HIGH SENSITIVITY INDUCTIVE SENSING SYSTEM FOR POSITION MEASUREMENT

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Abstract

In this study, high sensitivity inductive sensing system for position measurement is presented. The proposed sensing system has higher sensitivity than a conventional Linear Variable Differential Transformer (LVDT) system. By rearranging the conventional LVDT components and improving the structure, high sensitivity for sub-micro measurement is obtained. The proposed sensing system is asymmetric and a closed loop type. The high ferro-magnetic material in the secondary coil is used to draw the flux, the air-gap along the flux paths is reduced, and a closed loop type is accepted to decrease the flux loss. The elements that affect the system characteristics and sensitivity are turn ratio, the air-gap between the fixed and moving part, capacitance effect, excitation frequency, and etc. By experimental investigation, the influences of these elements are examined and parameters of elements are selected to obtain high sensitivity. The proposed system's sensitivity is about 2400[mV/(V·mm)] without amplification.

1. Introduction

LVDT transducers are used as good sensitive detectors of micro-order linear movement over several millimeters in the fields of instrumentation and measurement. Generally, the LVDT is cylindrical in shape and is composed of a primary coil, two secondary coils, and a core. The use of change in inductance of the secondary coils in the displacement measurement is well known.

In the previous study on the LVDT, the improvement of characteristic and robustness to disturbances (e.g. temperature, excitation current, and frequency) are attempted [1-3]. Also flat type LVDT transducers that can be attached to linear motors for precise positioning are developed [4-6]. In addition, there are lots of works about measurement using the LVDT principle.

Nowadays, it is increasing the demands of ultra precision measurement below micro order. A conventional LVDT has good characteristics in micro order resolution over a long range. But due to low sensitivity, difficulties exist in sub-micro order measurement. Generally, an output signal is amplified to overcome these difficulties. But the amplified signal is easy to be influenced by the external disturbance.

In this study, to overcome the difficulties, we focus our efforts on the development of high sensitive sensing system not by amplifying the signal but by restructuring the system. High sensitivity causes an improvement of resolution and that is easy in the ultra precision measurement. Also a high sensitive system is less affected by external noises and disturbances.

2. The Sensing System for Position Measurement

2.1. The conventional LVDT system

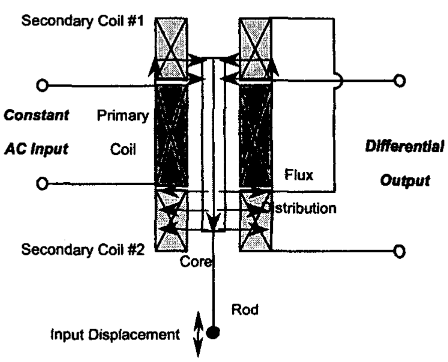

Fig. 1. Schematic view of the conventional LVDT and connection method of the secondary coils for differential output

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Figure 1 shows a schematic diagram of a conventional LVDT. An LVDT consists of a primary coil, two secondary coils, a ferromagnetic core, a former, and a shield case. The primary coil is excited with a sinusoidal AC voltage and generates a magnetic field within the system. As the core moves along with input displacement, there are flux differences in the two secondary coils. These flux differences are used as system output about displacement. Ordinary two secondary coils are connected to produce a differential output. The differential output voltage is proportional to the core's displacement and so it is proportional to the input displacement.

An LVDT principle is illustrated as Faraday's and Lenz' laws as shown in Eq. (1).

$$emf = -N\frac{d\phi}{dt} \quad (1)$$

where, *emf* is the electromotive force, N is the turns of coil, and ϕ is the flux. That is, a constant AC voltage excites a primary coil, flux derivative to the time is generated in the system. An emf is generated proportional to the flux and turns. When the two secondary coils are connected for a differential output, a system output is proportional to the flux difference crossing the secondary coils.

