Overview of Eddy Current Research at Saarbrücken

P. Höller
Institut für Zerstörungsfreie Prüfverfahren

R. Becker
Institut für Zerstörungsfreie Prüfverfahren

K. Betzold
Institut für Zerstörungsfreie Prüfverfahren

Follow this and additional works at: http://lib.dr.iastate.edu/cnde_yellowjackets_1979

Part of the Materials Science and Engineering Commons

Recommended Citation
http://lib.dr.iastate.edu/cnde_yellowjackets_1979/9
OVERVIEW OF EDDY CURRENT RESEARCH AT SAARBRÜCKEN

P. Höller, R. Becker, K. Betzold
Fraunhofer-Institut für zerstörungsfreie Prüfverfahren
D-6600 Saarbrücken 11, Germany

ABSTRACT

The development of an eddy current testing system is described which encloses a 4-frequency test device as well as extensive computer programs to optimize layout and adaptation to practical problems. Results obtained on the testing of welds and heat exchanger tubes are presented. The testing aim is to detect defects and to determine their type and size.

PHYSICAL BASIS

Starting our investigations in the field of eddy current testing we had to learn and then to enlarge the physical basis of the method. We studied the correlation between the impedance of the coil and the test parameters such as the metallurgical and geometrical properties of the specimen as well as the test frequency and the data of the coil itself. We had in hand the results of the work done by Förster /1/ and the theoretical approaches going back to Dodd, Deeds et al. /2/. So we built up a computer program system which allows the numerical evaluation of those test situations where all bordering areas of the coils and the specimens correspond with coordinate planes of the cylindrical coordinate system. Therewith the most important practical test situations can be treated:

- coaxial encircling coil for a bar or a tube
- coaxial inside coil in a tube
- pick-up coil above a plate.

The specimens can consist of one or two layers whereby the electric conductivity, the magnetic permeability and the thickness of the layers are the input parameters of the program. The cross section of the cylinder shaped winding is assumed to be rectangular and its outer and inner diameter as well as its height can be varied.

The numerical algorithm is based on the formulae published by Dodd, Deeds et al. The coil is composed of infinitesimal current loops. The Maxwell equations give the vector potential of the real coil and therewith its impedance is obtained by integrating the vector potential of the single current loop over the cross section of the coil.

In the following some results got by this proceeding are shown /4,5/. Figure 1 represents an impedance diagram for the problem of testing the walls of a reactor pressure vessel. The thickness of the cladding is about 6 mm; the ferrite content of the cladding causes a magnetic permeability of 2; the base material is ferrite. The dimensions of the pick-up coil are listed on the right side of Fig. 1. The abscissa and the ordinate axes represent the real and imaginary part of the coil impedance in presence of the test specimen, normalized by the inductance of the coil in air. The tips of the impedance vectors are moving as a function of the test parameters on locus curves in the impedance plane.

At four frequencies 10, 50, 150 and 400 kHz the effects on the coil impedance caused by variations of the material data of the cladding are calculated. The dotted lines (marked with A) are corresponding to a lift-off of the coil; The lines marked with B represent the variation of the magnetic permeability from 1 to 3; curve C shows the effect of the increase and decrease of the electric conductivity of the upper layer. In addition to these effects the measured impedance of a slit in the surface of the plate is plotted (D). The upper starting point of the locus curve, representing low frequencies, is typical for the special test configuration. Therefore testing of different specimens with the same coil at low frequencies allows to correlate the ordinate value with the magnetic permeability.

Figure 2 represents calculated results for a coil in presence of an aустенитic (lower curve) and a ferritic (upper curve) material. At the aforementioned frequency points the lift-off signals and the measured signals of defects are plotted. The low frequency values on the ordinate axis are 1 for the aустенитic specimen and about 1,28 for the ferritic material.
Figure 3 allows the comparison between two different coils above a two layer specimen. The increase in the coil diameter is correlated with greater real and imaginary parts of the impedance representing a stronger reaction between coil and material. Besides that there arise other phase angles between the different test parameters. These phase angles are, as we can see, a function of the test frequency and of the coil dimension and they are the basis of the later on explained multifrequency method. The eddy current computer-program system allows a short and fast overview of the effects and at least the optimization of the choice of frequencies.

To demonstrate the penetration of eddy currents into the test specimen the figures 4 and 5 show the calculated amplitude of the eddy current density of a pick-up coil in two different depths. The winding of the coil is above the maximum value. One can recognize that the decrease of the current amplitude in the radial direction of the coil is near the surface steeper than deeper below the surface.

