Simulation and design of ECT differential bobbin probes for the inspection of cracks in bolts

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Abstract. All Various defects could be generated in bolts for a use of oil filters for the manufacturing process and then may affect to the safety and quality in bolts. Also, fine defects may be imbedded in oil filter system during multiple forging manufacturing processes. So it is very important that such defects be investigated and screened during the multiple manufacturing processes. Therefore, in order effectively to evaluate the fine defects, the design parameters for bobbin-types were selected under a finite element method (FEM) simulations and Eddy current testing (ECT). Especially the FEM simulations were performed to make characterization in the crack detection of the bolts and the parameters such as number of turns of the coil, the coil size and applied frequency were calculated based on the simulation results.

1. Introduction

Oil filters for a use for vehicular parts are being used under the high temperature and cooling of the engine and defects could be generated under repetition in the operation environment as well as shape changes such as very high internal loss for the bolts [1]. Also, it is impossible to check the defect caused inside the bolt as shown in figure 1 visually. These defects could make engine efficiency dropped when operating the engine, and may lead to accelerated wear and damage to the engine parts by many abrasive particles contained in the lubricating oil, if not prevented in advance upon finding in its initial stage. Such things may affect the life and efficiency of auto engine leading to serious economic problems. Therefore, as an applicable method for detecting such fine surface defects of a few hundred μm inside the bolt, ECT techniques are known as the best among the non-destructive

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evaluation methods [2-9].

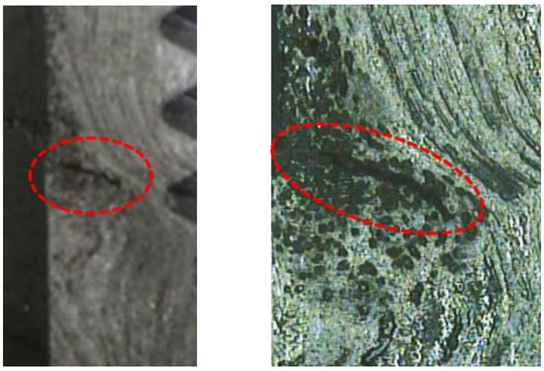


Figure 1. Internal defect of 1 mm size caused on the oil filter bolts

Oil filter bolts have high possibility of causing wears in the lubrication phase. Types of wear are of fusion, wear and burning respectively. By high temperature, cooling and high speed operation of engine, scant oil flow, foreign material from outside and particles in the oil may cause wear [2]. Defects developed on the surface were classified into circumferential crack, axial crack and angular crack respectively, and the work in this study has focused on the development of differential bobbin eddy current sensor that is applicable to detect the circumferential crack.

In this study, standard specimens with a rod type were prepared and differential bobbin eddy current sensor was designed, which can detect fully circumferential cracks on the surface of the specimen. Using the designed sensor, experiment was conducted for the standard specimen, and the results of the experiments were compared against each other. It was found that the differential bobbin eddy current sensor thus developed was appropriate for detecting cracks on the bolt.

2. Related theory

2.1. Eddy current testing

When AC current flowing coil is brought near to the conductor of test specimen, the primary magnetic field generated by the current flowing in the coil induces secondary magnetic field on the conductor. An eddy current coil developed from AC current can be obtained roughly by AC Circuit that includes resistance and inductance. Impedance, Z, the ratio between the voltage and current, is obtained by use of Ohm's Law. Impedance, Z, is shown as follows.

$$Z = \frac{V}{I} \tag{1}$$

When an AC current flow through coil inductance, L, at frequency f, impedance of coil is identical to the induced reactance of the circuit, X_L. Likewise, impedance of AC current flowing in the coil of resistance R and inductance L at operating frequency f is shown as the following formula.

$$\mathrm{Z} = \mathrm{R} + \mathrm{j}X_L = R + \omega jL = R + j2\pi fL \tag{2}$$

Magnitude of impedance in the coil and phase angle can be expressed as follows.

$$\mathrm{Z} = \sqrt{R^2 + {X_L}^2} \tag{3}$$

$$\theta = Tan^{-1}\left(\frac{X_L}{R}\right) \tag{4}$$

2.2. Standard penetration depth

When eddy current probe is placed on the test specimen, the eddy current induced into the test specimen is not distributed evenly in the test specimen. Density of the eddy current is highest in the surface of the test specimen, decreasing by the depth below the surface of the specimen. This is called skin effect. Equation of standard penetration depth is shown as below;

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma}} \tag{5}$$

By Eq. (5), standard penetration depth for frequencies has been calculated as shown in table 1 below.