In these analogue output type sensors, the sensitivity is defined as Eq. (2).

$$Sensitivity[\frac{mV}{V \cdot mm}] = \frac{Output[mV]}{Source[V] \cdot Input[mm]} \quad (2)$$

In the case of using a unit source, the smallest measurable input change, called resolution, is defined as Eq. (3).

$$Resolution[mm] = \frac{Noise[mV]}{Sensitivity[mV/mm]} \quad (3)$$

In order to be advantageous in the precision measurement and to have high resolution, the system sensitivity must be improved or the noise must be decreased. In this study, we made an effort to improve the system sensitivity.

Table 1. Specifications of Conventional LVDT [7]

Sensitivity [mV/(V·mm)]	78.74	157.48	220.08	277.6
Range [mm]	0.25	0.125	0.50	0.50
Linearity % of FS	0.50	0.25	0.25	0.20

A conventional LVDT transducer's structure is good in the usage of the flux. It has good characteristics in the micro region over a long range. But it lacks sensitivity, so it is not easy to measure the sub-micro order. Table 1 shows the specifications of conventional LVDT for precision measurement.

Recently, it is increasing the demand of precision measurement below micro order. To do this, higher sensitivity is more needed. But, in a conventional LVDT, the limitation exists to improve the sensitivity. The possible method to increase the sensitivity is an increase of the turn ratio (the ratio of the turns of primary coil to the turns of secondary coil). But, it also has a limitation due to LC resonance. So, an original signal is amplified to improve the sensitivity. In case of the signal amplification, the system is likely to be influenced by the environment elements and external disturbances. In this study, to increase the system original sensitivity, we tried to reform the mechanical structure. This is the way less sensitive to the external factors. Even if it is necessary to amplify an original signal for more precision measurement, it could be obtained more stable and high resolution relatively.

2.2. The proposed inductive sensing system with high sensitivity

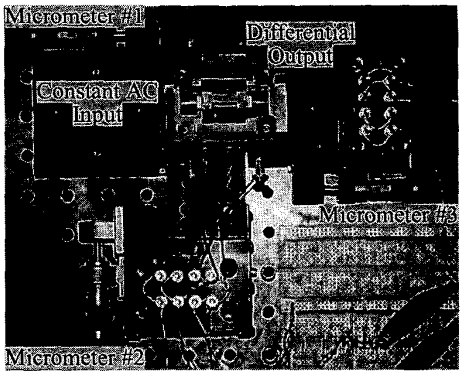

Fig. 2. The photo of proposed inductive sensing system

The proposed sensing system is shown in Fig. 2. The system is composed of primary coils, two secondary coils with cores and extra ferromagnetic materials. The cores are moved simultaneously along with the input displacement. According to the cores' displacement, the flux in the cores and secondary coils is changed and the differential voltage is generated by the change of flux. While it is the same as the conventional LVDT only in the components, some differences do exist; it is a closed loop type with a high ferromagnetic material. The flux produced by the primary coils is divided and it flows into each secondary coil through the small air-gaps. We put the high permeable material in the secondary coils to draw the flux and reduce the air-gaps between the fixed and the moving part along the flux paths to decrease the flux loss as soon as possible.

Figure 3 shows the flux paths. If the air-gaps are sufficiently small, the flux exchange is, for the most part, via path ①. That is, the flux separation by the cores is proportional to the contact area changes between the ferromagnetic material near the small air-gaps.

