INTRODUCTION

The important steps in eddy current testing for defects in test objects are: detection, classification and sizing. This paper concentrates especially on the last two items.

In general, defect signals cannot be measured separately by eddy current methods, because their signals are superimposed with a lot of disturbing signals. In steam generator tube inspection unwanted signals are caused by support plates, the tube sheet and the rolling of the tube in the tube sheet. Or if one looks at the surface inspection of cladded specimens such as a reactor pressure vessel, changes of magnetic permeability and electrical conductivity occur in different amounts in each weld. Besides that, the surface roughness causes a lift-off of the probe. The task to suppress the influence of such unwanted effects is solved, for example, with excellent quality by multifrequency projection methods. But projection methods can furnish only scalar results, and a scalar read-out value of a system is not sufficient to describe the variety of different defect types, including depth, shape and extension. This means that additional information on the defects has to be provided to solve the task of classification. This paper describes the different resources in detail and explains the total performance of the resulting system.

Multi-Multi-Frequency Evaluation

The first contribution to increase the information content on defects is shown in Fig. 1. The demonstrated procedure is called multi-multifrequency evaluation. Equivalent to the already existing
multifrequency mix in channel 1, an additional multifrequency evaluation process or additional mix is applied in a second parallel channel, which is fed with new and different information. According to information theory, this can be achieved by adding at least one additional measured value (this can be the real or imaginary part of a new testing frequency) or by replacing the test frequencies with entirely new ones. In both parallel mixes the signals caused by the disturbing parameters are suppressed. By feeding the read-out values to the horizontal and vertical deflection circuit of an oscilloscope, as shown in the upper right part of Fig. 1, a two-dimensional display is created in which various types of defects generally produce different phase angles. This means that the two sets of processed measured values react in a different manner upon the types of defects, while the disturbing signals are suppressed and concentrated at the zero point of the screen. The amplitude of the signals is related to the respective defect depth. For each special application and for each probe the determination of the optimum frequency combinations for the different mixes is performed by a computer program; optimum means large phase angle between different defect types and large amplitudes to provide good sensitivity for the detection of small defects. The test frequencies are selected from about 10 frequencies in the range between 1 kHz and 1 MHz according to the inspection problem, in steam generator tube testing the lowest used frequency is about 50 kHz.2

Fig. 1. Principle of multi-multi-frequency eddy current testing
The lower part of Fig. 1 demonstrates the principle for two different applications. On the left side it is shown that for an austenitic plate, the signals of surface slots lie in the first quadrant, whereas the signals of slots on the opposite side lie in the third quadrant, and they are turning their phase angle and varying their amplitude according to the remaining plate thickness and depth of the slots. For tube testing with inner pick-up coils this would correspond to the remaining wall thickness. On the right side the principle of defect classification is shown for steam generator tube inspection; this item will be discussed in more detail in the next section.

Defect Characterization in Steam Generator Tube Inspection; Bobbin Coils

Figure 2 shows in its center a steam generator tube with a ferritic tube sheet, an austenitic support plate and several types of defects. The inspection was performed with an absolute coaxial inner coil. By using the method described above and processing the two frequency combinations 200/340 and 100/200 kHz, one obtains the x-t records shown on the right side of the photo. If both read-out values are displayed in the manner described at the beginning on an oscilloscope, one gets the deflections shown on the left side. In this application the signals of tube sheet and support plate have been

Fig. 2. Classification of defect signals in steam generator tube testing.
suppressed; remaining signals due to non-complete suppression correspond to a thick zero point on the screen. For this special configuration the computer program produced a multi-multi-plane with a phase of about 90° between wastage-like defects on the outer and inner surface of the tube, while other defect types are lying between them. The upper picture differs from the lower in the depth of the outside slot (60 and 90 percent) and in the diameter of the hole (0.8 and 1.5 mm; both 100% of the wall thickness).

Figure 3 shows for the same test situations the indications for some other types of defect. Inner and outer axial and circumferential defects can also be classified by this method; the amplitude indicates the depth of the defects. It is important to investigate the influence of the presence of disturbing effects on the phase angles in these two dimensional displays. As shown on the left side of Fig. 4, the fact of outer axial slots having the tube sheet or the tube support plate superimposed on them does not change the phase direction. The amplitudes are slightly reduced as in the case of one dimensional evaluation. The photos on the right side show the results from drilled holes and inner axial slots in the region of the tube sheet.

Fig. 3. Classification of defect signals in steam generator tube testing.
What cannot be solved by this method is the classification of defects which are simultaneously measured by the coil; that means, for example, a superposition of different defect types which are circumferential on the tube wall. Stress-crack-corrosion damaged tube-specimens, provided by Battelle Northwest, contributed to intensify the investigations on this problem.

To solve the task, single frequency signals of a coaxial inner coil in absolute arrangement have been analyzed for a multitude of single, superimposed and circumferentially lying artificial defects of different types. The results are demonstrated in Fig. 5. With respect to the SCC-damaged tubes it is important to note that wastage-type defects of similar areas (A, B and C) are causing the same phase-angle as a machine made field of small slots (F). A major result was that the coaxial coil cannot provide enough information for defect classification because various combinations of single defects and various types of defects can produce the same signal.3

The next three figures represent typical SCC-defect areas of the damaged tubes produced by Battelle Northwest. Figure 6 shows one single axial crack with open rims. Figure 7 shows some smaller and larger separate single cracks and connected cracks, some of them with tight rims, others opened. The main crack direction is parallel to the tube axis, but the cracks occur in different circumferential angles. In Fig. 8 a field of small cracks with distances of about 40 microns between each can be seen. The agreement of the phase
Fig. 5. Single frequency testing of steam generator tubes with bobbin coils.

