VARIATION OF EDDY CURRENT DENSITY DISTRIBUTION AND ITS EFFECT ON CRACK SIGNAL IN EDDY CURRENT NON-DESTRUCTIVE TESTING

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Summary The paper deals with variation of eddy current density distribution along material depth and investigates an effect of the variation on a crack signal in eddy current non-destructive testing. Four coaxial rectangular tangential coils are used to induce eddy currents in a tested conductive object. The exciting coils are driven independently by phase-shifted AC currents; a ratio of amplitudes of the exciting currents is continuously changed to vary the distribution of eddy current density along material depth under a circular pick-up coil positioned in centre between the exciting coils. Dependences of a crack signal amplitude and its phase on the ratio are evaluated and special features are extracted. It is revealed that the dependences are strongly influenced by depth of a crack, and thus the extracted features can enhance evaluation of a detected crack.

1. INTRODUCTION

Eddy current testing (ECT) is a non-destructive inspection method used for surface testing of conductive materials. Principle of the method underlies in the interaction of induced eddy currents with a structure of examined body [1]. Inductance coil driven with AC current generates primary alternating electromagnetic field. When the coil is placed in proximity of a conductive body, the electromotive force is induced in the body and eddy currents flow there according to the electromotive force. Eddy currents generate secondary electromagnetic field which reacts to the primary field. When flow of eddy currents is influenced by presence of any discontinuity in the body, the mutual connection between the coil and the tested object is altered resulting in change of the coil impedance.

ECT is frequently utilized in many industrial fields due to indisputable advantages of the method [2]. However, it should be noted that ECT is mainly applied for detection while sizing of a detected crack is done using some other method, for example by ultrasonic testing, because inverse problem of ECT data analysis is ill-posed. Thus, it is quite difficult to determine parameters of a detected crack from a sensed ECT signal. Special computer inverse codes are used to tackle this task iteratively based on numerical simulations of forward problems. Several numerical techniques are employed to find global minimum of a defined function. However, there is possibility that a solution is trapped into some local minimum of the function. Moreover, duration of the iteration process is variable depending on proximity of initial and final solutions and on the function complexity. It would be beneficial if the inverse problem of ECT data analysis can be solved directly using simple formulae.

The paper proposes to use a novel ECT probe with phase-shifted excitation [3] for the purpose. It is possible to vary eddy current density distribution along material depth under a pick-up coil using the probe. Changes in a crack signal due to variations in the eddy current density distribution are evaluated and two features are extracted from the gained characteristics. It is shown that the features depend on a crack depth and thus this approach can be very helpful for direct determination of its value.

2. VARIATION OF EDDY CURRENT DENSITY DISRIBUTION ALONG MATERIAL DEPTH

A novel ECT probe originally proposed by the author for non-destructive inspection of near-side deep cracks in thick conductive structures [4] is shown in Fig. 1.

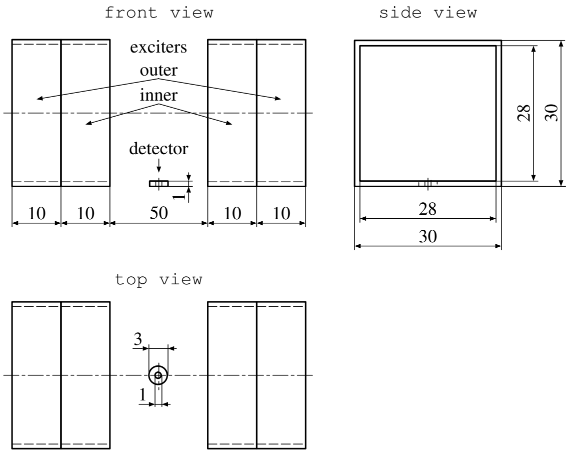

Fig. 1. Arrangement and dimensions of the novel eddy current testing probe

The probe consists of four coaxial rectangular tangential exciting coils divided into two detached sets separated by a space of 50 mm. The inner exciting coils and the outer ones of the sets are connected in series, respectively, and they are driven independently by phase-shifted currents of 180°. The signal is picked-up by a normal circular coil placed in centre between the two sets of the exciting coils.

