Numerical Evaluation of ECT Signals of Cracks with Inclination

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Some simplification models are proposed in order to sizing complicated shape defects practically, and the ECT signals of these simplified model cracks are calculated and the difference of ECT signal between the simplified models and its perpendicular to conductor surface counterparts is investigated phenomenally. The equivalency of depth sizing of these simplified models by using the method for its perpendicular to conductor surface counterparts is discussed also.

Keywords: Eddy Current Testing (ECT), Modeling, Crack Inclination, Depth Sizing

1. Introduction

Eddy current testing (ECT) is widely used for nondestruction inspection of electrically conductive structural components, in the nuclear, aerospace, petroleum, automobile industries, and etc [1,2,3]. ECT technology is actively studied numerically and experimentally. Most of the fundamental researches on ECT are carried out on Electrical Discharge Machining (EDM) notches [4], under the assumption that a crack is stand-alone and completely separated; most of the EDM notches are perpendicular to the conductor surfaces as well. However, in-site problems are much more complicated. Destructive tests of ruptured structural components show that most defects, such as stress corrosion cracks (SCC), have much more complex defect profiles than that of EDM notches [5, 6, 7]. Microscope observation shows that in many cases, a stress corrosion crack can be looked as a cluster of cracks [6, 7]. One crack can branch off to others; some of the breakings are partially contact so that eddy current can pass through, and they are not necessary perpendicular to conductor surfaces. The ECT signal we measured is affected by all the cracks in this defect cluster.

The defect's length and depth are the main concern in non destructive evaluation (NDE), and the objective of ECT defect sizing is to find the equivalent length and depth from signals. From the engineering point of view, it is neither necessary nor practical to tell the exact profile of a defect. Simplifying procedures are taken in numerical simulations. The most important issues in model simplification are:

- Can this simplification lead to equivalent defect length and depth?
- To which extent the equivalency is valid?

A variety of researches have been carried out on model simplification, and some effective simplification models have been proposed, for example, the incomplete breaking of a crack is modeled by a non-zero electric conductivity in defect region [8], in contrast to the zero conductivity in EDM notches. Further researches still needed for cracks with inclination, branch off cracks, multiple closely located cracks, etc., and the ECT recognition and sizing of complex shape defects, such as SCC, significantly depends on our knowledge of ECT on these simplification models.

In this work, a perpendicular to conductor surface crack is taken as reference, and cracks with inclination are studied numerically. The recognition of crack inclination from ECT signals and the effect of inclination on depth sizing are studied based on the analysis of numerical simulated ECT signals.

2. Numerical Study

10mm long, 0.2mm opening width cracks are assumed in a SUS304 plate (conductivity 1.41×10^6 S/m , relative permeability 2.2). A plus-point probe whose excitation coils are perpendicular to the conductor surface is utilized in the simulation. The outer diameters of coils are about 4.5mm, and the frequencies are 100 kHz and 400 kHz. The

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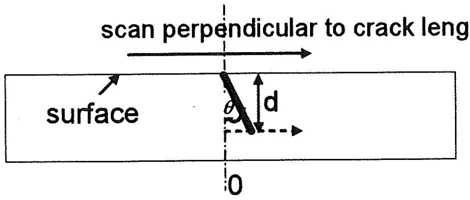


Fig. 1 Configuration of a crack with inclination.

probe is denoted as ZPP hereafter.

2.1 Study on Inclined EDM notches

The configuration of an inclined crack's cross section is depicted in Fig. 1, where d is crack depth, and θ inclination angle. According to our knowledge of the probe's depth sizing capability and the observation of SCCs, the assumed cracks are respectively 2mm, 4mm, and 8mm in depth, and the inclination angles are 0 (the reference case, perpendicular to plate surface), 10, 20, 30, and 40 degrees, respectively. The center of the crack opening on the test piece's surface is set to X=0. The inspection probe is assumed to scan perpendicular to the crack length direction and passing through the length center. The cracks are assumed to break completely and the crack conductivity is 0. Therefore, these are just EDM notches with inclination.

