8th International Symposium on Magnetic Bearing
August 26-28, 2002, Mito, Japan

DEVELOPMENT OF A LOW COST INDUCTIVE SENSOR USING SWITCHING NOISE DEMODULATION

Myounggyu D. Noh*, Min-Kyoung Jeong, Byung-Chul Park
Dept. Mechatronics Engineering, Chungnam National University, Daejon, Korea

Jong-Kweon Park, Seung-Kook Ro
Korea Institute of Machinery and Materials, Daejon, Korea

ABSTRACT

In this paper, a development of a low cost inductive sensor is described. The sensor is similar to a radial magnetic bearing in that the sensor stator is shaped like a heteropolar magnetic bearing and is driven by a switching amplifier. A demodulation filter extracts the gap information from the switching current ripples. A prototype sensor exhibits the resolution of 0.43μm and the dynamic bandwidth of about 800Hz. The dynamic performance can be improved by increasing the switching frequency. However, the eddy current effects become noticeable at high switching frequency, thus limiting the improvement of the bandwidth.

INTRODUCTION

One of the obstacles to the widespread use of magnetic bearings for industrial machines is the high cost of the magnetic bearing systems. Position sensors usually take up a large portion of the system cost. Commercially available position sensors such as eddy current probes and capacitive sensors are expensive, although they provide adequate performance for magnetic bearing systems.

The goal of this research is to develop a low cost inductive position sensor for magnetic bearing systems. Inductive sensors are inherently simpler and thus easier to manufacture than eddy current probes. The inductive sensor described in this paper is driven by a switching amplifier, utilizing the fact the switching noise is directly related to the gap information, which have been exploited in realizing self–sensing magnetic bearings [1, 2]. A demodulation filter can extract the gap information from the switching ripples.

Due to eddy current effects, the dynamic response of inductive sensors is typically inferior to that of eddy current probes. In order to improve the bandwidth of the inductive sensor, it is necessary to increase the modulation frequency (or switching frequency in our case). However the higher switching frequency results in the increase in the eddy current effects. If we have a proper model of the inductive sensor including the effects of hysteresis and eddy current effects, it would be possible to define the performance limits of the sensor.

In this paper, we describe an inductive sensor driven by a switching amplifier with constant duty cycle. The sensor probe is made by stacking silicon iron laminations and is very similar to magnetic bearings in shape. Also, we examine the effects of eddy currents on the sensor performance, using a sensor model based on the modified magnetic circuit theory.

DESCRIPTION OF SENSOR

The inductive sensor proposed in this paper consists of the sensor stator, amplifier and signal processing circuit. The sensor stator is designed and manufactured in a fashion similar to that of magnetic bearings. The stator is made by stacking silicon iron laminations with the thickness of 0.35 mm. The stator has 16 poles that are divided into four groups. Coils of each group of four poles are wired in series so that the sensor would pick up the average of the gap changes in the four poles. Figure 1 shows the schematic of the sensor stator.

The sensor amplifier is basically a switching power amplifier that is commonly used for magnetic bearing systems. Typically, inductive sensors use sinusoidal waves for modulation. In that case, the current requirement of the sensor necessitates the use of the linear amplifier [4]. In our research, we use a commercially available integrated H–bridge chip (National Instrument LMD18200) to drive the sensor coil. The duty cycle of the amplifier is maintained at 50% by using an oscillator as gate driver of the bridge chip.

