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Design and Fabrication of Low Cost Eddy Current Sensor for Position Control Applications

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Abstract

Background/Objectives: Eddy current sensors are noncontact displacement sensors of high resolution providing measurement of the absolute position or change in position of any electrically conductive target. They are most suitable in dusty, smoky, dirty industrial environments where most other sensors would fail. This paper presents a design method and fabrication of a low cost eddy current sensor used in real time servo-control feed-back in Active magnetic Bearing. **Method/Statistical Analysis:** The primary functional piece of the eddy-current sensor is the sensing coil. This is a coil of wire near the end of the sensor probe. This piece of coil forms a part of an oscillator circuit there by carrying an alternating current through it which creates an alternating magnetic field. This field creates an eddy-current to flow on the target material whose distance is to be measured. This variation in field is used to sense the distance to the target. The coil is encapsulated in plastic and epoxy and housed in threaded stainless steel housing. **Findings:** The designed sensor has a measuring range of 0-3 mm and displacement resolution of 7 microns at a speed of 20 kHz sampling rate. This sensor was designed for the purpose of servo control feed-back in Active Magnetic Bearing System for position control. In this feedback control system we have employed a novel method of using time to digital conversion which converts the time period of the eddy current sensor's square wave signal into digital counts using the 32bit timer counter of the enhanced capture module available in Texas Instruments C2000 controller. The digital counts give us the direct displacement value that can be used as feedback to generate the required error signal in the PID control loop. **Application:** The output frequency of the sensor is in the range of 700 kHz. We scale down this signal to 20 KHz by using the built-in divide by counter in the C2000 controller before feeding it to the capture module to capture the time period in a 32bit timer counter. This method of time period to digital count converter or displacement measurement helps reduce noise and errors in signal processing usually associated with ADC chips which converts analog voltage signal to digital counts.

Keywords: Active Magnetic Bearings, Eddy Current, Position Control, Servo Control

1. Introduction

Eddy current sensors are widely used for noncontact position and displacement measurement. A low cost eddy current sensor used for position sensing in active magnetic bearing application is shown in Figure 1. It operates on the principle of electro-magnetic induction and they are used for accurate measurement of position of metallic targets even in the presence of non-metallic materials such as plastics, non-conducting fluids and dirt in the measuring region[1]. The sensors are highly rugged and can operate over wide temperature ranges in contaminated environments where other sensors like optical, acoustic, and capacitive devices fail. An interesting area of application where eddy current sensors are most suitable is in the position feedback control in magnetic bearings. A single axis active magnetic bearing system showing the magnetic actuator, levitated steel bolt and eddy current position sensor is shown in Figure 2.

In a magnetic bearing assembly, a rotating shaft is suspended in a magnetic field to achieve frictionless rotation. To stabilize the suspended rotor, eddy current sensors are frequently used to provide position feedback to the controller unit[2–4]. Eddy current sensors may vary

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Figure 1. Low cost eddy current sensor used for position control in active magnetic bearing design.

Figure 2. A single axis magnetic bearing system showing the magnetic coil, levitated steel bolt and eddy current position sensor.

in diameter from a few millimeters to a meter and have maximum sensing ranges roughly equal to the radius of the coil. Linearity is typically 1% of the sensing range and noise levels of 1 $ppm_{rms}/\sqrt{Hz}$ are common. A small sensor can sense nanometer-size displacements and measure a 1 mm span to around 5 microns total accuracy. Bandwidths of 50 kHz can easily be achieved.

2. Basic Principle of Eddy of Current Sensor

The eddy current position sensor is similar to the inductive position sensor. A coil of wire is used as the probe as shown in Figure 3. This coil may have a ferromagnetic core or an air core as the inductive sensor. The operating frequencies of eddy current sensor are much higher than for the inductive sensors and operate in the region of 150 kHz to a few MHz. At these frequencies the eddy current losses are large and proportional to the coil's position relative to the target. Targets used with inductive and eddy current sensor must be a conductive material. The resolution of the eddy current sensor depends on the conductivity of the target material. The higher the conductivity of the target material the better is its displacement resolution. The higher excitation frequency means eddy current sensors are less susceptible to noise caused by power amplifier switching[5–7].