Figure 2 shows the Lissajous curves of 2mm and 4mm deep cracks' ECT signals assuming a 100 kHz frequency plus-point probe scans perpendicularly. In order to simulate the real inspection situation, 5% white noise is injected to the simulated ECT signals. The legend in the figure indicates the inclined angles in degree. The Lissajous curves crowd together and it is impossible to separate them one by one. The signal amplitude and phase angle with respect to each sampling position are depicted in Figs. 3 and 4. The peak amplitude increases with crack depth, however, because of the skin depth effect ECT signal gets saturate when a crack becomes deeper. The phase angle decreases with the increase of crack depth. The saturate depth of 100kHz frequency inspection is about 8mm.

Because of the inclination of crack along scanning direction, the ECT signal becomes asymmetric with respect to line X=0, where the crack opening is, and a pseudo-close loop is formed in the Lissajous curve, the area of this loop can be calculated and the equivalent length and width of this loop can be estimated, and the ratio of the equivalent width to

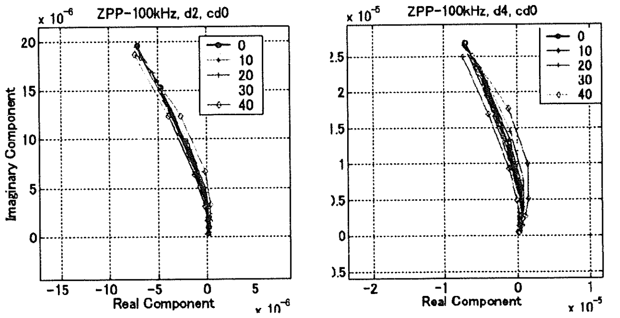


Fig. 2 Lissajous curves of depth 2mm and 4mm cracks, with different inclination angles, by ZPP probe at 100 kHz, perpendicular to crack length.

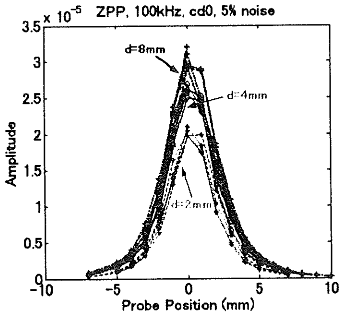


Fig. 3 Signal amplitude vs. probe position, ZPP probe at 100 kHz, perpendicular to crack length.

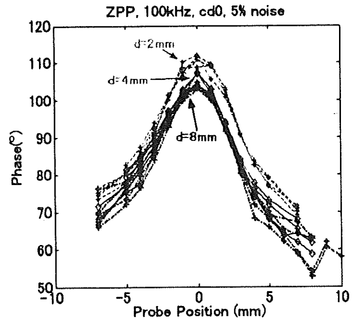


Fig. 4 Signal phase angle vs. probe position, ZPP probe at 100 kHz, perpendicular to crack length.

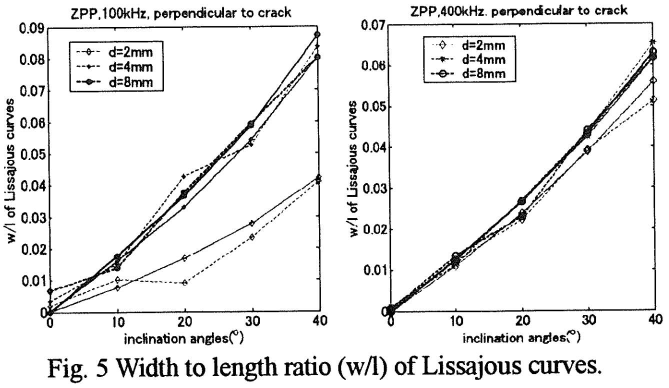


Fig. 5 Width to length ratio (w/l) of Lissajous curves.

length (w/l) of this loop can be calculated consequently. The ratios for the Lissajous curves with respect to different crack depth and inclination angle are depicted in Fig. 5, in which the solid line represents the parameter calculated from noise-free simulation signal, and the dashed line for 5% white noise injected data. The signal loop's width-to-length ratio increases with crack depth and saturates when a crack becomes deeper. For cracks with same depth, the width-to-length ratio increases with inclination angle. That is, the deeper the crack is and larger inclination angle a crack has, the easier the crack's inclination can be classified. A larger than 20 degree inclination can be recognized convincingly from either the 100 or 400 kHz signals presented in Fig. 5. The higher frequency data (400 kHz) are more robust to noise.

