Calibration Technique for Sensitivity Variation in RVDT Type Accelerator Position Sensor

Jong-Kyoung Lee, Young-Hun Ko, Sang-Gug Lee
Department of Electrical Engineering
Korea Advanced Institute of Science and Technology (KAIST)
Daejeon, Republic of Korea
Email : {jongkyoung_lee, gnsstar}@kaist.ac.kr, sglee@kaist.ac.kr

***Abstract*— This paper presents a calibration technique for RVDT sensitivity variation, which occurs as a result of using high excitation frequency and changing the distance between the coil printed on PCB and the magnetic core. An additional secondary coil and new signal processing are employed to calibrate the sensitivity variation. The output voltage amplitude of this additional coil is not affected from rotation of the magnetic core, and is changed by distance between the coil and the magnetic core. The proposed signal processing can calibrate the sensitivity variation without being influenced by environmental factors such as humidity and temperature. The proposed method calibrates sensitivity variation by 76% compared to the conventional method when the distance between the coil and the magnetic core changes by ±0.2 mm around 1.0 mm.**

Keywords*— Automotive sensor, RVDT, LVDT, Magnetic sensor

I. Introduction

As a car uses more electronic sensors, some kind of the angle sensors that has some characteristics such as high-reliability and high-linearity are needed. At that point, a RVDT (Rotary Variable Differential Transformer) can be a good solution. A RVDT can obtain the angle information about the RVDT's magnetic core. Fig. 1 illustrates the concept of the RVDT. The RVDT uses a transformer that has a primary coil that excites a magnetic field by applying a sinusoidal wave V_P and two secondary coils that exhibit sinusoidal voltage outputs V_1 and V_2 depending on the strength of the magnetic field and the turn ratio. A magnetic core that consists of ferromagnetic materials is situated between the primary and secondary coils. Rotation of the magnetic core changes the magnetic field density at two secondary coils. If the core is located closer to the secondary winding-1 than the secondary winding-2, the magnetic field at the former is stronger than the magnetic field at the latter. Thus, V_1 is a larger signal than V_2. The angle of the magnetic core can be calculated by using

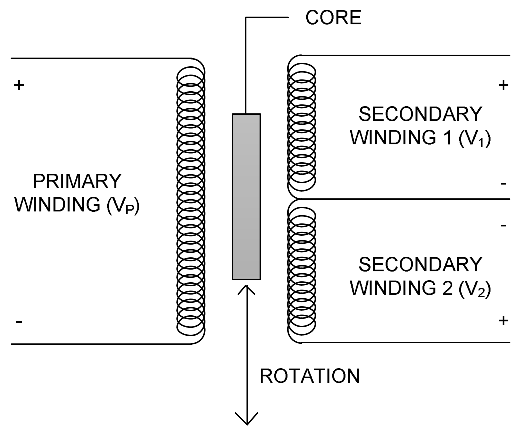

Figure 1. RVDT concept.

$$\theta = k\frac{V_1 - V_2}{V_1 + V_2} \quad (1)$$

in [1], where k is a gain parameter that is determined by structure of RVDT. V_1+V_2 represents total magnetic field and V_1-V_2 the angle information of the core. However, V_1-V_2 can be changed by many factors such as temperature, humidity, magnetic permeability of the core, frequency and amplitude of the excitation signal. Eq. 1 extracts the angle information without influence of these factors because of ratio-metric signal processing.