An eddy current displacement sensor consists of two components as shown in Figure 4. The sensor coil and sensor drive electronics with signal processing block which can be a circuit or a microprocessor algorithm. An AC current in the sensor coil generates an oscillating magnetic field, which induces eddy currents in the surface of the target[8,9]. The coil impedance changes with distance from target and this variation is converted to a linear output by the sensor's signal processing electronics.

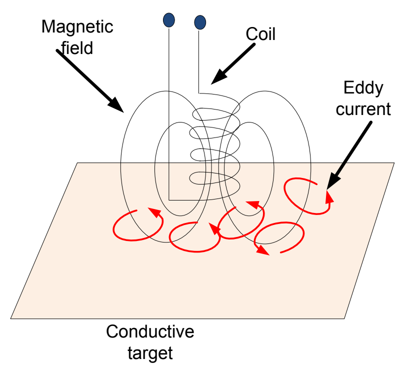


Figure 3. Eddy current displacement sensor working principle.

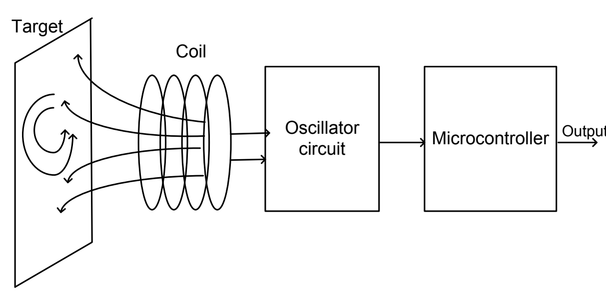


Figure 4. Components of eddy current displacement sensor.

When the sensor coil is driven by an AC current, it generates an oscillating magnetic field that induces eddy currents in any nearby metallic target. The eddy currents flows in a direction opposite to that of the coil, reducing the magnetic fluxes in the coil and so its inductance. The eddy currents also dissipate energy, increasing the coil's resistance. As shown in Figure 3, the coil and the target constitute the primary and (shorted) secondary of a weakly coupled air-core transformer. Movement of the target changes the coupling, and this movement is reflected as an impedance change at the terminals of the coil[10–12].

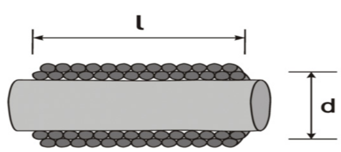
3. Design Steps for the Inductive Coil of the Sensor

The steps followed in the design of the coil are outlined below.

- A cylindrical bobbin made of plastic on which enameled copper wire can be wound.
- To have more focused beam of magnetic field generated by the wound coil, it is better to have the windings as close as possible to the target material.
- Choose minimum number of turns and have more layers instead of increasing the length of the coil for more focused beam.
- Calculate the required number of turns using the inductance equations given below.
- Keep value of $l<0.8$ R.
- For single layer coil

$$L = \mu_o N x^2 \frac{R^2}{l} K \tag{3.1}$$

- For multi-layer coil



$$L \approx N^2 \mu \frac{d^2}{4} \frac{\pi}{l} . \frac{1}{\left(1 + \frac{0.45d}{l}\right)} \tag{3.2}$$

Where L – Inductance, d - diameter of the core including coil thickness, l-length and n-number of turns of the coil.

- The cable capacitance, C_C is determined from the cable length and the manufacturer's specification of capacitance per unit length.
- For a two-layer coil the inter winding capacitance is given by

$$Crwc = \frac{1}{4} * \epsilon r * \epsilon o \frac{\pi(R)}{h} \tag{3.3}$$

where ϵr is relative dielectric constant (ε_r) and ε_o = permittivity of free space and h = thickness of coil in meters.

