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A SURVEY OF EDDY CURRENT DISPLACEMENT SENSORS: IMPERFECTIONS AND SIGNAL CONDITIONING METHODS

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In this paper, we focus on eddy current sensors (ECSs) as important candidates for measuring short-range displacements. First, the imperfections of these sensors are discussed, and then signal conditioning methods are addressed. The benefits and the drawbacks of each technique, which should be considered by the designer, have been mentioned. The focus of the survey is on high performance ECSs. The discussions are based on theoretical and experimental results.

Keywords: ECS, imperfections, signal conditioning methods, qualitative comparison.

1. INTRODUCTION

Measuring displacement is one of the important demands in the sensor world. Next to direct measurement of the displacement, displacement sensors are utilized also for detecting other measurands such as pressure, acceleration, etc., making the application range of these type of sensors very wide.

Based on the conversion principle, the currently most often used displacement sensors can be classified in the following five groups [1]: laser interferometry, ultrasonic sensors, capacitive sensors, magnetic sensors, and eddy-current sensors (ECSs).

An ECS comprises a moving target, (an) excitation coil(s), and a signal conditioning circuit. With respect to capabilities and operating principles, the closest competitor to the ECS is the capacitive sensor. Unlike the capacitive sensors, the ECSs have the advantage to be much less sensitive to a number of environmental variations like: contamination, temperature, humidity, etc. [1-3]. As disadvantages of the ECS, compared with capacitive sensors, a limitation of choosing the target thickness due to the penetration depth effect, parasitic components with more effective roles, and no wide-range of target materials can be mentioned. An experimental comparison between capacitive and eddy current sensors has been presented in [4]. The main conclusion is that ECS is a good candidate for measuring short displacements, particularly in severe conditions. Potential applications using ECSs include: wear bearing sensors, small gap measurements, accelerometers, etc.

In this paper, the imperfections and the methods for signal conditioning of the ECS are surveyed, based on theoretical and experimental results. The initial results are useful for sensor design and application selection.

2. ECS IMPERFECTIONS

Most often ECSs are constructed in such a way that a sensing coil, being usually planar, is placed in front of a metallic (conductive) target. As a result of Lenz's law, by stimulating the coil with an AC current a mutual inductance appears between the coil and the target. The equivalent magnetic circuit is modeled by an air-coil transformer [1, 3, 5] such that the mutual inductance is related to the displacement x.

Figure 1 shows the electrical model of the sensor probe, where L, R, and C are the equivalent inductance, resistance, and capacitance of the sensor probe, respectively. The equivalent inductance and resistance are formulated as [5]:

$$R = R_1 + \frac{(2\pi f)^2 M^2}{R_2^2 + (2\pi f L_2)^2} R_2 \quad (1)$$

$$L = L_1 - \frac{(2\pi f)^2 M^2}{R_2^2 + (2\pi f L_2)^2} L_2 \quad (2)$$

where R_1, L_1, and R_2, L_2, are related to the geometric dimensions of the coil and the target, respectively; f is the frequency of the excitation signal; M is the mutual inductance between the coil and the target, which is inversely related to x^2 [6]. As can be realized from Figure 1, and also eq.1 and 2, the quality factor $Q = 2\pi fL/R$ of the sensor head is limited by the presence of R. Whenever the target moves, the series resistance changes are opposing the $2\pi fL$ changes (see eq.1 & 2) and as a result, the sensitivity is limited. Therefore, this phenomenon affects the sensor accuracy negatively (see Figure 2b). Typically, R varies between R_1 and $2R_1$, (R_1 is the coil resistance in the target absence case) [3].

Because of the nature of the coil, formed by some winded wire turns, an inter-winding capacitance appears in the model. Additionally, in some architectures, such as planar coils, the coil is constructed by some layers creating extra parasitic capacitances. This capacitance affects the sensor accuracy, as well as the parasitic resistance. This capacitor is not dependant on the measurand value - displacement x. ECS is not well sensitive to the displacement of the targets being farther away from the sensing coil. In practice, the maximum practical distance that can be measured by an ECS, depends on the coil radius. The recommended ratio between the measured distance and the coil radius is between 0.05 and 0.15 [5], but in the less demanding applications can reach 0.5 [7].

