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Impedance Evaluation of a Probe-Coil's Lift-off and Tilt Effect in Eddy-Current Nondestructive Inspection by 3D Finite Element Modeling

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Abstract: The probe-coil's lift-off and tilt variations will cause noise signals that can obscure the valuable signals when the surface inspection is performed. Prevention of noise signals due to lift-off and tilt variations is an important element in most eddy current inspections. In this paper, the electromagnetic field and impedance of a cylindrical probe-coil have been calculated numerically for arbitrary lift-off and tilt angle above a conducting plate using three-dimensional Finite Element Modeling. The probe's liftoff and tilt effect on impedance change produced by a crack have been also investigated. The results show that the tilt curve are almost straight line and is characteristics of same phase with lift-off curve when probe's tilt angle is less than a certain angle. Moreover, the phase of impedance locus due to a crack is approximately vertical to lift-off and tilt curve at the optimum excitation frequency. Phase rotation method can be used to remove simultaneously the probe's tilt disturbance to crack impedance change with lift-off noise. The numerical results are confirmed by experiment measurement and the proposed method can be effectively applied to an actual eddy current testing.

Keywords: probe tilt; lift-off; impedance locus; phase rotation; eddy-current testing

1. Introduction

Eddy current testing is widely used in a range of industrial applications including inspection of aerospace structures and engines, in-service inspection of tubing at nuclear and fossil fuel power utilities, quality inspection of pipe, wire, rod and bar stock in manufacturing process, etc[1-4]. When a test probe is moved over the specimen, its impedance change is as a function not only of the concerned variables such as material conductivity, coating thickness, size of surface or subsurface discontinuities, etc., but also of probe's lift-off or tilt variation, which causes noise signals that obscure the valuable signals. So, it is essential to suppress the noise signals for accurate interpretation of the valuable signal in eddy current testing[6-12]. In this paper, impedance plane of a cylindrical probe-coil, which is the most common eddy-current probe, have been calculated numerically for arbitrary lift-off and tilt angle above a conducting plate using three-dimensional Finite Element Modeling. Furthermore, lift-off and tilt effect on crack signal have been also investigated. In the equivalent signal plane, which is obtained by a novel transformation method, the phase of crack signal is approximately vertical to lift-off and tilt curve at the optimum excitation frequency. As a result, phase rotation can be used to eliminate lift-off and tilt noises. The detailed discussion is described in the following sections.

2. Problem Formulation and Modeling

Consider a cylindrical coil above a conducting plate containing a surface crack, as shown in Figure 1. The problem is one of determining the electromagnetic field distribution and the change in the coil impedance due to lift-off and tilt angle variations. Two cases are considered. (1) θ=0°, $0 \le l_0 \le 10r_2$. (2) l_0 is constant, $0° \le \theta \le 90°$. The coil is wound with *N* wire turns and is excited by a time-harmonic current Ie^{jwt} , thus producing a time harmonic field, where w is the angular frequency, I is the current amplitude. Conducting plate is assumed to have a constant conductivity σ and magnetic permeability μ .

It is a general 3-D eddy-current problem and is solved using finite element method. The problem domain is restricted to a finite range in $-R \le x, y, z \le R$, where R is chosen enough large that edge effect can be neglected. On the outer boundaries ($x, y, z = \pm R$), A homogeneous Dirichlet condition for magnetic field is imposed. Considering the frequency is sufficiently low ($< 10MHz$), the displacement current can be neglected and the quasi-static approximation can be used. The Maxwell's equations are expressed in terms of the magnetic vector potential $\vec{A}$ and electric scalar potential ϕ . Coulomb gauge is taken into to decouple vector and scalar potential equations. So, the governing equations can be written as[2]:

In the conducting region:

$$\nabla \times \frac{1}{\mu} \nabla \times \vec{A} - \nabla(\frac{1}{\mu} \nabla \cdot \vec{A}) + \sigma \frac{\partial \vec{A}}{\partial t} + \sigma \nabla \phi = 0 \qquad (1)$$

$$\nabla \left(\sigma \frac{\partial \vec{A}}{\partial t} + \sigma \nabla \phi \right) = 0 \qquad (2)$$

In the air region:

$$\nabla \times \frac{1}{\mu_0} \nabla \times \vec{A} - \nabla(\frac{1}{\mu_0} \nabla \cdot \vec{A}) = \vec{J}_s \qquad (3)$$

Where $\vec{J}_s$ denotes the source current density. μ_0 is the free-space permeability.

