International Journal of the Korean Society of Precision Engineering, Vol. 2, No.3, September 2001.

Inductive Micro Displacement Detecting System with High Sensitivity and Low Linearity Error

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ABSTRACT

A newly designed inductive micro displacement detecting system is presented. The proposed inductive system consists of driving coils, position-detecting coils, cores, and closed-loop formed magnetic blocks. The cores and magnetic blocks are made of Mn-Zn ferrite. When AC sine wave is applied to the driving coils, the time derivative flux is generated within the system, and then induced voltages arise in the position-detecting coils according to the core's position. Putting the cores to be moved proportionally to the input displacement, the induced voltage is proportional to input displacement. The parameters that affect the system characteristics are turn ratio, air-gap size, excitation frequency, overlap area, load resistance, capacitance effect, and so forth. Based on the experimental results, the system parameters are selected in such a way as to have high sensitivity and stable responses. The sensitivity of the proposed inductive displacement-detecting system is greater than 2800mV.V-1mm-1 and the linearity error is below ±0.10% in the range of ±200 μm.

Keywords : inductive, flux, coil, displacement, sensitivity, resolution, linearity

1. Introduction

As the precision and semi-conductor industries are rapidly developing, system integration is more complex and the required minimum displacement-detecting level is decreasing. In the inspection and measurement process, displacement detection plays an important role and the required precision and resolution are at the sub-micron level over the range of the several hundreds micrometers.

An inductive displacement measurement system is the one of the widely used devices in the measuring, monitoring, and inspecting devices. These inductive measurement systems have many advantages, such as good linearity over a wide range, high reliability, and sufficient durability. Furthermore, they are easy to reduce their size and their production cost is relatively low [1].

Research studies on inductive systems to measure the physical properties such as stress, strain, force, and pressure have been performed [2-4]. Of all the physical measurand, displacement is probably the most measurable quantity. Inductive system has been widely used to detect the displacement and applied to various fields [5-9]. One of the most generally used displacement sensors to utilize the changes in inductance is a linear variable differential transformer (LVDT) [10].

However, the above mentioned devices are used when a larger displacement up to several ten millimeters is to be detected. The characteristics and advantages are related to the large range. In spite of an extensive literature survey on inductive sensors related to precision and small displacement, sufficient information could not be obtained. The demands in the industries have already reached the sub-micron level. And the required specification is decreasing in size, and increasing in accuracy and precision. In this study, a new inductive displacement measurement system for detecting the sub-micron level is introduced and the characteristics related to the detection of the small displacement are evaluated. The proposed device is designed to have high sensitivity, high linearity, and high resolution over the several hundreds micrometers region.

In sensors based on the magnetic flux, the resolution - the smallest measurable input change - is defined as follows.

$$Resolution = \frac{Noise}{Sensitivity}$$

The resolution is related to noise and sensitivity. When the system output is linearly proportional to its source voltage and input displacement, the sensitivity can be defined as below:

$$Sensitivity = \frac{Output}{Source \cdot Displacement}\left[\frac{mV}{V \cdot mm}\right].$$

High sensitivity means that the system output is large for the reference displacement and source amplitude. In order to improve the resolution, the system sensitivity should be improved or the noise should be decreased. Noise level varies with external conditions and is not a fixed value. Of course, noise level can be minimized and reduced. However, we focus our attention on the sensitivity. To be advantageous for detection of small variations in displacement in spite of external condition's changes, the system should have high sensitivity and linearity.

Noise could not be known from its source and its magnitude is apt to be changed by the various internal and external factors. A filter could be used to reduce the noise, but it is impossible to remove the noise. When the resolution is referred in precision system, it is defined as the generally obtainable minimum value, selecting the obtainable minimum noise level, such as 1mV, etc. To enhance the resolution and keep it stable, the sensitivity should be increased. However, most of the displacement detecting system have low sensitivity, and are difficult to measure ultra precision level such as nanometer or angstrom. An electrical signal amplifier is utilized to overcome the low sensitivity. However, when its original sensitivity is low, it is impossible to amplify the original signal infinitely, and the gain of the signal amplifier is sensitive to environment and other external factors. Furthermore, this sensitiveness has a tendency to be intense according as the gain of the amplifier increases.

