NUMERICAL STUDY ON PULSED EDDY CURRENT THICKNESS MEASUREMENT FOR STEEL PLATES WITH THICKNESS LOSS

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ABSTRACT

As one of thickness measurement methods for steel members, the pulsed eddy current testing method (PEC) is used to detect corrosion in pipelines, risers, and port structures. The method is very efficient because it does not require the surface preparation. PEC is said to give an average thickness of a certain area called "footprint", and is usually used in a screening process.

The objective of this study is to investigate how surface profile of steel plate affects characteristics of eddy currents and induced magnetic field in the pulsed eddy current testing. To achieve the objective, PEC output signals on steel plates with different surface profiles are examined in the dynamic magnetic field analysis by finite element method.

Based on the numerical analysis results, it is found that the average thickness of footprint can be evaluated by the PEC output signal. Moreover, the shape of footprint is found to be an ellipse for the configuration of coils considered in this study.

Keywords: Pulsed eddy current testing, corrosion, thickness, steel structures, dynamic magnetic field analysis.

1. INTRODUCTION

Maintenance and management of civil structures is one of the challenging problems that the civil engineering society is now facing. In Japan, steel has been used in different civil structures such as port facilities and highway bridges, and many steel structures are becoming older than 50 years old. It is imperative to inspect existing steel structures and keep them in a healthy condition.

One of the major deterioration factors of steel structures is corrosion. Since corrosion reduces a cross sectional area of steel member leading to a decrease in load carrying capacity, an inspection of steel structure involves a thickness measurement of steel plate. Currently, the ultrasonic testing method (UT) is the most popular thickness measurement method. Although UT would yield an accurate measurement, a surface preparation to remove surface coating and rust is needed, which requires time and resources. Therefore, more efficient ways of measuring steel thickness are desired.

One of such efficient thickness measurement methods is the pulsed eddy current testing method (PEC) (Robers and Scottini 2002, Lozev et al. 2005, Crouzen and Munns 2006, Park et al. 2013), which does not require the surface preparation. PEC has been used to detect corrosion in pipelines, risers, and port structures. PEC is said to give an average thickness of a certain area called “footprint”, and is usually used in a screening process. After detecting corrosion by PEC, a more accurate measurement is usually conducted by removing surface coating and rust.

The objective of this study is to investigate how surface profile of steel plate affects characteristics of eddy currents and induced magnetic field in the pulsed eddy current testing. By understanding a relationship between surface profile of steel plate and the PEC output signal, PEC measurements may be used not only in a screening process but also in the evaluation of structural condition.

2. METHOD OF APPROACH

To obtain PEC output signals for steel plates with various surface profiles, the dynamic magnetic field analysis by finite element method is carried out using a commercial finite element software, EDDY of PHOTO-Series (PHOTON 2014).

2.1. Analytical Procedure

The numerical model includes a steel plate, transmitter coils, receiver coils, and surrounding air as shown in Figure 1. Coil models are shown in Figure 2, which are based on coils used by van den Berg (2003). In the analysis, pulsed current shown in Figure 3 is applied to transmitter coils as an input, where current directions in the two transmitter coils are opposite. Induced voltage in the receiver coils after the input current is shut down is examined to obtain diffusion and decay characteristics of eddy current. A time increment of 1.0×10^{-6} sec. is used in the analysis.

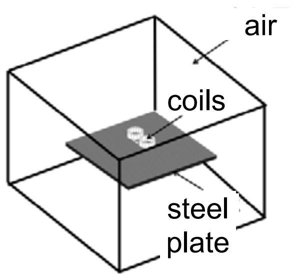
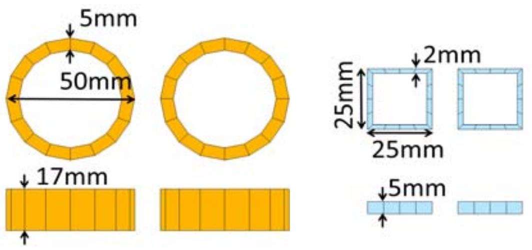