Table 1. Standard depth of penetration.

Frequency (kHz)	δ(mm)	2δ(mm)
1	0.6426	1.2851
5	0.2874	0.5747
10	0.2032	0.4604
15	0.1659	0.3318
20	0.1437	0.2974
30	0.1173	0.2346
40	0.1016	0.2032
50	0.0909	0.1817
100	0.0643	0.1285

2.3. Wheatstone bridge

Two general systems are used; i.e. electrical bridge circuit and filter circuit. These two systems make impedance, Z, the value related with basic signal, electrically equilibrium. As shown in figure 2, Wheatstone Bridge was employed in the experiment. Formula of equilibrium is as follows.

$$\frac{Z_1}{Z_2} = \frac{Z_3}{Z_4} \tag{6}$$

Once the condition of Eq. (6) is reached, the system becomes equilibrium and the volt meter reads zero (0). Therefore, phase value and amplitude are measured using Wheatstone Bridge [5].

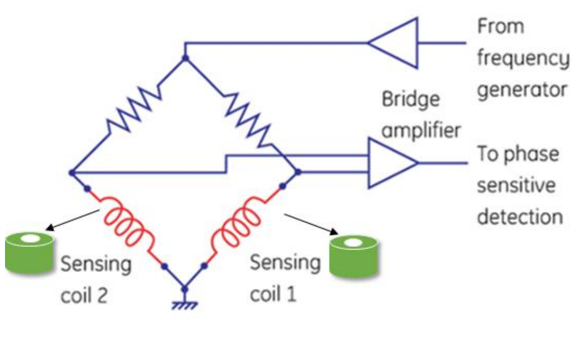


Figure 2. Wheatstone bridge.

Figure 3. Standard Test specimen.

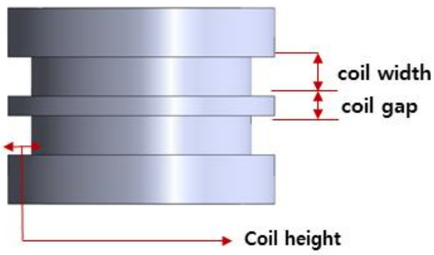
3. Developing eddy current sensor for bolts

3.1. Eddy current design and manufacture

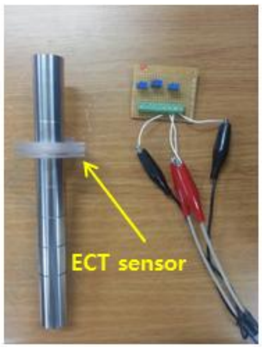
In this study, the ultimate objective can be realized by use of interior eddy current sensor when detecting the surface defect developed in the oil filter bolts. Interior eddy current sensor is structurally identical to the exterior eddy current sensor for detecting exterior surface defect in the simulation test specimen as shown in figure 3.

Design parameters required for designing eddy current sensors can be thought of coil wire diameter, coil gap, coil width, height, coil turns, lift-off, frequency and others as shown in figure 4(a).

In this work, coil gap, coil width and frequency were selected as design parameters. For coil wire, coil of 0.1 mm in diameter was used, with 100 coil turns and 0.5 mm lift-off. With consideration of other parameters, a most optimum eddy current sensor was developed. Lift-off is one of important design parameters in designing eddy current sensor. Smaller lift-off makes the magnetic field induced in the test specimen stronger. So, lift-off was set to 0.5 mm. Using the bobbin eddy current sensor thus manufactured, defect signal of fully circumferential cracks were detected by moving the test specimen in axial direction. Experiment was conducted for change of test frequency and for change of coil width and gap.

