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A NEW APPROACH IN EDDY-CURRENT NON-DESTRUCTIVE EVALUATION

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Abstract: *The paper proposes a novel approach for enhancing eddy-current non-destructive evaluation. A detected crack is inspected using several probes that provide different distributions of eddy-currents. Thus, more information about the crack is obtained. The crack signals gained using the probes are superposed and unique features are extracted from the mixed signals. Numerical investigations as well as experimental verification reveal that the features provide clear indication about the depth of the detected crack. In addition, they enable one to evaluate the depth of a defect that is much deeper than the standard depth of penetration.*

Key words: *eddy-currents, non-destructive evaluation, crack, probe, signal superposition, depth*

INTRODUCTION

Scheduled in-service inspection (ISI) is necessary for the maintenance of structural components in many industrial fields. When a defect is found during the inspection, the cracked component is usually allowed to stay in service. However, the integrity of the component must be assured, i.e. the dimensions of the crack can not exceed the critical sizes until the next ISI. Thus, evaluating the depth of the defect non-destructively becomes very important in order to clarify the effect of the defect on the integrity of the structure. Frequently, ultrasonic-based methods are used for this purpose. However, such methods are not effective in the inspection of highly anisotropic or inhomogeneous materials [1]. Such materials include, for example, Inconel welds that have recently been found to cause problems in nuclear industries [2]. In contrast, the signals of electromagnetic testing methods are affected by more macroscopic structures [3]. Thus, one can expect that utilizing not only ultrasonic but also electromagnetic non-destructive testing methods in order to evaluate defect depths would lead to the higher reliability of structures.

One of the conventional electromagnetic methods utilized for the inspection of conductive materials is eddy-current non-destructive testing (ECT) [4]. The principle of the method underlies in the interaction of the induced eddy currents with a structure of an examined body. Disturbances in the eddy currents due to the presence of anomalies are detected.

ECT signals are integral values and do not carry explicit information about the crack's dimensions. Therefore, evaluating the depth of a defect from ECT signals is quite difficult. Several papers proposed to use numerical inversions for this purpose [5]. However, the ill-posedness of the problem is not yet fully revealed [6]. In addition, the skin-effect concentrates induced currents on the surface of a tested material, and this means that obtaining information about the depth is essentially difficult. Further improvements in the interpretation of the data gained using ECT are therefore still necessary.

This study proposes a novel approach in eddy-current non-destructive evaluation for enhancing the sizing ability of the method. The key point is to use several probes with different distributions of eddy currents during the inspection and to gain more information about a crack. Measured signals with various distributions of eddy currents can provide a clear indication about the depth of an inspected defect. Numerical results and consecutive experimental verification approve the effectiveness of the proposed idea. In addition, it enables one to evaluate the depth of a defect that is much deeper than the standard depth of penetration.

1 PRINCIPLE OF A NEW APPROACH

Two mutual induction type eddy-current probes are utilized to inspect a crack. Both the probes consist of the same coils. Dimensions of the coils and configuration of the probes are given in Fig. 1. Eddy currents are driven by two coaxial rectangular exciting coils positioned tangentially regarding the surface of a tested object. The signal is sensed by a pancake pick-up coil located in centre between the exciting coils. The only difference between the two probes is diverse position p_e of the exciting coils concerning the location of the pick-up coil: $p_e = 30$ mm for the first probe and $p_e = 40$ mm for the second probe. Variable positioning of the exciting coils assures a different profile of eddy current density along the material depth under the pick-up coil. [7], [8]

