INVERSE PROBLEMS OF EDDY CURRENT TESTING AND UNCERTAINTIES EVALUATION

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Summary This paper deals with the problem of uncertainties evaluation when the procedure of inverse problems is used for processing the eddy current testing data. First the general inverse problem algorithm is described. Next the influence of different types of errors to the results of this algorithm is theoretically analyzed and some results are shown. These results show that the proper choice of the eddy current testing probe is important for achievement of accurate results of the inverse problem solution.

1. INTRODUCTION

Recently the techniques for nondestructive testing (NDT) of materials attract a lot of interest [1, 2]. NDT is promising tool for improving the safety in such a branches of industry like atomic power plants, aerial and space industries. Using NDT the reliability of the crucial components can be tested.

Among NDT techniques the eddy current testing (ECT) is very often used. This technique is based on the idea of inducing eddy current into conductive specimen and then measuring the response using coil sensors. Many research groups are involved in deploying this technique into industrial environment. As the ECT technique evolves, the requirements to the capabilities of it are rising. The most recent challenge is the ability of the reconstruction of the defect using measured signal [3,4]. It means, that not only the location of the defect is determined, but also other important characteristics like the profile of the defect and it's depth are extracted. During the process of the defect characterization many factors influence the resulting values. Several approaches were proposed to take into consideration these factors [5].

2. ECT TECHNIQUE AND INVERSE PROBLEMS

Let us consider conductive plate of infinite size and some coil above the surface of it. Using the coil the electromagnetic field can be introduced into the plate. Because of it's conductivity the eddy current occur and can be detected. The detected signal is the same all around the plate provided the electromagnetic characteristics of the plate are homogeneous. But if this homogeneity is disturbed so is the signal. If the sensor is calibrated using referential specimen, the change of the measured signal signalizes the change of electromagnetic characteristics of the specimen under investigation which can be classified as defect of the material. When scanning around the specimen, the defects can be localized.

To consider the importance of the discovered defect other characteristics than location have to be known - it's dimensions, value of conductivity in the defect area and so on. These characteristics can be determined using the inverse analysis approach. This approach is well known and used in many scientific areas. It is based on the basic assumptions:

- **the defect observability** - it must be possible to measure the signal caused by defect
- **the existence of direct problem solver** - there must exist the computational model which enables to calculate the signal for different electromagnetic and geometrical characteristics of the defect

Provided these assumptions are fulfilled, the following algorithm can be used to determine the characteristics of the defect region using the measured signal:

1. Make initial guess of the characteristics of the defect (geometrical and electromagnetic characteristics) and create computational model
2. Calculate signal using computational model
3. Compare calculated signal with one obtained by measurement
4. If required accuracy is achieved, then the parameters of the model are the parameters of the real defect. Stop the iteration
5. Adjust the parameters of the model and continue with step 2

The important parts of this algorithm are the criteria of comparison the measured and calculated signals and the way of adjusting the parameters of the model.

The former can be performed introducing the suitable norm, for example such as [3]:

$$d(\mathbf{Z}_c, \mathbf{Z}_m) = \sum_{k=1}^{M} \left| Z_{ck} - Z_{mk} \right|^2 , \qquad (1)$$

where $\mathbf{Z}_c$ represents the values calculated using the computational model at the scanning points $1,\ldots,M$ and $\mathbf{Z}_m$ is vector representing the values of the signal measured at the same scanning points.
Values $\mathbf{Z}_c$ depend on two sets of parameters: $\mathbf{p}_g$ represents the geometry of the defect and $\mathbf{p}_m$ represents the properties of the model (computational algorithm, system parameters, properties of the used probes, etc.).

For proper adjusting the parameters of the model, we can use following approach [5]. It is clear, that when the two vectors are identical then $d = 0$. Unfortunately both values are affected by errors, so this problem has to be formulated as looking for $\mathbf{Z}_c$ such, that minimizes the value of d. Equation (1) then represents an optimisation problem. There are available many approaches, for example conjugate-gradient method.

