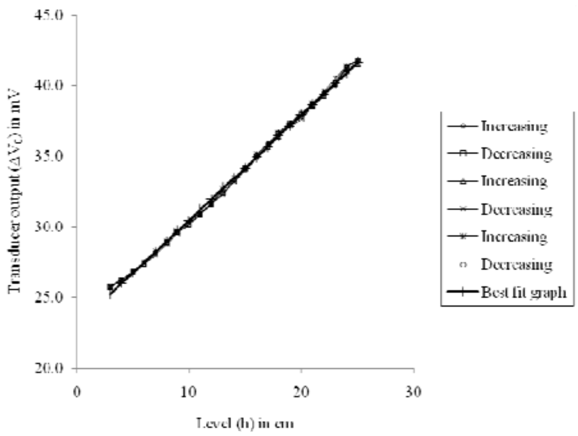

Fig. 4. Static characteristic graph of the proposed level transducer.

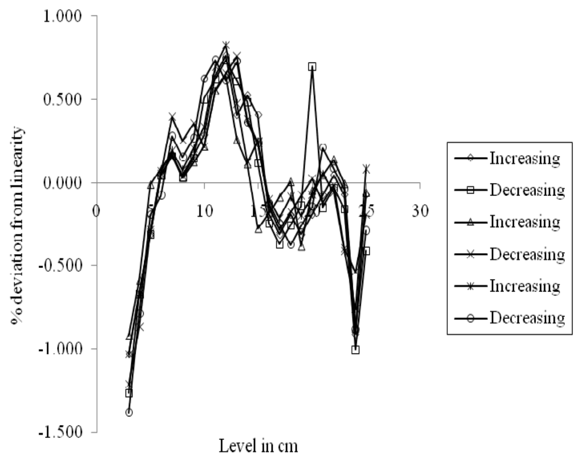

Fig. 5. Percentage deviation graph from linearity of the level transducer.

In the second part of the experiment, the transducer output terminals are connected with the input of signal conditioner unit as shown in Fig. 3 and adjustments are made in order to obtain 1 Volt dc when the level is at datum level and 5 Volt dc when the level is at maximum level.

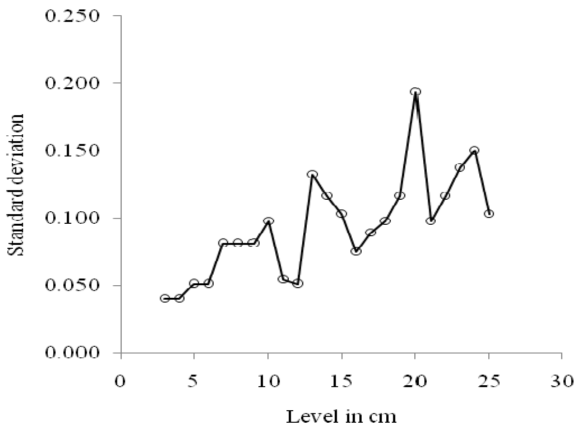

Fig. 6. Standard deviation graph of the level transducer.

After this adjustment level is increased in steps and at each step signal conditioner output is measured by a 3½ digit digital multi-meter and the corresponding level is measured from the gauge glass. The experiment was repeated in both increasing and decreasing modes and experimental data were observed and recorded for three days. The static characteristic graphs of the signal conditioner for three increasing and three decreasing modes along with the ideal best fit graph are drawn by plotting the signal conditioner output V_0 against level h as shown in Fig 7. The percentage deviation from linearity and standard deviation are shown in Fig. 8 and Fig. 9 respectively.

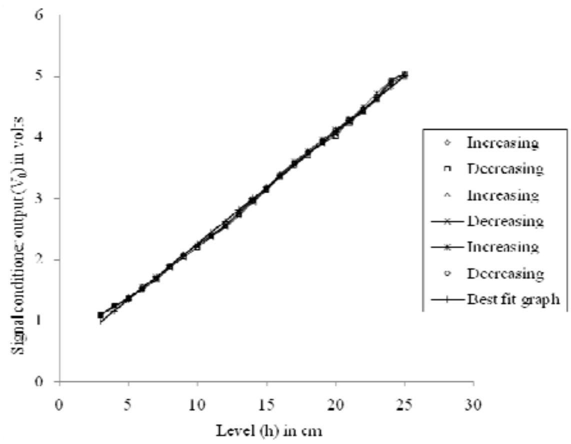

Fig. 7. Static characteristic graph of the signal conditioner.