In order to investigate the influence of inclination angle on depth sizing, the peak amplitude and the phase angle at this peak point are extracted and depicted in Figs. 6 and 7, in which the solid and dashed lines correspond to noise-free and 5% white noise injected cases, respectively. With the increase of inclination angle, the peak amplitude decreases and the phase angle increases. This tendency is consistent with that when crack depth decreases, therefore, an inclined crack's depth can be estimated using a perpendicular model. The difference of peak amplitude is summarized in Table 1 in the crack conductivity $\sigma = 0$ part. The estimation depths are: by using the 100 kHz frequency signal, a 2mm deep, 40 degree inclined crack's equivalent depth is 1.9mm, and an 8mm deep, 40 degree inclined crack's equivalent depth is 7.5mm. These estimations are quite acceptable. Therefore, it is practical to use a perpendicular to conductor surface model to estimate a complete breaking inclined crack's depth, as far as the inclination angle is smaller than 40 degrees.

2.2 Study on a partial-contact inclined cracks

In order to simulate the incomplete breaking of a crack, 1% of the conductor's conductivity (σ_0) is endowed to the crack region to simulate the by-pass of eddy current. And the influence caused by crack conductivity and inclination is investigated.

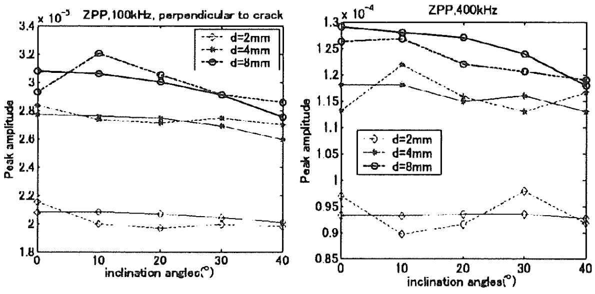


Fig. 6 Variation of peak amplitude with respect to crack depth and inclination angle.

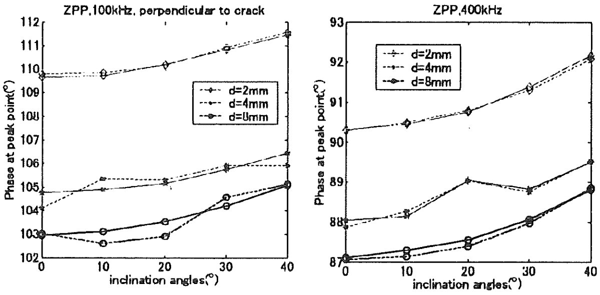


Fig. 7 Variation of phase angle at peak point with respect to crack depth and inclination angle.

Table 1: Peak amplitude of cracks (% of the peak amplitude of reference case)

σ (σ_0)	f (kHz)	$\theta(^o)$ d(mm)	10	20	30	40
0	100	2	95	98	97	95
		4	97	100	100	97
		8	101	100	98	**94**
	400	2	93	94	101	**95**
		4	108	102	100	**103**
		8	100	97	95	**94**
1%	100	2	99	96	94	**88**
		4	95	94	**89**	**76**
		8	95	**84**	**85**	**73**

Figure 8 shows the Lissajous curves of depth 2 and 4mm cracks with different inclination angles. And Fig. 9 is the comparison of signal amplitude and phase angle between cracks with 0 and 1%σ_0 conductivity. The peak amplitude is about 25% decreased, and the phase angle is about 5 degrees deceased when 1%σ_0 conductivity is endowed to the crack region, comparing with that of an EDM notch. Fig. 10 shows that the phase angles of ECT signals keep almost unchanged with inclination angles for depth 2 and 4mm cracks, and the 5% noise also does not affect the phase so much, however, the phase angle of the 8mm deep crack changes significantly due to the 5% noise. This indicates that the signals for 8 mm deep cracks are not robust and therefore the 8 mm deep, 1% σ_0 conductivity cracks are removed from our further discussion. The peak amplitude change significantly with inclination angle in Fig. 11. The variation of peak amplitude in noise free case is summarized in Table 1, in the crack conductivity $\sigma = 1\%\sigma_0$ part. The signal's peak amplitude of a 40 degree inclined, 4 mm deep crack is only about 3/4 of its perpendicular counterpart's. Since the amplitude to phase angle relation (decrease of amplitude, with decreased phase angle) is opposite to that of perpendicular to conductor surface EDM cracks, the sizing method applied to EDM notches is not applicable. By utilizing the method we proposed for partial contact cracks [9], in which the crack is assumed perpendicular to conductor surface, the equivalent estimated depths for 4mm deep, 10, 20, 30, and 40 degrees inclined cracks are respectively 3.8, 3.8, 3.6, and 3mm, the result is quite acceptable except the 40 degree inclination crack. Therefore, for partial contact inclined cracks, when the inclination angle is less than 30 degrees, reasonable depth sizing result can be achieved using a non-zero crack conductivity, perpendicular to conductor surface model.