Because the transformer that is a part of the RVDT has large inductance, these magnetic sensors typically use a magnetic field less than 1 MHz and the magnetic core with a high permeability magnetic material. The RVDT has differential output and good characteristics such as long period reliability, high-resolution and high-linearity. On this basis, it is widely used in industrial application that requires high-resolution and high-linearity. In spite of these strong characteristics, these sensors require a transformer that makes a RVDT large, heavy and expensive. Therefore, for low weight, small volume, and low price application or

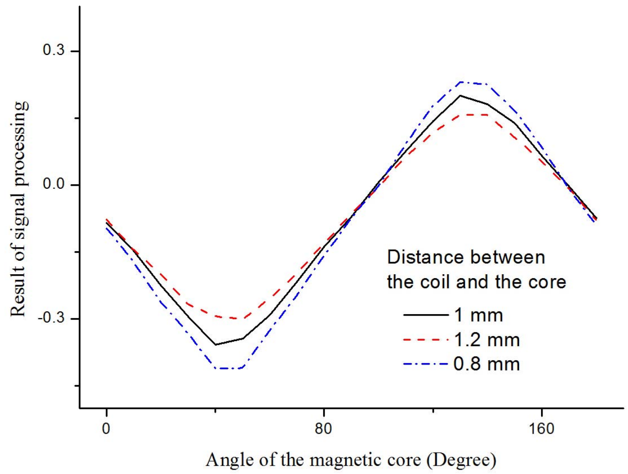

Figure 2. Results of conventional signal processing at high frequency.

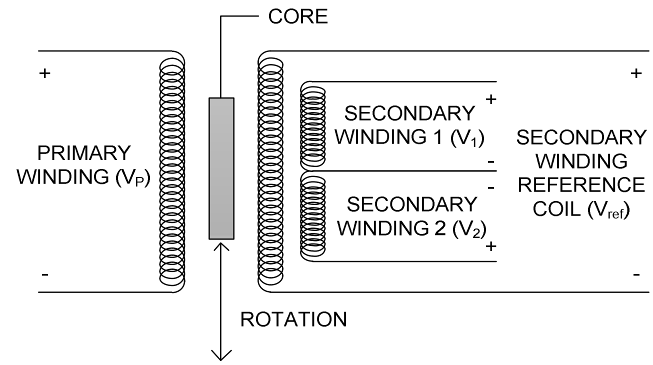

Figure 3. Concept of reference coil

commercial application, RVDTs are not widely used.

However, in 1990s, differential transformers printed on PCB were developed for use in RVDTs, greatly reducing the RVDT size. Due to the smaller size and longer reliability period, the car sensors are changed from mechanical sensors that guarantee a less than 10 years reliability period to contactless magnetic sensors. However, a small size RVDT has some problems that need to be resolved. First, a differential transformer printed on PCB limits the size of the transformer. Therefore, the inductance is small. Second, due to the small inductance value, the RVDT should use a high excitation frequency of over 1 MHz. At low frequencies of less than hundreds-kHz, a core that consists of high permeability materials can be easily fabricated. However, at high frequencies of more than 1MHz, producing a core using a high permeability is challenging, as the permeability of most ferromagnetic materials is reduced or their characteristics are altered, which reduces the magnetic field at high frequency due to eddy current. Hence, for using a RVDT at high frequency, these problems can be solved by using special ferromagnetic materials that have high permeability at high-frequency or by utilizing magnetic field loss. Ferromagnetic materials with high permeability that operate at high frequency are, however, expensive. As a result, this method is not appropriate for sensor applications where cost and size are issues. Therefore, for high frequencies applications, many have attempted to obtain angular information by detecting the magnetic field loss.