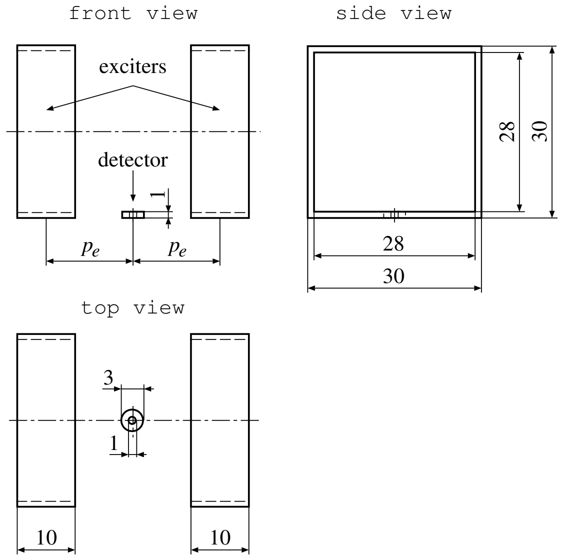

Fig. 1: Configuration of the probes and dimensions of the coils

A detected crack is inspected twice with the two probes, respectively. The probes scan right over the crack along its length; the windings of the exciting coils are perpendicular to the crack length. The two sensed signals are linearly superposed according to the following relationships:

$$Re = C_1 \cdot Re_1 - C_2 \cdot Re_2\,,\ Im = C_1 \cdot Im_1 - C_2 \cdot Im_2 \quad (1)$$

where Re_1, Re_2 are the real parts of the complex signals of the probe 1 and 2, respectively; Im_1, Im_2 are the imaginary parts of the complex signals of the probe 1 and 2, respectively; and C_1, C_2 are arbitrary numbers defining a ratio of the superposition:

$$\alpha = C_1 / C_2\,. \quad (2)$$

The numbers C_1, C_2 are changed in such a way, that the ratio is increased from zero to infinity. The resulting superposed complex crack signal (Re, Im) is evaluated in respect to the value of ratio.

2 NUMERICAL INVESTIGATIONS

Numerical simulations have been carried out to investigate effectiveness of the proposed approach.

2.1 *Numerical model*

A plate specimen shown in Fig. 2 is inspected in this study. It is made of a stainless steel SUS316L. The electromagnetic characteristics of the material include a conductivity of $\sigma = 1.4$ MS/m and a relative permeability of $\mu_r = 1$. Thickness of the specimen is 25 mm. An electro-discharge machined (EDM) notch of the rectangular shape with a length of $l_c = 40$ mm, a width of $w_c = 0.5$ mm and variable depth models the crack. Frequency of 10 kHz is adopted in the inspection.

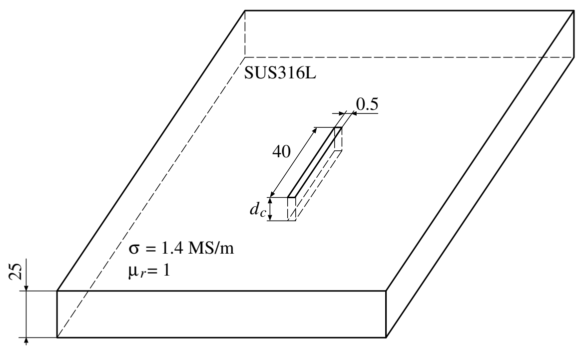

Fig. 2: Configuration of the plate specimen

2.2 *Numerical method*

A three dimensional finite element (FEM) and boundary element (BEM) hybrid method based upon **A**-V formulation is used for the numerical analysis. The governing equations of the **A**-V formulation for the low frequency eddy-current problems are as follows:

$$\frac{1}{\mu}\nabla^2\mathbf{A} = \sigma\left(\frac{\partial\mathbf{A}}{\partial t} - \nabla V\right), \quad (3)$$

$$\nabla \cdot \sigma\left(\frac{\partial\mathbf{A}}{\partial t} - \nabla V\right) = 0 \quad (4)$$

in the conductor region and

$$\frac{1}{\mu}\nabla^2\mathbf{A} = -\mathbf{J}_0 \quad (5)$$

in the air region outside the conductor. **A** denotes the magnetic vector potential, V is the electric scalar potential, $\mathbf{J}_0$ is the vector of the exciting current density, σ is the electric conductivity and μ is the magnetic permeability. In simulation of eddy-current inspection it is very convenient if the analyzed region is localized in the conductor, otherwise a new mesh has to be made for each scanning position of the probe. The FEM-BEM hybrid method is a typical technique to fulfil this requirement. The method treats the effect of free space through the boundary element scheme and couples the FEM and BEM through the boundary conditions.