Figure 1: Model setup



(a) Transmitter coils (b) Receiver coils

Figure 2: Coils

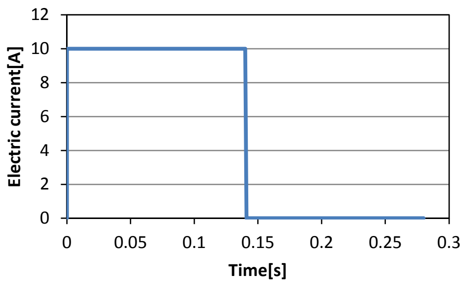


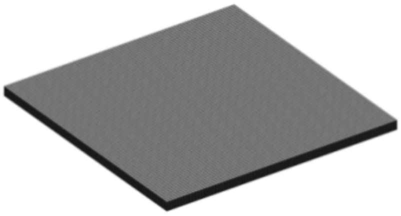
Figure 3: Pulsed current

2.2. Analytical Models

Relative permeability and conductivity of steel used in the analysis are assumed to be 200 and 6.7×10^{6} S/m in all analyses. Several steel plate models with different surface profiles are created. In this report, analyses of four different series of models are summarized. Details of steel plate models are described below. In all analyses, the distance from the bottom surface of steel plate to the bottom face of coils is 30 mm.

2.2.1. Flat Plate

Model 1 is a model of a flat steel plate with a uniform thickness as shown in Figure 4. The thickness examined ranges from 4 mm to 12 mm. Model 1-1 with a thickness of 12 mm is assumed to be a reference case. The plate size is 300 mm x 300 mm.

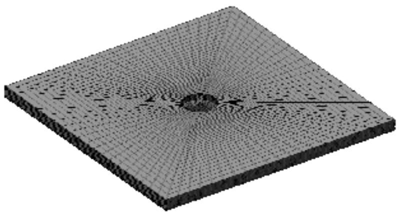


Model	Plate thickness (mm)
Model 1-1	12
Model 1-2	10
Model 1-3	8
Model 1-4	6
Model 1-5	4

Figure 4: Plate with a uniform thickness (Model 1)

2.2.2. Plate with Pits

Model 2 is a steel plate with a single pit as shown in Figure 5. By changing the pit diameter from 40 mm to 200 mm, four models are created. The plate thickness is 12 mm, and the pit depth is 8 mm, resulting in the remaining thickness of 4 mm at the pit. The plate size is 300 mm x 300 mm.

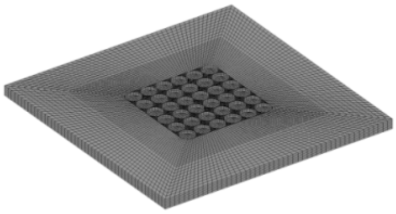


Model	Plate thickness (mm)	Diameter of pit (mm)	Pit depth (mm)
Model 2-1	12	40	8
Model 2-2	12	70	8
Model 2-3	12	100	8
Model 2-4	12	200	8

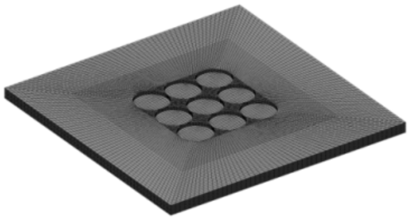
Figure 5: Plate with one pit (Model 2)

Model 3 is a model of a steel plate with multiple pits in an area of 120 mm x 120 mm as shown in Figure 6. As a diameter of pit, 20 mm and 40 mm are used. For each case, two different pit depths of 4 mm and 8 mm are considered. The original plate thickness is 12 mm, and the size of plate is 300 mm x 300 mm.

Model 4 is a steel plate with varying thickness as shown in Figure 7. Model 4-1 is a plate tapered in one direction, where the thickness of one edge is 4 mm, and that of the opposite edge is 12 mm. At the center of Model 4-1, the thickness is 8 mm. The size of Model 4-1 is 300 mm x 300 mm. Model 4-2 has the minimum thickness of 4 mm at the mid length and its thickness linearly increases toward the two edges where the thickness is 12 mm. The size of Model 4-2 is 300 mm x 300 mm. Model 4-3 is a plate with a conical depression of a diameter of 400 mm. At the center of the Model 4-3, the plate thickness is 4 mm. The thickness linearly increases with the distance from the center, and it becomes 12 mm at the distance of 200 mm from the center. The plate size of Model 4-3 is 500 mm x 500 mm.



