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Novel Displacement Transducers for Magnetic Levitation System

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ABSTRACT

Background: The position of the levitated object plays an important role in satisfactory working of electromagnetic attraction type of magnetic levitation system. It was observed that position sensors like optical and Hall Effect sensors used for this purpose are clumsy and prone to failure. Two novel self sensing circuits based on resonance technique and synchronous demodulation method have been designed and developed. Two coils are placed on the lifting magnet to perform the lifting and sensing function. These coils are decoupled from each other. The position sensing coil is excited by a 50 Hz source and in the first method (resonance technique) change in impedance of the measuring coil which is in parallel with a capacitor is measured to measure the displacement Y, whereas in the second method, phase difference between the coil voltage and current is measured to measure the displacement. The performance of both the techniques is compared. Hardware results for synchronous demodulation technique are obtained for analog and digital circuits developed. **Objective:** To develop two novel self sensing techniques for magnetic levitation system. **Results:** two self sensing techniques namely Synchronous demodulation and resonance techniques have been developed and compared The response of the Resonance technique is slower compared to that of synchronous demodulation technique, but it requires less components and the circuit is simple and hence more reliable. Synchronous demodulation technique responds faster but its circuit is complicated. Hence depending on the application any one of the sensing circuits developed can be used. **Conclusion:** Two new position sensors are proposed. One is based on synchronous demodulation technique where the change in displacement is measured by measuring the phase angle between the coil voltage and current. Simple circuits are developed to achieve the same. Near linear relation between displacement of the levitated object and voltage output of the sensor has been realized. The results are verified by MATLAB and PSPICE simulation and also by experimentation. An alternative circuit based on resonance technique is developed. A capacitor is connected across the winding and is so chosen that the circuit resonates at 37.5 Hz for Y = 0.01meters. With the exciting frequency 50 Hz, the coil voltage increases with $|\mathbf{Y}|$ due to decrease of inductance and the circuit approaches resonance. Near linear relationship between voltage V_1 and Y is observed for the chosen parameters. Effects of non linearity of sensors have been discussed.

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INTRODUCTION

In magnetic levitation system there is no contact between the levitated object and the electromagnet. This eliminates friction and increases the resolution and accuracy of the positioning device. Hence this technique is now being used for medical applications, transportation, development of bearing less motors and robotics etc as proposed by Wu *et al* (2012), Hijikata *et al* (2011) Behbahani *et al* (2012), Li *et al* (2013), Chiba *et al* (2005), Craig and Khamesee (2007) respectively. But it is an open loop unstable system. Hence appropriate close loop control is required for which exact position of the levitated object is a must. Sensors like optical and Hall Effect sensors require additional attachments and are undesirable as they make the system clumsy and prone to failures as proved early by Deshpande and Mathur (2011). Two self sensing techniques are introduced wherein the core of electromagnet is designed with novel placement of windings. With this arrangement two windings are made available, one being used for sensing the distance ‘Y’ of the moving object from the magnet and the other for lifting the object.

MATERIALS AND METHODS

The electromagnet (EM) and the levitated object (LO) are made of transformer laminations. The

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typical set up used in the laboratory is shown in Figure 1. The nut bolt arrangement is used to manually vary the distance of the object from the electromagnet and simultaneously for each small variation in distance the corresponding change in inductance of the coil is measured by using Maxwell's bridge.

The lifting winding (LC) is formed by two identical windings placed on the side limbs of the magnet and connected in series in such a way that the fluxes Φ_1 and Φ_2 produced by them cancel each other in the central limb as shown in Figure2. Therefore there is no mutual coupling between the coils on the side limbs (lifting winding) and that on the central limb (sensing winding SC). The novel arrangement of the windings also does not induce voltage in the SC winding due to current flow in the LC windings and problem due to cross talk hence is not prominent.

Fig. 1: Set up of Magnetic Levitation system.