In this work, the new model based on the mechanical design is introduced to have high sensitivity, and thus the resolution enhancement is followed.

Another important consideration is material of the component which has to have good magnetic properties [11]. Mn-Zn Ferrite is considered in this study for its good magnetic characteristics and cost. Ferrite derives its usefulness from high magnetic permeability and high electrical resistivity, which concentrates and reinforces the magnetic field and limit the amount of flow of electrical current in the ferrite.

We focus our efforts on detection of sub-micron levels and analysis of its characteristics. The proposed system can be widely applied to the various systems, such as a detecting part for sub-micron displacement detection [12].

2. The Proposed Inductive Displacement Detecting System

Figure 1 shows the schematic design of the inductive displacement detecting system. The dimensions of the prototype is 58mm×35mm×6.5mm. It consists of driving coils, position-detecting coils, movable cores, and closed-loop formed magnetic blocks. The driving coils are connected in series and the position-detecting coils are connected to produce a differential output. Ferrite is used for the cores and other magnetic blocks.

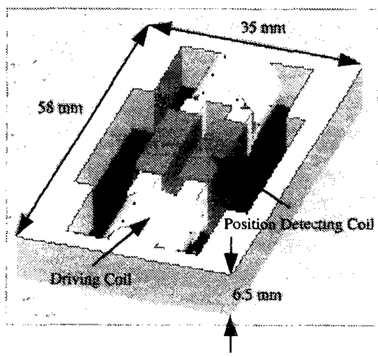


Fig. 1 3D view and the dimension of the proposed inductive system

When the driving coils are excited with a sinusoidal AC voltage, a magnetic field is generated within the system. The cores are moved in a direction, which is proportional to input displacement. The ferrite core is put inside the position-detecting coil to draw the flux. To generate a strong flux, only narrow gaps between the magnetic blocks and the movable cores are allowed. This design attempts to produce a large amount of flux difference even at a small variation in displacement.

The principle of the proposed sensing system is explained by Faraday's and Lenz's Laws. When there are N turns in coil, the total flux linkage is Nϕ, then the induced electro-motive force (emf) is as follows:

$$v = -N\frac{d\phi}{dt}. \tag{1}$$

When the cores move together proportionally to the input displacement, the amount of flux at each core is varied. The flux difference between the two cores generates a differential AC output voltage that is linearly proportional to the magnitude of the displacement.

Using the magnetic circuit theory, generated flux is given below:

$$\phi = N_1 i_1 \cdot \wp \tag{2}$$

where, N_1 is the turn of the driving coil, i_1 is the exciting current of the driving coil, and $\wp$ is the permeance which is determined by the form of the system.

The permeance of a piece of material with the flux path length, d and the cross sectional area of flux path, S is given by:

$$\wp = \frac{\mu S}{d} \tag{3}$$

where, μ is permeability.

The flux paths near the cores are shown in Fig. 2; path ①, ②, ③. Path ① is the shortest path through the air gap between the fixed magnetic blocks and the cores. Figure 3 shows the flux path and density obtained by the Maxwell simulator. Fig. 3-(a) shows flux density at core's center position and (b) shows magnified view near the cores. The bright color means high flux density, so we guess that most flux is passed through path ①. On the other hand, flux through path ③ is little. Path ② is the fringing path and path ③ is the leakage path. The fluxes through path ① and ② pass the cores, which could contribute to produce an induced voltage, however, the flux through path ③ do not contribute to.

l_g is the air-gap size between the fixed magnetic blocks and cores, and l_c is the length of core. When $l_g << l_c$, most flux would interchanges through path ①. The flux through path ② and ③ could be operated as nonlinear effect of the system, however, the quantity is negligible. The system nonlinearity is small as shown in Section 3.