In Fig. 6 equivalent evaluations for coaxial outside coils are demonstrated. The lines marked with A are corresponding to an austentic tube with a wall thickness of 1.2 mm while the curves marked with B are corresponding to an austenic bar. For the input data of the program therefore follows that the electrical conductivity of region 1 in the upper part of Fig. 6 must be 0 in the first case (tube) and 1,1 m/Ωmm² in the second (bar).

At lower frequencies there is an obvious difference between the eddy current density in tubes and in bars; the difference decreases with increasing frequency.
At least one representative plot shows in Fig. 7 the effects and the problems concerning the testing of built-in heat exchanger tubes with inside coils.

At six frequencies in the range of 30 kHz to 400 kHz the changes of impedance caused by variations of the following parameters has been calculated: electric conductivity, magnetic permeability, inner and outer diameter of the tube, the effects of the ferritic tube plate and of a ring shaped austenitic tube support plate can be simulated in the computer program by the material data of a second layer. All parameters standing in the schedule in the right half of Fig. 7 (R1 inner and outer radius of the coil; L length of the coil; N number of turns; L inductance, s diameter of the wire) are input parameters and they can be varied to get a complete overview of static effects in tube testing.

In order to know the capability of the theoretical and numerical results for the application on real problems a measuring device has been built up. There was a good agreement between predicted and experimental locus curves.

THREE MAIN PROBLEMS OF THE EDDY CURRENT METHOD

As demonstrated by the examples the impedance of the coil carries the information about the test parameters; it is measured and interpreted. But generally, the impedance simultaneously is affected by several parameters, also by those which not at all are the subject of the testing. The type of the parameter which has caused the detected variation of the impedance cannot be recognized at once. Therefore, the first of the problems applying the eddy current test method is to eliminate the contributions of the parameters to the impedance and to suppress the contributions caused by undesired or disturbing parameters.

In this connection the detection limit for the different parameters is important. Related to defects the detection limit indicates how great the defect size must be that the variation of the impedance caused by the defect is just as strong as the maximum of the disturbing background. Principally, the detection limit is decreased to more advantageous small values by the suppression of the signals caused by the disturbing parameters. But generally, the suppression succeeds not completely, additionally the contributions of the interesting parameters do not remain unaffected by the procedures applied to realize the suppression of the disturbing parameters. Therefore the second of the problems is the optimization of the detection limit of the interesting parameters.

Finally after the suppression of the disturbing signals, as the third of the problems remains the classification and interpretation of the variation of the impedance. Especially for the testing of defects it is necessary to distinguish which type of defect has caused the measured change of impedance before the defect size can be determined.

MULTIFREQUENCY TEST EQUIPMENT /6/

At an early state we understood that the described problems only could be solved by a multifrequency or multiparameter approach originally published by Libby /3/. Therefore, we developed and built a multifrequency equipment. After a first simple laboratory device a present a fully developed prototype exists which is suitable to application in the field. Figure 8 shows the prototype.

In contrast to the common concept where the several test frequencies are fed simultaneously into the coil and processed in parallel channels, we have realized the multiplexing concept. The principle is shown in Fig. 9. The frequency is changed sequencely step by step so fast that the time needed for one cycle is so small that, depending on the scanning speed the test parameters remain unchanged. The lowest frequency limits testing speed.
Under the condition that the clock frequency is sufficiently high, both concepts yield the same results. But concerning the realization and the universal and flexible applicability the multiplex concept has some advantages:
- the electronic expense is independent of the number of frequencies,
- the frequencies can be tuned continuously and in a wide range; there is no need for band filters,
- cross talk between the frequency channels does not exist.

In Fig. 11 the frequency control is drawn separately. Four variable DC-voltages are fed into the VCO-input of a generator. Varying the voltages the 4 test frequencies can be adjusted in the range of 50 Hz to 1 MHz. The test frequency generator yields two output voltages with 90° phase shift one against the other. The multiplexer is controlled by the clock frequency oscillator.

The further processing of the two components of the voltage at the coil is performed digitally. At first, there is a network to compensate a given voltage at the coil and to fix any zero point in the impedance plane. The following network performs the suppression of the disturbing signals. This network is controlled by a µ-Processor and composed of fast computer modules to execute additions and multiplications.

