CHAPTER 1 : INTRODUCTION

A sensor is a device that detects or measures a physical quantity. A transducer is that part of a sensor which converts the energy to be measured into another measurable form such as electrical energy. With the increase in automation of different processes, the need for sensors has increased dramatically. This is due to the need to measure different parameters of the process and then control the process automatically depending upon the values of these parameters. This need has also driven sensors to be located in-situ to the actual process enabling a real-time observation of the process parameters. In recent years, the miniaturization of sensors also has been stressed in order to make the sensors more efficient, faster, robust, and to be able to study local phenomena without affecting the actual process itself.

1.1.0 Proximity Sensors

A proximity sensor is a sensor that measures the distance between the transducer and a target. In this document, an eddy-current proximity sensor, using inductors as the transducer, will be studied. The design and fabrication aspects of the eddy-current proximity sensor to be studied are the transducer design and the design and fabrication requirements for miniaturization and compatibility to conventional integrated circuit processes and applications. The motivation behind the study of this type of eddy-current proximity sensor was the ARPA Project entitled, “Journal Bearings with Actively Deformable Surfaces” [4].

A survey of proximity sensor types was performed. A summary of the proximity sensors investigated is given below (the list is not all inclusive).

1.1.1 Mechanical Proximity Sensors

Perhaps the simplest proximity sensor is a mechanical sensor [5] or a probe, which makes physical contact with the object or target whose position is to be determined. As the object moves, the probe in contact with it moves too and by measuring the amount of movement relative to the original position, we can calculate the final position. This method has the advantage of having a simple operating principle and of being independent of the material of the object.

The main drawback of this method is that we need to make contact with the surface of the target. Also since the sensor is a mechanical device, the response would be comparatively slower than electronic and electrical sensors.

1.1.2 Laser Interferometry

When two waves of the same phase meet, the resultant wave is one of greater amplitude due to constructive interference. This means that the two waves result in a reinforced wave. If the two waves are 180° out of phase with each other and of equal amplitude, the resultant wave has an amplitude of zero due to destructive interference. The degree of interference thus depends upon the phase difference between the two waves. Now for two coherent sources whose waves are in phase with each other, the movement of one by a distance of half a wavelength would change the interference from constructive to destructive or visa-versa. By using a wave of shorter wavelength the change in distance needed for a transition from constructive to destructive interference could be made very small making the laser interferometer a very sensitive proximity sensor.

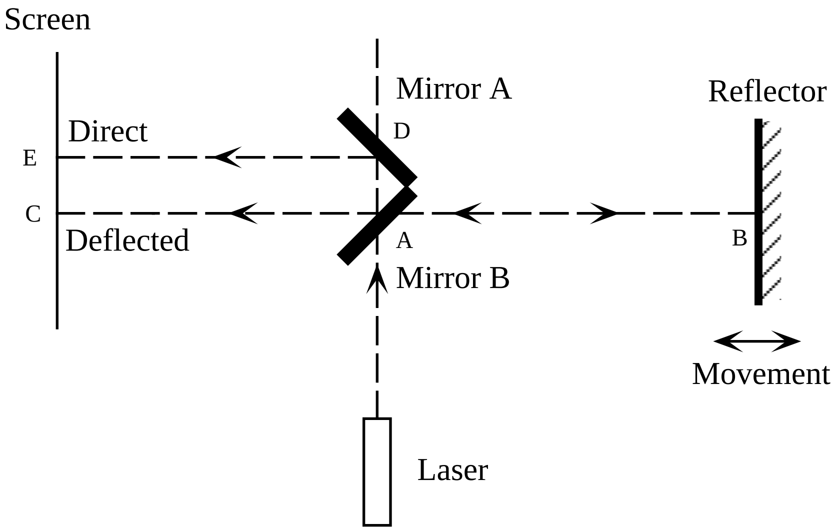

Fig. (1-1): A schematic diagram of a laser interferometer.

Shown in Fig. (1-1) is a schematic of a laser interferometer used to measure distances. Instead of using two coherent sources whose waves are in phase with each other, a single coherent light source is used to generate two light paths. A laser is used as the coherent light source. The light from a laser is directed on the two glass mirrors A & B. Mirror A causes the laser beam to be reflected from point D directly onto the screen. Mirror B causes the laser beam to be reflected from point A onto the Reflector at point B. The reflector then reflects the beam to point C on the screen. The two beams (direct and indirect) interfere with each other depending upon their phases (and since they are from the same coherent source, the phase difference depends only upon the path length difference of the rays). Thus by counting the number of times constructive or destructive interference occurs, the relative position of the reflector can be determined. The constraint on using laser interferometry is that the distance to be measured should not be greater than the coherence length of the laser.

