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Numerical Analysis of Through Transmission Pulsed Eddy Current Testing and Effects of Pulse Width Variation

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Abstract By using numerical analysis methods, through transmission type pulsed eddy current (PEC) testing is modeled and PEC signal responses due to varying material conductivity, permeability, thickness, lift-off and pulse width are investigated. Results show that the peak amplitude of PEC signal gets reduced and the time to reach the peak amplitude is increased as the material conductivity, permeability, and specimen thickness increase. Also, they indicate that the pulse width needs to be shorter when evaluating the material conductivity and the plate thickness using the peak amplitude, and when the pulse width is long, the peak time is found to be more useful. Other results related to lift-off variation are reported as well.

Keywords: Nondestructive Testing, Pulsed Eddy Current, Through Transmission, Numerical Analysis

1. Introduction

Pulsed eddy current (PEC) testing differs from sinusoidal eddy current testing in that a pulse of current is induced in the test specimen. A pulse can be analyzed into infinite train of harmonically related sinusoidal waveforms. Because of this broadband nature, PEC testing is expected to be rich of information and to have deeper penetration than conventional eddy current testing (Renken, 2001; Tai et al., 1996; Lebrun and Baboux, 1997; Safizadeh et al., 2001). Numerical model had been developed for the prediction of pulsed eddy current distribution in metals and compared with the analytical solution (Ludwig and Dai, 1990). In this paper, through transmission method of PEC testing is modeled and PEC signal responses due to various material conductivity, permeability, thickness, lift-off and pulse width are investigated.

2. Numerical Analysis of Pulsed Eddy Current Testing

Pulse coil current induces eddy currents in a conducting test specimen and their magnitude change continuously with time. In such a case, a transient analysis is required to predict their behavior so that the backward difference method is used for temporal analysis. For the spatial modeling, the finite element method is used (Ludwig and Dai, 1990). These are programmed into a self-written FORTRAN code.

The governing equation for PEC testing is

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \overline{A} \right) = \overline{J_s} - \sigma \left(\nabla V + \frac{\partial \overline{A}}{\partial t} \right) \tag{1}$$

where $\mu, \sigma, V, \overline{A}$ and $\overline{J_s}$ are permeability, conductivity, magnetic scalar potential, magnetic vector potential and source current density vector, respectively. In this work, the cylindrical coordinate system is used to solve eqn. (1).

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Applying the finite element formulation for the space, the following type of matrix equation is obtained.

$$[S]\{A\}+[C]\left\{\frac{\partial A}{\partial t}\right\}=\{Q\} \tag{2}$$

To treat time, the backward difference method is used where all the values are evaluated at a new time, $t^{n+1}=t^{n}+\Delta t$, and the time derivative term is expressed as

$$\left\{\frac{\partial A}{\partial t}\right\}^{n+1}=\frac{\{A\}^{n+1}-\{A\}^{n}}{\Delta t} \tag{3}$$

where $\{A\}^{n}$ is the magnetic potential evaluated at time, t^{n}.

Rewriting eqn. (2) by using eqn. (3), the following recurrence relation is obtained and the magnetic potential at any time step can be calculated.

$$\left[\frac{1}{\Delta t}[C]+[S]\right]\{A\}^{n+1}=\{Q\}^{n+1}+\frac{1}{\Delta t}[C]\{A\}^{n} \tag{4}$$

The test signal in PEC testing is the electromotive force induced in the sensor coil so that it can be calculated as follows.

$$V_{emf}=\frac{\{A\}^{n+1}-\{A\}^{n}}{\Delta t}2\pi r_{c} \tag{5}$$

where r_c is the centroidal radius of a coil element.

Analysis model of through transmission type PEC is shown in Fig. 1. Exciter coil is placed on one side of the test plate and sensor coil with ferrite core is placed on the other side of the plate. Their dimensions are summarized in Table 1.