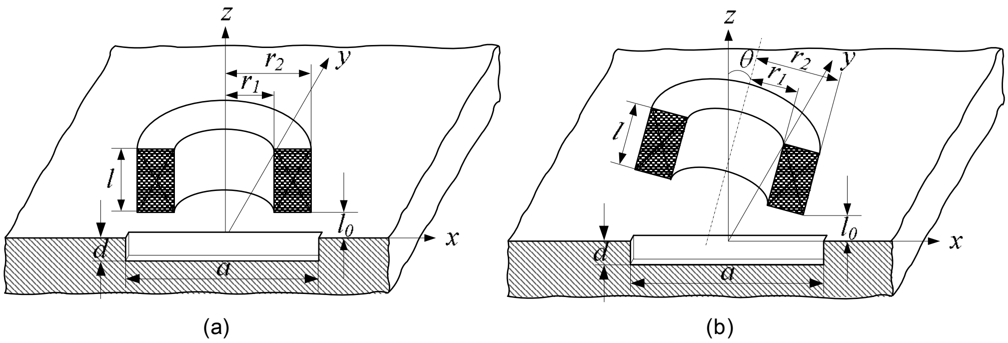


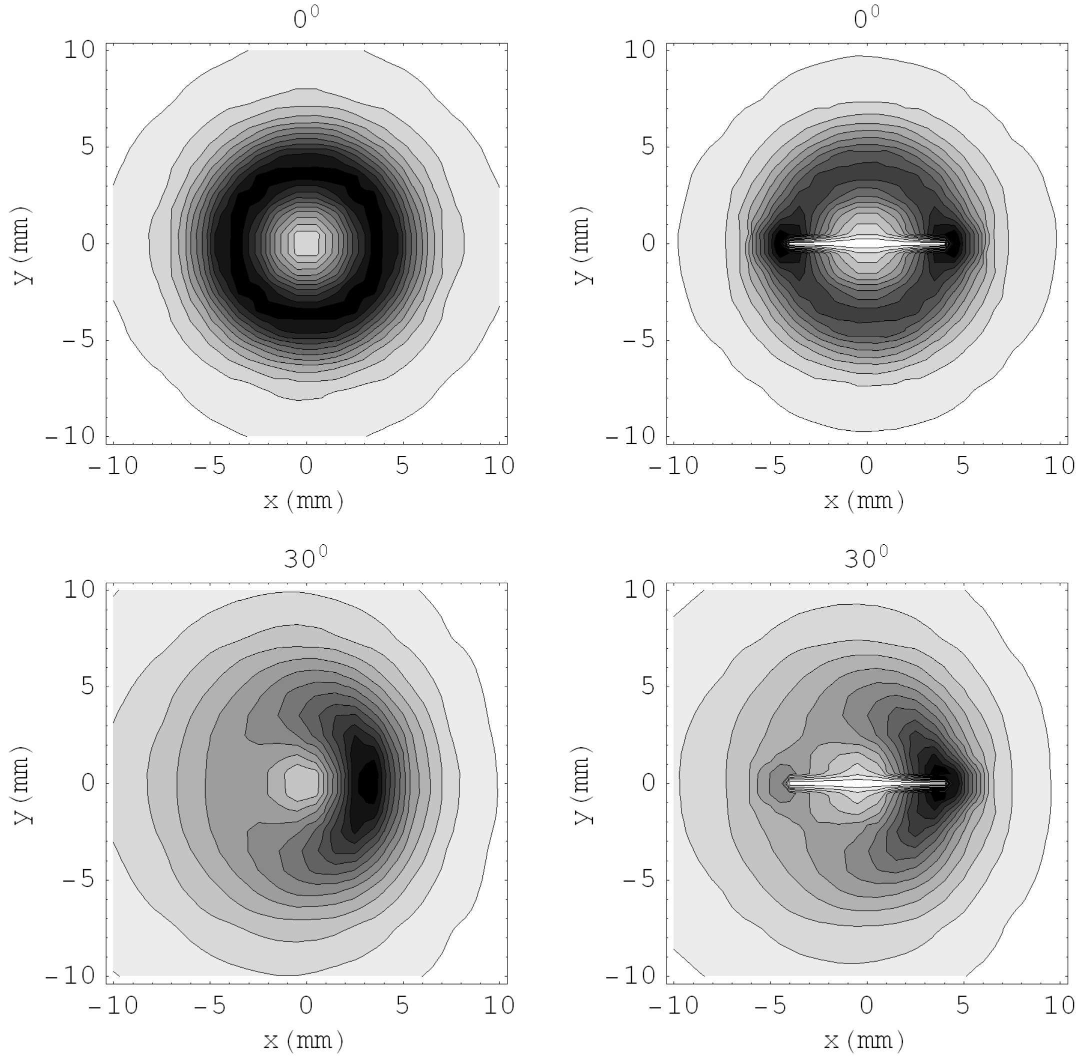
Figure 1 . Schematic diagram of the modeling