A plate specimen shown in Fig. 2 is inspected in this study. It is made of stainless steel SUS316L which is frequently used as a base material for design of structural components in nuclear power plants; ECT is employed for non-destructive inspection of those components. Thickness of the specimen is 25 mm and electromagnetic characteristics of the material are: conductivity of σ = 1.4 MS/m and relative permeability of μ_r = 1.

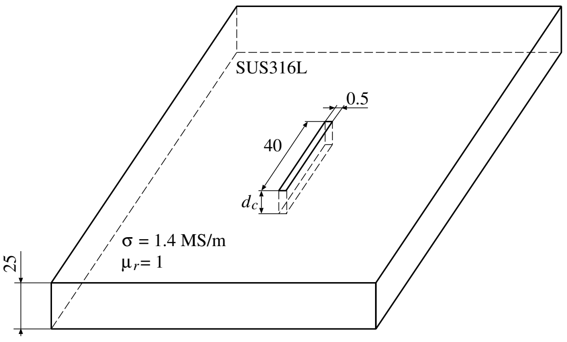

Fig. 2. Test-piece

An electro-discharge machined (EDM) notch – crack with a length of 40 mm, a width of 0.5 mm is introduced into near-side of the specimen, Fig. 2. A depth of the notch is changed from 0 to 100% of the material thickness.

A three dimensional finite element code is used to calculate distribution of the magnetic vector potential and of eddy currents in a considered volume. The voltage induced in the pick-up coil is then calculated.

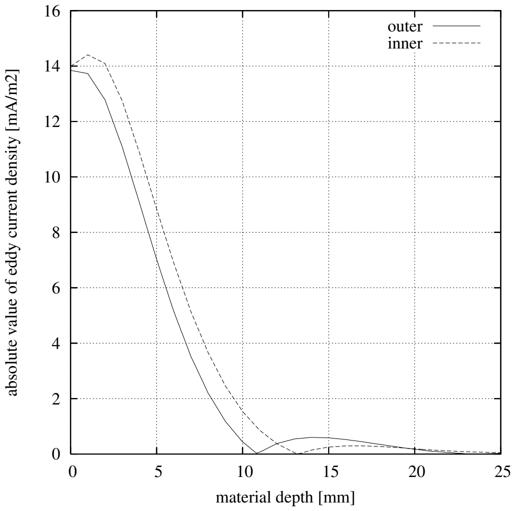

Fig. 3. Dependence of absolute value of eddy current density on material depth for the outer exciting coils and for the inner exciting coils, respectively

Distance between the exciting coil and the pick-up coil influences the distribution of eddy current density under the pick-up coil. The situation is shown in Fig. 3 for two cases: 1) only outer exciting coils of the novel probe are driven; 2) only inner exciting coils of the novel probe are driven. As it can be seen, there is a difference between the characteristics due to different positions of the exciting coils concerning a position of the pick-up coil. Those differences can be also observed in the calculated crack signals; only one pair of the exciting coils, i.e. a pair of the inner coils or a pair of the outer coils, is utilized to drive eddy currents, Fig. 4, 5.

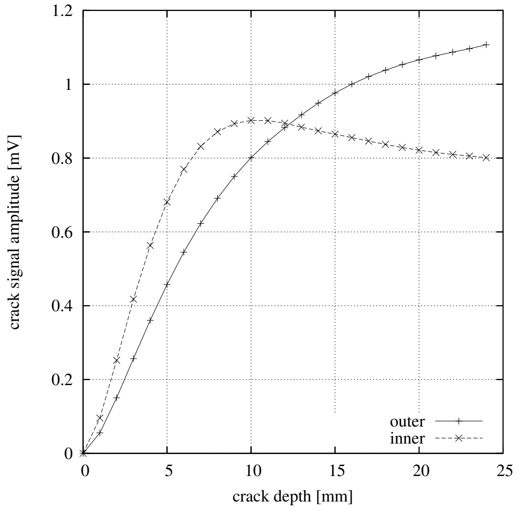

Fig. 4. Dependence of the crack signal amplitude on the crack depth gained with the novel probe when only outer exciting coils or the inner exciting coils are driven