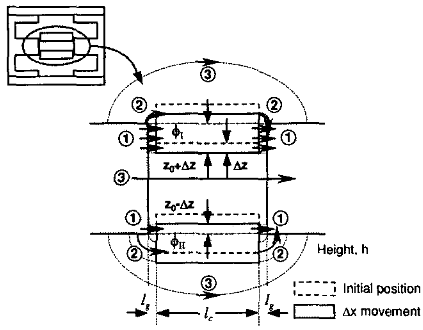
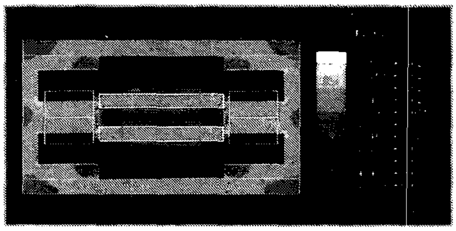
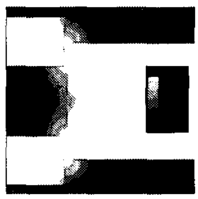


Fig. 2 Flux paths near the cores



(a) Flux path and density



(b) Magnification near the cores

Fig. 3 Flux simulation by the Maxwell package simulator

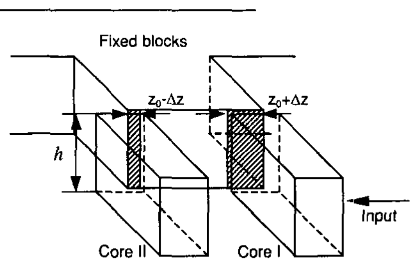


Fig. 4 Overlap-area according to movement of the cores

Figure 4 shows parameter variations in overlap area according to movement of the cores; from hz_0 to $h(z_0+\Delta z)$ and $h(z_0-\Delta z)$, respectively. The initial overlap length, z_0 is determined to cover its maximum measurement range.

The generated flux could be obtained from Eq. (2) and (3).

$$\phi_I = N_1 i_1 \frac{\mu_0 h(z_0 + \Delta z)}{2l_g} \quad (4)$$

$$\phi_{II} = N_1 i_1 \frac{\mu_0 h(z_0 - \Delta z)}{2l_g} \quad (5)$$

where, μ_0 is the permeability in the air, and h is the height of the cores.

The induced voltage in the position-detecting coils is as follows:

$$v_{diff} = -\frac{N_1 N_2 \mu_0 h \Delta z}{l_g} \cdot \frac{di_1}{dt}. \quad (6)$$

where, N_2 is the turn of the position-detecting coil.

If the current source, $i_1 = I_1 \sin(2\pi f t + \theta_0)$ is supplied, the magnitude of the generated differential voltage is as follows:

$$|v_{diff}| = -\frac{N_1 N_2 2\pi f \mu_0 h I_1 \cdot \Delta z}{l_g}. \quad (7)$$

That is, the induced differential voltage is linearly proportional to input displacement, Δz.

If the voltage, $v_{in} = L_1 \cdot (di_1/dt) + R_1 i_1$ is connected to the input port, the transfer function will be as follows:

$$\frac{V_{diff}(s)}{V_{in}(s)} = -\frac{N_2}{N_1} \cdot \frac{N_1^2 \cdot \frac{\mu_0 h}{l_g} \Delta z \cdot s}{N_1^2 \cdot \frac{\mu_0 h}{l_g} z_0 \cdot s + R_1} \quad (8)$$

where, $V_{diff}(s)$ and $V_{in}(s)$ denote the Laplace transform of $v_{diff}(t)$ and $v_{in}(t)$, respectively.

The induced differential voltage is also linearly proportional to input displacement, Δz.

3. Experimental Results

The experiment was performed in the prototype. Figure 5 shows the experimental setup and its signal. A dynamic signal analyzer (HP35670A) supplies a source signal, and gathers an output voltage. The range of the source frequency was up to 50kHz. An optical stage with a micrometer allowed the cores and the magnetic blocks to move. The air-gap size and input displacement are regulated by the micrometers.