3. Probe-coil's Lift-off and Tilt Effect Analysis

3.1 Eddy Current Flow Characteristic for Various Tilt Angles

When unimpeded by the intrusion of material boundaries or discontinuities, eddy-current distribution characteristic is determined by the orientation of the probe-coil to the test material. So eddy-current flow pattern can not be changed by the probe-coil's lift-off, but affected intensely by the coil's tilt angle to the test material. Amplitude contours of eddy current on the surface of the conducting plate at four tilt angles with a constant l_0 are shown in Figure 2(a). For a perpendicular coil with θ =0°, eddy currents flow in closed, concentric loops. Eddy-current density is minimum, even approximately zero in the center of the conducting plate. While for a parallel coil with θ =90°, eddy currents flow distribution is uniform underneath the coil but tends to a circular pattern on either side of the coil. Eddy-current density is maximum in the central region under the coil. For a coil with θ=30° and θ=60°, the flow pattern is an intermediate form. Eddy-current density is more intense on the side which is closer to the coil.

Figure 2(b) shows flow pattern of the perturbed eddy current by a crack at four tilt angles. The coil is centered above the crack and l_0 is kept constant. The presence of a crack makes eddy current deflect from its original path and flows along the crack edge. At each end of a crack, eddy currents are concentrated. The more intense eddy-current density around a crack's end is, the more heavily the degree of concentration is. It is obvious at the crack's end which is closer to the coil at θ=30° and θ=60°. For θ=0° and θ=90°, the flow pattern is characteristic of symmetrical distribution about the center of a crack. As is well-known that a crack is detectable by the eddy current method in proportion to the degree to which it disturbs the flow pattern. Thus, a crack is least detectable when its longest dimension is parallel to eddy current flow paths and most detectable when the longest dimension is perpendicular to the flow paths. In order to detect a crack reliably, eddy current distribution of the designed test coil is an important element.