However, when utilizing the magnetic field loss, new problems occur at high frequencies. In the case of using a ferromagnetic material, the strength of the magnetic field in the ferromagnetic material is very strong compared to the strength of the magnetic field without ferromagnetic material. As a result, the output signal of the transformer's secondary coil that is not shaded by the magnetic core can thus be ignored, compared to the output signal of the transformer's secondary coil that is not shaded by the magnetic core. Therefore, the results of basic signal processing, which are calculated by using Eq. 1, are ideally between -1 to 1 depending on the angle of the core. On the contrary, in the case loss of the magnetic field is used, the output signal of the secondary coil that is shaded by the magnetic core is smaller than the output signal of the secondary coil that is not shaded by the magnetic core. In this case, two output signals of the secondary transformer's coils are not substantially different. Therefore none of the output signal from transformer's secondary coil can be ignored. Therefore, the results of basic signal processing that is calculated by utilizing Eq. 1 are between –k to k depending on the angle of the core. The value of k is less than 1 and is proportional to the loss of the magnetic field energy. And the distance between the core and the coil, and the type of the core material determine the loss of the magnetic field energy. As a result, closer distance between the coil and the core, larger k. If x and y-axis represent the angle of the core and results of signal processing, respectively, the slope (or sensitivity) will change depending on the distance between the core and the coil. If this position sensor is used for accelerator position sensor, accelerator sensitivity can be changed by abrasion. Even if accelerator is not being stepped on, the car system recognizes as acceleration which can lead to unintended acceleration. Fig.2 represents this slope variation as a function of gap variation, in this case the k value is around 0.3, which is a small value compared to that obtained with a core that consists of ferromagnetic material. In addition, when using a LVDT(Linear Variable Differential Transformer) which operates as a same principle of RVDT and has same problems of RVDT, sensitivity variation also occurred.

To solve these problems, [6],[7] use multi-coil for a LVDT or RVDT and [2],[3],[4],[5] adopt additional secondary coil for a LVDT or RVDT to obtain the information of the distance between the coil and the core. This paper suggests a method that adds a coil to obtain the distance information between the coil and the core and to remove environmental factors.

II. PROPOSED STRUCTURE AND SIGNAL PROCESSING

The authors propose a new method that entails adding a third coil in the secondary part of the transformer which the output signal is not changed by the angle. Rather the output signal is changed by applying excitation signal and varying the distance between the coil and the core. This third coil will be referred to hereafter as a reference coil. The concept of a reference coil is illustrated in Fig. 3. By using a high

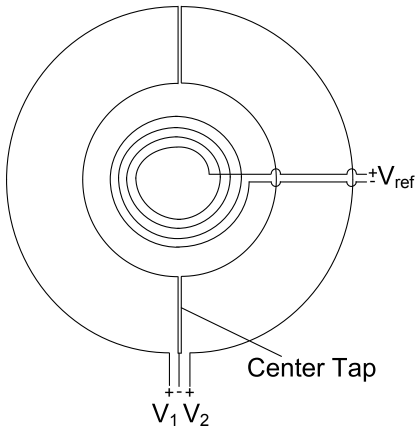

Figure 4. Structure of secondary coil.

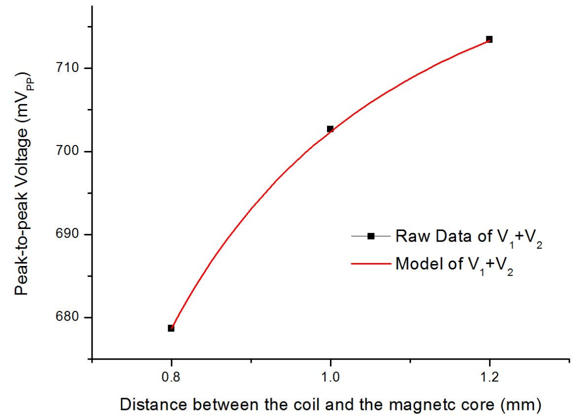

Figure 5. Raw data and Model of V_1+V_2.

frequency magnetic field, because of eddy current, smaller distance between the coil and the core results in a weaker output signal due to the large magnetic field energy loss. Fig. 4 represents a example of secondary winding including reference coil. When the distance between the coil and the core is changed, sensitivity variation in the signal processing results represented in Fig. 2 can be prevented by using this phenomenon. As described in section 1, results in Fig.2 calculated by conventional signal processing Eq. 1 show the reduction in RVDT sensitivity by increasing the distance between the coil and the core. On the contrary, the output signal of the reference coil increases by increasing the distance between the coil and the core. In order to take advantage of these phenomena, equation can be derived as