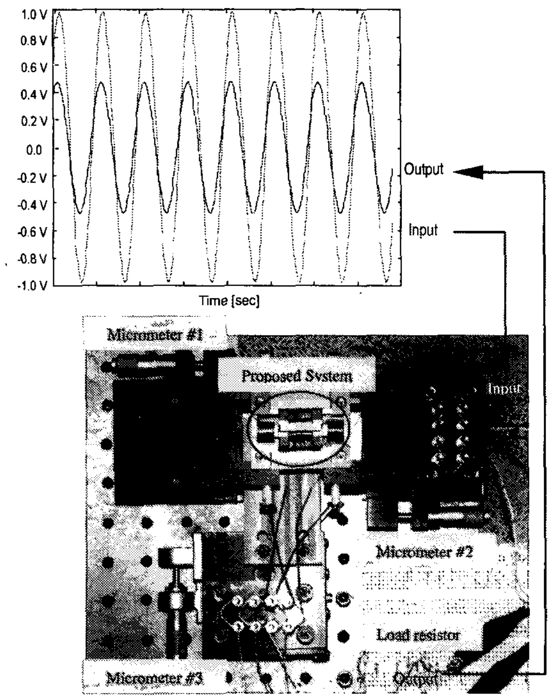


Fig. 5 Signal and photograph of the experimental setup

The input was an 1.0 V_{pp} sinusoidal AC wave and the system output is the differential output of the position-detecting coil. The turn number of the driving coil is limited to the allowable maximum current of the source. 150 turns is selected to consider these limits. First, we choose 250 as the turn number of the position-detecting coil at random. The overlap length, z_0 is set to 1.2mm to cover the measurement range up to mili-order. The preliminary experiment was performed in the above parameters, such as turns ratio, air-gap size between the fixed magnetic blocks and movable cores, the excitation frequency, and load resistance.

Frequency responses according to the input displacement are shown in Fig. 6. As the input value increases, the output voltage (gain) increases. The gain is also increased as the source frequency increases.

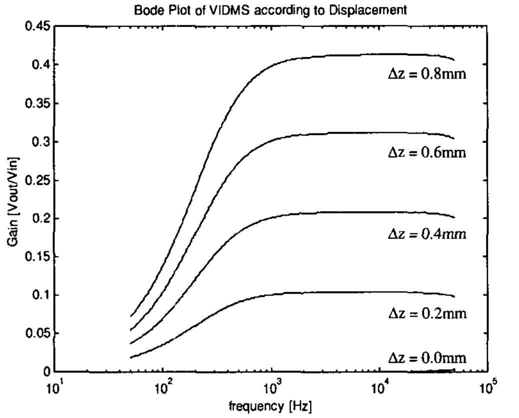


Fig. 6 Frequency responses according to input displacement

Frequency responses according to the turn ratios are shown in Fig. 7. The turn ratios are 150:250, 150:450, and 150:750. In case of 150:750 turn ratio, the resonance could be seen in the about 30kHz region. The resonance is caused by the capacitance and inductance of the position-detecting coil.

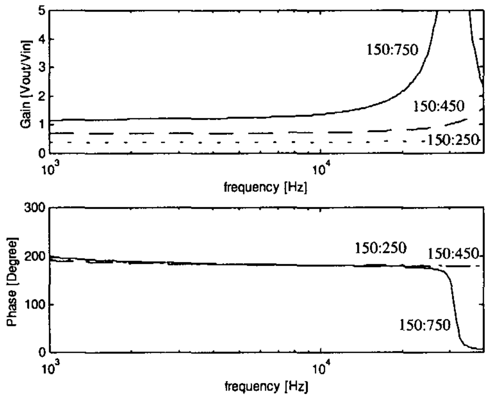


Fig. 7 Frequency responses according to turn ratios

If the turn ratio is further increased, the LC resonance point will move down to a lower frequency, and then, it affects the system response in the commonly operating frequency. Increases and fluctuations due to resonance are greatly influenced by external conditions and environment. Therefore, sensitivity increase due to resonance should be avoided.