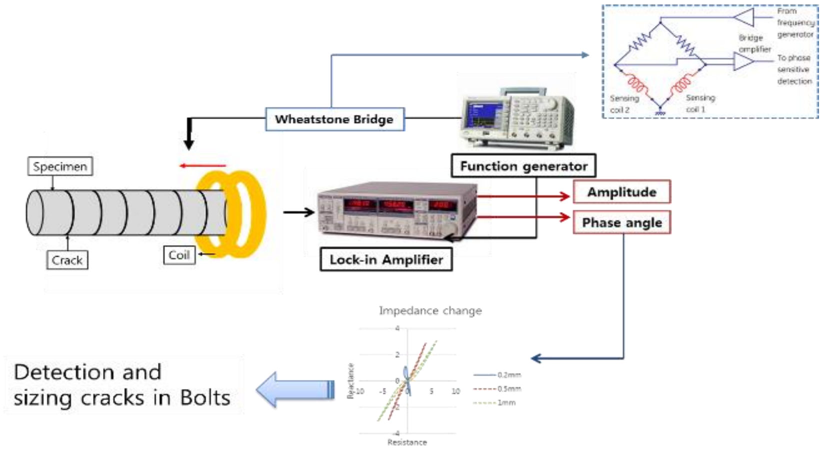


(a) Coil parameter



(b) Manufactured Probe

Figure 4. Differential bobbin probe.



(a) Eddy current testing system configuration for bobbin probe

(b) Experiment setup

Figure 5. Eddy current testing system.

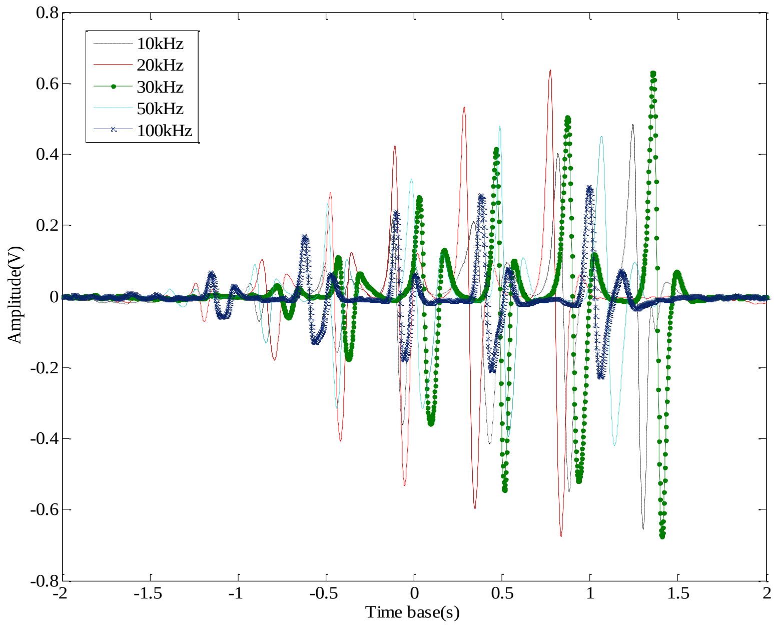
3.2. Making standard test specimen

Simulating oil bolt of 25 mm inner diameter as shown in figure 2, rod shape standard test specimen of 25 mm outer diameter and 231 mm length was made for inspecting exterior surface defects. Among the defects that may be generated outside, circumferential cracks of 0.5 mm width and 0.1, 0.2, 0.4, 0.6, 0.8 and 1 mm depths respectively that may be possible to inspect by the bobbin were artificially notched by EDM on the test specimen. Standard Test Specimen was of AISI 1045 Steel.

3.3. Eddy current test systems

In order to evaluate the signal property of the differential bobbin eddy current sensor applicable to detect defects in the test specimen, eddy current system was developed by application of Wheatstone Bridge as shown in figure 5(a).

In order to make Bobbin Eddy Current Sensor possible to evaluate defect detecting property of test specimen having fully circumferential cracks, frequency generating system has employed Function Generator of Tektronix having frequency band of 100 MHz. Through these Lock-in amplifier and Oscilloscope, change of amplitude value, i.e. amplitude change of impedance and change of phase value could be obtained. Experiment instruments used for sensor design and performance evaluation were as shown in figure 5(b).



(a) Comparison of amplitude value for test frequency

(b) Comparison of phase valves within the test frequency range

Figure 6. Comparison of amplitude and phase value ((a), (b)) for frequencies of 10, 20, 30, 50 and 100 kHz.