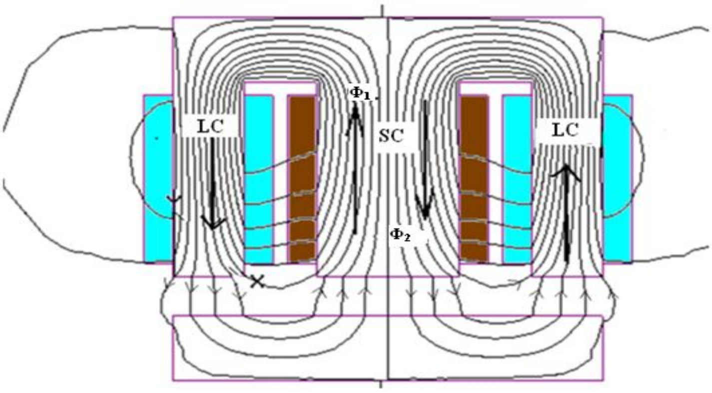

Fig. 2: Flux pattern due to current in the lifting coils.

The set up in Fig 1 developed is for levitating the object over a very small distance, the maximum being 1.5cm. Hence the magnitude of the current is small and saturation of the core is hence neglected. The sensing coil (SC) is used for measuring the gap 'Y' and is placed on the central limb. It is used to obtain a voltage which is a function of variation in inductance of the coil with 'Y' and hence is a function of 'Y'. The inductance of the coils varies inversely with Y. The position of the object is obtained in terms of variation of inductance hence these sensors can be called as transducers. Generally transducers are implemented in communication applications as suggested by Kongu *et al* (2012). A number of other researchers like Bandal and Vernekar (2010), Lim and Cheng (2011) and Yang *et al* (2010) have used a single coil for the measurement of Y as well as for lifting the object. Self sensing techniques are also discussed by Hanson and Levesley (2004), Vischer (1993). Due to magnetic decoupling, the proposed method is less susceptible to errors as compared to the case when the same coil is used for measurement as well as lifting.

For the considered parameters, exponential fit was found more appropriate than the normally used power series [5] to represent the relation between inductance of the coil and Y as it gave less RMS error. The relation is represented by equation (1) and (2) for LC and SC winding respectively.

$$\mathbf{L_1(y) = a * exp(-b * y) + c * exp(-d * y) + L_m} \quad (1)$$

$$\boldsymbol{L_2(y) = a_1 * \exp(-b_1 * y) + c_1 * \exp(-d_1 * y)} \quad (2)$$

Where L_1(y) and L_2(y) are inductance of the LC and SC coils respectively with respect to Y and L_m the inductance of the coil without object in vicinity.

Values of various constants for Equation (1) are: a = 0.09085, b = 10.5, c = 2.369, d = 227.2 and a_1 = 0.2971, b_1 = 147.3, c_1 = 0.2294, d_1 = 404.3 for equation (2). For Equations (1 and 2) exponential fit tool available in the MATLAB was used to obtain a range of values of a, b, c and d. Values of a, b, c and d giving minimum R.M.S. error were identified by trial and error. The values of inductance obtained by curve fit and by actual measurement for LC and SC windings are plotted in Figure 3 and 4 respectively.

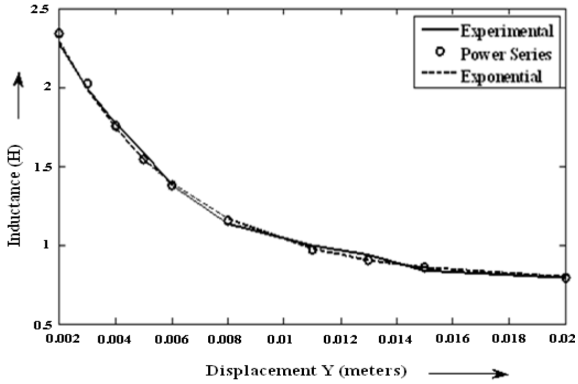

Fig. 3: Inductance versus Displacement for LC winding.