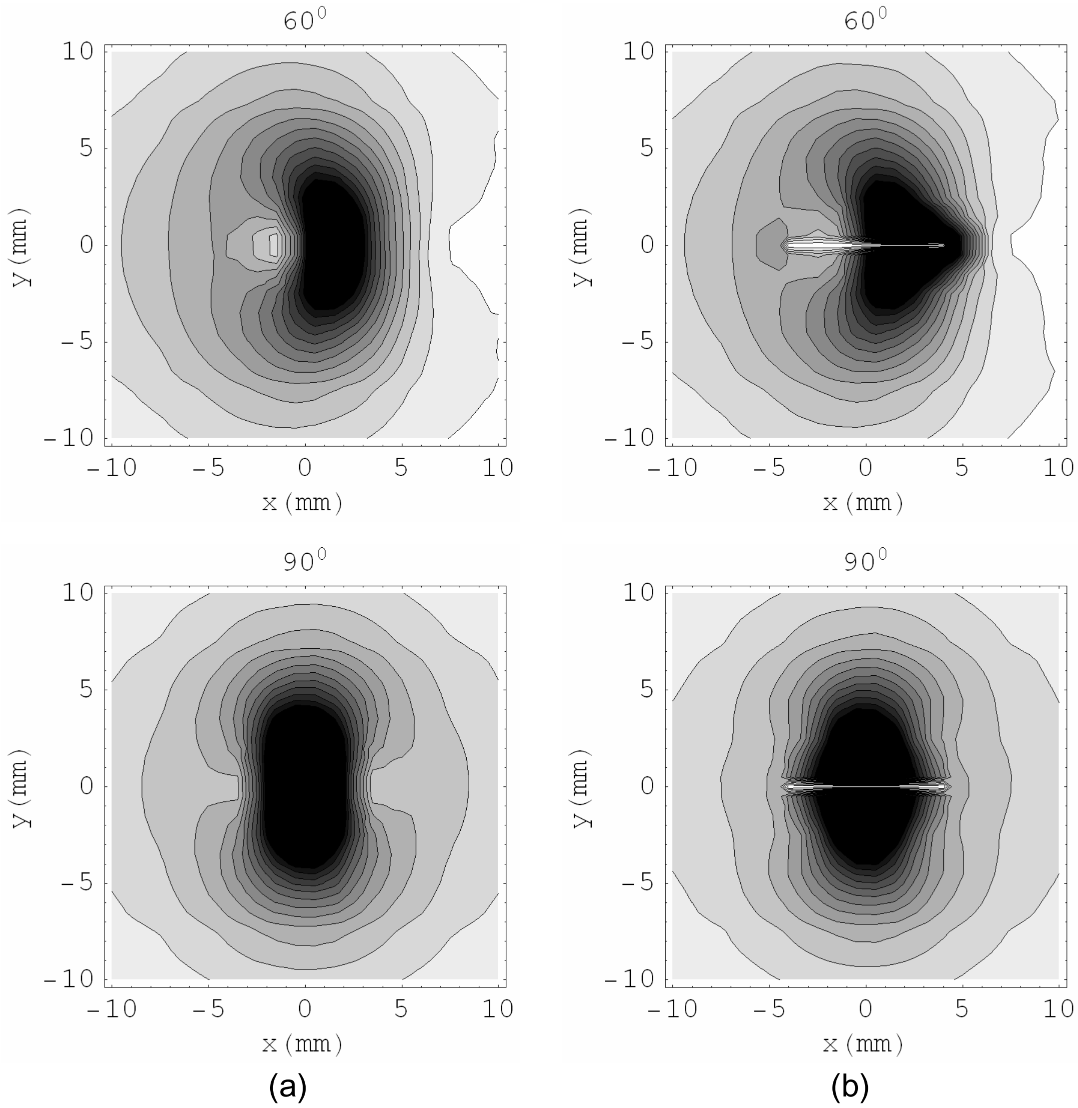


Figure 2．Amplitude contours of eddy currents induced by a cylindrical coil at various tilt angles with a constant l_0 (a) without a crack (b) with a crack

3.2 Probe-coil impedance loci of lift-off and tilt angle

Figure 3 shows the impedance plane of an air-cored cylindrical probe-coil for two cases: (1) the impedance loci of a coil as a function of lift-off l_0 with θ=0°, which is referred to it as "Lift-off curve", as shown in Figure3 (a); (2) the impedance loci of a coil as a function of tilt angle θ with a constant l_0, which is referred to it as "Tilt curve", as shown in Figure 3(b). X -axis is the normalized resistance change $(R-R_0)/X_0$ and Y -axis is the normalized reactance X/X_0, where R_0 and X_0 is the probe resistance and reactance in the free-space separately. These curves are given at the frequency f :$1kHz$,$10kHz$,$100kHz$ and $1000kHz$.