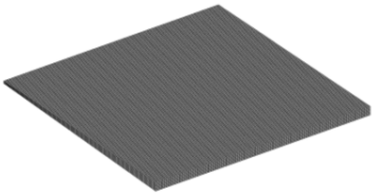
(a) Model 3-1



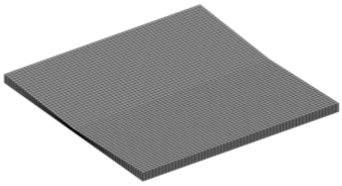
(b) Model 3-3

Model	Plate thickness (mm)	Diameter of pit (mm)	Number of pits	Pit depth (mm)
Model 3-1	12	20	36	4
Model 3-2	12	20	36	8
Model 3-3	12	40	9	4
Model 3-4	12	40	9	8

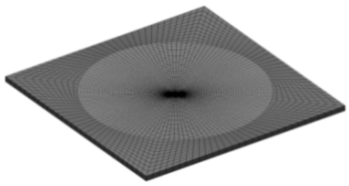
Figure 6: Plate with multiple pits (Model 3)



(a) Model 4-1



(b) Model 4-2



(c) Model 4-3

Model	Profile	Plate thickness (mm)	
		Min.	Max.
Model 4-1	Tapered in one direction	4	12
Model 4-2	Valley	4	12
Model 4-3	Conical depression	4	12

Figure 7: Plate with varying thickness (Model 4)

2.2.3. Purposes of Different Models

Model 1 is a model to examine whether the plate thickness can be evaluated by using Eq. (1) based on the PEC signal. Model 2 is a model to examine how a single pit will affect the diffusion process of eddy currents in the PEC measurement depending on the pit size. Model 3 is an extension of Model 2, and is a model to examine how multiple pits will affect the PEC signal. Model 4 is a model to examine whether PEC can really measure the average thickness of footprint and to identify the size of the footprint area.

2.3. Thickness Determination

Based on results from the analysis, a time history of induced voltage in the receiver coils is obtained as shown in Figure 8, from which the time at which diffusion of eddy currents ends is identified. To compare the ending time of diffusion, τ, with that of reference plate, τ_{ref}, the thickness of plate, d, can be identified by the following equation:

$$d = d_{ref}\sqrt{\frac{\tau}{\tau_{ref}}} \quad (1)$$

where d_{ref} is the thickness of reference plate.

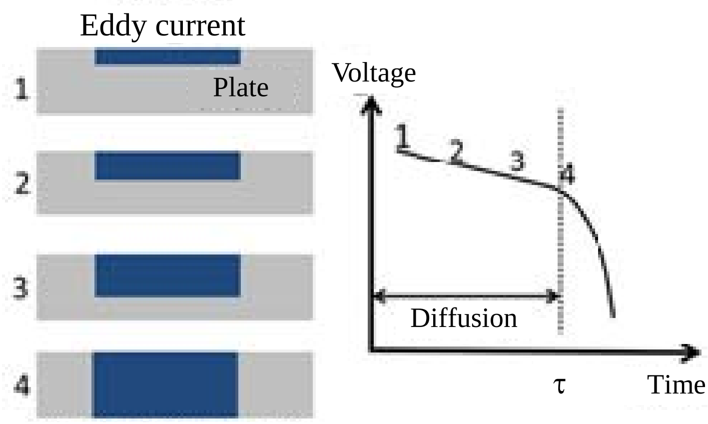


Figure 8: Diffusion process of eddy currents and induced voltage in receiver coils

3. RESULTS

3.1. Flat Plate (Model 1)

Figure 9 shows the obtained PEC signals from analyses of Model 1, and Table 1 summarizes the time at which diffusion of eddy current ends and the plate thickness calculated by Eq. (1). Time in Figure 9 is a time after the input current is shut down. It can be observed from Figure 9 that duration of the diffusion process becomes shorter as the thickness becomes smaller. Differences between actual thicknesses and those calculated by Eq. (1) are found to be smaller than 0.4 mm.