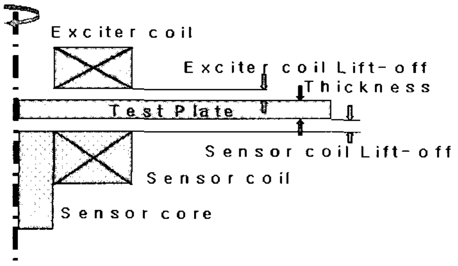


Fig. 1 Through transmission type probe

3. Numerical Analysis Results

3.1 Effects of Material Conductivity

PEC signal variation due to material conductivity is investigated. First, the response from step input current is investigated to decide the pulse width. As shown in Fig. 2, peak amplitudes of step responses from various materials with different conductivities appear at different times. The times taken to reach the peak amplitudes are investigated in the step responses that are obtained from various conductivities and thickness, and are summarized in Table 2. The peak time increases as the conductivity or the thickness increases.

Table 1 Dimensions of coils

		Exciter coil	Sensor coil	Sensor Core
Coil Size	OD	6.6 [mm]	6.6 [mm]	4.2 [mm]
	Axial length	3.0 [mm]	6.0 [mm]	12.0 [mm]
	ID	4.2 [mm]	4.2 [mm]	Relative permeability = 1000

Table 2 Peak time of step responses from various conductivities and thickness

Thickness	1.8 mm	2.1 mm	2.7 mm	3.0 mm	6.0 mm	6.6 mm	7.5 mm	9.0 mm
Copper	48 [μs]	63 [μs]	94 [μs]	111 [μs]	-	-	-	-
Aluminum	40 [μs]	47 [μs]	71 [μs]	84 [μs]	-	-	-	-
Tungsten	18 [μs]	22 [μs]	33 [μs]	40 [μs]	-	-	-	-
Titanium	-	-	-	-	14 [μs]	16 [μs]	20 [μs]	27 [μs]
Inconel 600	-	-	-	-	7 [μs]	8 [μs]	10 [μs]	13 [μs]

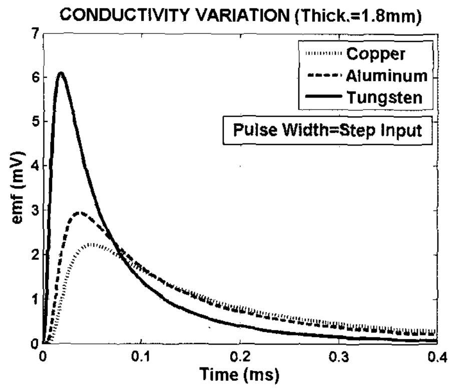
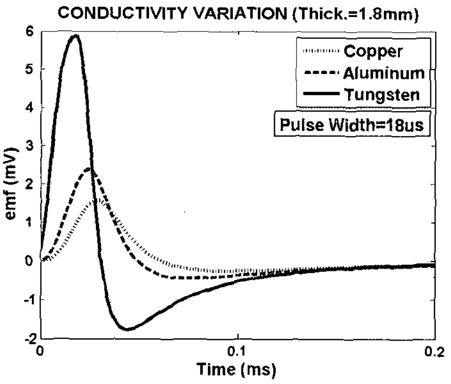
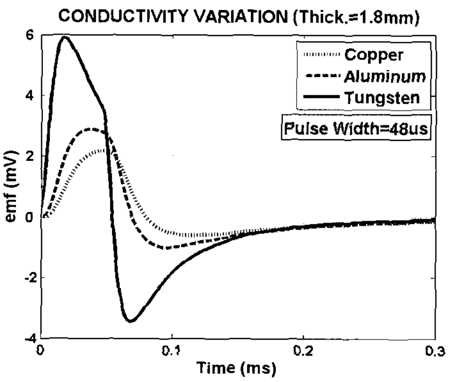


Fig. 2 Step responses from plates with various conductivities

Fig. 3 shows PEC signals obtained by using different pulse widths. In Fig. 3(a), the peak time of tungsten (18 μsec) is used as the pulse width and that of copper (48 μsec) is used in Fig. 3(b).