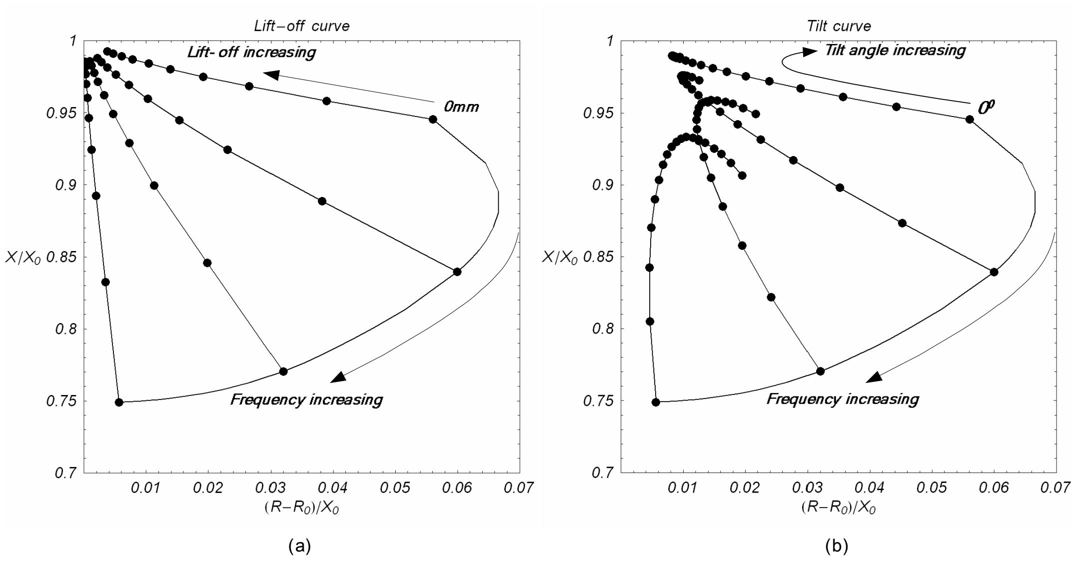


Figure 3 . Normalized impedance loci of (a) lift-off (b) tilt angle

It is clear that Lift-off curve is a straight line at four frequencies and the coil impedance change is nonlinear with lift-off. When a probe-coil is closer to conducting plate, impedance is changing more rapidly with lift-off. With a probe-coil far from the conducting plate, coil impedance is slightly affected by lift-off. All Lift-off curve are eventually ending at point (0, 1), which denotes the coil impedance in the free-space. Unlike Lift-off curve, Tilt curve is not always straight in a range of 0°~90° and appears curving as tilt angle is closer to a certain angle θ_0 . It is because that the electromagnetic coupling of the probe-coil with the conducting plate is getting weaker with tilt angle increasing. Until tilt angle is equal to θ_0 , the coupling is weakest and the probe-coil impedance change is minimal. We observed that θ_0 is around 69°, which is independent of coil size and lift-off, and gets slightly smaller than 69° with frequency increasing. Furthermore, it is observed that tilt curve is almost straight line and in close proximity to Lift-off curve when tilt angle is comparatively small. That is, both impedance loci are characteristics of constant phase, which is advantageous greatly for suppressing lift-off and tilt noises.

3.3 Lift-off and tilt effect on impedance change by a crack

Normalized Impedance loci by cracks with different depth from *0.5mm* to *4.0mm* are shown in Figure 4. It is obvious that the deeper a crack is, the larger the probe-coil impedance change is. But impedance change by a crack is affected adversely by the probe-coil's lift-off and tilt variation. As shown in Figure 4(a), impedance loci of five cracks are close to lift-off curve and can be obscured by lift-off variation at $f = 5kHz$. Whereas, even a small crack can be discriminated from impedance plane when the excitation frequency f is set to $500kHz$. It is because the phase difference between impedance locus caused by a crack and lift-off curve is large enough that lift-off effect on impedance change due to a crack is reduced remarkably. Similarly, impedance change due to a crack is covered up by tilt curve and can not be detected until a suitable frequency is used in Figure 4(b).

In practice, phase rotation method, based on the characteristic of the useful signal approximately vertical to lift-off curve or tilt curve at the optimum excitation frequency, can be adopted to eliminate lift-off or slightly tilt noise. However, considering that the coil resistance change to reactance change is comparatively small, a novel normalized approach using affine transformation is adopted to transform probe-coil impedance from impedance plane to equivalent signal space, in which the phase rotation can be accomplished.