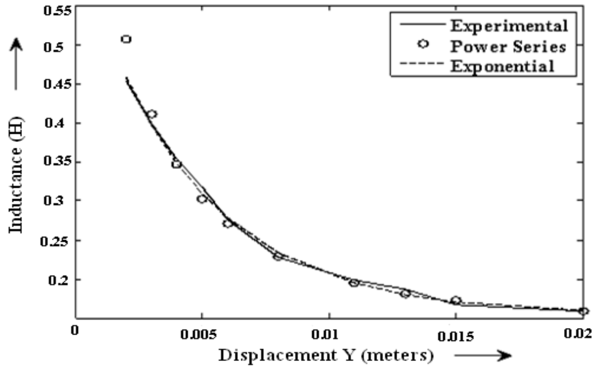

Fig. 4: Inductance versus Displacement for SC winding.

Self Sensing Techniques:

Based on the observations made in the previous section, self sensing techniques based upon measuring the change in inductance of the coil placed on the lifting magnet due to change in position of the levitated object was implemented. Two novel techniques viz; resonant method and synchronous demodulation method have been developed. Both these techniques measure the inductance of the sensing coil placed on the lifting magnet but decoupled from the lifting coil. The position sensing coil is excited by a 50 Hz source and in the resonance method the change in impedance of the measuring coil which is in parallel with a capacitor is measured to measure the displacement Y, whereas in the synchronous demodulation method, phase difference between the coil voltage and current is measured to measure the displacement.

Resonance Technique (Amplitude Sensing Technique):

This technique to measure the distance Y has been schematically shown in Figure 5. The sensing coil SC is excited by a 10V, 50 Hz source E in series with a resistor R_1 of 100 ohms. A capacitor C_3, 88 µF is connected across SC. The capacitor connected across the winding is so chosen that the circuit resonates at 37.5 Hz for Y = 0.01meters. As the exciting frequency is 50 Hz, the coil voltage increases with $|Y|$ due to decrease of inductance and the circuit coming closer to resonance. This voltage is passed through a precision rectifier and a low pass filter to obtain voltage V_1. Near linear relationship between voltage V_1 and Y was observed for the chosen parameters.

Mathematical Analysis:

Inductance of the coil is as given by Equation (2). The coil impedance (Z) is

$$\mathbf{Z = R_c + j * w * L_2} \tag{3}$$

Where R_c is coil resistance
Let

$$\mathbf{Z_2 = (Z*Xc)/Z+Xc}$$

Xc = capacitive reactance of c_3
Therefore

$$\mathbf{Z_3 = Z_2 + R_1} \tag{4}$$

The voltage across the coil is

$$\mathbf{V_{coil} = (E/Z_3)Z_2} \tag{5}$$

Therefore

$$\mathbf{V1 = (2\sqrt{2}/\pi)*|Vcoil|} \tag{6}$$

Therefore from equations (2 to 6) it is observed that as Y varies, L_2 varies and coil impedance and hence voltage across the coil and voltage V_1 varies. Hence V_1 is a function of Y. Variation of voltage V_1 with distance Y is shown in Figure 6. For the set up of Figure 4, the nut bolt arrangement was used to vary the distance and corresponding change in output voltage was noted. A near linear fit is obtained for variation of 'Y' between 0.002 and 0.01 meters.

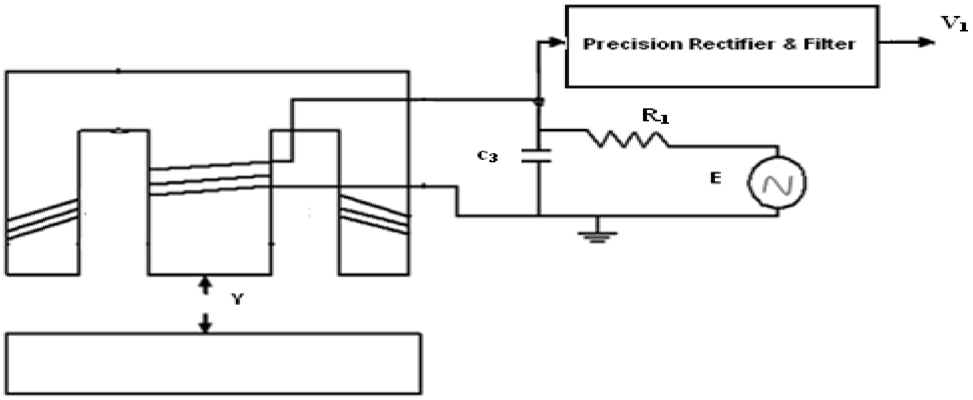

Fig. 5: Resonance Technique.