(a) pulse width = 18 μs

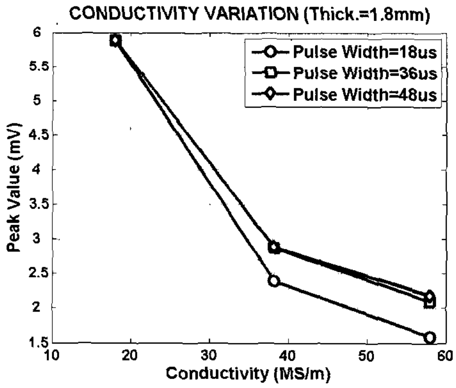


(b) pulse width = 48 μs

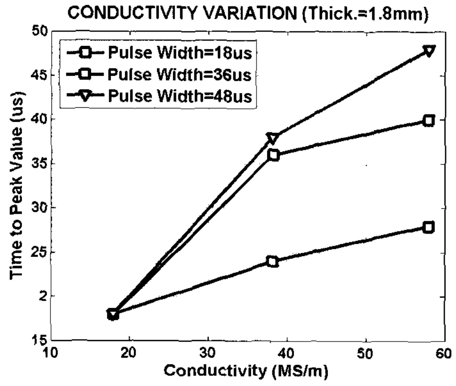
Fig. 3 PEC signals from different conductivity and pulse width

As the conductivity increases, the peak amplitude gets reduced and the peak time is increased. When the pulse width is long enough, signal passes the peak point and reduces somewhat before the steep drop caused by the pulse-off. If the pulse width is short, the peak amplitude is less than that of step response. When the pulse width is long, the signal drop is greater although the peak amplitude does not change.

Peak amplitudes and peak time from various conductors are investigated and effects of the pulse width on them are studied as shown in Fig. 4. These results indicate that the pulse width needs to be shorter to evaluate the material conductivity using the peak amplitude and the peak time is more useful when the pulse width is long.



(a) peak value

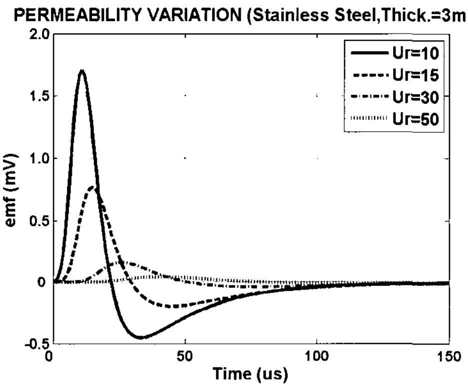


(b) peak time

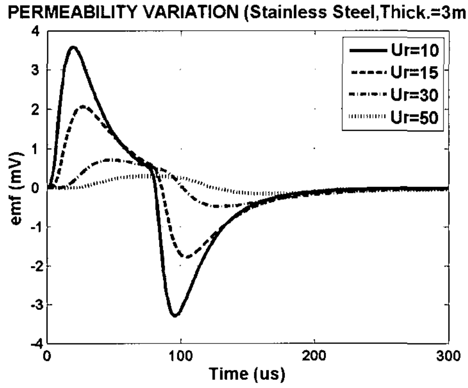
Fig. 4 Comparison of (a) peak value and (b) peak time from different conductivity and pulse width

3.2 Effects of Material Permeability

Fig. 5 shows PEC signals due to material permeability and pulse width variation. If we compare signals from the same permeability in Fig. 5(a) and (b), we can see that the peak amplitude is smaller when the pulse width is short. Also, the peak time increases when the pulse width gets longer. Fig. 6 shows variation of peak value and peak time as the material permeability changes. The peak amplitude is inversely proportional to the material permeability and the peak time increases linearly with the permeability.