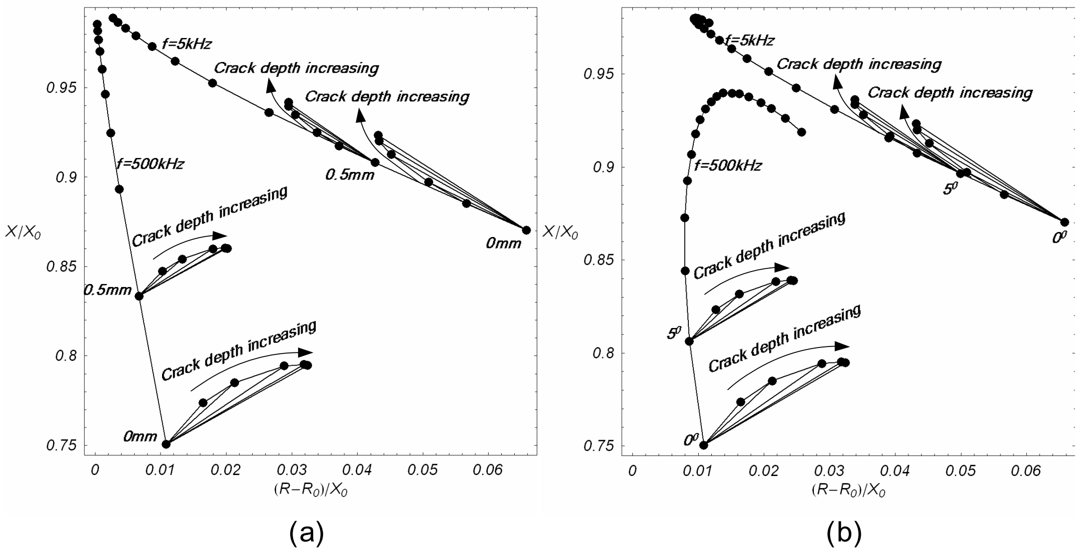


Figure 4．Normalized impedance loci produced by cracks at (a) lift-off (b) tilt angle

4. Experiments and Discussion

In order to detect very small impedance variations, a bridge circuit[1-2], which is composed of two resistors, a test probe-coil and a reference coil, is adopted in the experiment. Coil dimensions and parameters are shown in Table 1. Figure 5 shows that defect signals and lift-off curve for a test probe-coil above the aluminum plate, whereas a reference coil in the air. The bridge output, ΔU , produced by the probe-coil impedance change, is decomposed into ΔU_x and ΔU_y, which are normalized and then displayed on x-axis and y-axis separately in the graph. The lift-off is varying from *0mm* to *5mm,* at intervals of *0.5mm,* with tilt angle less than $\pm 5°$. Five defects are machine slots: *10mm×1mm×0.5mm, 10mm×1mm×1.0mm, 10mm×1mm×2.0mm, 10mm×1mm×3.0mm* and *10mm×1mm×4.0mm.* As the probe-coil is scanned across a defect, the maximum bridge output is recorded.

Table 1．Coil dimensions and parameters

test probe-coil				reference coil			
r_1	*2.25mm*	*resistance* R_0	*36.22ohm*	r_1	*2.25mm*	*resistance* R_0	*35.76ohm*
r_2	*3.75mm*	*inductance* L_0	*1.458mH*	r_2	*3.75mm*	*inductance* L_0	*1.455mH*
l	*3.0mm*	*N*	*552*	*l*	*3.0mm*	*N*	*552*

In accordance with numerical results, the coil impedance is not linear with lift-off variation. The closer the coil is to the aluminum plate, the stronger lift-off effect on impedance is. Taken into consideration of experiment error, lift-off curve in Figure 5 is almost a straight line. Moreover, the defect signal is deviating remarkably from lift-off curve at $f = 20kHz$. Combined with numerical simulations result, it is reasonable conclusion that the optimum excitation frequency can be attained to make valuable signal along the direction vertical to lift-off or tilt noise signal. On the basis of that, phase rotation method will eliminate thoroughly noise signals.