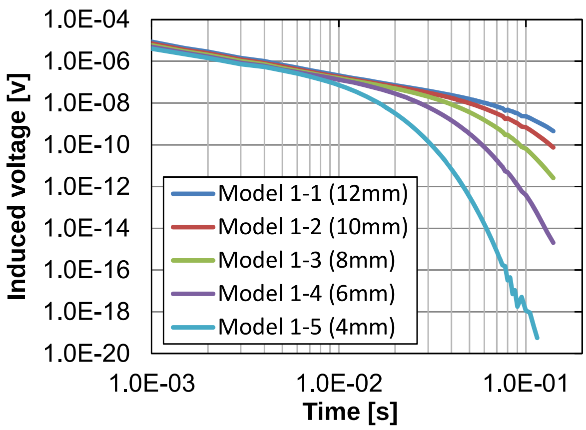


Figure 9: PEC signal (Model 1)

Table 1: Results summary (Model 1)

Model	τ (sec)	Thickness by Eq. (1) (mm)
Model 1-1	0.0627	12.0 (ref.)
Model 1-2	0.0428	9.92
Model 1-3	0.0277	7.98
Model 1-4	0.0163	6.12
Model 1-5	0.0082	4.35

3.2. Plate with Pits (Model 2 and Model 3)

Figure 10 shows the obtained PEC signals from analyses of plates with a single pit (Model 2), and Table 2 summarizes the time at which diffusion of eddy current ends and the plate thickness calculated by Eq. (1). In the analysis, the center of coils coincides with the center of the plate. Model 1-1 is used as the reference measurement. Since a pit depth is 8 mm, a remaining thickness at the pit is 4 mm in Model 2. However, when the diameter of pit is smaller than 200 mm, the thickness evaluated by Eq. (1) is far from 4 mm. When the diameter of pit is 200 mm (Model 2-4), the thickness evaluated by Eq. (1) is 4.8 mm, and an error is 0.8 mm, 20% of the thickness.

Therefore, to make an error smaller than 10% of a thickness, a pit diameter will have to be larger than 200 mm for the measurement configuration assumed in this study.

Figure 11 shows the obtained PEC signals from analyses of plates with multiple pits (Model 3), and Table 3 summarizes the time at which diffusion of eddy current ends and the plate thickness calculated by Eq. (1). In the analysis, the center of coils coincides with the center of the plate. Model 1-1 is used as the reference measurement. The remaining thickness of at the pit is 8 mm in Model 3-1 and Model 3-3, and that is 4 mm in Model 3-2 and Model 3-4. The average thickness of 120 mm x 120 mm area where pits exist is about 9 mm for Model 3-1 and Model 3-3 and about 6 mm for Model 3-2 and Model 3-4. As can be seen in Figure 11, decaying rates of PEC signals in Models 3-2 and 3-4 are faster than those of Models 3-1 and 3-3. Thicknesses evaluated by Eq. (1) are in good agreement with the average thickness of the pitting area of 120 mm x 120 mm, especially for Models 3-1 and 3-3. The maximum error of the four models is about 1 mm.

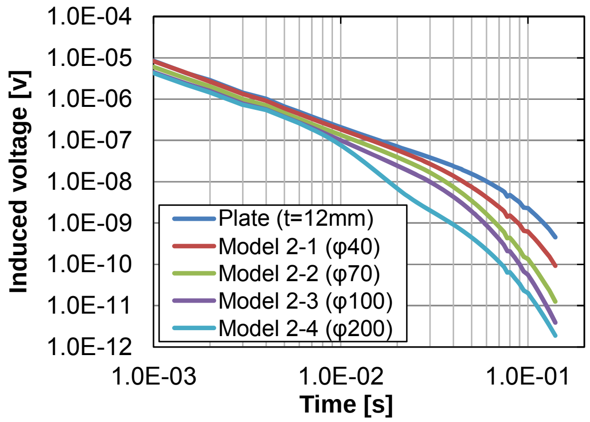


Figure 10: PEC signal (Model 2)