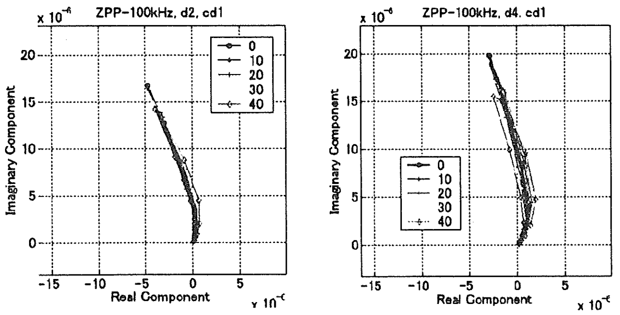


Fig. 8 Lissajous curves of 2 and 4 mm deep cracks, 1% crack conductivity endowed.

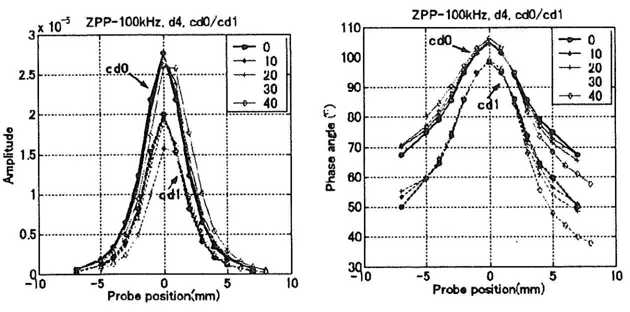


Fig. 9 Comparison of signal amplitude and phase angle of 0 and 1% conductivity cracks.

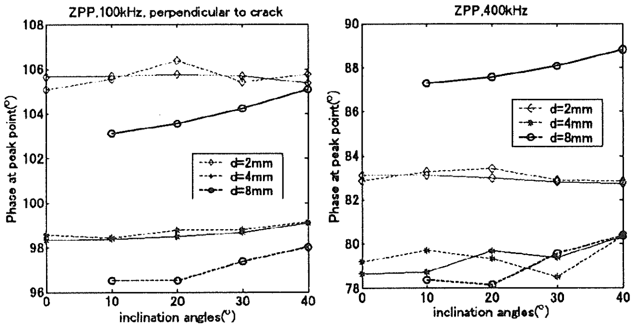


Fig. 10 Variation of phase angle at peak point with respect to crack depth and inclination angle (1%σ_0).

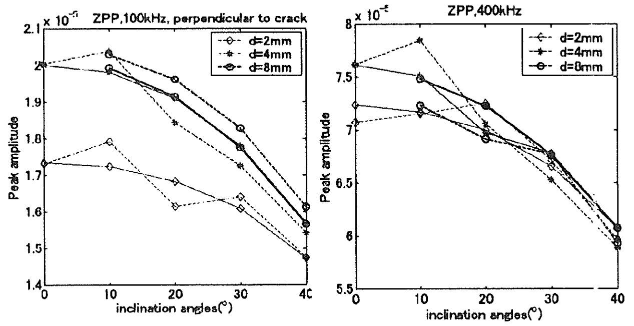


Fig. 11 Variation of peak amplitude with respect to crack depth and inclination angle (1%σ_0).

2.3 Study on branch-off defects

So far, we have investigated the ECT signal of a single inclined crack. However, branch off of cracks is very frequently observed in destructive test. And in this case, the ECT signal is affected by all the branches of a defect.

A '$\wedge$' shape crack is taken as an example of branch off defect and depicted in Fig. 12. Cracks divergence from the X=0 opening on the surface, and progress symmetry, the angle in between is 2θ, and the crack depth is *d*. The crack conductivity is assumed 0.