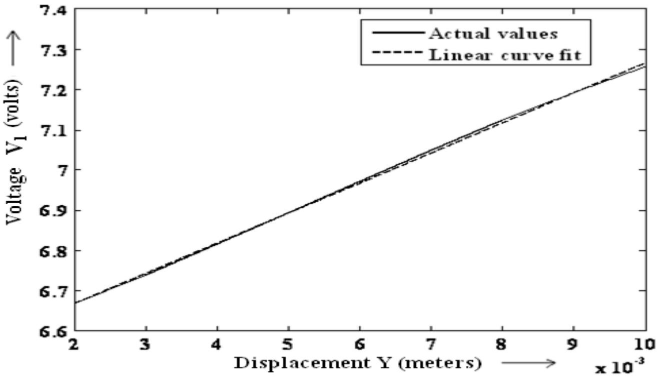

Fig. 6: Variation of V_1 with displacement Y (from 0.002 to 0.01 meters).

Transient response of the resonant transducer:

The transient response for the resonant type of displacement sensor obtained with PSPICE simulation is shown in Figure 7. When the object moves from one position to the other at 0.5 sec, its impedance changes and the output voltage changes from 6.4 V to 4 V in 0.3 sec.

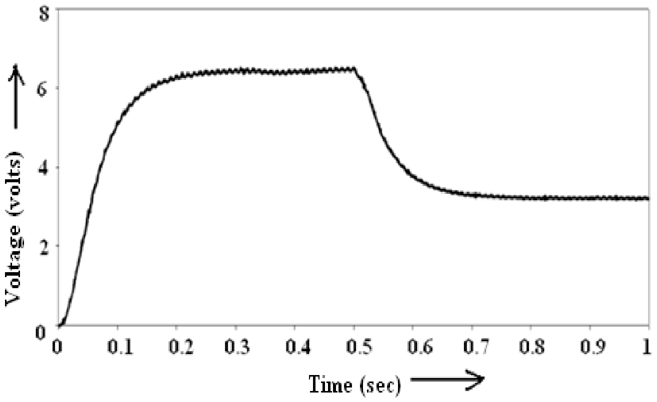

Fig. 7: Transient response of the resonant transducer.

Synchronous Demodulation Technique:

In this technique a signal proportional to voltage across the coil and another signal proportional to current in the coil are obtained. Phase difference between the voltage and current is determined by converting the current signal into a square wave and multiplying it with the voltage wave. Due to conversion of current into square wave, its magnitude information is lost but its phase information is retained. Multiplication of square wave with a sinusoidal voltage signal is accomplished by optocoupler switches. Average value of the resultant wave is a near linear function of displacement.

In the developed circuit, the sensing coil of the transducer is excited by a 10V 50Hz voltage and variation in phase angle of its current is measured with respect to voltage by synchronous demodulation method. Transient response of this system is also obtained for change in the position of the levitated object. By simulation as well as through experimental set up it is observed that a minimum delay equal to one and a half times the cycle time of the exciting frequency is always present. The delay further increases with increase in the order of the filter. This was observed while simulating the developed circuit in PSPICE with various filters. In magnetic levitation applications, mechanical frequency of the levitated object is generally below 10 Hz and therefore a delay of around 30 milliseconds with an exciting frequency of 50 Hz is always present. Simulation and experimentation has shown that the system can be stabilized even with this time delay. This is because the cycle time of the natural frequency of oscillations is very large as compared to this delay. Simplicity of the circuit and its immunity to high frequency changes in current in LC are its attractive features.