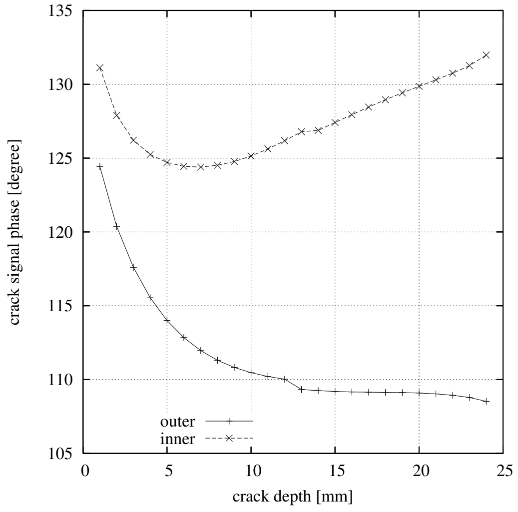

Fig. 5. Dependence of the crack signal phase on the crack depth gained with the novel probe when only outer exciting coils or the inner exciting coils are driven

When the inner and the outer exciting coils of the two sets are driven at the same time independently from each other by phase-shifted currents of 180 , the distribution of eddy current density under the pick-up coil depends on a ratio of densities of those exciting currents. It means that the distribution of eddy current density can be changed by changing the ratio. An example is shown in Fig. 6. The eddy current density distribution under the pick-up coil along the material depth is plotted for the ratio of the inner and the outer exciting currents densities of $J_i/J_o = 6.4/10$. As it can be seen, with proper adjustment of the exciting currents densities it is even possible to suppress eddy current density on the surface of material to zero.

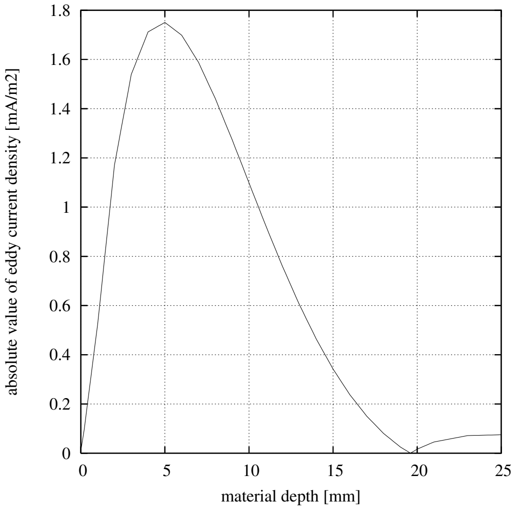

Fig. 6. Dependence of absolute value of eddy current density on material depth, the inner and the outer exciting coils are driven at the same time with currents shifted by 180°, the ratio of exciting currents is $J_i/J_o = 6.4/10$

It has been found out that the distribution of eddy current density along material depth under the pick-up coil influences amplitude, phase as well as shape of a crack signal. Therefore, by changing the ratio it is possible to rotate the crack signal and to vary its amplitude. The next section investigates these dependences.

3. INFLUENCE OF THE EDDY CURRENT DISTRIBUTION ON CRACK SIGNAL

ECT signal of the crack with a length of $l_c = 40$ mm, a width of $w_c = 0.5$ mm, and a depth of $d_c = 0 – 100\%$ of the material thickness (Fig. 2), is calculated for different values of the ratio J_i/J_o. Influence of the ratio on the crack signal behaviour is investigated by means of numerical simulations.