2.3 Numerical results

Principle of the new approach lies in inspection of a crack using several distributions of eddy currents. Diverse positions of the exciting coils concerning the location of the pick-up coil (Fig. 1) for the two probes make it possible to locally drive eddy currents of different distributions under the pick-up coil. The situation is shown in Fig. 3 for the SUS316L plate specimen. The two dependences of the absolute value of eddy current density along material depth differ depending on whether the exciting coils of the first or of the second probe are driven.

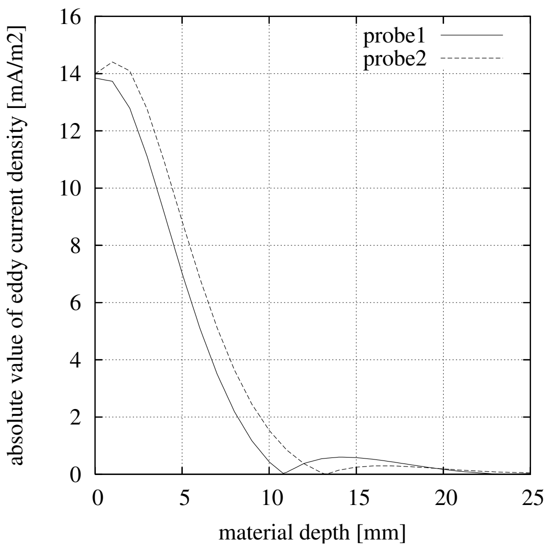

Fig. 3: Profile of eddy current density along material depth

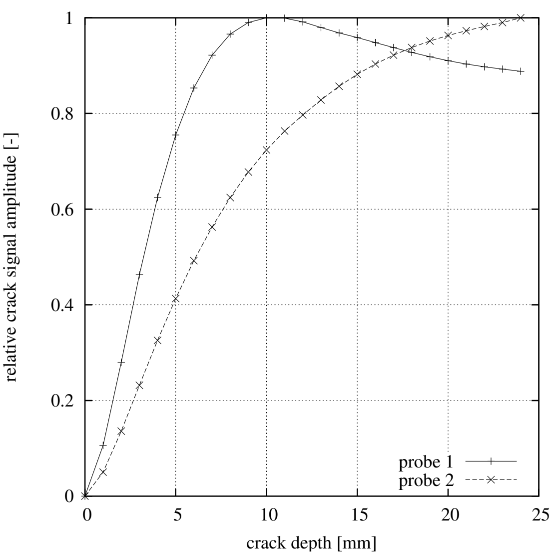

Fig. 4: Dependences of the relative crack signal amplitude on the crack depth

The EDM notch of a variable depth d_c (Fig. 2) ranging from 0 to 25 mm with a step of 1 mm is numerically inspected with both the probes. Dependences of the relative crack signal amplitude and its phase on the crack depth are shown in Fig. 4 and 5, respectively. It can be observed, that the dependences are different for both the probes due to different distributions of the eddy currents driven by the exciting coils of the two probes.