$$\theta = k\frac{V_{ref}}{V_P}\frac{V_1 - V_2}{V_1 + V_2} \tag{2}$$

where k is a gain parameter that is determined by structure of RVDT, V_{ref} is a output voltage of reference coil and V_P is excitation signal of transformer primary coil. Eq. 2 compensates the effect of changing the distance between the coil and the core by using the ratio of V_P and V_{ref}. However, V_{ref} can be changed by the excitation signal V_P and environmental factors such as humidity and temperature. Eq. 2 can compensate only V_P variation. Therefore, a method to compensate environmental factors is also needed. To address this problem, two reference coils that have different slopes reflecting the change in the distance between the coil and the core can be used. Environmental factors can also be compensate by using

$$\theta = k\left(m + \frac{V_{ref1} - V_{ref2}}{V_{ref1} + V_{ref2}}\right)\frac{V_1 - V_2}{V_1 + V_2} \tag{3}$$

where k is a gain parameter that is determined by structure of RVDT, m is an important variable that is needed to compensate the offset determined by the relation of two different reference coils and V_{ref1} and V_{ref2} are output voltage of two different reference coils. In order to eliminate effect of environmental factors, Eq. 3 using a ratio-metric signal processing. However, this method needs two additional coils, thus increasing its cost. As such, it is necessary to minimize the number additional coils. In the experiment for obtain Fig. 2, the V_1+V_2 signal is not changed by rotation of the core. Rather, V_1+V_2 is changed by distance of the coil and the core. V_1+V_2 can thus replace one reference coil. Therefore, Eq. 3 can be changed to

$$\theta = k\left[m + \frac{V_{ref1} - (V_1 + V_2)}{V_{ref1} + (V_1 + V_2)}\right]\frac{V_1 - V_2}{V_1 + V_2} \tag{4}$$

where variables are already explained in Eq. 1 or Eq. 3. In Eq. 4, only one reference coil is needed to compensate the variation of the distance between the coil and the core and other environmental factors.

III. MODELING AND VERIFICATION

To verify the compensation method, this section describes the modeling between the output voltage of transformer's secondary side coil and distance between the coil and the core. The high frequency magnetic field excited by the primary coil loses the magnetic energy by the core. This magnetic power loss determines the reduction in the output voltage of the secondary coil. The loss of the magnetic energy is proportional to the strength of the magnetic field in the core. According to the electromagnetic theory, the strength of the magnetic field is inversely proportional to the square of the distance. The model curve was obtained by applying

$$V_{OUT} = k_1 - \frac{k_2}{(d - k_3)^2} \tag{5}$$

where k1 represents the amplitude of the output voltage without magnetic energy loss caused by the core, k2 represents the voltage loss determined by the material and shape of the core and the d which has mm units, indicates the distance between the coil and the core. However, some error