3.4. Evaluation of ECT property by change of frequency

For frequencies used in this work, amplitude and phase value were obtained as test results by lock-in amplifier and oscilloscope as shown in figure 6. The experiment was carried out with frequencies of 10, 20, 30, 50 and 100 kHz, and values of amplitude and phase were shown in figures 6(a). It could be observed that deeper the depth of defect in the specimen made bigger the change of amplitude and phase value. Frequencies used in the experiment were overlapped as shown in figures 6(a) and 6(b). In figure 6(a), it was found that signals from 20 kHz and 30 kHz were of similar strength each other and stronger than from other frequencies. This indicates that these frequencies are capable to detect defects of 0.2 mm depth since the values of 2 δ for frequency of 20 and 30 kHz are 0.29 mm and 0.23 mm respectively in table 1.

Therefore, in this study, frequencies of 20 kHz and 30 kHz could be selected as finally applicable for depth of defect minimum 0.2 mm [10]. In this study, frequencies of 10, 20, 30, 50 and 100 kHz were used in the experiment, which is the frequency range decided by Eq. (5) and table 1. With changing of frequencies, surface defect signals from the test specimen were obtained. As shown in figure 7, differences of amplitude and phase value by change of defect depth could be observed. From the experiment, it could be found that frequency of 50 and 100 kHz had lower sensitivity of detecting defect signals than the other 3 frequencies of 10, 20 and 30 kHz.

In figure 7, 20 kHz and 30 kHz showed similar level of change, and phase value became smaller by the order of 10, 20, 30, 50 and 100 kHz. Even though 10 kHz made the biggest change of phase value, it was excluded in further experiment since this is not adequate for detecting defect of 0.2 mm depth, the final objective of this study. So, it was found that frequency of 20 kHz could be a best case for detecting cracks due to higher sensitivity.

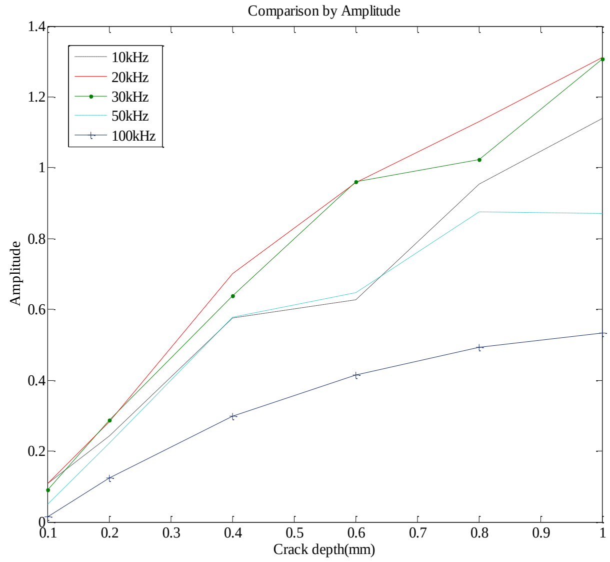
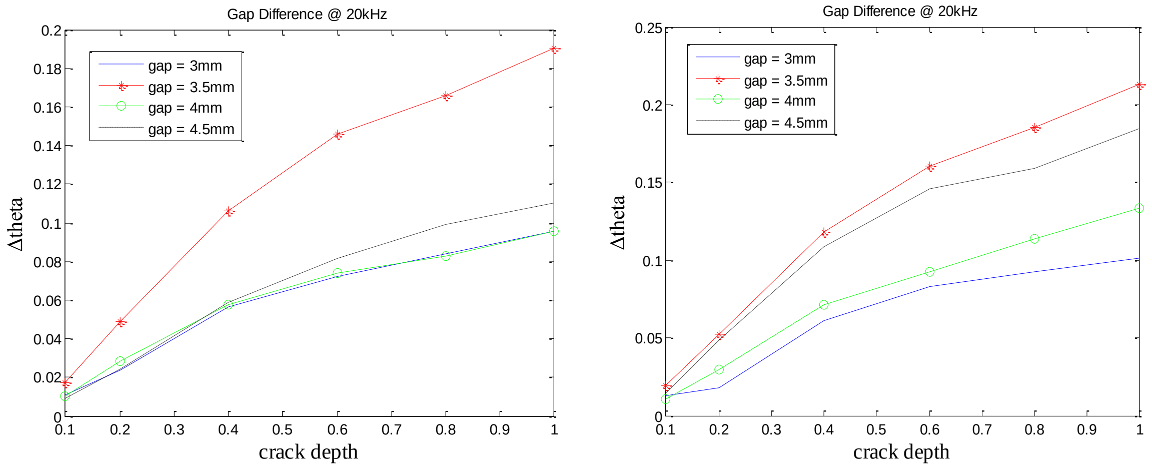


Figure 7. Comparison of amplitude value difference of bobbin eddy current sensor by change of test frequency.