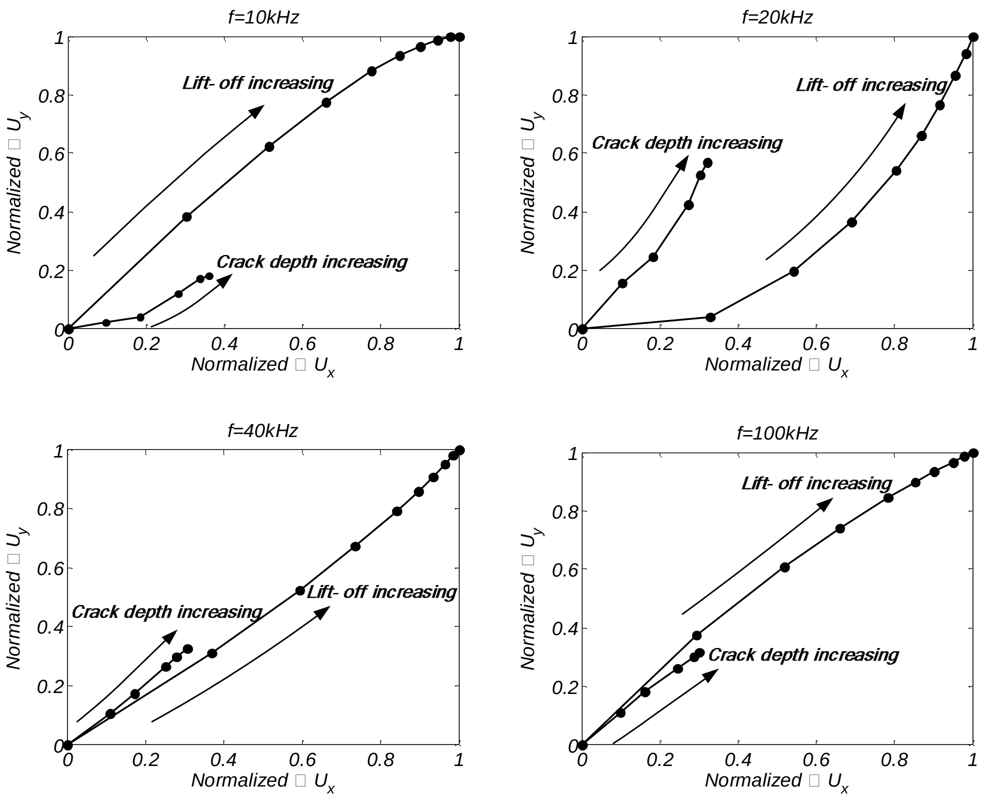


Figure 5 . Defect signals and lift-off curve for a probe-coil above aluminum plate

5. Conclusions

The electromagnetic field and the Impedance loci of a cylindrical air-cored probe-coil with various lift-off and tilt angle above a conducting plate have been calculated by 3-D Finite Element Method. In order to suppress the lift-off and tilt noises in most practical eddy current inspections, lift-off and tilt effects on a probe-coil impedance change caused by a crack have been investigated in this paper. The theoretical analysis, based on numerical calculation, is further confirmed by experiment data. Conclusions are as followed:

- Lift-off curve is approximately a straight line. That is, it is the phase of impedance loci that is not changed by lift-off varying from zero to infinity.
- Tilt curve is in close proximity to Lift-off curve and is almost a straight line when tilt angle is comparatively small. But tilt curve tends to curving when tilt angle is closer to θ_0 , at which the electromagnetic coupling of the probe-coil with the conducting plate is weakest and the probe-coil impedance change is minimal.
- At a well-selected frequency, phase difference between impedance locus due to a crack and Lift-off curve is large enough, even approaching to 90°, that lift-off effect on impedance change due to a crack is reduced remarkably.
- Phase rotation method can be applied effectively to suppress these noises, such as lift-off, slightly tilt, in equivalent signal space to impedance plane.

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