In reality, eddy currents penetrate in the target. This effect is characterized by the skin depth δ. If the thickness of the target is 2-3 times larger than δ, the skin effect can usually be neglected among the effective parameters in the measurement [8]. Utilizing small-surface targets cuts the eddy currents due to the narrow lateral and/or vertical width of the target. In this case, the eddy current distribution is difficult to be predicted analytically [7]. To avoid this effect, it is recommended that the diameter of the target should be at least two times bigger than that of the coil [2]. Eq.1 and 2 reveal that whenever the frequency of the excitation signal changes, the values of L and R change, as well. This effect appears as a serious problem if the frequency drifts because of a changing factor such as the temperature. As an unwanted result, the signal conditioning circuit may show displacement, while in reality the target doesn't move.

Shielding should also be taken into account due to external electromagnetic interferences. The non-homogeneity of the permeability of ferrous materials can affect the eddy current density [3]. Thus, conductors are the best candidates for the target material.

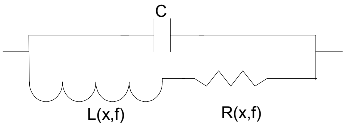


Figure 1. Electrical model of an ECS with the parasitic components

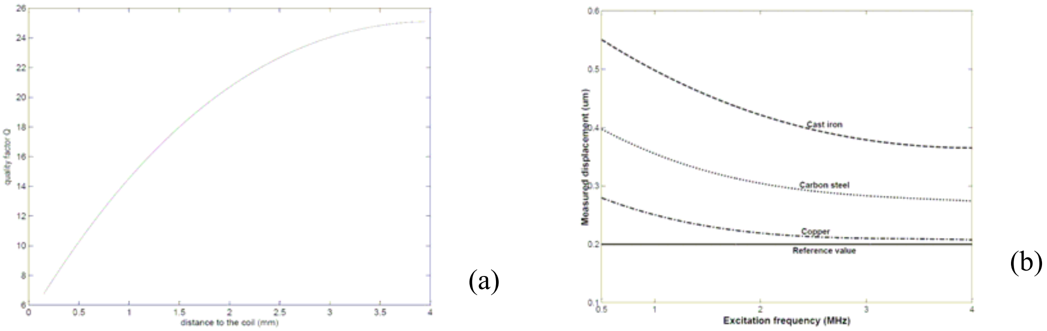


Figure 2. Typical attributes of ECSs (a) Quality factor of an ECS probe with 15mm-diameter coil; (b) Influences of material and frequency on measured values (the higher the frequency, the bigger the quality factor)

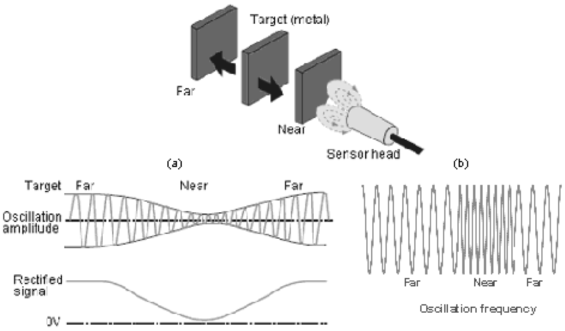


Figure 3. ECS signal conditioning: (a) AM-based, (b) FM-based

3. SIGNAL CONDITIONING IN ECS

In this section we discuss some possibilities for the signal conditioning of the ECS, taking into account the imperfections mentioned earlier. The method of the signal conditioning can be classified as: (i) using an external excitation signal; and (ii) self-oscillation (SO). Principle (i) is based on measuring the amplitude of the signal exciting the coil. In the alternative interfacing method, the coil is a part of an oscillator. The information of interest can be the frequency or the amplitude. Based on this, the SO method can be either AM- (amplitude modulation) or FM- (frequency modulation) oriented (see figure 3).