3.5. Evaluation of ECT Characteristics by Change of Coil Gap

Experiment was conducted with change of Coil Gaps for test frequency of 20 kHz and for coils of 1 mm and 2 mm width respectively. With change of Coil gaps in 0.5 mm levels by 3 mm, 3.5 mm, 4 mm and 4.5 mm respectively, change of signal characteristics for 4 coil gaps could be obtained as shown in figure 8, and made analysis.

When compared at test frequency of 20 kHz as shown in figure 9, ΔPhase value of coil gap for coil width of 1 mm and 2 mm respectively, it was found that the ΔPhase value was the biggest at coil gap of 3.5 mm, and the value became bigger when coil width was 1 mm [10].



(a) coil width 1 mm @ 20 kH (b) coil width 2 mm @ 20 kHz

Figure 8. Comparison of ΔPhase value by change of coil gap (Frequency 20 kHz).

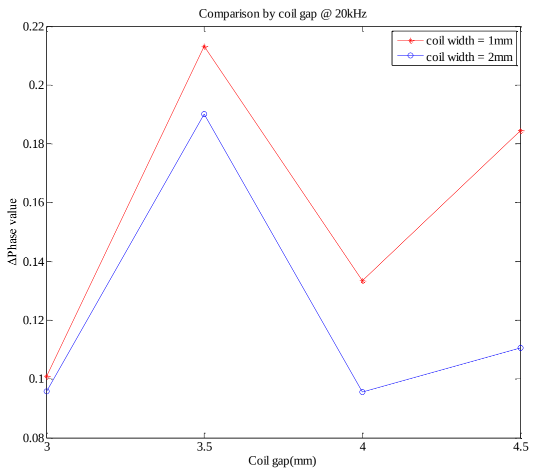


Figure 9. 20 kHz, Comparison of ΔPhase values for coil width of 1mm and 2 mm and coil gaps when depth of defect is 1 mm.

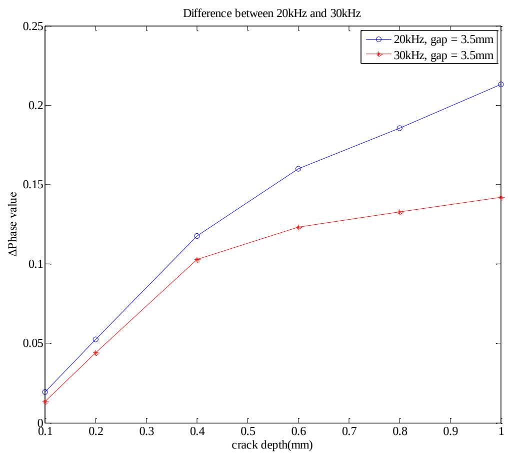


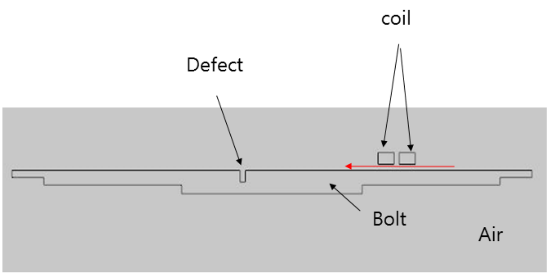
Figure 10. Comparison of ΔPhase value when coil width is 1 mm and 3.5 mm gap for frequency of 20 and 30 kHz.