5. Discussions

From the static characteristic graph of the proposed level transducer shown in Fig. 4, it is observed that the transducer has a good linearity over a wide range. The percentage deviation from linearity is within tolerable limit as shown in Fig. 5.

Experimental data for three increasing and decreasing modes observed over three days appeared to give good repeatability as indicated in the short term standard deviation graph in Fig. 6. Static characteristic graphs of the whole measuring unit are shown in Fig. 7 and also appear to have good linearity. The percentage deviation graphs from linearity of these data are shown in Fig. 8 and appear to remain within tolerable limit. The standard deviation graph for all these data is shown in Fig. 9 and appears to reveal a good repeatability of the whole measuring unit.

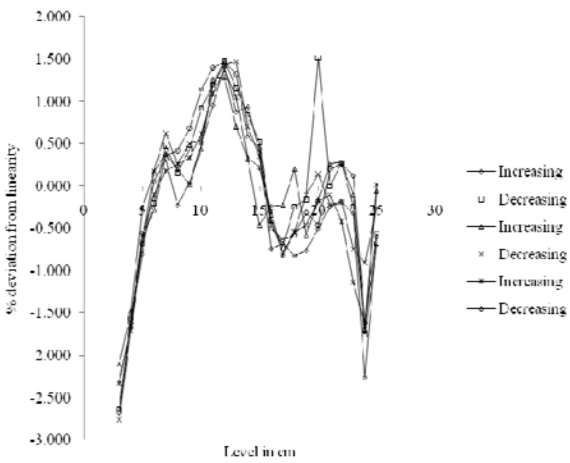

Fig. 8. Percentage deviation graph from linearity of the signal conditioner.

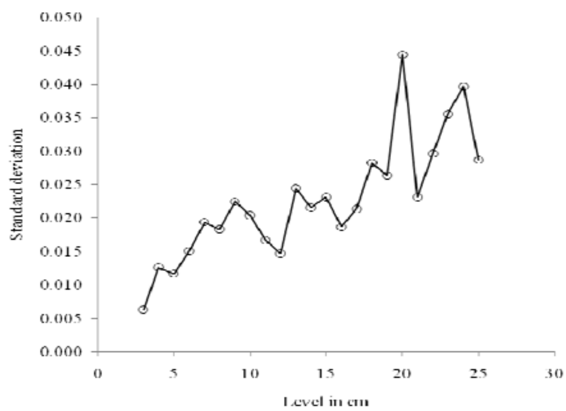

Fig. 9. Standard deviation graph of the signal conditioner.

Since the two coils are identically wound on the same cylinder, so the nonlinear end effects of the two coils are identical and cancel each other. Moreover the electromagnetic induction effects from external sources are also identical and cancel each other when difference of inductances is taken. Thus the static characteristic of the proposed transducer is quite linear as explained above. This linearity is much greater than single inductive pick-up type or LVDT type level transducer.

In the conventional inductance measurement circuit such as Maxwell's bridge, Anderson's bridge, Hay's bridge etc., the bridge output signal is found to be affected by the stray capacitance between bridge components as well as between bridge components and ground. But in the proposed transducer network the identical inductive elements are connected to the inverting input terminals of OPAMPs A_1 and A_2 as shown in Fig. 3. Since this terminals are at the same virtual ground potential, so the stray capacitance effect, between these two terminals as well as between each terminal and ground is eliminated, if the common terminal of the transducer circuit is connected to rigid ground.

In the present design the range of the level transducer has been restricted to 25 cm since; the length of each coil on the guide cylinder is selected to be 25 cm. However, the range of the transducer may be increased by selecting larger length of each coil.

In ordinary bridge method of inductance measurement, the sensitivity of the bridge circuit depends on quality factor of the inductance coil and there are different ranges of inductance and quality factor for different bridge methods. But in the proposed transducer circuit, no such restriction is introduced since difference of inductances of the two identical coils is considered. This also reduces the effect of inter-winding capacitance of each coil, since this is identical for both the coils.

The design of the proposed transducer is very simple and rugged with good repeatability. The materials and components of the transducer are of little cost which reduces the cost of the whole transducer. There may be error due to stuck-up of float in the wall of the sensing cylinder or in the guide cylinder due to friction. In the proposed design this is minimized by selecting sensing cylinder with inside polished surface and by selecting the float in spherical shape, as well as selecting the acrylic cylinder as guide. This may be further improved by using Teflon as material of float, sensing cylinder and guide cylinder. This will slightly increase the cost of the transducer.

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