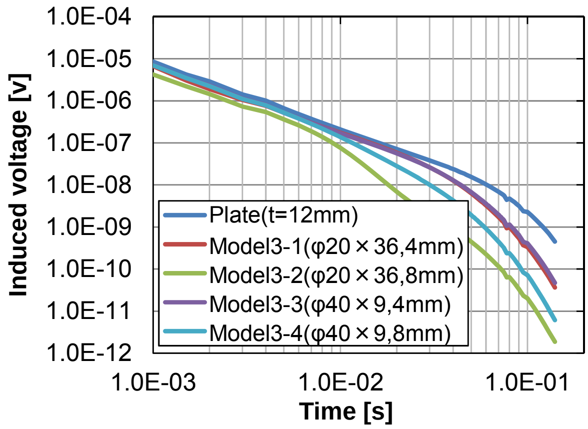


Figure 11: PEC signal (Model 3)

Table 2: Results summary (Model 2)

Model	τ (sec)	Thickness by Eq. (1) (mm)
Model 1-1	0.0627	12.0 (ref.)
Model 2-1	0.0401	9.59
Model 2-2	0.0311	8.45
Model 2-3	0.0260	7.72
Model 2-4	0.00999	4.79

Table 3: Results summary (Model 3)

Model	τ (sec)	Thickness by Eq. (1) (mm)
Model 1-1	0.0627	12.0 (ref.)
Model 3-1	0.0331	8.72
Model 3-2	0.0107	4.97
Model 3-3	0.0356	9.04
Model 3-4	0.0117	5.18

3.3. Footprint (Model 4)

Since the thickness linearly varies in one direction in Model 4-1, the average thickness of footprint coincides with the thickness of the plate below the center location of coils whatever the area of footprint is. Three locations of coils are examined: 25 mm from the center toward the minimum thickness edge (-25 mm), at the center, 25 mm from the center toward the maximum thickness edge (+25 mm). Plate thicknesses of the three locations are 7.33 mm, 8.00 mm, and 8.67 mm, respectively. Figure 12 shows the obtained PEC signals from analyses of Model 4-1, and Table 4 summarizes the time at which diffusion of eddy current ends and the plate thickness calculated by Eq. (1). Thicknesses by Eq. (1) are in excellent agreement with the average thicknesses of footprint, and an error is smaller than about 0.2 mm. Therefore, by using Eq. (1) on the PEC signal, the average thickness of footprint can be evaluated.

Figure 13 shows the obtained PEC signals from analyses of Models 4-2 and 4-3, and Table 5 summarizes the time at which diffusion of eddy current ends and the plate thickness calculated by Eq. (1). The center of coils is located above the center of plate. Thicknesses evaluated by Eq. (1) are 6.60 mm and 6.72 mm for Models 4-2 and 4-3, respectively. The size of the footprint can be estimated so that the thickness obtained from PEC will be equal to the average thickness of the footprint area. By assuming the shape of footprint is either circular or elliptic, the size of footprint is identified for Models 4-2 and 4-3 as shown in Table 6. It can be said that the sizes of footprint for Models 4-2 and 4-3 do not differ much whether the shape of footprint is assumed to be a circle or an ellipse. Figure 14 shows a superimposed figure of a contour plot of eddy current of Model 1-1 shortly after the shutdown of the input current and circular and elliptic footprints identified from Models 4-2 and 4-3. As can be seen from the figure, the footprint area coincides with the region where eddy currents are strong.