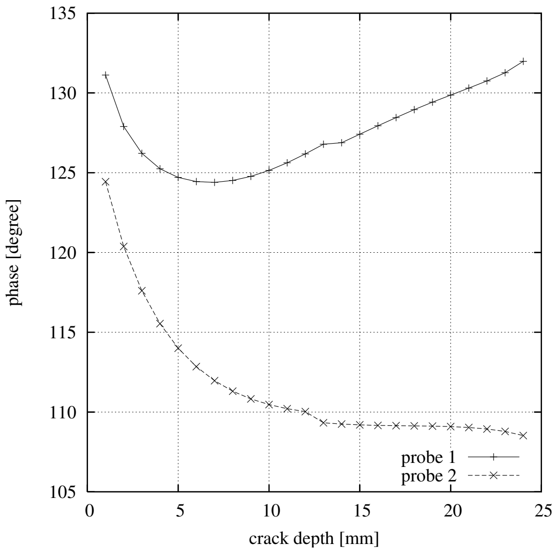

Fig. 5: Dependences of the crack signal phase on the crack depth

The signals gained with the two probes are superposed according to (1). Value of the ratio is changed from zero to infinity in small steps. Figure 6 displays five superposed complex crack signals of the crack with a depth of $d_c = 10$ mm for five values of the ratio.

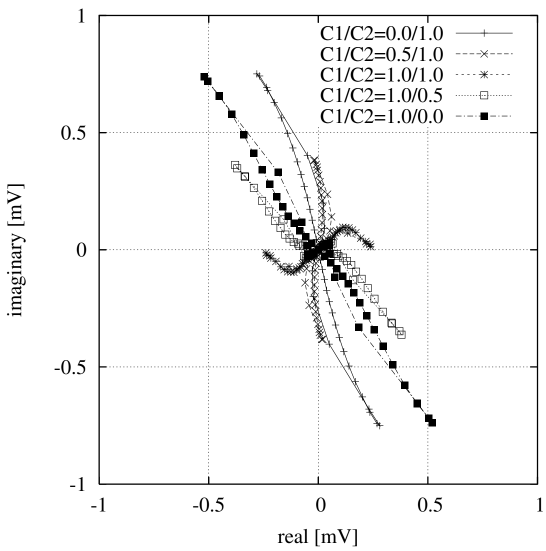

Fig. 6: Superposed signals of the crack with a depth of d_c = 10 mm for different values of the ratio of superposition $\alpha = C_1/C_2$

As it can be seen, the crack signal rotates clockwise increasing the ratio of superposition while the amplitude of the crack signal changes. Dependences of the crack signal amplitude and its phase on the ratio of superposition for the crack with a depth of d_c = 10 mm are shown in Fig. 7. Although the ratio is changed in the wide range, the dependences are plotted only for a range from 0 to 3 as it is sufficient to observe changes in the superposed crack signal. It can be seen that the crack signal amplitude decreases until a certain point when increasing the ratio and then increases again while the phase of the crack signal changes of almost 180º.

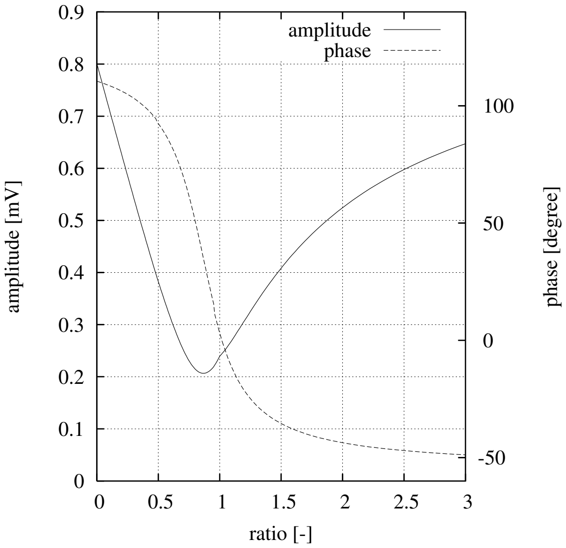

Fig. 7: Dependences of the superposed crack signal amplitude and its phase on the ratio of superposition for the crack with a depth of d_c = 10 mm