An auto-balanced bridge circuit is depicted in Figure 4a [9]. The transfer function is:

$$\frac{V_o}{V_i} = \frac{z_4 / z_3 - z_2 / z_1}{1 + z_4 / z_3} \qquad (3)$$

By expressing $z_2=z_0(1+u)$, $z_1=z_0/k$, and $z_3=z_4=z_0$, where z_0 is the reference impedance, u is the impedance variation coefficient (varies due to the displacement), and k is defined by the designer by choosing z_1, we can rewrite expression (3) as:

$$\frac{V_o}{V_i} = \frac{1 - k - ku}{2} \qquad (4)$$

$$\beta = \frac{z_1}{z_1 + z_2} = \frac{1}{1 + k(1+u)} \qquad (5)$$

where β is the feedback factor. Regarding eq.4, by choosing a big k, it is possible to magnify the variation of u. The transfer function can be linear by using simple calibrations. Nevertheless, increasing k causes the feedback factor to be low (see eq.5) and thus the bandwidth of the operational amplifier will be limited (for a specified power consumption). Moreover, inductors contain series resistances. Because of it k is a complex number, resulting in a phase shift, which can make the loop unstable.

Figure 4b shows another signal conditioning option for an ECS using an external excitation signal. A Gm block converts the AC voltage, applied from a stable oscillator, to an AC current, which is then injected into the coil. The Gm block can be realized with a single transistor. Unfortunately this will result in Gm dependency on the input signal level, as well as it will be highly sensitive to temperature variations. Therefore, it is required to make a stable Gm circuit. Due to this requirement, the Gm block should be realized as a multiple transistor solution, which will increase the noise level and the power dissipation. The peak detector (or an AC-DC converter) should also have a very low thermal drift.

An alternative circuit, based on the same principle, is shown in Figure 4c. Compared with the former scheme, in this circuit the peak detector is eliminated, which will improve the stability in general, in the cost of increased sampling rate requirement for the ADC (analog-to-digital converter). The demodulated signal is obtained by mathematical operations done by the microprocessor. Such a solution can be a good choice whenever power consumption is not a concern.

In the considered architectures, the coil has to be designed in such a way that the inter-winding capacitor is kept quite small. Otherwise it can lower the sensitivity to the displacement considerably because it is in parallel with the variable inductor. This parallel impedance causes the total impedance to become small. Besides, the natural resonance frequency of the coil, related to this capacitor, should be considered. The excitation frequency should be far from the coil resonance frequency.

In another approach depicted in figure 5a, the information of interest is the frequency of the signal rather than the amplitude. The sensor is a part of an LC network causing oscillation. Changing L decreases/increases the frequency of oscillation (see Figure 3b). Because of using an LC network, acting as a band-pass filter, this approach has an increased immunity to electromagnetic interferences (EI) [9, 10] as well as the high sensitivity to the sensor signal due to the nature of resonance. Using differential coils for the oscillators improves the sensitivity and the linearity of the output. The interface solution in Figure 5a can demonstrate a high-resolution, but its main drawback is the high power consumption, mainly due to the need of a high resolution PLL (phase locked loop), requirement. Moreover, the oscillators should have a low phase noise and thermal drift, and the thermal drift of the mixer has to be very low, as well. The design complexity and the high power consumption of this system are the main reasons that it cannot be a proper low-power candidate for the ECS signal conditioning.