Figure 8 shows frequency responses according to variations in air-gap size. The experimental conditions are N_1:N_2=150:750 and Δx=0.5mm. And the air-gap sizes are 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.8, and 1.0mm. As the air-gap size decreasing, the gain of the responses increases. As the air-gap decreases, however, the system becomes more difficult to guide the cores. In case of real field usage, the core moving along the input displacement should be guided by the mechanism. It is difficult to maintain the narrow gap between fixed magnetic blocks and movable cores. The design will be more difficult to maintain an air-gap as its size decreases. Therefore, the mutual supplement should be considered between the sensitivity and the guide design criteria. Moreover, in the case of 0.15mm, the system response is influenced by the resonance.

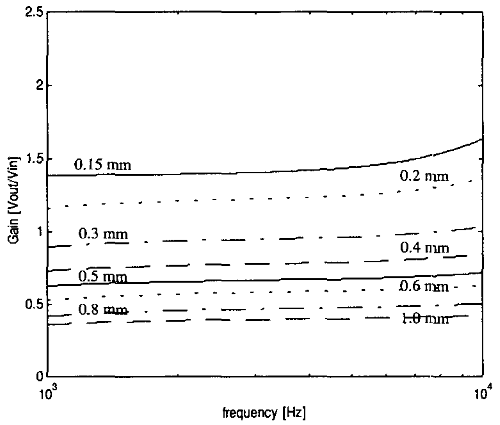


Fig. 8 Frequency responses according to air-gap dimensions

The experimental results on load resistor of 5kΩ, 10kΩ, 15kΩ, and 20kΩ are marked in Fig 9. When the load resistor is relatively small (5kΩ, 10kΩ, and 15kΩ), the responses are decreased. The resonance effects are also disappeared, however, the resonance effect is not perfectly removed. As the load resistor is increasing, the resonance effect is also being appeared. The load resistor should have the gain increase due to resonance to be attenuate and at the same time, system responses not to be cut down. If we choose the operating frequency range up to about 20kHz, the load resistor of 15kΩ will be appropriate.

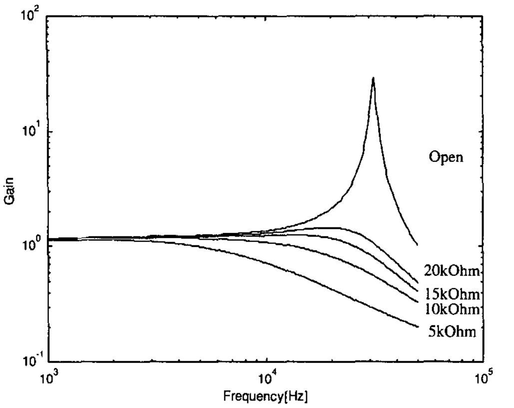
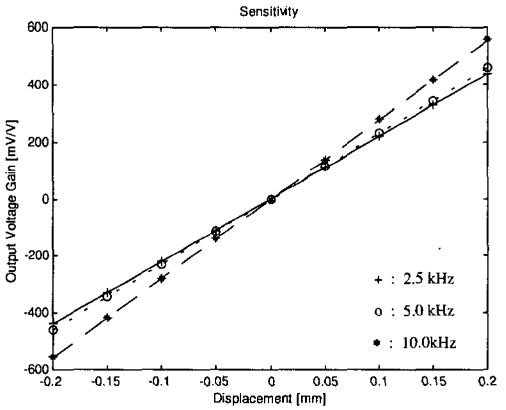
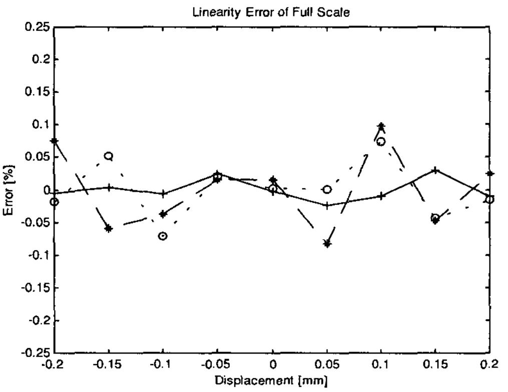