- The self-resonant frequency (fr) is calculated to be

$$fr = \frac{1}{2\pi\sqrt{L(Ccable + Crwc)}} \tag{3.4}$$

- The DC resistance of the two layer coil is calculated to be

$$R_{dc} = 2\pi N\rho\left(\frac{r1 + r2}{2}\right) \tag{3.5}$$

r1 = radius of inner coil winding.
r2 = radius of outer coil winding.ρ= resistivity of the wire.
N=number of turns of the coil.

- Estimate the AC resistance which is usually higher than the DC resistance because of the skin effect and proximity effect.

$$R_{ac}=2R_{dc} \tag{3.6}$$

- Calculate the unloaded Q. (The Q of the free coil with no target.)

$$Q = \frac{2\pi Fmin * L}{Rac} \tag{3.7}$$

- Consider having an Unloaded Q > 15 for a typical design. If Q is not high enough, increase the number coil turns or layers.

4. Sensor Electronics

The most common commercial eddy current sensors have analog voltage as their output signal. This analog voltage is proportional to the distance between sensor and target[13–15]. In this work the sensor electronics converts displacement directly into frequency variation of a square wave form. A simple way to convert the displacement to frequency is to drive the sensor coil as resonant circuit of an oscillator. The design of a simple self-oscillating circuit using TTL logic gates is presented in Figure 5. A Piccolo microcontroller is used to directly digitize the frequency of the output pulses by means of pulse capture counters. The purpose of designing this position sensor is to keep the cost low and affordable at the same time provide enough band width for servo control application in positioning systems.

In order to reduce size of the sensor module, signal conditioning circuitry of the sensors is fabricated using SMD devices. Figure 6 given shows the sensor's conditioning circuit and plastic encapsulation for the sensor coil. The output of the oscillator is a square wave whose frequency is a function of displacement.

The finished assembly produced a stable pulse wave form shown in Figure 7 with no targets at its vicinity. The

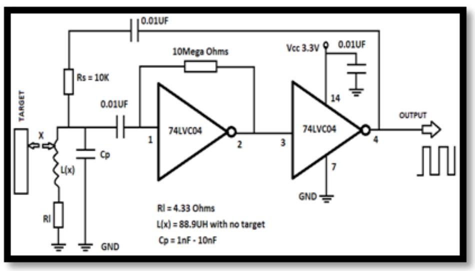


Figure 5. Oscillator circuit used for the Eddy current.

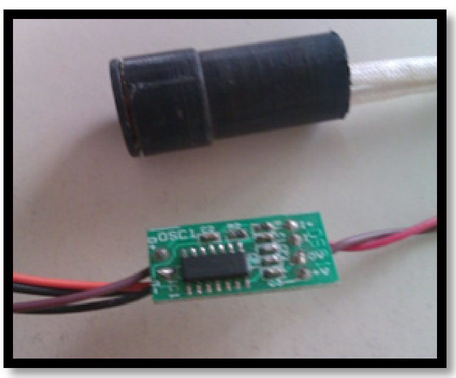


Figure 6. Plastic Encapsulated sensor and its conditioning circuit.

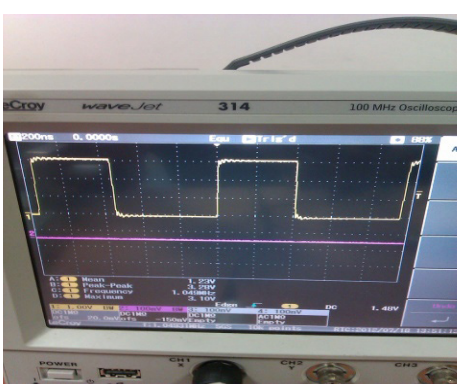


Figure 7. Encapsulated sensor oscillator output waveform.

sensor produced linear variation in frequency of the pulse wave form as it is brought nearer to the target material.