Circuit Description:

The overall diagram for the developed system is shown in Figure 8. In Figure 7 the SC is excited by a 10V 50Hz source. Impedance angle (Φ+ α) of the sensing winding is a function of the distance Y. Φ is the impedance angle when displacement Y is equal to Y_{ref}. α varies with Y. Opamp1 forms a current sensor which converts the coil current into a proportional voltage without introducing any impedance in the measuring circuit. Opamp2 converts this voltage into a square wave at point A. A signal proportional to the voltage across the coil is appropriately phase shifted by Opamp3. This phase is so shifted that at Y_{ref}, phase difference between voltage at terminal A and C is 90 degrees. The method chooses from two signals, one in-phase, the other in quadrature. Voltages at points A, B and C are multiplied by an opto-coupler multiplier.

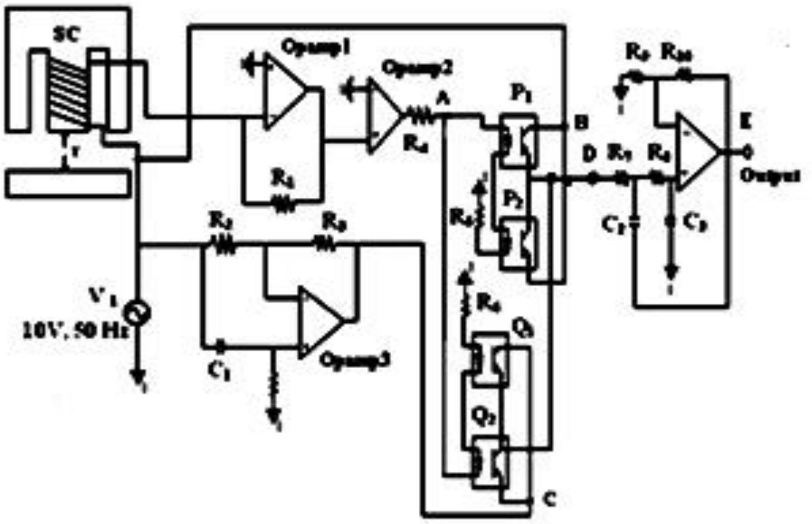

Fig. 8: Synchronous demodulation circuit.

LEDs of opto-couplers P_1 and P_2 are connected in series. These LEDs are ON when the voltage at point A is positive. Similarly LEDs of optocouplers Q_1 and Q_2 are ON when A is negative. Collectors and emitters of BJTs of P_1 and P_2 are connected in anti parallel and similarly, collectors and emitters of BJTs of Q_1 and Q_2 are also connected in anti parallel. A conducting path is established between B and D when A is positive and between C and D when A is negative. Wave shape of the voltage at terminal D is shown in Figure 9 for Y=0.002 meters. Proportions of the positive and negative areas depend on the phase difference between sinusoidal voltage at points B and C and square wave voltage at point A and hence on ‘Y’. The circuit is simulated using PSPICE software.

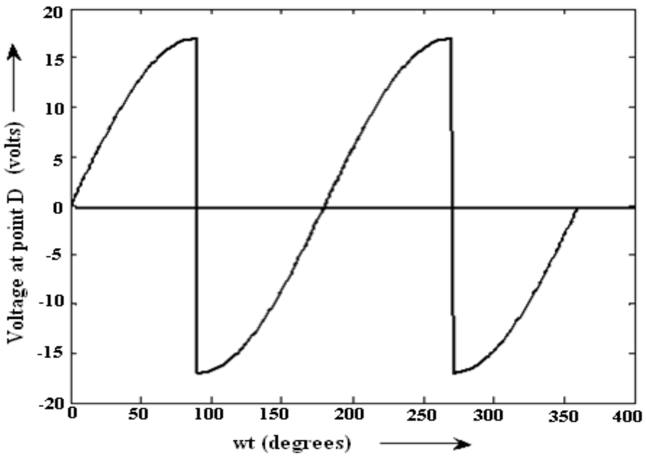

Fig. 9: Waveform of voltage at terminal D versus ωt.