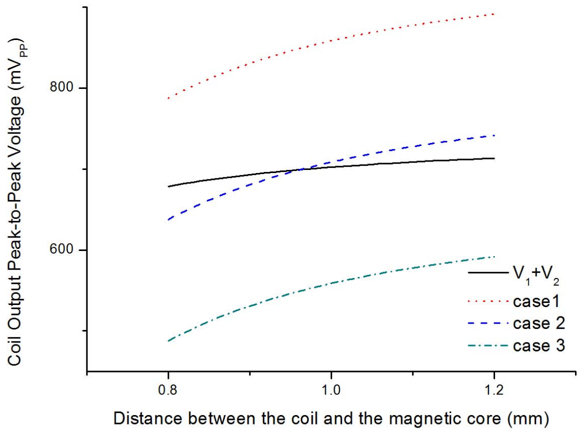

Figure 6. Model of V_1+V_2 and Expected three cases model of reference coil

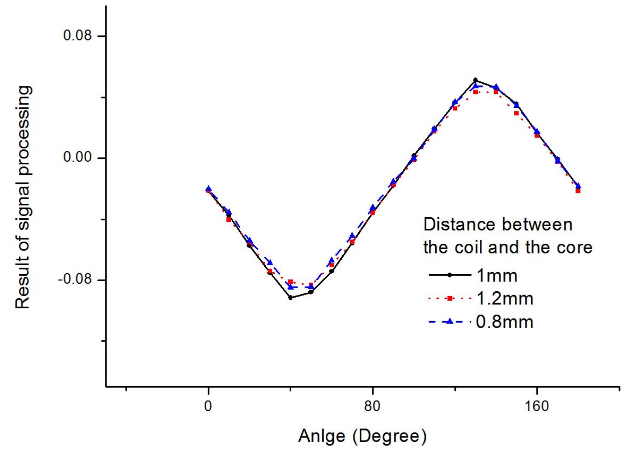

Figure 7. Results of advanced signal processing at high frequency.

terms can exist in the equation. Therefore, it is necessary to correct the error using the k3 variable. Fig. 5 represents a fitting model of V_1+V_2 and actual V_1+V_2 value that the results of the experiment depending on the distance between the coil and the core, by setting the distance between the coil and the core and the amplitude of V_1+V_2 as x and y-axis. This paper assumes that the output signal of the reference coil varies more than the V_1+V_2 signal depending on the distance between the coil and the core. Note that it is easy to make the output signal of the reference coil vary more than the V_1+V_2 signal depending on the distance between the coil and the core by larger number of windings in the reference coil than the other secondary coil. Three cases about the output signal of reference coil are modeled. These three case shows how much sensitivity variation of RVDT is calibrated. In case 1, the reference signal amplitude is larger than the V_1+V_2 signal. In case 2, the reference signal amplitude is similar to the V_1+V_2 signal. In case 3, the reference signal amplitude is smaller than the V_1+V_2 signal. Fig. 6 shows these three cases' output signal of reference coil and V_1+V_2 signal that has similar characteristics with reference coil. Fig. 7 shows results calculated by using Eq. 4 for these three cases of the reference signal shown in Fig. 6 and the secondary coil signal shown in Fig. 2. In Fig. 7, slope variation is much smaller than that in the Fig. 2. Sensitivity variation, m value in Eq. 4 and degree of sensitivity calibration is represented in

TABLE I. PERFORMANCE COMPARISON OF RVDT

	Conventional RVDT		Case1		Case2		Case3	
Gap (mm)	0.8	1.2	0.8	1.2	0.8	1.2	0.8	1.2
Sensitivity Variation (%)	+16	-14	-6	-7	-5	-7	-6	-7
m value			0.18		0.04		0.37	
Sensitivity calibration (%)			76		76		76	

In table-1, gap represents the distance between the coil and the core, sensitivity variation results calculated by comparing the sensitivity (or slope) at 1.0 mm gap. Sensitivity calibration can be calculated by using

$$SC = 1 - \frac{SVWR}{SVWOR} \tag{6}$$

where SC indicates sensitivity calibration, SVWR sensitivity variation with the reference coil and SVWOR sensitivity variation without the reference coil. By exploiting the conventional signal processing technique without a reference coil, the slope of the output signal changes from -14% to 16% by changing the gap by ±0.2 mm around a 1.0 mm. To compensate this variation, by using the new method, the slope of the output signal is expected to change from -7% to 0% by changing the gap by ±0.2 mm around a 1.0 mm. The variation of the sensitivity decreases by 76% with use of the reference coil compared to the case without the reference coil.

IV. CONCLUSION

This paper proposes new structure and signal processing to solve problem that is sensitivity variation of RVDT. By adding one additional coil and utilizing a ratio-metric signal processing, sensitivity variation and environmental factors are compensated. By using model that represents the relationship between output signal of the coil and distance between the coil and the core, this paper predicts how the effect of the distance variation between the coil and the core is compensated. In case that changing the distance between the coil and the core by ±0.2 mm around a 1.0 mm, sensitivity varies from -14% to 16% by utilizing conventional structure and signal processing, sensitivity varies from -7% to 0% by utilizing proposed one. Therefore, it can be said that the sensitivity variation of RVDT can be decreased by 76%, by exploiting proposed structure and signal processing.

V. ACKNOWLEDGEMENTS

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