The algorithm applied to suppress the disturbing signals is described in Fig. 12 for a particular example.
It can be seen from Fig. 12 that the described algorithm not only suppresses the signals caused by the disturbing signals but also reduces more or less the defect signals. A measure for the projection losses is the angle \( \alpha \) between the defect vector \( \mathbf{P} \) and the read-out vector \( \mathbf{V} \). This angle is a function of the applied test frequencies. Therefore a frequency combination is optimal when the angle \( \alpha \) is as different to 90° as possible. Especially when the quantity of the needed frequencies is high there are many frequency combinations which must be examined. Therefore we have developed a computer program which performs the choice of the frequencies automatically. Applying the method described in the first section we determine numerically the relevant disturbing vectors as a function of the test frequency and the coil dimensions. Therewith and with the measurement of a reference defect vector the angle \( \alpha \) is computed for all possible frequency combinations. Figure 13 shows the result for a particular example in the field of heat exchanger testing. To suppress the disturbing signals caused by the tube plate, tube support plate, by variation of conductivity of the tubes we must apply 3 frequencies. In the suitable frequency range of 30 to 400 kHz we designate the 9 frequencies coming into account and listed at the right of Fig. 13. Beside the frequency table the material properties and the coil data are described (\( \mu \) electric conductivity, \( \mu \) relative magnetic permeability, \( R_1 \) and \( R_2 \) inner and outer diameter of the tubes, \( L \) length of the coil, \( N \) number of turns, \( L \) inductance, \( s \) diameter of the wire). Diagonally through the picture tables with squares are depicted. The triples of numbers in the squares characterize the frequencies of the corresponding combinations.

![Fig. 12](image1.png)

The task shall be to detect defects in a heat exchanger tube. Disturbing signals are caused by the tube sheet and by variations of the diameter of the tubes. A general rule says that to suppress the signals of \( n \) disturbing parameters at least \( n+1 \) independent measured values are necessary. Therefore in our example we need three independent measured values which can be the real and imaginary part of the voltage at the first frequency and the real or imaginary part of the voltage at the second frequency. These measured values produce a 3-dimensional vector space; its coordinate system is plotted in Fig. 12. In a first step the calibration of the multifrequency system must be performed. The reference point of the measurement is a defined position on the tube where no disturbances exist. Now the coil is brought at a position below the tube sheet, outlined at the left of Fig. 12. The alterations of measured values related to the reference point form the 3-dimensional vector \( \mathbf{P}_R \). In the same way the measured values at a position shown at the top of Fig. 12, where the diameter of the tube is decreased, give the vector \( \mathbf{P}_D \). Both vectors spread out in the 3-dimensional space a plane grey-coloured in Fig. 12. In this plane lie all measured vectors which are caused by the two disturbing parameters in each combination and superposition. The strength of the alteration of the disturbing parameters is expressed in the coefficients \( c_R \) and \( c_D \). Obviously the coefficient \( c_P \) only can have the two values 0 or 1. In a computing step consisting in solving a linear equation system the read-out vector \( \mathbf{V} \) is determined in such a manner that it is perpendicular to the plane of the disturbing parameters.

With the knowledge of the vector \( \mathbf{V} \) the calibration step is finished. Now testing can be carried out, where the measured values arising during the actual test performance are projected onto the read-out vector \( \mathbf{V} \). In the severest case, outlined at the bottom of Fig. 12 we have a simultaneous superposition of the defect signal \( \mathbf{P}_D \) and two disturbing signals. But realizing the projection the contributions of the disturbing parameters are suppressed and only a defect signal is read.

![Fig. 13](image2.png)

The table at the left contains all combinations with the first frequency, the following table the combinations with the second frequency etc. Beside the numbers in each square a sign is written which weights the ability of the appertaining frequency combinations. The signs are declared at the left at the top in Fig. 13 and correspond to the angle \( \alpha \). The test frequencies with the smallest projection losses and therefore with the best defect detection limit are marked by crosses. The result shown in Fig. 13 is valid for an artificial slit at the
outside of the tubes and a depth of 0.7 mm. The wall thickness of the tube is 1.3 mm.

SEVERAL APPLICATIONS

Testing of welds - In Figure 14 on the right, a ferritic specimen is outlined which is cladded by an austenitic steel. In the welding two pulsed fatigue cracks are present. Just there, the distortions caused by material alterations (o and p) and lift-off are especially strong. The testing is made with an absolute pick-up coil which is moved in several traces over the surface.

In Fig. 14 on the left the results of testing with one frequency (100 kHz) and with two frequencies (100 and 300 kHz) are compared. Slits with different depths are used to weight the defect depths. The signals caused by these slits are shown on the left of the plots, followed by signals which appear along an inspection trace over the actual specimen. It can be seen that at the bottom of the plot the disturbing signals are reduced strongly; the remaining signals have the same indication peak as a slit of 0.5 mm depth. The pulsed fatigue cracks give signals which correspond to a slit of 3 mm depth.