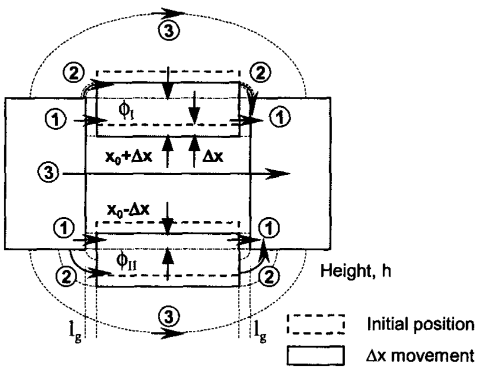

Fig. 3. Flux paths near the air-gaps

In each core, the flux is defined as Eq. (4) and (5). The flux difference between the two cores is proportional to the input displacement. After crossing the cores, the flux is rotated along the ferromagnetic material. Where, the flux along with path ¶, @ which is not considering here operates the system nonlinearity.

$$\phi_I = N_1 i_p \frac{\mu_0 h(x_0 + \Delta x)}{2l_g} \quad (4)$$

$$\phi_{II} = N_1 i_p \frac{\mu_0 h(x_0 - \Delta x)}{2l_g} \quad (5)$$

$$\phi_I - \phi_{II} \propto emf \propto \Delta x \quad (6)$$

where, N_I is the turns of the primary coil, i_p is the input current, μ_0 is the permeability, h is the system's height, l_g is the air-gap, x_0 is the initial overlap length, and Δx is the cores' movement according to the input displacement.

The emf is produced proportional to the flux difference and also proportional to the input displacement. So, the sensing system is produced the output signal proportional to the input displacement. Where, the elements that affect the system characteristics and sensitivity are primary turn, secondary turn, turn ratio, the size of air-gap between the fixed and moving part, capacitance effect, excitation frequency, current, and etc. By experimental test, the system parameters are obtained and the improvement of characteristics is attempted.

3. Experimental Results and Discussions

The dynamic signal analyzer (HP35670A) is used. The range of the source frequency is from 1kHz to 50kHz. The source input is 1.0 V_{pp} sinusoidal AC sinusoidal wave and the system output is secondary coil's differential output. The signal analyzer gathers frequency responses between the source input and differential output. The optic stages with micrometers are used to adjust the air-gaps and set up experimental conditions like an input displacement. Due to the current limit of the source input, the turn of primary coil is limited to 150 turns.

Frequency responses according to the turn ratios are shown in Fig. 4. The input displacement is 0.5mm.

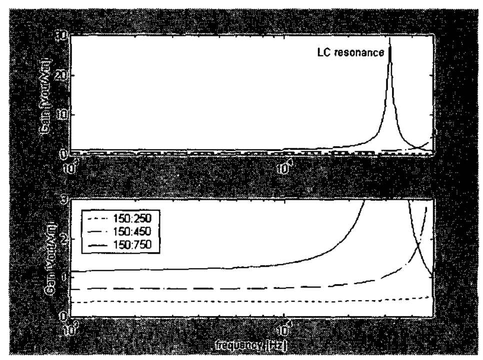

Fig. 4. Frequency responses according to the turn ratio

To obtain the high sensitivity, high turn ratio is advantageous. But, the system response must not be affected by LC resonance in the commonly using frequency range. LC resonance frequency moves to low frequency as the increase of secondary coil turns. So it has the limit of secondary coil turns. In the fixed turn of a primary coil, the turn of secondary coil increases, like 250, 450, 750. Generally an LVDT uses a several kHz range AC sinusoidal wave, and could be used even in the 10kHz source. From the Fig. 4, as increasing of the turn ratio, LC resonance affects the system characteristic. LC resonance point is very sensitive to external circumstance, temperature change, and etc. In the above 750 turns of secondary coil, LC resonance affects the system performance.

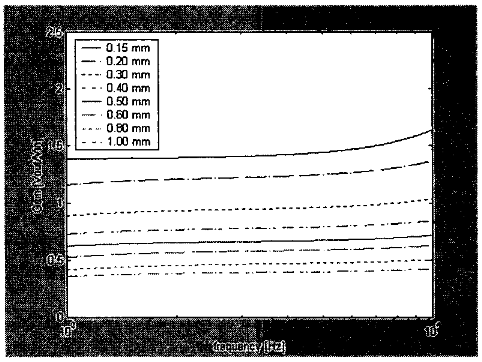

Fig. 5. Frequency responses according to the air-gaps

Figure 5 shows the results of sensitivity measurement according to the air-gaps. The input displacement is 0.5mm. As the air-gaps decrease, the sensitivity increases. But as the air-gaps decrease, the system has more difficulties in setting, and it is influenced by the resonance and increases the nonlinearity.