3. IMPACT OF ERRORS

As was mentioned above, the values of both of the vectors in (1) are not precise, but affected by measurement and calculation errors. Afford was made to consider the influence of the errors to the reliability and robustness of the sizing procedure. One possibility was proposed in [5]. To take into consideration the noise of the measured signal, we can write:

$$\mathbf{Z}_m = \mathbf{Z}_{mo} + \Delta\mathbf{Z}_m , \qquad (2)$$

where $\mathbf{Z}_{mo}$ are the precise values of the signal, and $\Delta\mathbf{Z}_m$ represent the measuring errors including both systematic and stochastic component.
To consider the computational errors, we state:

$$\mathbf{p}_m = \mathbf{p}_{mo} + \Delta\mathbf{p}_m , \qquad (3)$$

where $\Delta\mathbf{p}_m$ represents the errors of estimation of the model parameters and numerical accuracy of the algorithm and $\mathbf{p}_{mo}$ is the vector of precise values of the model.

Then equation (1) can be written as:

$$d(\mathbf{Z}_c,\mathbf{Z}_\mathbf{m}) = \sum_{k=1}^{M} \left| Z_{ck}\left(\mathbf{p}_g, \mathbf{p}_{mo} + \Delta\mathbf{p}_m\right) - \left(Z_{mok} + \Delta Z_{mk}\right)\right|^2 \qquad (4)$$

When considering $\Delta\mathbf{p}_m = 0$ and $\Delta\mathbf{Z}_m = 0$, equation (4) becomes:

$$d_o(\mathbf{Z}_c,\mathbf{Z}_m) = \sum_{k=1}^{M} \left| Z_{ck}\left(\mathbf{p}_g, \mathbf{p}_{mo}\right) - Z_{mok}\right|^2 , \qquad (5)$$

which represents *nominal distance*. Because of the lack of errors, *nominal solution* $\mathbf{p}_{go}$ satisfies the equation:

$$d_o(\mathbf{Z}_c,\mathbf{Z}_m) = \sum_{k=1}^{M} \left| Z_{ck}\left(\mathbf{p}_g, \mathbf{p}_{mo}\right) - Z_{mok}\right|^2 = 0 \qquad (6)$$

In cases when $\Delta\mathbf{p}_m \neq 0$ and/or $\Delta\mathbf{Z}_m \neq 0$, solution $\mathbf{p}_g = \mathbf{p}_{go} + \Delta\mathbf{p}_g$ minimizes equation (5).

4. INVESTIGATION OF THE MODEL PARAMETERS ERRORS INFLUENCE TO THE DEFECT DIMENSIONS DETERMINATION

The most important parameters which characterise the defect are its length and depth. When determining these parameters, it is important to understand how the model parameters influence this procedure. This understanding helps to explain, why the results of the inverse procedure are sometimes unreliable [6].

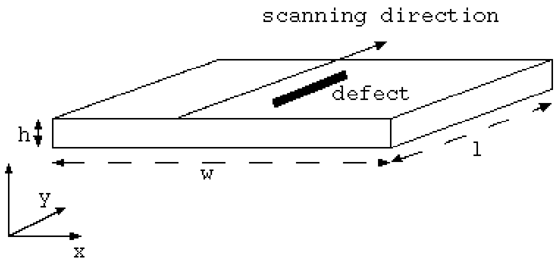

Fig. 1. Experimental arrangement of specimen and defect

To consider the influence of the model parameters to the possibility of determination of these parameters, following model was taken into consideration (fig. 1). The specimen is INCONEL plate with dimensions (w=100, l=140, h=20) mm.

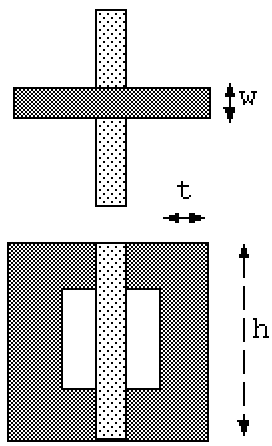

Fig. 2. Plus-point probe

The defect of dimensions (w=0.2, l=10, h=8) mm is located in the centre of the specimen. Signal is calculated for plus-point probe (fig.2) consisting of two square coils perpendicular to each other. Dimensions of the probe are (h=12.5, w=2.5, t=2.5) mm. Scanning path is along the defect length, probe is located symmetrically with respect to the defect.