Mathematical Analysis:

Consequent to a 50 Hz, 1p.u. (peak) voltage V is applied to the coil SC and its current I is given by

$$I = \frac{V}{Z} = \frac{VR_c}{Z^2} - j\frac{VX_L}{Z^2} \tag{6.1}$$

Where Rc is the SC coil resistance, X_L the SC coil inductive reactance and Z the SC coil impedance all in ohms.

$$V = \sin\theta \tag{6.2a}$$

$$jV = \cos\theta \tag{6.2b}$$

Where

$$\theta = 2\pi * 50 * t,$$

$$I(t) = \frac{(R_c \sin\theta - X_L \cos\theta)}{Z^2} \tag{6.3}$$

since I is a square wave it is expressed as:

$$I = 1 \text{ for } -\frac{\pi}{2} \le \theta \le \frac{\pi}{2} \tag{6.4a}$$

$$I = -1 \text{ for } \frac{\pi}{2} \le \theta \le \frac{3\pi}{2} \tag{6.4b}$$

Average value of voltage at point E can be expressed as:

$$V_E = \frac{1}{2*\pi*Z^2}\left[\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} (R_c \sin\theta - X_L \cos\theta)d\theta + \int_{\frac{\pi}{2}}^{\frac{3\pi}{2}} \begin{pmatrix} -R_c \sin\theta + \\ X_L \cos\theta \end{pmatrix} d\theta \right] \tag{6.5}$$

$$\text{Average } (V_E) = \frac{1}{\pi * Z^2} X_L \tag{6.6}$$

Therefore from Equation (6.6) it may be noted that the average value of V_E is a function of the inductive reactance and hence of the position of the levitated object.

Voltage output of the low pass filter at point E (Figure 8) is shown for various values of Y in Figure 10. The nut bolt arrangement was used to vary the distance and corresponding change in output voltage was noted.

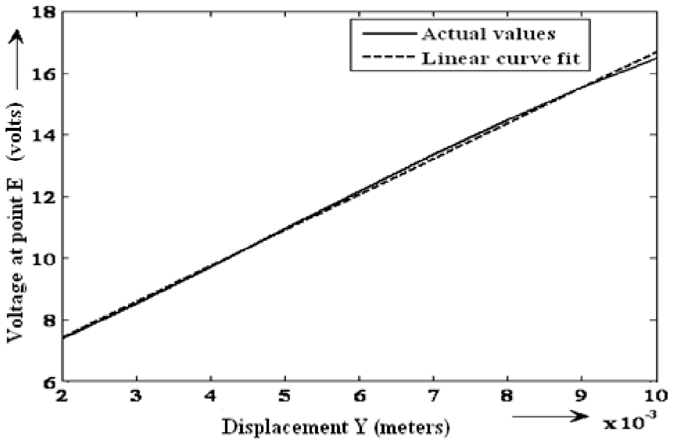

Fig. 10: Voltage at point E versus Y (from 0.002 to 0.01 meters).

Results:

Experimental set up and Transient Response of the proposed system:

The experimental set up for sensing technique implementing synchronous demodulation is shown in Figure 11. The simulation and experimental output of the filter circuit, for ‘Y’ = 0.01meters is shown in Figure 12 and 13 respectively.

The switch in the set up is used to obtain the transient response. A change was made in the displacement ‘Y’ from 0.01 meters to 0.02 meters after 500 microseconds and corresponding change in V_E was recorded as in Figure 14 using digital storage oscilloscope.The voltage V_E took a time of about 30 milliseconds to change from one steady state value to the other. This time delay is one and half times the cycle time of the exciting frequency of 50 Hz for the coil SC. The experimental result obtained for transient response is as shown in Figure 14.