1.1.3 Ultrasonic Proximity Sensors

Ultrasonic proximity sensors [5] measure distance by reflecting a beam of ultrasonic waves, emitted by a transmitter, off the target and receiving the reflected beam at a detector. Ultrasonic sensors use ultrasound frequencies, i.e. frequencies greater than the audible range (> 20 kHz). If the velocity of the wave and the time of flight for the transmitted and reflected beam are known, the distance can be calculated. For air (speed of sound is 331.3 m/sec), this means that we should be able to measure time intervals in the order of nanoseconds to measure changes of 1 μm in distance. This time interval decreases in liquids and solids since sound travels faster in these materials. For a good resolution we also need a very high frequency. The absorption of sound by air increases as the frequency increases. Thus with increase in resolution we get a decrease in the range of the sensor.

Ultrasonic sensors are particularly useful in applications which are not well suited for capacitive and magnetic types.

1.1.4 Capacitive Proximity Sensors

Capacitive proximity sensors [2] use the capacitance that exists between two metal plates. As the distance between the plates increases, the capacitance decreases.

For a parallel plate capacitor:

$$C = \frac{\varepsilon A}{d}, \qquad \text{Eq. (1-1)}$$

where A is the area of the plate, d is the distance between the plates, and ε is the permittivity of dielectric between the plates.

For capacitive sensors the electric field is affected by metallic and dielectric objects. This makes the capacitive sensor very susceptible to external noise sources. For large distance measurements, the area of the capacitor has to be increased in order to increase the capacitance to be measured.

1.1.5 Magnetic Proximity Sensors

In magnetic proximity sensors, the transducer produces a magnetic field which penetrates the target material. If the target material has a high permeability, the reluctance of the magnetic path is decreased due to the presence of the target. As the target is brought closer, the reluctance continues to decrease. By measuring the change in reluctance, the distance between the sensor and the target can be gauged.

The reluctance of an air gap in a magnetic circuit is given by:

$$R = \frac{d}{\mu A}, \qquad \text{Eq. (1-2)}$$

where d is the distance between the magnetic pole and target, A is the area of the magnetic pole, and μ is the permeability of air.

Thus magnetic proximity sensors [1][2][3] use the high permeability and low conductivity of the target material. The low conductivity decreases the eddy currents produced in the target. Eddy currents are also decreased by operating at low frequencies (< 500 Hz). Low frequencies also result in a greater penetration of the field into the target material.

1.1.6 Eddy-current Proximity Sensors

Eddy-current sensors [1][2][3], like the magnetic sensors, use a magnetic field to sense objects. However, unlike the magnetic sensors, the eddy-current sensors use the conductive properties of the target material. The transducer produces a magnetic field which penetrates the target. This magnetic field produces eddy-currents which in turn produce an opposing magnetic field. Thus there is an increase in reluctance of the magnetic path due to the presence of the target. This reluctance increases as the target is brought closer. High frequencies (> 100kHz) are used so that the penetration of the magnetic field in the target is on the order of a skin depth. Any current density established at the surface of a good conductor decays rapidly as we progress into the conductor. The skin depth, δ, is defined as the depth into the conductor at which the current density drops to e^{-1} of its value at the surface (where e is the base of the natural logarithm). The skin depth, δ, is given by,

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}, \qquad \text{Eq. (1-3)}$$

where ω is the angular frequency, μ is the permeability of the target, σ is the conductivity of the target.

The magnetic field patterns for eddy-current sensors and magnetic sensors is shown in Fig. (1-2).

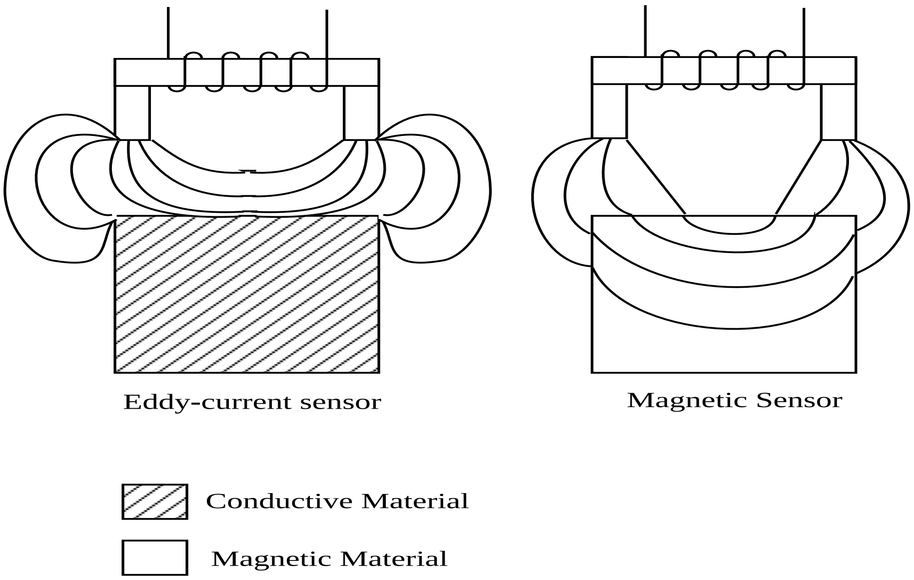

Fig. (1-2): Pattern of magnetic field in eddy-current and magnetic sensors

1.2.0 Motivation

The ultimate goal of the ARPA Project entitled, “Journal Bearings with Actively Deformable Surfaces” [4] is the design and demonstration of a smart bearing capable of using embedded sensors and actuators to dynamically change the surface geometry of the bearing. The ability to actively deform bearing surfaces would allow for the design of bearings which are less prone to failure, the design of bearings with better load carrying abilities, and a fundamental study of the effect of surface geometries and fluid conditions on bearing performance. Shown in Fig. (1-3) is the cross-section of a journal bearing. The region of importance is the hydrodynamic wedge of lubricant formed under load conditions. By actively deforming the bearing surface in the region of the wedge, we can change the load carrying capacity of the journal bearing.