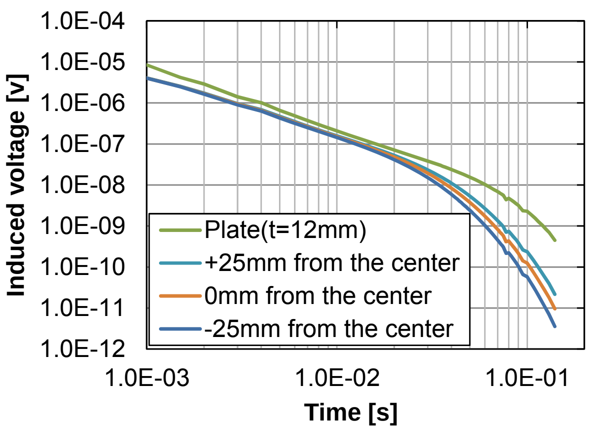


Figure 12: PEC signal (Model 4-1)

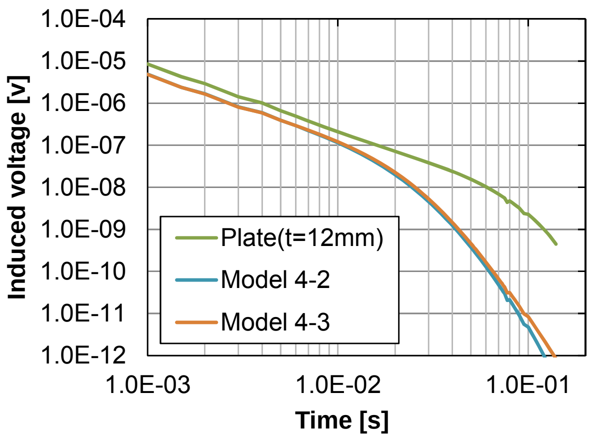


Figure 13: PEC signal (Model 4-2, 4-3)

Table 4: Results summary (Model 4-1)

Location of coil from the center of plate	τ (sec)	Thickness by Eq. (1) (mm)
-25 mm	0.0234	7.33
0 mm	0.0280	8.02
+25 mm	0.0313	8.48

Table 5: Results summary (Model 4-2, Model 4-3)

Model	τ (sec)	Thickness by Eq. (1) (mm)
Model 4-2	0.0110	5.02
Model 4-3	0.0127	5.39

4. CONCLUDING REMARKS

By using the dynamic magnetic field analysis, PEC output signals on steel plates with various surface profiles were examined. Findings from this study are summarized in the following.

1) The average thickness of footprint can be evaluated by the PEC output signal.

2) The shape of footprint can be assumed as either a circle or an ellipse for the configuration of coils considered in this study. In the case where the coils are located 30 mm from the bottom surface of the steel plate, a radius of the circular footprint is about 50 mm, and the major axis of the elliptic footprint is about 65 mm and the minor axis is 45 mm.

3) Due to the footprint size shown above, a single pit with a diameter smaller than 100 mm cannot be identified by the PEC signal accurately.

Table 6: Estimated footprint area (Model 4-2, Model 4-3)

Model	Circle	Ellipse	
	Radius (mm)	Major axis (mm)	Minor axis (mm)
Model 4-2	45.5	65.0	45.5
Model 4-3	51.0	61.1	42.8

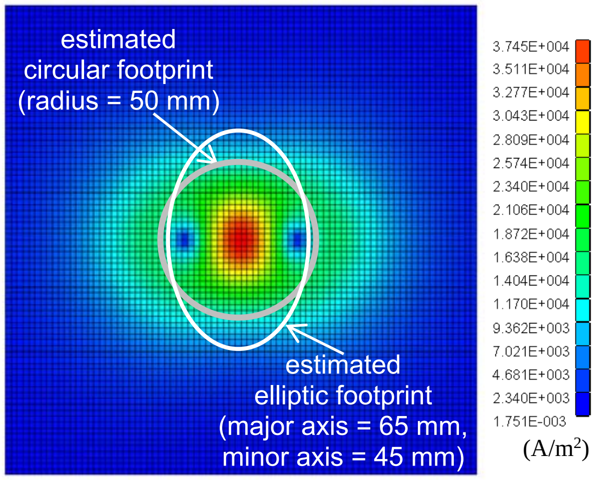


Figure 14: Eddy current density on the surface of Model 1-1 1.0x10^{-4} sec. after the shutdown of the input current

5. ACKNOWLEDGEMENTS

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