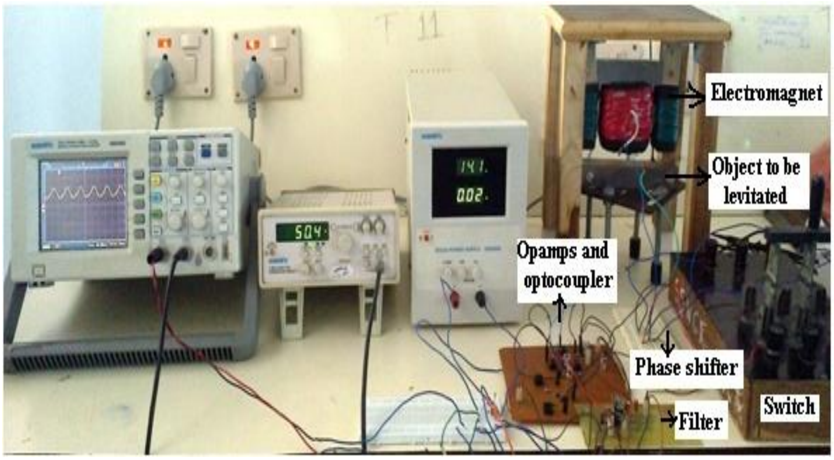

Fig. 11: Experimental set up for synchronous demodulation.

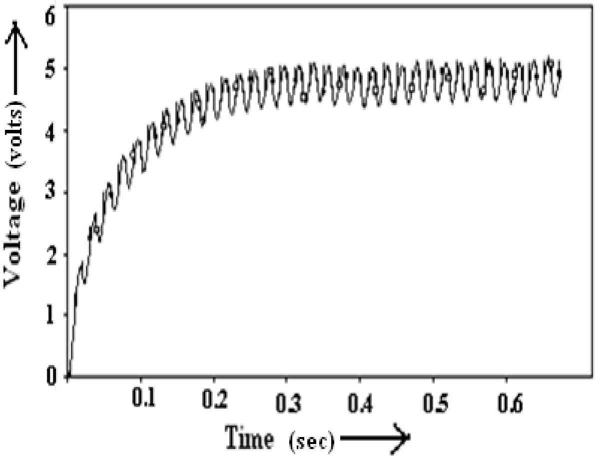

Fig. 12: Filter output at point E by simulation.

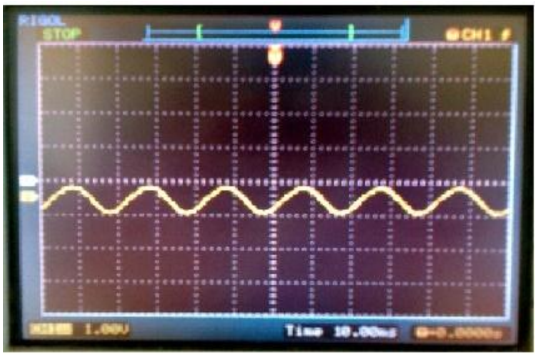

Fig. 13: Experimental Filter output at point E.

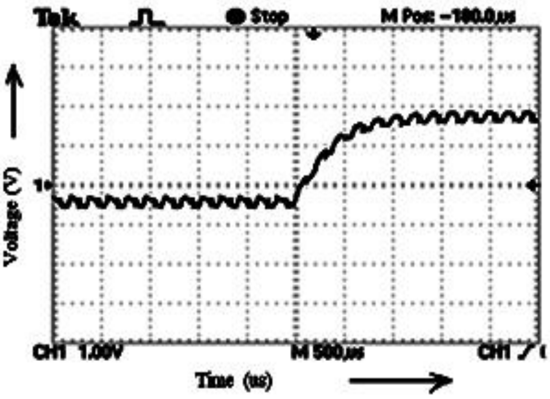

Fig. 14: Transient response of the proposed transducer obtained experimentally.

Discussion:

Comparison of both the sensing techniques developed:

The response of the Resonance technique is slower compared to that of synchronous demodulation technique, but it requires less components and the circuit is simple and hence more reliable.

Synchronous demodulation technique responds faster but its circuit is complicated. Hence depending on the application any one of the sensing circuits developed can be used.