3.6. Evaluation of ECT Characteristics by changes of frequency for coil gap

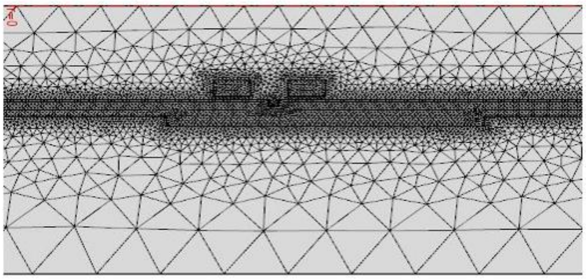
Since good performance was shown with 1mm coil width and 3.5 mm coil gap in Charter 3.5, values analysed there were made base for obtaining the graph of figure 10. In order to find which frequency shows bigger phase value change among frequencies of 20 kHz and 30 kHz, graph of figure 10 was obtained. From figure 10, bigger change of phase value was observed for frequency of 20 kHz than that of 30 kHz [10].

4. ECT Sensor Design Parameters based on FEM Simulation

ECT sensor design parameters were set up in order to simulate the signals of the eddy current based on FEM-based eddy current simulation as shown in figure 11 and simulation was carried out for the defect signal of eddy current probe. Exciter and receiver were utilized as shown in figure 11(a) and the variation of signals in the eddy current was simulated to arrow direction in bolts. Figure 11(b) shows a case of mesh generation in ECT simulation. Figure 12 shows the simulation results of the distribution and signals of the eddy currents for the bolt internal defects with 0.15 mm, 0.2 mm, 0.5 mm and 1 mm in defect depth under the difference coil gaps (3.5 mm, 4.0 mm and 4.5 mm). It was found that higher impedance variations of Lissajous plane (relation between resistance and reactance) were generated in case of the gap of 3.5 mm as shown in figure 12(a). This result in the gap of 3.5 mm is the most reasonable signal and it could be applied to design parameter in differential probe. Therefore, the design parameters for bobbin-types were optimized under Eddy current FEM simulations.

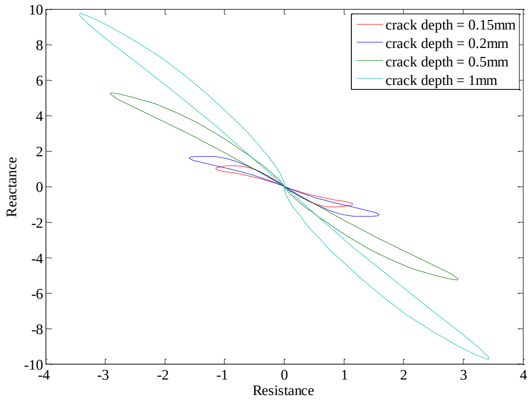


(a) Simulation setup

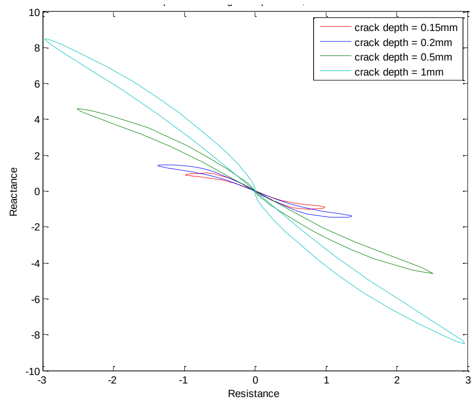


(b) Mesh generation

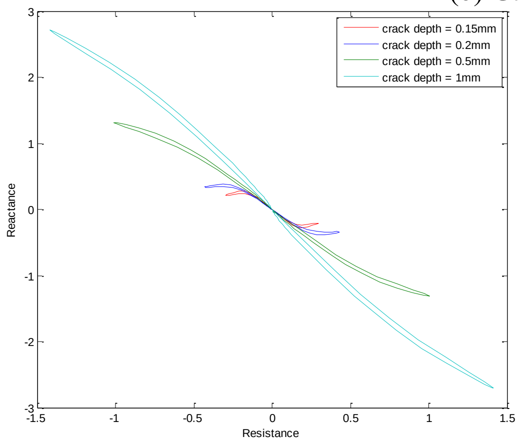
Figure 11. Simulation setup of bobbin ECT probe.



(a) Gap of 3.5 mm



(b) Gap of 4.0 mm



(c) Gap of 4.5 mm

Figure 12. Simulation results of Bobbin ECT probe under frequency of 20 kHz and coil width of 1 mm.