Figure 15 describes the results of testing an austenitic welded joint. The material properties between the welding and the basic material differ. The two outlined pulsed fatigue cracks in the welded joint are measured. At first the signals caused by saw cuts are shown on the left of the plots, followed by signals along an inspection trace which meet both cracks in the welded joint.

The signals caused by the cracks are totally masked if the testing is performed by means of one frequency (100 kHz), whereas they are clearly read out if the testing is performed by means of two frequencies (100 and 300 kHz). The disturbing signals caused by the welding are suppressed as well as those caused by lift-off. The remaining disturbing signals have the same indication peak as a saw cut of 0.5 mm depth. The pulsed fatigue cracks are indicated with different height related to their different depth; they produce the same signals as slits of 2 mm and 3 mm depth.

Testing of heat exchanger tubes - The testing is performed with an absolute coaxial inside coil which is moved through the tubes. Figure 17 shows the testing result obtained with the three frequencies 75, 200 and 400 kHz. At the bottom of Fig. 17 the defect signals are superimposed by disturbing signals caused by the tube sheet, by the tube support plate, by variations of the inner and outer diameter of the tubes and by coil wobble. After the processing of the signals
obtained at the three frequencies the upper plot in Fig. 17 indicates only defect signals.

Fig. 17

One can recognize three times the indications of three slits (0.85, 0.7 and 0.4 mm depth, 0.5 mm width, 1.2 mm wall thickness of the tubes) which are located as well in the free part of the tubes as below the tube sheet and tube support plate.

Figure 18 indicates the defect detection limit for the same application. The plots show

1a: disturbing signals caused by the tube sheet, the ring shaped and the grid shaped tube support plate;

1b: the remaining underground of the disturbing signals after the processing;

2a: disturbing signals as in 1a but superimposing defect signals;

2b: the same signals as in 2a but after the suppression of the disturbing signals. The defects are outside slits in the axial direction of the tubes; their depth related to the wall thickness is marked in the Fig. 17;

3: defect signals of outside slits in the azimuthal direction of the tubes.

The results show that the 30 % axial and the 25 % azimuthal slit can be detected certainly even when they are located below the tube sheet or tube support plate. It shall be emphasized that in all cases an absolute coil is used.

INTERPRETATION AND CLASSIFICATION OF THE DEFECT SIGNALS

The multifrequency algorithm described in chapter 4 yields a one-dimensional read-out value. As be done in the preceding chapter the read-out value can be weighted by artificial reference defects with known depths and equivalent indication peaks. But it is not possible to distinguish which type of defect has really caused the read-out value. It is obvious that before the defect size can be determined it is necessary to know the defect type. To enable this we apply the following method. By means of adding at least one additional measured value (this can be the real or imaginary part of a new test frequency) or replacing the test frequencies by completely new ones the multifrequency algorithm is applied two times. In both parallel channels the signals caused by the disturbing parameters are suppressed. Under the condition that the two combinations of the processed measured values react in a different manner upon the different types of defects one obtains a two-dimensional read-out value. Displaying the two channels on the horizontal and vertical deflection of an oscilloscope one achieves the results:

- the disturbing signals are suppressed and concentrated in the zero point of the screen;
- the defects give indications with different phase angles corresponding to the different defect types;
- the peaks of the defect indications are correlated with the defect size.

Using a computer program similar to that described in an earlier chapter, the angles between the phase directions belonging to the different defect types can be optimized.

In the middle of Fig. 19 a heat exchanger tube with the tube sheet, the tube support plate and several types of defects is outlined. Realizing the above described method and processing the two frequency combinations 200/340 kHz and 100/200 kHz one obtains at the right of Fig. 19 the indications caused by the named defect types.

Displaying both read-out values in the described manner on an oscilloscope one obtains the deflections shown at the left of Fig. 19. The upper picture differs from the lower in the depth of the outside notch (50 % and 90 % of the wall thickness) and in the diameter of the hole (0.8 mm and 1.5 mm, both 100 % of the wall thickness deep). Both times the alterations of the diameters are the same.

Figure 20 shows for the same test situations the indications for some other type of defects. In each case the plot and the picture beside them belong together.
Fig. 19

Fig. 20

Summarizing Fig. 19 and 20 one can see that applying the described procedure it is possible to determine uniquely the types of the defects detected after the suppression of the disturbing signals. In the case of simple defect structures the obtained indication peaks are a measure for the defect size.

REFERENCES