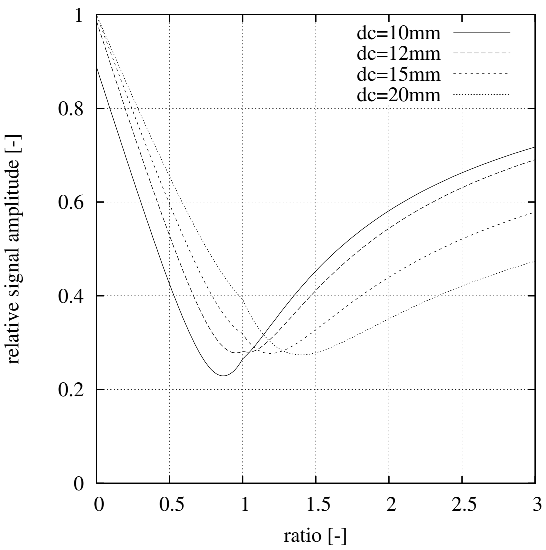

Fig. 8: Dependences of the crack signal relative amplitude on the ratio of superposition for the cracks with depths of d_c = 10, 12, 15 and 20 mm

Similar characteristics of the crack with different depths of d_c = 10, 12, 15 and 20 mm are shown in Fig. 8, 9. The amplitudes are given in relative values and changes in the signal phase for the four cracks are displayed. It is evident that the ratio where the amplitude of the crack signal reaches its minimum as well as rotation of the crack signal depend on the crack depth. Thus, two unique features can be extracted from the characteristics: 1) value of the ratio where the crack signal amplitude reaches its minimum; 2) value of the ratio where the crack signal rotates in half the angle of its overall rotation.

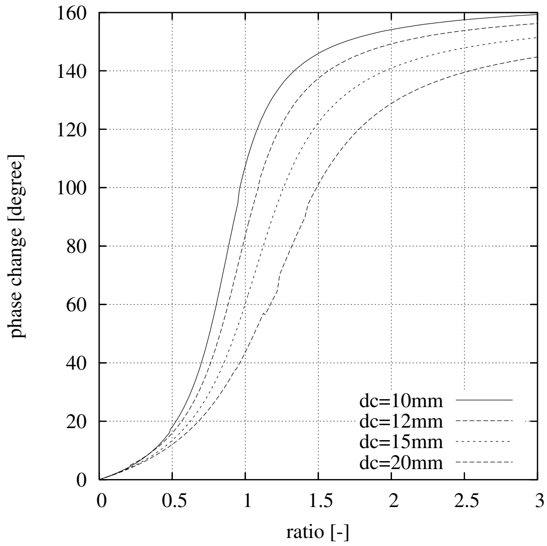

Fig. 9: Dependences of the crack signal phase change on the ratio of superposition for the cracks with depths of d_c = 10, 12, 15 and 20 mm

Dependences of the ratio of superposition on the crack depth for the two extracted features are shown in Fig. 10.

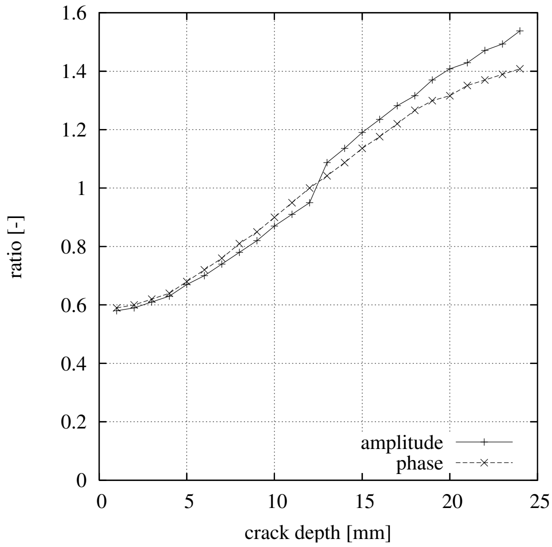

Fig. 10: Dependences of the ratio of superposition on the crack depth for the two extracted features

The dependences for both the features are almost the same. As it can be seen, the features provide clear

indication about the crack depth. In addition, the dependences are almost linear within the investigated range and thus, the cracks much deeper than the standard depth of penetration ($\delta = 4.25$ mm for the given parameters) can also be unambiguously evaluated.
The numerical results are experimentally verified in the next section.