The Lissajous curves of 4mm deep, '$\wedge$' shape cracks are

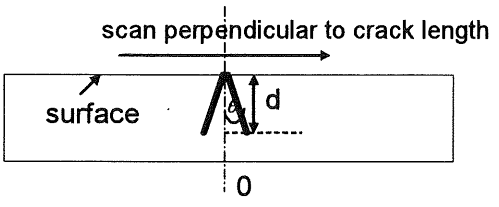


Fig. 12 '∧' shape divergenced crack.

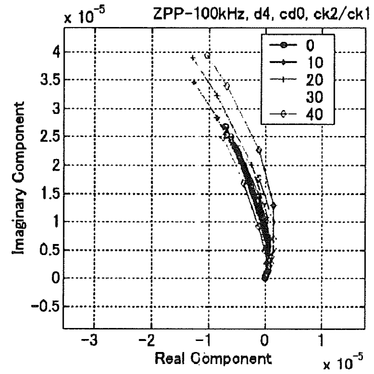
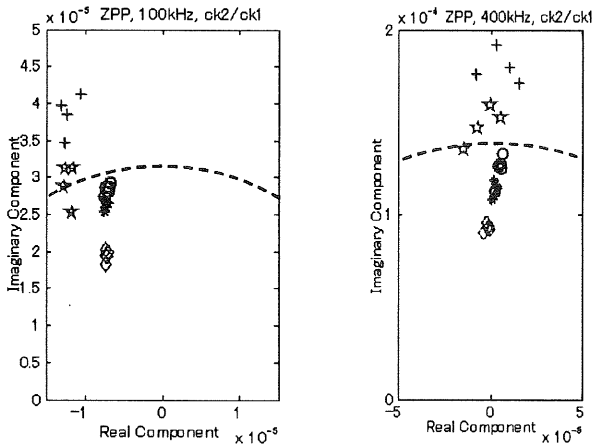


Fig. 13 comparison of Lissajous curves of one single crack and ∧shape crack.



single crack: ◇ d2mm, * d4mm, · d8mm
∧shape crack: ☆ d2mm, + d4mm

Fig. 14 Comparison of peak signals in impedance plane.

depicted in Fig. 13. Because the ECT signal is giving by the additional effect of the two crack branches, the signal of ∧ shape defects is significantly larger than that of a single crack. As we know, the output of the ZPP probe gets saturate when crack is about 8mm deep, therefore, an upper limitation of signal's peak amplitude of a single crack can be set. The peak signal corresponding to each crack configuration are extracted and depicted in Fig. 14, in which the red diamond (◇), blue * (*), and black circle (▪) denotes the peak signal of single, inclined, 2mm, 4mm and 8mm deep cracks. The red star (☆) and blue plus (+) indicates the signals of 2mm and 4mm deep '∧' shape defects. The black dashed line represents the upper limitation of 100 and 400 kHz frequency signals due to a single crack, respectively. Signals from single crack should be located under the limitation line in the impedance plane, and the signal indicated in the impedance plane over the limitation line should be affected by more than one single crack. This becomes the basic guideline for single and multiple crack recognition. By applying the depth estimation method proposed in [10], the depth of multiple or divergence cracks' can be estimated.

3. Conclusion

Model simplification is carried out on complicated shape defect. The simplified models include a typical EDM notch, an EDM notch with inclination, a partial contact inclined crack, and ∧ shape divergence crack, etc. As a preliminary study of depth sizing of complicated shape defects, the ECT signals of these simplified models are calculated and the differences of ECT signal between the simplified models and their perpendicular to conductor surface counterparts are investigated phenomenally. The equivalency of depth sizing of these simplified models by using the method for their perpendicular to conductor surface counterparts are discussed also. It is found that,

1) An acceptable equivalent crack depth can be obtained for a complete breaking inclined crack by utilizing a perpendicular model, as far as the inclined angle is smaller than 40 degrees.

2) A less than 4mm deep partial contact inclined crack's depth can be estimated by using a perpendicular to conductor surface's partial contact crack model. As far as the inclination angle is smaller than 30 degrees, the equivalent depth is acceptable.

3) A branch off defect's signal is significantly larger than that of its single counterpart. The understanding of the signal can be enhanced from a close study of both signal's amplitude and phase angle.

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