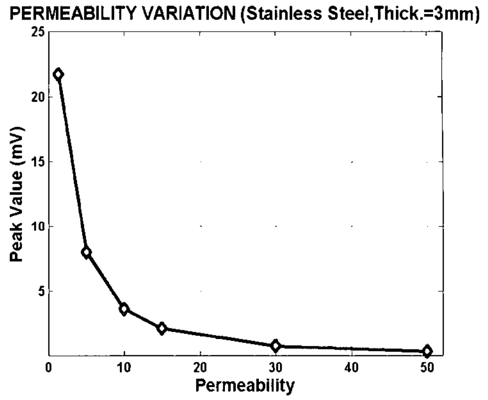


(a) pulse width = 4 μs

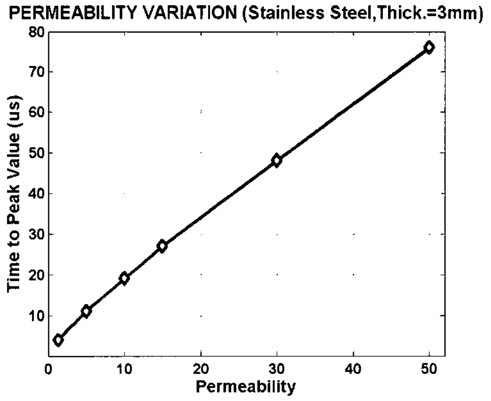


(b) pulse width = 76 μs

Fig. 5 PEC signals from different permeability and pulse width



(a) peak value



(b) peak time

Fig. 6 Variation of (a) peak value and (b) peak time due to the change of material permeability (pulse width = 4 μs)

3.3 Effects of Thickness Variation

PEC signals due to plate thickness variation are investigated. As mentioned earlier, step response is first sought to decide the pulse width. Fig. 7 shows step responses from various aluminum plate thickness. Fig. 8 shows PEC signals obtained by using different pulse widths. In Fig. 8(a), the peak time (40 μsec) of thin plate (1.8 mm) is used as the pulse width and that (84 μsec) of thick plate (3 mm) is used in Fig. 8(b). As the thickness increases, the peak amplitude is decreased and the peak time is increased. Peak amplitude and peak time of various thickness are investigated and effects of the pulse width on them are studied as shown in

Fig. 9. These results indicate that the shorter pulse width is needed to evaluate the plate thickness using the peak amplitude and the longer pulse width is desired to evaluate them using the peak time.

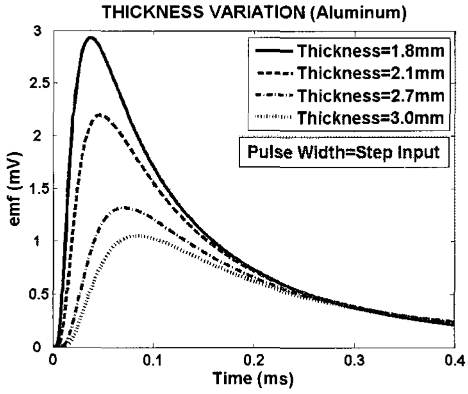
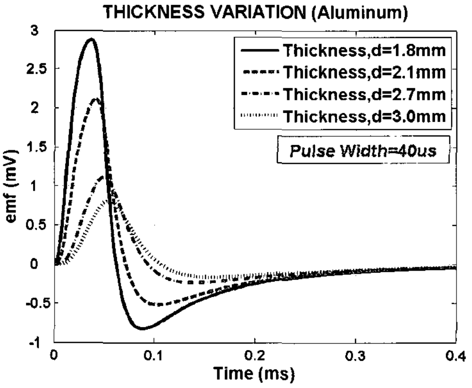
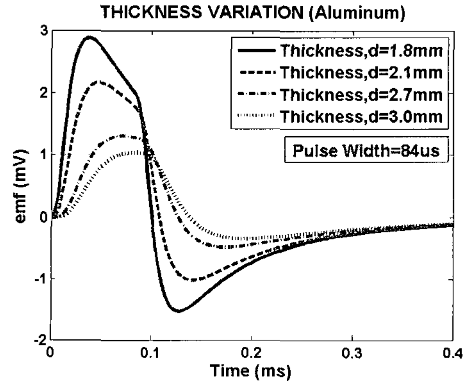