3 EXPERIMENTAL VERIFICATION

Four rectangular EDM notches are experimentally inspected to confirm the numerical results. The notches measure $l_c = 40$ mm in length, $w_c = 0.5$ mm in width and $d_c = 10, 12, 15, 20$ mm in depth. The notches are introduced into an SUS316L plate specimen with a thickness of 25 mm.

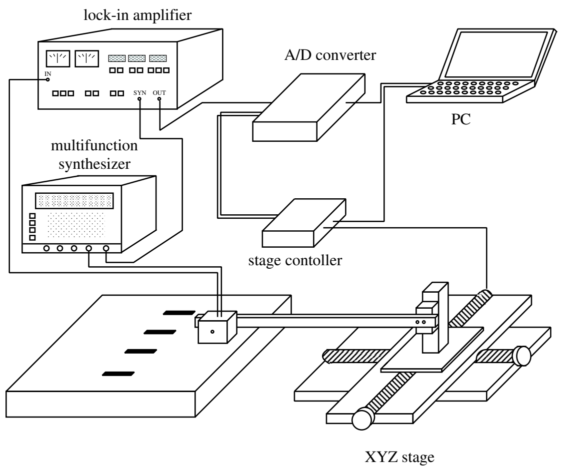

Fig. 11: Experimental set-up

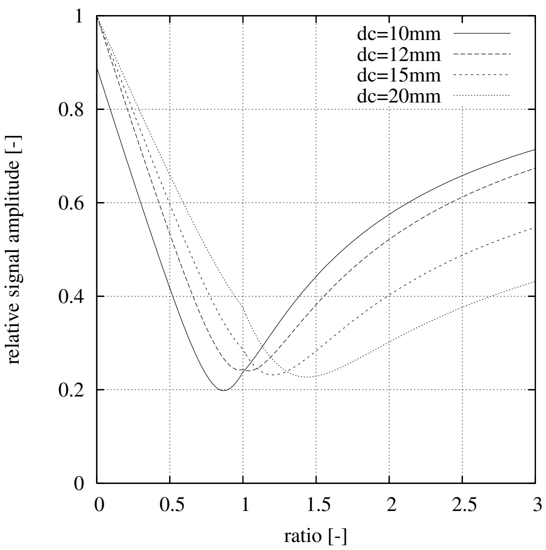

Fig. 12: Dependences of the crack signal relative amplitude on the ratio of superposition for the cracks with depths of d_c = 10, 12, 15 and 20 mm

The parameters of the specimen and of the crack are the same as ones used in the numerical investigations (Fig. 2). The probes (configurations and dimensions are given in Fig. 1) scan at the near side over each crack along their length. A function synthesizer is utilized to drive the exciting coils of the probes. A frequency of 10 kHz is used for the inspection. The crack signal is picked-up by a lock-in amplifier and stored in a PC through an A/D board. Experimental set-up is shown in Fig. 11. It should be noted that all the instruments used in the experiments are the ones that are also utilized in the conventional ECT. Both the signals for each crack are linearly superposed based on (1).

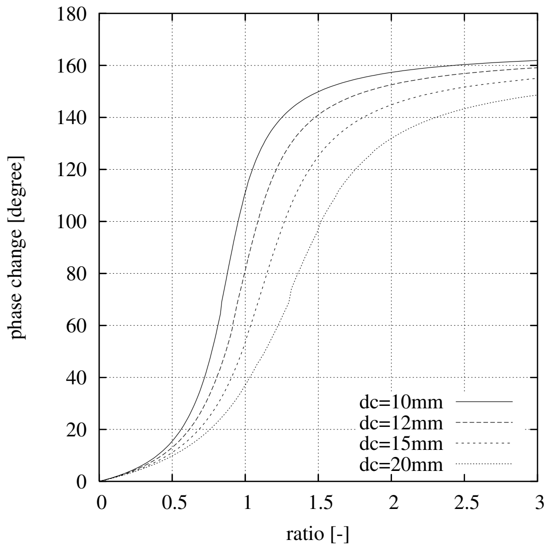

Fig. 13: Dependences of the crack signal phase change on the ratio of superposition for the cracks with depths of d_c = 10, 12, 15 and 20 mm