Five signals of the crack with a depth of $d_c = 10$ mm for five different values of the ratio J_i/J_o plotted in the complex plane are shown in Fig. 7. It is evident that the crack signal rotates clockwise with increasing of the ratio while its amplitude decreases up to a certain value of the ratio and then increases again. This dependence can be more clearly observed in Fig. 8. Although the ratio was changed in a wider range, the dependences of the crack signal amplitude and its phase on the ratio are shown just up to $J_i/J_o = 3$ as this range is sufficient to explore considered changes in the crack signal.

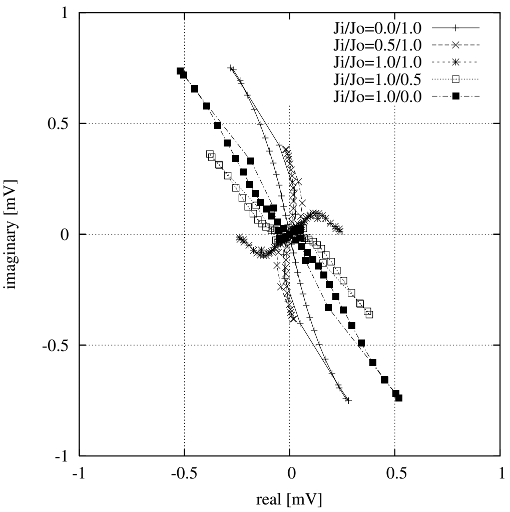

Fig. 7. Signals of the crack with a depth of $d_c = 10$ mm for different values of the ratio J_i/J_o

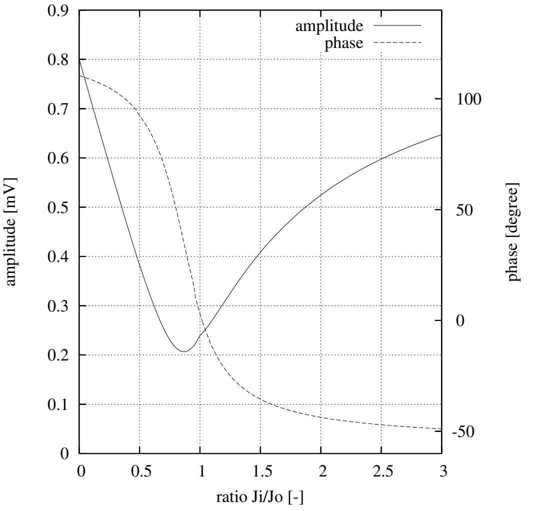

Fig. 8. Dependences of the crack signal amplitude and its phase on the ratio J_i/J_o for the crack with a depth of $d_c = 10$ mm

Similar dependences for the crack with depths of 5, 10, 15 and 20 mm are shown in Fig. 9, 10. The amplitudes are plotted in unite values referred to a maximum amplitude of the signal for whole range of the ratio and for each depth of the crack. The change of the crack signal phase is referred to a value of the phase when only outer coils are driven ($J_i/J_o = 0$). It can be seen that depth of the crack determines a value of the ratio when the crack signal amplitude reaches its minimum (Fig. 9). Rotation of the crack signal with increasing value of the ratio also depends on the crack depth (Fig. 10). Thus, two features can be extracted from these characteristics for the crack with a certain depth: 1) value of the ratio when amplitude of the crack signal reaches its minimum; 2) value of the ratio when the crack signal rotates of an angle defined as a half value of the total crack signal rotation.