The signal processing circuit is composed of the current transducers and the demodulation filter. The current transducers measure the current ripples in the coils, produced by applying the switching voltage to the coils. The current ripples are then processed by the demodulation filter which is similar to the one described in [5]. Unlike the position estimator in [5], however, the parameter

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*Corresponding author; `mnoh@cnu.ac.kr`

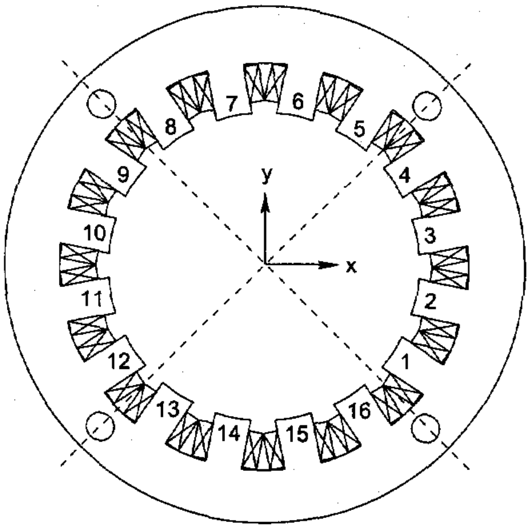

FIGURE 1: Schematic of the sensor stator

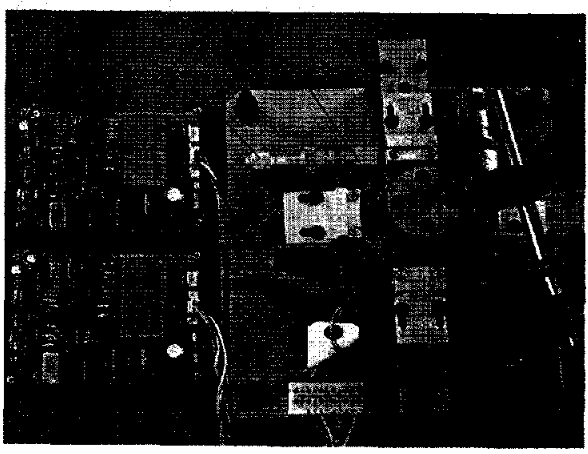

FIGURE 2: Experimental setup

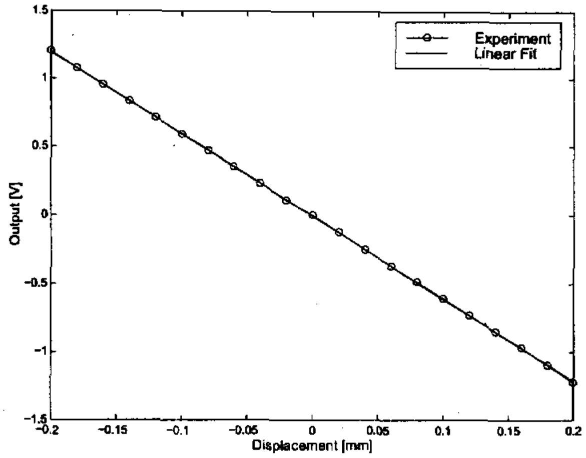

FIGURE 3: Static sensor output

estimation scheme is unnecessary, because the sensor is driven by the switching voltage with fixed duty cycle.

The demodulation filter consists of three components: a high-pass filter, a full-wave rectifier and a low-pass filter. The high-pass filter removes spurious low frequency noise from the signal. The combination of the full-wave rectifier and the low-pass filter extracts the amplitude information from the switching ripple of the coil currents. To enhance the signal to noise ratio, two opposing sensor probes are processed differentially. Figure 6 illustrates the structure of the signal processing circuit.

PERFORMANCE OF SENSOR

A prototype sensor is designed and built. The sensor is driven by the voltage of 48V switching at 20kHz. The nominal radial air gap is 0.5 mm. The sensor stator has 16 poles, each of which carries 80 turns of wire. The outside diameter of the stator is 70mm, and the journal diameter is 44mm. The thickness of the lamination is 0.35mm with a total of nine laminations to provide the axial thickness of 3.15mm. In the signal processing circuit, a second–order butterworth filter with the cut–off frequency of 4.08kHz is used as the high–pass filter. Another second–order butterworth filter is implemented as the low–pass filter with the cut–off frequency of 1.59kHz.