5. Die Tool Design and Fabrication

A plastic injection die tool has been developed for the fabrication of plastic bobbin part on which sensor coil is wound. Stainless steel housing with mm pitch thread was fabricated for housing the sensor circuit and sensor coil. Drawings of the plastic bobbin parts and samples manufactured using the Die is shown in Figure 8, 9 and 10 respectively.

6. Measured Results and Discussions

A Micrometer setup shown in Figure 11 is used to measure displacement characteristics of the fabricated eddy current sensor against an alloy steel target. The sensor was fixed to be stationary with an appropriate fixture and target material is kept movable with the help of the micrometer. The distance between the sensor and the alloy steel target is varied by adjusting the micrometer and corresponding output frequency of the eddy current sensor is recorded with help of an oscilloscope. The sensor's output frequency (measured using a digital

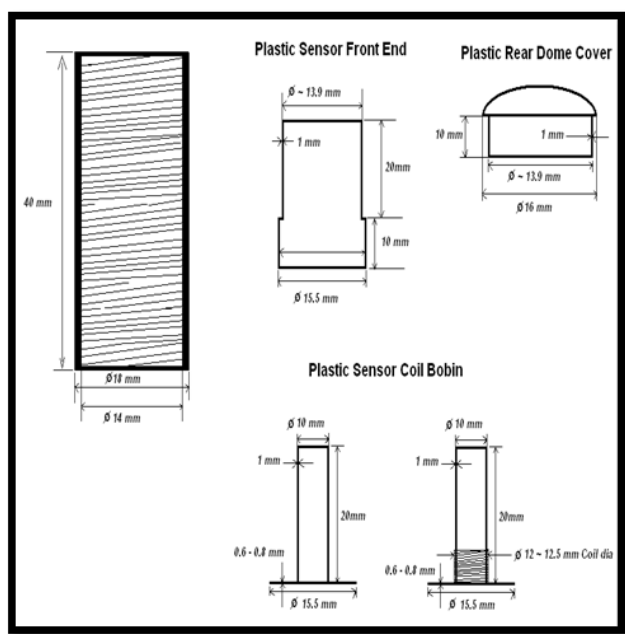


Figure 8. Sensor mechanical drawing.

Figure 9. Fabricated plastic bobbin samples and stainless steel metal housing for the sensor.

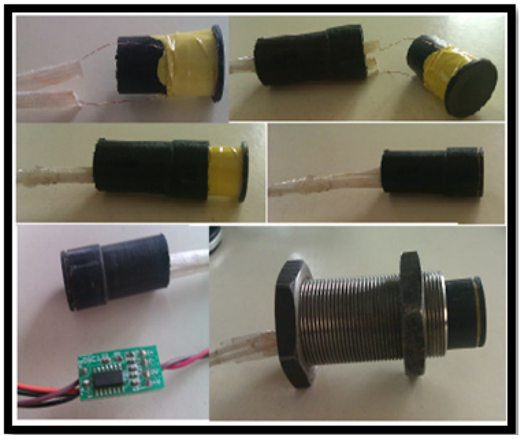


Figure 10. Various stages in assembling the sensor.

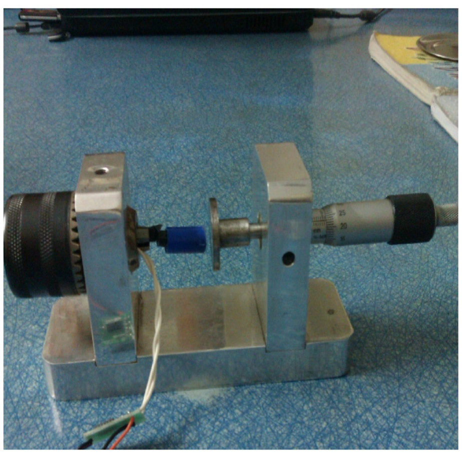


Figure 11. Micrometer setup for measurement of displacement from target (EN19 Alloy Steel).

oscilloscope) was plotted against displacement (measured using micrometer) and their results are shown in Table 1 and Table 2 for two different sensor coil specification and for two different target materials.