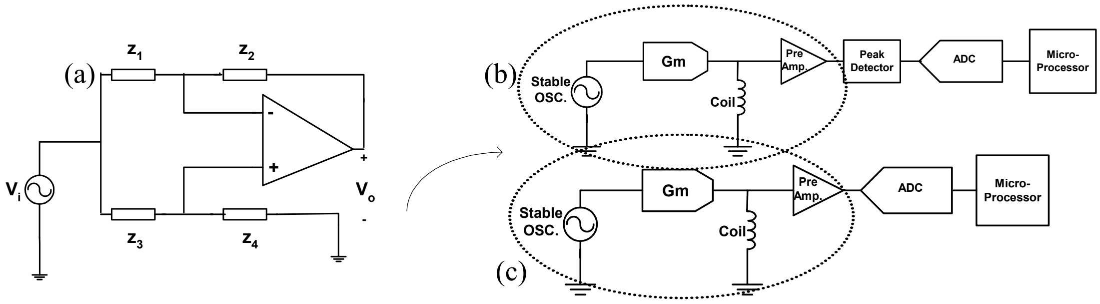


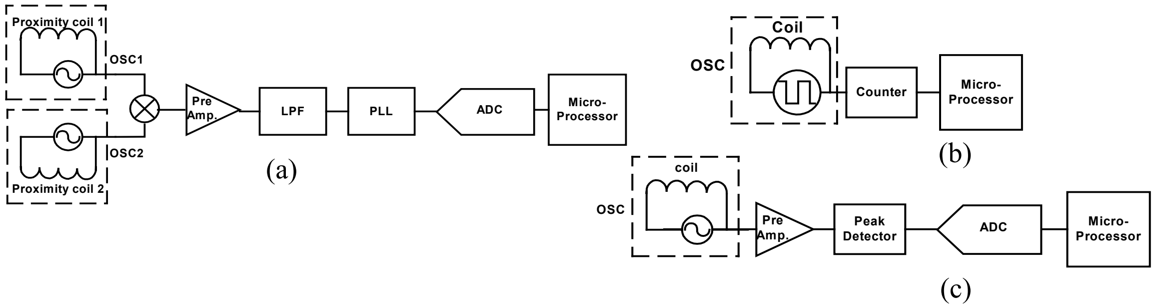
Figure 4. ECS signal conditioning regarding the amplitude (a) with auto-balanced circuit (can be replaced as the preceding stage in (a) or (b)) (b) with peak detector (c) without peak detector

Figure 5b depicts another relatively simple interface possibility with digital frequency (or duty cycle) measurement. The sensing coil is a part of a relaxation/harmonic oscillator, and defines its oscillation frequency [11], [12]. Suppose that the working frequency changes between 1MHz and 2MHz. If we want to distinguish the period with 16-bit resolution, it implies that the clock frequency of the counter should be:

$$f_{clk}=1/t_{clk}=2^{16}/1\mu s \approx 65GHz \qquad (6)$$

where t_{clk} is the period of the clock signal of the counter. This simple calculation shows that considering such values of the clock frequency, direct measurement is not logical. One solution to go around this problem is the working period to be multiplied by a large number (e.g. 1000). Another source, which affects the resolution and should be taken into account, is the clock jitter. In the relaxation oscillator version of this interface usually an operational amplifier is used - in the role of a comparator. This operational amplifier is a serious source of the noise, as well as the thermal drift. Therefore, temperature compensation is required, as it has been done in [13], by using special components.

The AM-oriented SO method is shown in figure 5c. The dependency of the output amplitude of the oscillator on the inductance makes the circuit sensitive to the displacement. Potentially, this architecture can be utilized for very high resolution applications because harmonic oscillators, commonly used as an option for implementing the front-end oscillator, include only 1-2 transistor(s). Therefore, the imposed level of noise is quite low. Additionally, it seems that the Gm block is eliminated, compared to its AM-based counterpart (see figure 4b). If utilizing differential coils with a ratio metric type of signal reading, problems coming from the frequency drift can be eliminated considerably. In this approach, immunity to EI is also seen like FM-based schemes.



(a)

(b)

(c)

Figure 5. SO ECS signal conditioning with: (a) analog frequency measurement; (b) digital frequency measurement; (c) amplitude measurement

Table I Presents a qualitative comparison of the considered architectures, based on the most important parameters. As mentioned, the equivalent components are frequency dependent. So, frequency drifts due to the external factors, can introduce serious problems, such as showing an unreal displacement, particularly in FM-Based schemes.

Table I. Qualitative comparisons of different schemes

System type	Design complexity	Variations of working frequency	Expected resolution	Thermal drift	Power dissipation	sensitivity	Considerations
1:Fig. 4b	medium	-	medium/high	medium/high*	medium	medium	*dependent on the Gm block
2:Fig. 4c	medium	-	high	low	very high	medium	-
3:Fig. 5a	high	high*	high	medium/high	high	high	*some MHz
4:Fig. 5b	medium	high	medium	medium*	low/medium	high	*maybe temp. comp.
5:Fig. 5c	medium	low*	medium/high	low/medium	low	medium	*with differential coils

4. CONCLUSION

In this paper the imperfections of the eddy current displacement sensors are discussed. Additionally, the signal conditioning methods for ECSs have been considered and compared qualitatively. Based on the article, the designer can select a proper option regarding the application. As discussed, AM-based SO technique utilizing ratio metric measurement is a proper candidate for implementing a low-power high-resolution ECS.

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