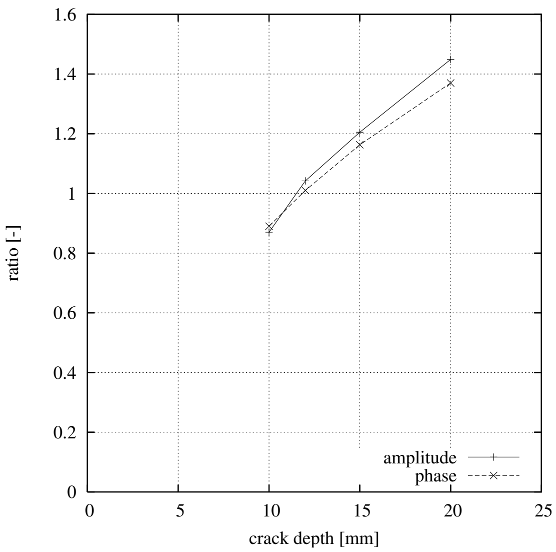

Fig. 14: Dependences of the ratio of superposition on the crack depth for the two extracted features

The experimentally gained dependences of the crack signal relative amplitude and the crack signal phase change on the ratio of superposition for the four EDM notches are shown in Fig. 12 and 13, respectively. The behaviour of the experimental crack signals is very similar to the one obtained using the numerical simulations (Fig. 8, 9). Dependences of the ratio of superposition on the crack depth for the two extracted features are shown in Fig. 14. Similarly as in the case of the numerical results (Fig. 10), the dependences for both the features are approximately the same and they show almost linear relationship between the ratio of superposition and the crack depth.

Comparison of the experimental data with the simulated dependence of the ratio of superposition on the crack depth for the phase feature is shown in Fig. 15. Very good coincidence between the numerical and the experimental results can be observed.

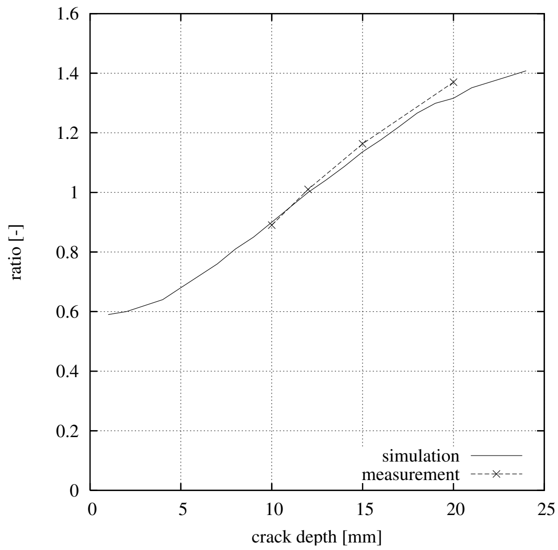

Fig. 15: Dependences of the ratio of superposition on the crack depth for the phase feature, comparison of the numerical and the experimental results

The experimental results prove the effectiveness of the proposed approach for the crack depth evaluation from ECT signals. The extracted features provide clear indication about the crack depth. Moreover, the approach is applicable also for evaluating cracks which are much deeper than the standard depth of penetration.

4 CONCLUSION

The paper presented a novel approach for enhancing sizing ability in eddy-current non-destructive evaluation. Two probes providing different distributions of eddy currents were used for the inspection. The crack signals gained with the two probes were linearly superposed. Feature values of the ratio were extracted from the superposed signals for each crack. It was shown, that the values provide clear indication about the crack depth. Moreover, cracks much deeper than the standard depth of penetration can be sized based on the proposed idea.

5 ACKNOWLEDGEMENT

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