Figure 12, 13, 14 or the graphical plots of the variation in output frequency of the sensor versus the distance of the target form the sensor probe.

The designed prototype air core eddy current sensor with 80 turns of 39-SWG copper wire was tested against stainless steel and EN19 Alloy steel target material. Figure 12, 13 shows that the designed sensor exhibits a fair good linearity from 0 to 2.5 mm displacement for both EN19 alloy steel and Stainless steel target.

Table 1. Displacement vs sensor output frequency for two different target materials (Coil specification: 80 turns (40 turns x 2 layers) of 39 SWG copper wire; Inductance = 70.7uH; Resistance = 3.72 Ohms (Measured using HTC LCR – 4070 meter)

Gap (mm)	Oscillator Output frequency in KHz for Stainless steel target	Oscillator Output frequency(KHz) for EN19 Alloy steel
0	703.397	677.423
0.1	700.448	676.595
0.2	698.283	675.766
0.3	696.549	674.975
0.4	694.847	674.304
0.5	692.685	673.682
0.6	690.498	673.041
0.7	688.923	672.374
0.8	687.705	671.739
0.9	686.483	671.189
1	684.825	670.682
1.1	683.168	670.162
1.2	681.985	669.62
1.3	681.125	669.098
1.4	680.177	668.644
1.5	678.907	668.23
1.6	677.631	667.817
1.7	676.732	667.376
1.8	676.083	666.946
1.9	675.369	666.57
2	674.38	666.244
2.1	673.379	665.896
2.2	672.691	665.53
2.3	672.207	665.172
2.4	671.657	664.869
2.5	670.857	664.595

Table 2. Displacement vs sensor output frequency for 70 turns of coil wire (Coil specification: 70 turns (35turns x 2 layers) of 39 SWG copper wire)

Gap(Mils)	Gap(mm)	Oscillator Output For EN19 Alloy Steel(MHz)
0	0.00	1.4006
10	0.25	1.3996
20	0.50	1.3989
30	0.75	1.3983
40	1.00	1.3976
50	1.25	1.3971
60	1.50	1.3965
70	1.75	1.3961
80	2.00	1.3957
90	2.25	1.3954
100	2.50	1.3951
110	2.75	1.3948
120	3.00	1.3945
130	3.25	1.3943
140	3.50	1.3941
150	3.75	1.3939
160	4.00	1.3937

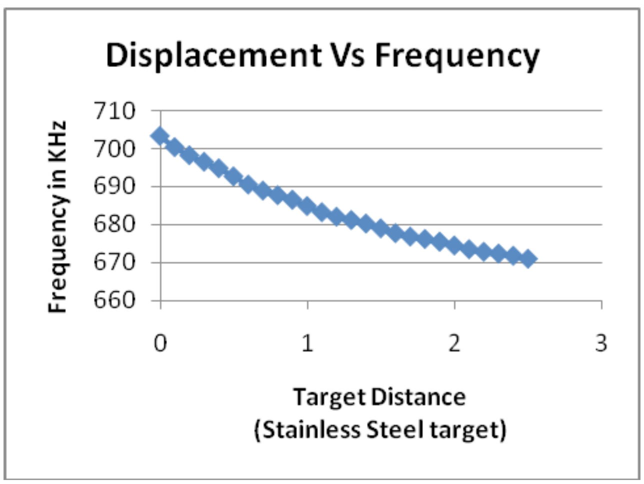


Figure 12. Plot of target distance vs sensor output frequency for stainless steel target.

When the sensor coil turns were reduced from 80 turns to 70 turns in our sensor design the output frequency increased as shown in Table 2 and Figure 14. At such high output frequency the digital counts obtained by the capture module of the C2000 microcontroller got reduced and hence resulting in decreased resolution of displacement measurement.