To measure the static performance of the sensor, a test rig is built. The test rig consists of a x–y positioner, a sensor holder and an eddy current gap sensor for reference signal. Figure 2 shows the experimental setup.

The sensor exhibits excellent linearity in the measuring range, which is from -0.2mm to $+0.2$mm. Figure 3 demonstrates the linearity of the sensor output. The maximum linearity error is less than 0.5%. The signal to noise ratio is about 59dB, which results in the position resolution of 0.43 μm. The noise is mostly due to the switching noise that was not filtered out. Since the sensor measures the average gap across four poles in either direction, some crosstalk between x and y direction can be expected. In the measuring range, the amount of this crosstalk is less than 1%.

The dynamic characteristics of the sensor is also examined. Using a magnetic bearing as an exciter, the frequency response of the sensor is obtained. Figure 4 shows the typical frequency response, where the experimental data (solid line) is compared with the simulation result. The phase bandwidth of the sensor is about 800Hz. In order to improve the dynamic bandwidth, the switching frequency can be increased. However, the higher switching frequency introduces more eddy current effects, which is described in the next section.

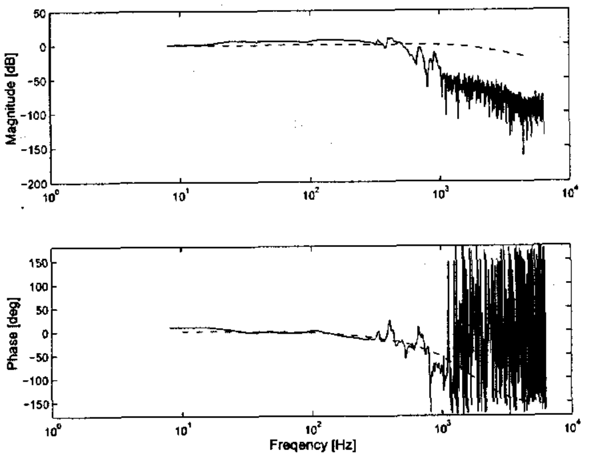

FIGURE 4: Frequency response of the sensor (simulation and experiment)

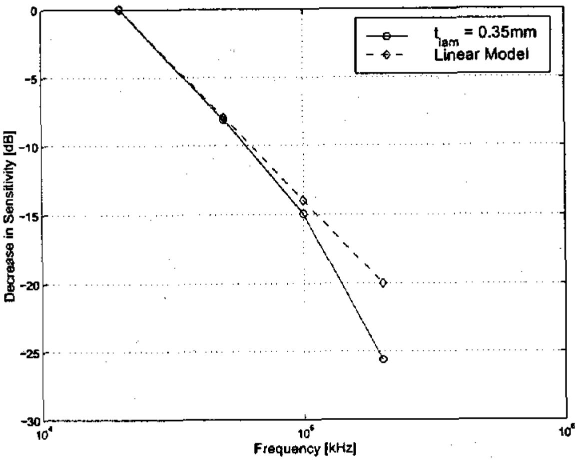

FIGURE 5: Sensitivity change with respect to switching frequency

EFFECTS OF EDDY CURRENTS

The performance of the position sensor can be defined by the accuracy and the dynamic bandwidth. The key parameter that affects both of these performance criterion is the modulation (switching) frequency. The cut–off frequency of the low–pass filter in the demodulation filter is set at about one tenth of the switching frequency. The dynamic bandwidth of the sensor is directly related to the cut–off frequency of the low–pass filter. Therefore, the dynamic performance of the sensor can be improved if the switching frequency is increased. However, the increased switching frequency results in the reduced sensitivity. Furthermore, the eddy current effects accelerates the degradation of the sensitivity. Thus, we need to find out the maximum switching frequency that still guarantees the minimum sensitivity.