Fig. 7 Step responses from plates with various thicknesses

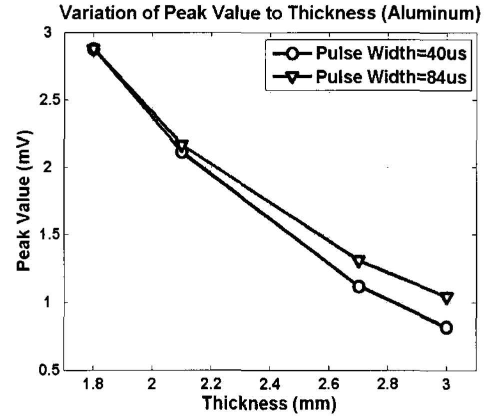


(a) pulse width = 40 μs

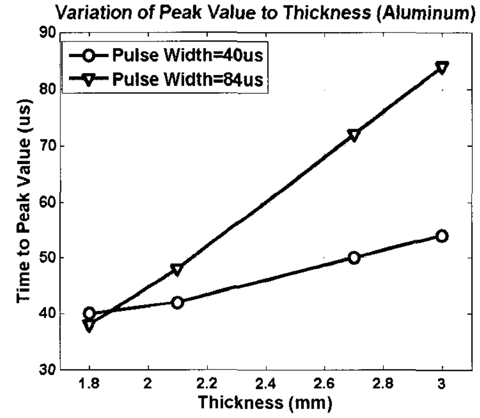


(b) pulse width = 84 μs

Fig. 8 PEC signals from different pulse widths



(a) peak value



(b) peak time

Fig. 9 Comparison of (a) peak value and (b) peak time from different thickness and pulse width

3.4 Effects of Lift-off

PEC signal due to lift-off variation is investigated and results are shown in Fig. 10. As the lift-off increases, the peak amplitude of the signal decreases. However, the peak time does not change. Fig. 10 also compares the lift-off of exciter coil and that of sensor coil and shows that the resulting signals are almost the same. That is, PEC signal does not vary with the lift-off variation of individual coil as long as the distance between the two coils is maintained.

Furthermore, even if the distance between the two coils is varied, PEC signals are found to intersect each other at a common point as shown in Fig. 11. This point is called the lift-off point of intersection (LOI) (Giguère and Dubois, 2000; Lefebvre and Mandache, 2005; Tian and Sophian, 2005). In other words, they have the same signal strength at a particular time. By comparing signal values at that time, thickness variation can easily be identified as can be seen in Fig. 11. This phenomenon cannot be noticed in the step response signal and it appears only when the current pulse is dropped down. Fig. 12 shows the effects of lift-off on the peak amplitude. The peak value is affected more sensitively when the test specimen is thin.