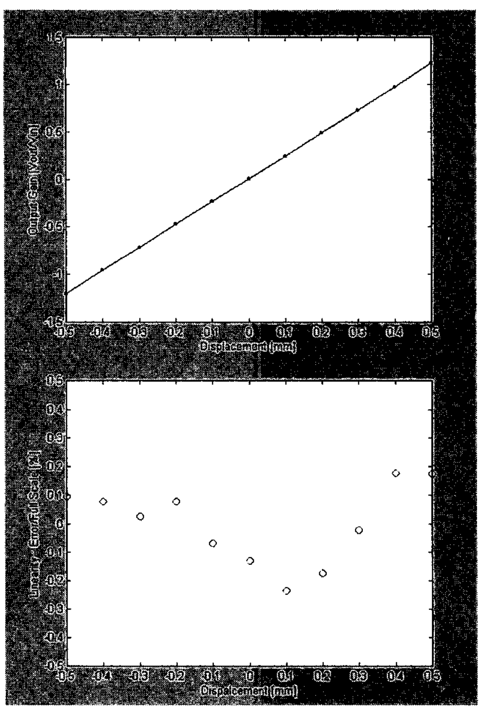

Fig. 6. System sensitivity and linearity test; where, 'o' denotes the experimental results and the solid line is a fitting line

The system sensitivity and linearity test results are shown in Fig. 6. Where, the turn ratio is 150:750, the air-gap is 0.2mm, and the source input frequency is 5.0kHz. The cores are moved by micrometers. The results are obtained at every 100μm steps, the system sensitivity is about 2400 [mV/(V·mm)], and the linearity is ±0.20% over the ±500μm range.

Next, a sub-micro order configuration is measured by the proposed sensing system using an original sensor signal without amplifying the output signal. The block diagram of test system is shown in Fig. 7.

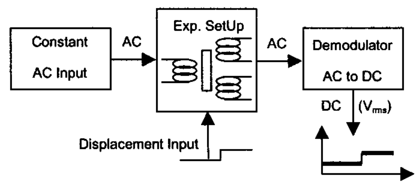

Fig. 7. System block diagram for step measurement

Figure 8 is the result of 0.5μm step measurement. An original AC signal is converted to DC only by a demodulator.

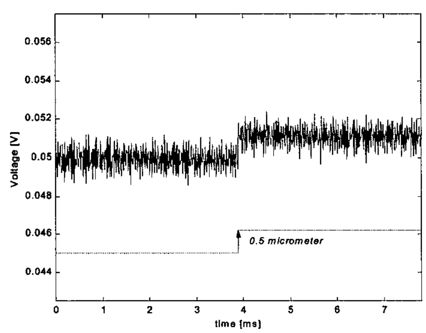

Fig. 8. Measurement of the 0.5μm Step; where, the signal is before amplification

The newly devised sensing system could measure a sub-micro configuration without an amplifier. In the case that an original signal is amplified, it is possible to measure the ultra precision configurations.

Conclusion

This paper introduced a high sensitivity inductive sensing system for position measurement based on the LVDT. By adopting a closed loop and reducing the air-gaps along the flux paths, the system sensitivity is improved. The important elements that affect the system characteristics and sensitivity are turn ratio, the air-gap between the fixed and moving part, capacitance effect, excitation frequency, and etc. By experimental investigation, the influences of these elements are examined and parameters of elements are selected to obtain high sensitivity. A proposed system already could measure the sub-micro order configuration without amplifying signals. If necessary, by amplifying signals, it is possible to measure the displacement of ultra precision range.

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