A model of the inductive sensor including the eddy current effects can be used for this purpose. Previously, a magnetic circuit model of magnetic bearing was developed [3]. This model includes the effects of hysteresis and eddy currents. Since the inductive sensor in this paper has the same magnetic circuit topology as the radial magnetic bearings, we can use the bearing model to investigate the effects of eddy currents on the sensitivity of the sensor.

Briefly explained, the sensor model is described by a set of nonlinear matrix equations

$$\phi = \mathcal{F}(\mathbf{H}, \mathbf{H_g}, \mathbf{v}) \tag{1}$$

$$\mathbf{i} = \mathcal{G}(\mathbf{H}, \mathbf{H_g}, \mathbf{v}) \tag{2}$$

where ϕ is the vector of fluxes in all magnetic paths (48 in our case), and $\mathbf{i}$ is the vector of coil currents. The air–gap magnetization vector $\mathbf{H_g}$ is determined from

$$\mathbf{H_g} = \frac{1}{\mu_0 A}\phi$$

and the magnetization vector $\mathbf{H}$ for the core (stator and rotor) is related to the flux vector as

$$\mathbf{H} = \frac{1}{\mu_0 \mu_r(\phi) A}\phi$$

Here, the relative permeability $\mu_r(\phi)$ describes the nonlinear magnetic characteristics such as hysteresis and saturation. In equation (1) and (2), $\mathbf{v}$ is the vector of applied voltages.

The effect of eddy currents is modeled by assuming that eddy currents are generated from single–turn fictitious coils wrapped around the flux paths [5]. Once the amount of flux linked by this eddy current loop and its electrical resistance is estimated, the eddy current effects can be properly approximated. A detailed derivation of the model can be found in [3].

Figure 5 shows the simulation result that demonstrates the effect of eddy currents on the sensitivity of the sensor. With the increasing modulation frequency, the sensitivity linearly decreases if eddy currents are not considered. However, the eddy currents cause the sensitivity decrease more substantially at high switching frequency. Therefore, the maximum switching frequency acceptable at the given signal–to–noise ratio would be smaller with the eddy current effect considered than when the eddy current effects are not considered.

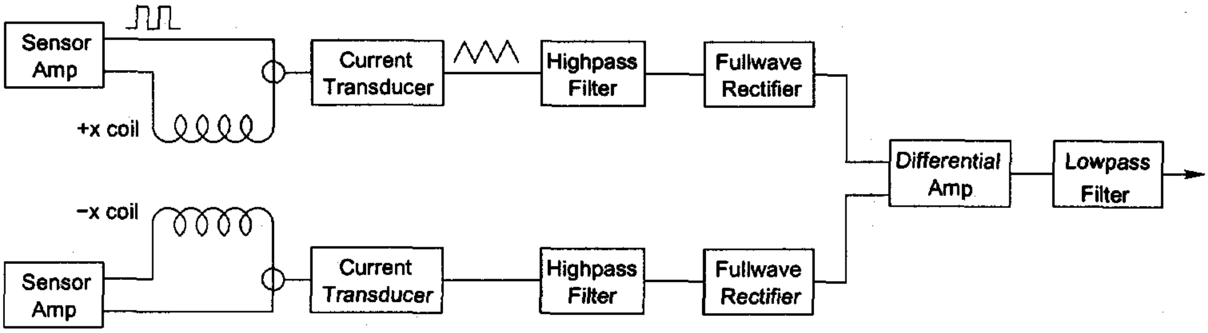

FIGURE 6: Sensor signal processing circuit

CONCLUSION

An inductive sensor driven by a switching amplifier is developed. A prototype sensor promises adequate static performance. For the target specification (resolution 1μm and bandwidth 5kHz), the dynamic performance needs to be improved. By increasing the switching frequency, it would be possible to obtain better dynamic performance. However, the performance gain is limited by the eddy current effects. If the switching frequency is increased, the signal processing circuit must accommodate the loss of the sensitivity to preserve the static performance.

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