Methods to Enhance the Linear Range of the Sensors:

Linear range of both the sensors is limited due to nonlinear relation between Y and L_2. The linear range can be further extended by cascading a nonlinear amplifier at the output stage or a digital processor. To improve the linear range of the sensor, a DSP processor TMS320C5416 is used. The analog signal proportional to distance is converted to digital by the help of an A/D converter available in the same processor. This signal is linearized using a look-up table. This linearized digital signal is processed by a digital IIR filter algorithm present in the same processor. Finally the digital signal is converted into analog by using a D/A converter present in the same processor. The output of the digital filter and the overall experimental set up is as shown in Figure 15.

Fig. 15: Experimental set up for Synchronous demodulation method (digital).

Conclusion:

Two new position sensors are proposed. One is based on synchronous demodulation technique where the change in displacement is measured by measuring the phase angle between the coil voltage and current. Simple circuit is developed to achieve the same. Near linear relation between displacement of the levitated object and voltage output of the sensor has been realized. The results are verified by MATLAB and PSPICE simulation and also by experimentation.

An alternative circuit based on resonance technique is developed. A capacitor is connected across the winding and is so chosen that the circuit resonates at 37.5 Hz for Y = 0.01meters. With the exciting frequency 50 Hz, the coil voltage increases with $|Y|$ due to decrease of inductance and the circuit approaches resonance. Near linear relationship between voltage V_1 and Y is observed for the chosen parameters. Effects of non linearity of sensors have been discussed.

REFERENCES

Bandal, V.S. and P.N. Vernekar, 2010. “Design of discrete time sliding mode controller for magnetic levitation system using multi-rate output feedback”, American Control Conf. USA, 12(4): 4289-4294.

Behbahani, H., H. Yaghoubi and M.A. Rezvani, 2012. “Development of technical and economical models for widespread application of magnetic levitation system in public transport,” International Journal of Civil Engineering, 10(1): 13-24.

Chen Li, Han Bei, Wang Yanhong, Yu Hongxia 2013, "Active Disturbance Rejection Control for Suspension System of Bearingless Motor with Rectifier Circuit," ICMTMA, Fifth International Conference on Measuring Technology and Mechatronics Automation, 143-146.

Chiba, A., T. Fukao, O. Ichikawa, M. Oshima, M. Takemoto and D. Dorrell, 2005. “Magnetic Bearings and Bearingless Drives”, Elsevier Publications.

Craig, D.G. and M.B. Khamesee, 2007. “Motion control of a large gap magnetic suspension system for microrobotic manipulation”, Journal of Physics D: Applied. Physics, 40: 3277-3285.

Deshpande, M. and D.B. Mathur, 2011. Transient response of a novel displacement transducer for magnetic levitation system. Am. J. Applied Sci., 8: 1131-1134.

Hanson, B. and M. Levesley, 2004. “Self-sensing applications for electromagnetic actuators”, Sensors and Actuators, 116(2): 345-351.

Hijikata, W., T. Mamiya, S. Shinshi and Takatani, “A cost-effective extracorporeal magnetically-levitated centrifugal blood pump employing a disposable magnet-free impeller, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 8.

Kongu, T.A., P. Thangaraj and P.P. Kongu, 2012. Wireless sensor networks fault identification using data association. J. Comput. Sci., 8: 1501-1505.

Lim, T.M. and S. Cheng, 2011. “Magnetic levitation of one DOF system using simultaneous actuation and displacement sensing technique”, Mechatronics, Elsevier, 21(3): 548-559.

Vischer, D., 1993. “Self-sensing active magnetic levitation”, IEEE Transactions on Magnetics, 29(2).

Wu, H., Z. Wang and Y. Hu, 2012. “Study on support properties of axial maglev blood pump,” Applied Mechanics and Materials, 150: 187-193.

Yang, H.J., Y.S. Lee and O.K. Kwon, 2010. “Development of force modeling equipment for magnetic levitation system”, International Conference on Control and Automation and Systems, Korea, 29-33.