First the influence of the fluctuation of the length of the defect is considered. To perform this task, equation (4) has to be evaluated for different values of defect length, which yields the dependence of the value *d* with respect to the model parameter *l* - the length of the defect. To neglect the influence of measurement errors, instead of measured signal the signal calculated using mathematical model was used when evaluating equation (5). Because the measurement errors were not considered ($\Delta \mathbf{Z}_m = 0$), we would expect a curve with global minimum value equal to zero. The obtained figure is depicted in fig. 3.

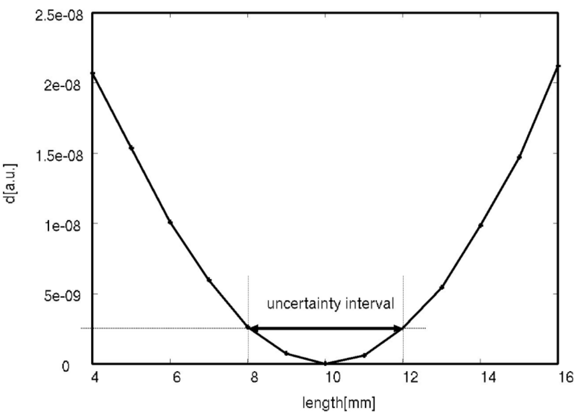

Fig. 3. Dependence of the difference between the referential signal and the signal evaluated usign numerical model for different values of the length of the defect

In step 4 of the algorithm described in section 2 the value of the distance *d* between the measured signal and the signal calculated using model is compared with value ε which is one of the parameters of the model. If the difference between signal obtained by model and referential signal (according equation (5)) is smaller than required accuracy ε, then the parameters of the model are considered to be the sufficient approximation of the defect under investigation. It can be seen, that the uncertainty interval of the length determination depends on the value ε of the criteria for stopping the algorithm for the inverse procedure. As is shown on fig. 3, for value $\varepsilon = 2{,}5.10^{-9}$, the uncertainty interval is <8, 12> mm.

Similarly it is possible to investigate the influence of the variation of the defect depth. The results (fig. 4) show that the uncertainty interval is different for different values of the real value of the defect depth. Uncertainty interval for the defect with depth *h*=4mm is shown, but it can be seen that the uncertainty interval for the defect with depth *h*=8mm is significantly large. It is clear, that when increasing the defect depth, the uncertainty interval is also increasing and it is necessary to consider the suitability of the experimental setup to the task of determination the defect dimensions.

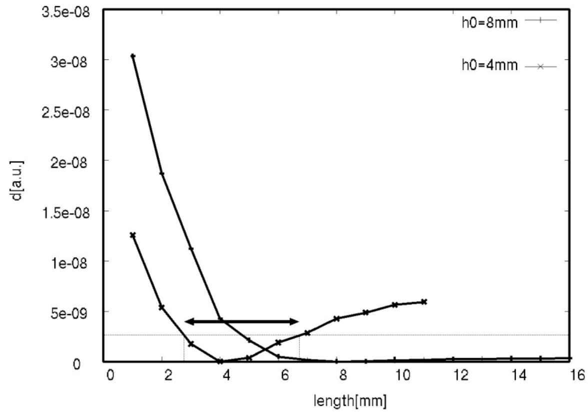

Fig. 4. Dependence of the difference between the referential signal and the signal evaluated usign numerical model for different values of the depth of the defect

5. CONCLUSION

This article shows one approach to the investigation of the uncertainties of the inversion procedure. When the inverse procedure is based on the optimisation methods, the convergence criterion is important part of the numerical model. The proper choice of the convergence criteria can influence the width of the uncertainty interval of the defect dimensions. The methodology mentioned in this article can be used to compare the properties of the different probes used to determine the defect dimensions. This can help to develop the optimal probe for determination the defect with particular geometrical and electromagnetic characteristics.

It can be also used to consider the influence of the different parameters of the numerical model to the uncertainty of the determination of the defect properties.

Acknowledgement

The results presented in this paper were obtained using the simulation codes of the International Institute of Universality, Tokyo, Japan during authors stay in this institute.

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