Fig. (1-3): Cross-section of a Journal Bearing.

An “Experimental Slider Bearing System” was used to serve as a platform on which to perform laboratory experiments. The slider bearing was intended for use as a linear approximation of a journal bearing [4].

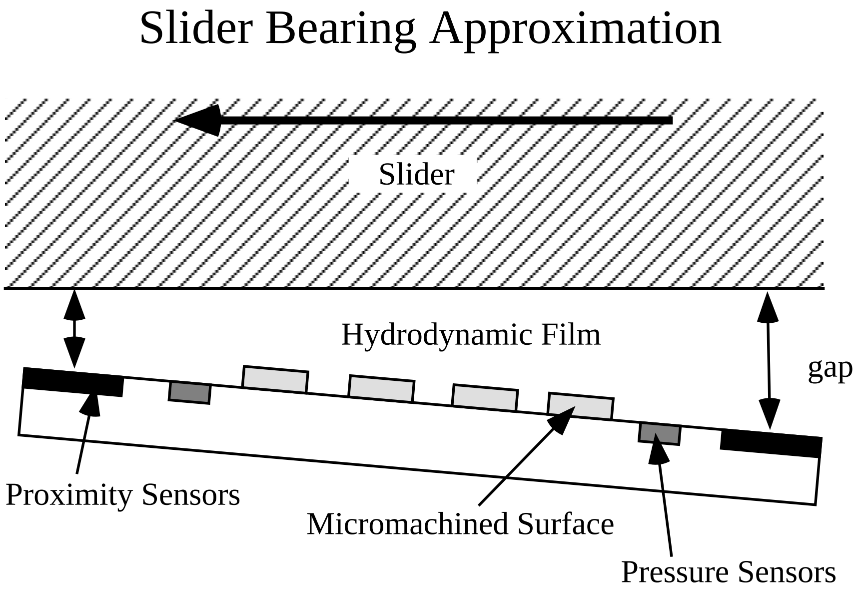

Fig. (1-4): The Slider Bearing approximation.

A schematic of the slider bearing with the bearing pad is shown in Fig. (1-4). The bearing pad was micro-machined to produce the required surface. Pressure sensors are to be placed on the bearing pad to measure the pressure of the lubricant. A critical aspect in the measurement and modelling of the bearing performance is knowledge of the absolute distance between the bearing pad and the moving slider. Macroscopic proximity sensors, installed on the assembly block holding the bearing pad, measure the approximate distance between the bearing pad and the slider. A more accurate measurement, however, requires fabricating in-situ proximity sensors on the bearing pad. This lays some constraints on the type of proximity sensor that can be used.

Since the proximity sensor is to be fabricated on the pad itself, it should be very small in size so that it occupies a very small area on the pad. With the pad surface produced by micromachining techniques, the fabrication of the sensor also needs to be compatible with integrated circuit fabrication techniques. The environment in the gap is very hostile due to the speed of rotation of the bearing and due to the flow of lubricant in the gap. The presence of the lubricant poses another challenge since the refractive index, permeability and viscosity (density) of the lubricant changes with temperature. Further, since the slider is rotating, a non-contact type of proximity sensor is needed. Finally an absolute gap measurement is needed.

Using these factors as a selection tool the eddy-current proximity sensor was judged as the best solution to the problem at hand.

1.3.0 Summary of Chapters

Eddy-current sensors usually use a coil or inductor as the transducer to produce the magnetic field. Since the sensor needed to be miniaturized and made compatible to integrated circuit fabrication techniques, the coil needed to be planar. Chapter 2, titled “Single Coil Design”, explains the calculation procedure for the inductance and resistance of a coil. With the target as the metal slider, the calculation of the mutual inductance produced between the coil and the metal slider is also described. The results of the impedance measurements for the single coils are shown. The results are explained and the “best” coil design is discussed. The scaling of the single coil and the problems it produces is also elaborated.

Chapter 3, titled “Two Coil Design”, talks about the gain/phase measurements of two coil transformers. The two coil transformers are simulated using PSpice and the calculations required to obtain the various circuit components for the PSpice model are discussed. The superiority of the two coil design over the single coil design is elaborated.

Chapter 4, titled “Fabrication Issues” discusses the important fabrication issues involved in actually fabricating the coils on the bottom of an etched hole, on the backside of a dielectric membrane.

Finally, Chapter 5, titled “In Conclusion” summarizes the entire thesis. It also addresses the addition work which needs to be performed.

References

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