5. Performance evaluation of bobbin eddy current sensor

From the results of above experiment, optimum coil width, coil gap and operating frequency were selected. Based on these selected parameters, differential bobbin probe was designed and manufactured finally as shown in figure 13. Performance of the eddy current sensor designed under the same experimental condition done as above using the designed probe was verified. Result of performance evaluation for the bobbin eddy current sensor is shown in figure 14. Figure 14(a) shows resistance of differential bobbin eddy current sensor at frequency of 20 kHz, and (b) is reactance. From (a) and (b) and Eqs. (2) and (3), graph plotted with resistance in X-axis and reactance with Y-axis gives impedance plane of figure 14(c). As can be seen in figure 14(c), magnitude of impedance becomes bigger by bigger size of defect. Therefore, it was found that the differential bobbin eddy current sensor designed through the process of selecting design parameters as above is suitable for detecting the target surface defect of 0.2 mm depth at frequency of 20 kHz [10].

Figure 13. Finally designed differential bobbin probe.

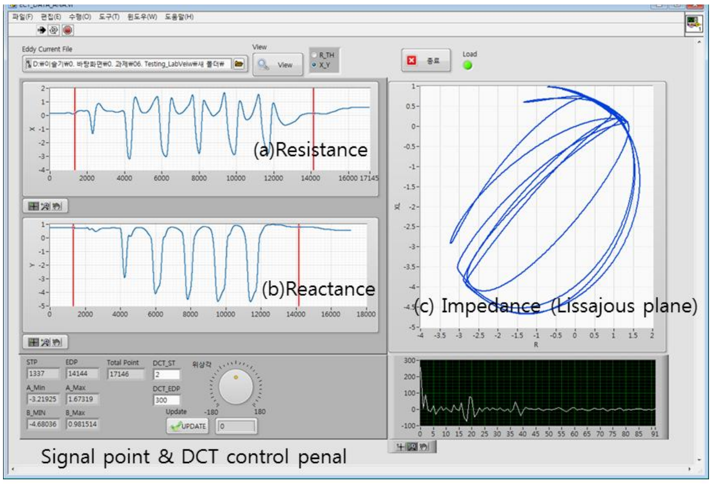


Figure 14. Signal characteristics of bobbin eddy current sensor at frequency of 20 kHz.

6. Conclusions

In this study, a differential bobbin eddy current sensor for detecting surface defects on the test specimen was developed through experiment, and the base for manufacturing interior bobbin eddy current sensor was worked out. Introduced conclusions are as follows;

- It was found that the phase value and amplitude becomes gradually bigger with depth of the test specimen deeper at the respective test frequencies as based on the experiment for standard test specimen of 25 mm outside diameter AISI 1045 Steel and differential bobbin probe having 0.1 mm diameter and 1 mm coil width in 100 turns of winding conducted with 3.5 mm coil gap at test frequency of 10, 20, 30, 50 and 100 kHz respectively.
- In an effort to make the frequency band to be applied on the differential bobbin eddy current sensor narrower, pertinent amplitude and phase value were obtained by use of lock-in amplifier. Frequency of 20 kHz was found most adequate followed by 30 kHz next, Frequency of 100 kHz was found making defect signal saturated for defect larger than 0.2 mm.
- Among coil width of 1 mm and 2 mm, change of phase value was bigger in case of 1 mm, and 3.5 mm coil gap was the best for change of phase value among the 4 coil gaps. With the defect becoming bigger, 20 kHz frequency was found showing better sensitivity for signal characteristics in both cases of coil width. Therefore, it was decided to select the coil of 1 mm width and 3.5 mm gap as the coil parameter for final design. The coil thus fabricated is judged applicable to experiment at frequency of 20 kHz.
- Parameter finally selected in this study was 1 mm coil width, 3.5 mm coil gap and 20 kHz operating frequency. Under this condition, it was possible to design differential bobbin eddy current sensor suitable for detecting 0.2 mm defect successfully, the final objective defect. FEM simulations show the impedance becomes bigger in the impedance plane with depth of defect going deeper as ECT experimental results.
- It is possible to design interior eddy current probe for inspecting oil filter bolt based on the results and ECT simulation of this work.

Acknowledgments
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