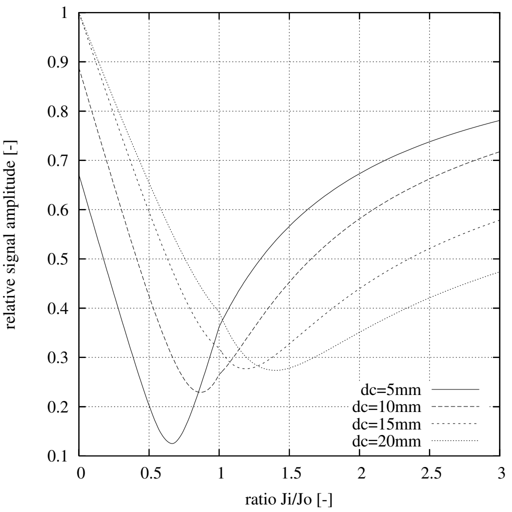

Fig. 9. Dependences of the crack signal relative amplitude on the ratio J_i/J_o for the crack with depths of d_c = 5, 10, 15 and 20 mm

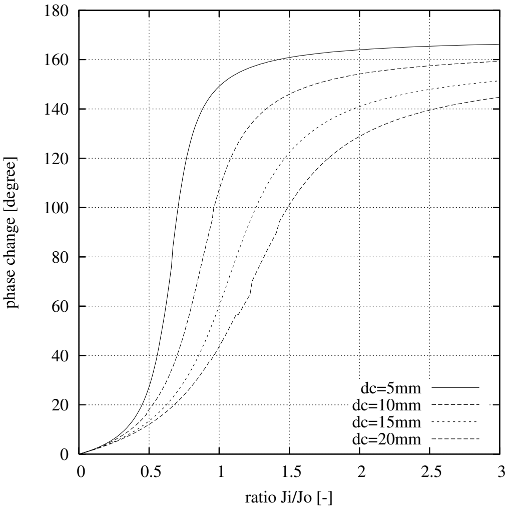

Fig. 10. Dependences of the crack signal phase change on the ratio J_i/J_o for the crack with depths of d_c = 5, 10, 15 and 20 mm

Dependences of the ratio J_i/J_o on the crack depth for the two extracted features are shown in Fig. 11. As it can be seen, the dependences for both the extracted features are nearly the same and they are almost linear. It can be concluded that for each depth of the crack there is a unique value of the ratio where the crack signal amplitude reaches a minimum value and the signal rotates in a defined angle. Therefore, when a detected crack is inspected using the novel probe with different adjustments of the ratio, it is possible to find a value of the ratio for the two extracted features and thus to directly estimate a depth of the crack.

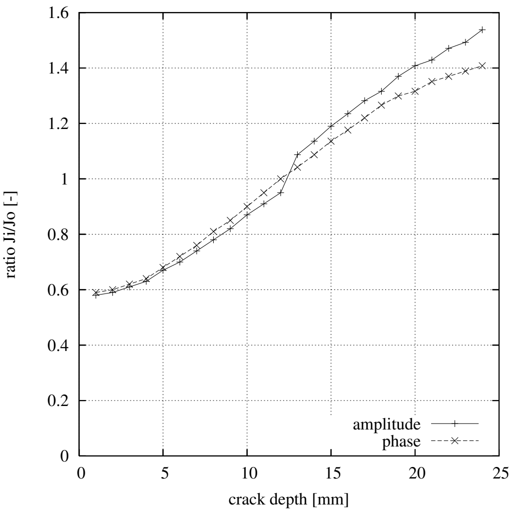

Fig. 11. Dependences of the ratio J_i/J_o on the crack depth d_c for the two extracted features

4. CONCLUSION

The paper dealt with the investigation on how distribution of induced eddy currents influences the signal of a detected crack in non-destructive eddy current testing. A novel eddy current testing probe utilizing phase-shifted excitation was used to drive eddy currents of various distributions controlled by changing the ratio of the exciting currents densities. It was shown that amplitude and phase of the crack signal depend on the distribution of eddy currents and thus on the ratio. Signals of considered crack were calculated for wide range of the ratio by means of numerical simulations. Two features were extracted from the obtained complex crack signal characteristics; first one for the signal amplitude and the second one for the signal phase. It has been proved that the extracted features can be very helpful in direct estimation of a crack depth.

Further numerical investigations and experimental verifications will be carried out to reveal efficiency of the newly proposed approach for direct evaluation of a crack depth in eddy current non-destructive testing.

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