Fig. 9 Frequency responses according to load resistors



(a) Sensitivity



(b) Linearity error of the full scale

Fig. 10 Sensitivity and linearity error of the proposed system

Figure 10 shows output data according to the source frequency. Based on the experimental results, the turn ratio of 150:750 and 0.2mm air-gap size is selected. The alternating currents of 2.5, 5, 10 kHz are used as the source frequency. System responses are obtained at each discrete steps of 0.05mm. A laser displacement meter (Keyence LC2420), having 10nm resolution, is used to confirm the accuracy of the each step. For each measured data point, curve fitting is performed using the non negative least square fitting method.

Table I shows the obtained results. The results are a sensitivity of 2200~2800 $mV \cdot V^{-1}mm^{-1}$ and the linearity error of ±0.029~0.097% in the range of ±200 μm. However, the range is limited by the range of the laser calibration equipment. The proposed system can measure the value over 1mm, which is dependent on the core's width and its overlap length. Table 2 shows the specifications of the conventional inductive displacement measurement system Considering the conventional system has a sensitivity of about 200 $mV \cdot V^{-1}mm^{-1}$ and a linearity error of about ±0.25%, the proposed system seems to have high sensitivity and good, linear characteristic.

Table I Sensitivity and linearity error of the proposed inductive system

Source frequency	Sensitivity [$mV \cdot V^{-1}mm^{-1}$]	Linearity error of full scale
2.5 kHz	2188.65	±0.029 %
5.0 kHz	2289.70	±0.075 %
10.0 kHz	2779.54	±0.097 %

Table 2 Specifications of the conventional LVDT

Maker & Series	Sensitivity [$mV \cdot V^{-1}mm^{-1}$]	Linearity error of full scale
Schaevitz. LBB	271.70	±0.20 %
Daytronics. DS	78.40	±0.50 %
Sensortc PVLX	220.08	±0.25 %

The noise level in the proposed system in Fig. 11 is as low as ±1mV. Furthermore, the noise level can be further improved by using the filter and noise rejection circuit. Considering the sensitivity is greater than 2200 $mV \cdot V^{-1}mm^{-1}$ and the noise level is below 1mV, the proposed instrument can detect the sub-micron level in spite of not having an amplifier.

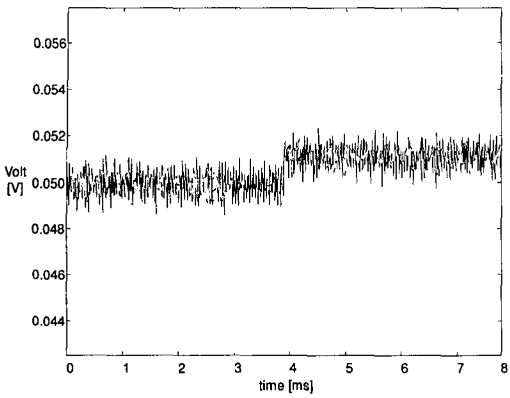


Fig. 11 Noise level of the prototype

4. Conclusions

The newly designed precision inductive displacement detecting system is proposed and analyzed its characteristics. The proposed system is designed to detect the small variations in displacement. A symmetric and closed-loop form is accepted to generate strong flux and to reduce the flux loss. The appropriate turn ratio is selected to generate high sensitivity, considering LC resonance. The important elements that affect the system characteristics and sensitivity are turn ratio, the air-gap size, excitation frequency, overlap area, load resistance, and capacitance effect. The obtained results show that the sensitivity was greater than 2200 $mV{\cdot}V^{-1}mm^{-1}$ with an linearity error below $\pm0.10\%$ over a ±200 μm and its noise level is below ±1mV. These results were caused by its structure and material: overlap-area type structure with small air gap and ferrite with good electric and magnetic properties.

The magnetic position sensing system developed here can be applicable to many types of position, displacement or surface measurement systems.

Acknowledgement

This work was supported in part by the Brain Korea 21 Project.

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