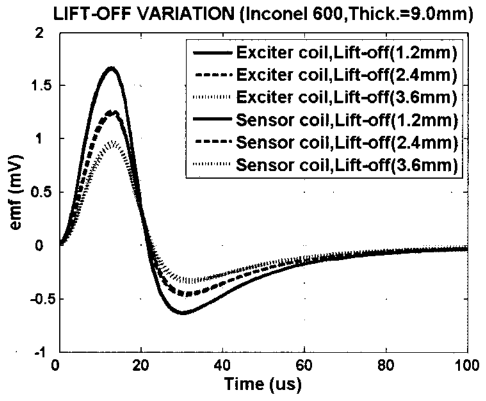


Fig. 10 Comparison of lift-off signals

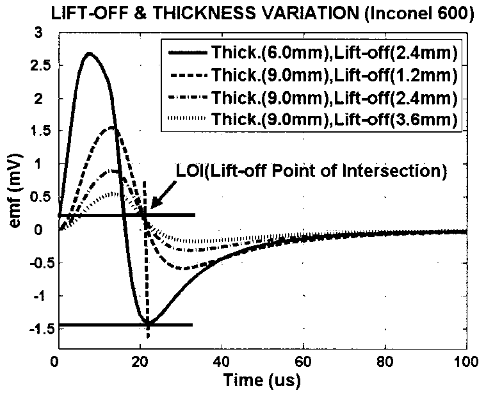


Fig. 11 Lift-off point of intersection (LOI)

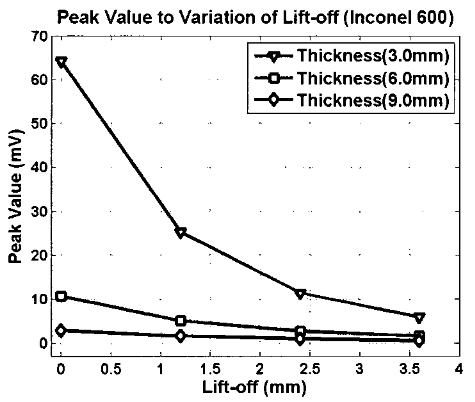


Fig. 12 Effects of lift-off on the peak amplitude

4. Conclusion

Numerical modeling study of the through transmission type pulsed eddy current testing is performed in this work. At first, PEC signals due to various material properties and test environments are investigated and it was found that the peak amplitude of PEC signal decreases, but the time to reach the peak amplitude increases as the material conductivity, permeability and specimen thickness increase. Then, after examining step responses, effects of pulse width on the PEC signal are investigated. Results indicate that the shorter pulse width is needed to evaluate the material conductivity and the plate thickness using the peak amplitude and the longer pulse width is desired to evaluate them using the peak time. Lift-off variation study shows two interesting results. PEC signal does not change as long as the distance between the two coils is maintained. The other curious result is the presence of LOI. By using these phenomena, lift-off effects could be effectively avoided.

References

Giguère, S. and Dubois, S. J. M. (2000) Pulsed Eddy Current: Finding Corrosion Independently of Transducer Lift-off, in: D. O. Thompson and D. E. Chimenti (Eds.), *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 19, American Institute of Physics, Melville, New York, pp. 449-456

Lebrun, B., Jayet, Y. and Baboux, J. C. (1997) Pulsed Eddy Current Signal Analysis: Application to the Experimental Detection and Characterization of Deep Flaws in Highly Conductive Materials, NDT & E International, Vol. 30, No. 3, pp. 163-170

Lefebvre, J. H. V. and Mandache, C. (2005) Lift-off Point of Intersection (LOI) Behavior, *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 24, American Institute of Physics, Melville, New York, pp. 523-530

Ludwig, R. and Dai, X. W. (1990) The Numerical and Analytical Modeling of Pulsed Eddy-Currents in a Cnducting Half-Space, IEEE Trans. Mag., Vol. 26, No. 1, pp. 299-307

Renken, C. J. (2001) The Use of a Personal Computer to Extract Information from Pulsed Eddy Current Tests, Materials Evaluation, Vol. 3, pp. 356-360

Safizadeh, M. S., Lepine, B. A., Forsyth, D. S. and Fahr, A. (2001) Time-Frequency Analysis of Pulsed Eddy Current Signals, J. NDE, Vol. 20, No. 2, pp. 73-86

Tai, C. C., Rose, J. H. and Moulder, J. C. (1996) Thickness and Conductivity of Metallic Layers from Pulsed Eddy-Current Measurements, Rev. Sci. Instrum. Vol. 67, No. 11, pp. 3965-3972

Tian, G. Y. and Sophian, A. (2005) Reduction of Lift-off Effects for Pulsed Eddy Current NDT, NDT & E International, Vol. 38, pp. 319-324