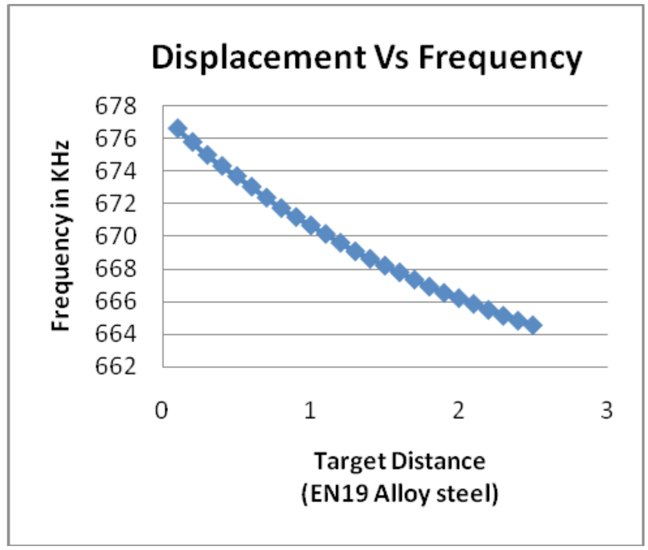


Figure 13. Plot of target distance vs sensor output frequency of the designed air core eddy current sensor with 80 turns of 39-SWG copper wire (for EN19 Alloy steel).

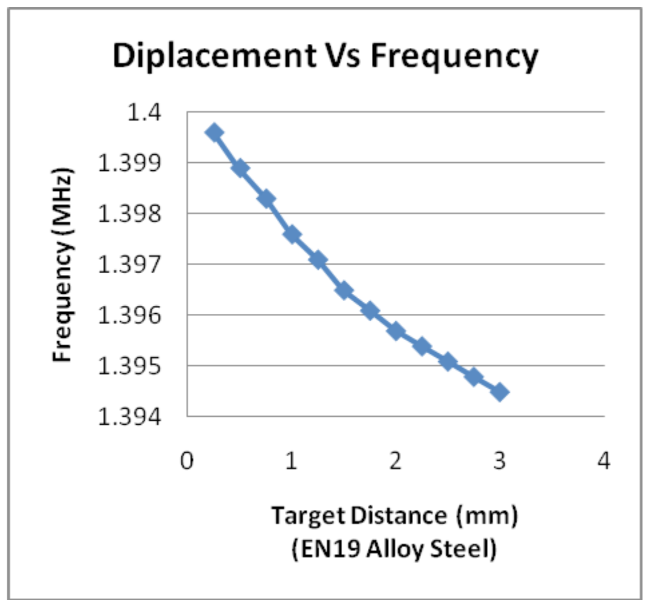


Figure 14. Plot of target distance vs sensor output frequency of the designed air core eddy current sensor with 70 turns of 39-SWG copper wire with EN19 Alloy steel target.

7. Conclusion

In this paper, design and fabrication of air core eddy current sensor has been presented. The designed eddy current sensor has an outer diameter of 18 mm and millimeter pitch thread made of stainless steel housing. The sensor head part has a diameter of 10 mm plastic bobbin on which copper wire of 39 SWG was wound.

The sensor has a measuring range of 0-3 mm and displacement resolution of 7 microns at a speed of 20 KHz sampling rate. This was achieved using Texas Instruments C2000 DSP controller. The Enhanced Capture module (System on Chip) was used to get accurate time stamp and time period of the square signal. This time period translates to direct digital counts after applying offset error calculations. The resolution greatly improves with reduction in the sampling frequency. Since the requirement is for digital control of active magnetic bearing the preferred sampling rate would be 20 KHz.

The target material greatly influences the digital counts obtained from the sensor and hence its resolution. Better the electrical conductivity of the material the better was the total amount of digital counts obtained and hence its resolution. Some good targets which resulted in higher counts accuracy are stainless steel, aluminum and brass.

8. References

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