Fig. 6. SCC-damaged tube area.
Fig. 7. SCC-damaged tube area.

Fig. 8. SCC-damaged tube area.
angle of the signals of this natural crack field and the artificial slot in Fig. 4 was very good.

Defect Characterization in Steam Generator Tube Inspection; Pancake Coils

The appropriate tool for tackling these problems by eddy currents are inner pick-up coils in absolute arrangements. Figure 9 points out one characteristic difference between the signals of pick-up coils and those of inner coaxial coils. In the right photo the impedance changes due to a support plate and an outer axial crack can be seen; the amplitude of the defect is fairly small compared with the amplitude of the unwanted signal that has to be eliminated. The photo on the left side shows an increase of the ratio of crack signal to disturbing signal of about 7 for the same frequency when applying pick-up coils.

The following photos represent results achieved with inner rotating absolute coils. The first one (Fig. 10) shows the scanning of artificial defects on the outside of the tube: a crack-like defect, a wastage and a machine made field of slots. It can be seen that the behavior of wastage and a field of slots is similar because the dimensions of the coil (outer diameter of about 4 mm) do not allow the resolution of the single slots. The decrease of the coil dimensions for having better resolution is combined with a decreasing penetration depth and it is therefore limited. Figure 11 shows a result for natural defects; on the left side the signal of a single crack with a depth of about 90% of the wall thickness can be seen. The other signal is caused by a field of cracks with a depth of about 30%. In Fig. 12 it can be seen that even a single deep crack in a crack-field can be resolved.
Fig. 10. Steam generator tube testing with pancake coils.

Fig. 11. Steam generator tube testing with pancake coils.
Fig. 12. Steam generator tube testing with pancake coils.

Such pictures suggest that we use the signal dynamic as a further tool for classification. Especially useful is the evaluation of the signal dynamic after having suppressed the disturbing signals because these dynamic curves are exclusively related to defects in the specimen. What the eye of the human does when looking at a C-scan can be done in an objective way by a computer. In order to investigate the capability of the procedure in the laboratory, computer programs have been written which are evaluating the rise-time, the time of maximum signal amplitude, number of close maxima and maximum gradient of the curves. In tube testing with inner coaxial coils where only one inspection pass exists, this procedure alone provides separation of pitting from other defects and it indicates the axial extension of all defects. As these dynamic signals are produced by the probe movement, there have to be investigated the requirements concerning the constancy of the probe velocity. When scanning several passes, a correlation between the signals in related passes is performed; it is something like a neighborhood criterion that is applied.

Principle of Automatic Eddy Current Defect Characterization

Figure 13 shows the working together of the single parts of our evaluation method; it represents the principle of automatic eddy current defect characterization. In the calibration step a multitude of both dynamic patterns and multi-multi-frequency patterns is stored for different defect types. When a defect signal is detected during the inspection in the read-out channels after suppression of disturbing effects, the actual signal is compared with the stored patterns. That corresponds to the classification. When the specimen can be tested in different passes, the correlation of different scan passes contributes to determine the extension of the defect. The depth of the special type of defect can now be found by evaluation of the amplitudes of the multi-multi-frequency pattern.
Defect Characterization in Plate Inspection

The next part of this paper is concerned with the application of the described multi-multi-frequency method to austenitic plates. The object that has been inspected was a 6 mm thick part of a wall of an austenitic vessel used in the chemical industry with stress-corrosion cracks on the inside. The inspection of such a vessel can be performed usually only from the outside. The goal was

- to detect the inside cracks,
- to separate them from outer surface cracks,
- to determine the remaining wall thickness.

Figure 14 shows the result of an optimization of the frequency combination for defects below the surface. While the amplitude of a 1 mm surface slot in the right hand arrangement is larger than the signal of a 4 mm deep subsurface slot with 2 mm remaining wall thickness, the optimization on the left side produces a larger amplitude for the subsurface slot than for a 2 mm surface slot. Moreover, it can be seen that the signals of the surface defects have quite different phase angle than those of the subsurface defects. The outer diameter of the coils was 20 mm.

According to theoretical predictions it could be proved that the penetration depth can be increased not only by using lower frequencies but also by increasing the outer diameter of the coil. But the choice of the probe is correlated with the smallest defect size which must be detected. The detection limit for subsurface defects
is dependent on the relation between defect size and coil dimensions and on the disturbing parameters of the special application. For this special arrangement it was demonstrated that a 2 mm deep crack at the opposite side of a 8 mm thick austenitic plate could be detected when it had a length of about half the diameter of the coil. Figure 15 shows a sketch of a part of the damaged austenitic vessel. There are deep separate cracks, cracks with different larger and smaller branches and fields of small cracks together with deep cracks. Scanning the wall with the 20 mm coil from the inner side gives the right hand signals, scanning it from the outside produces the lower left hand signals. All defects could be detected and assessed according to their phase angle and amplitude. Cracks No. 4 and 5 are plotted in the same picture in order to show the turning phase angle; the open loops of the signals No. 2 and 3 are due to superpositions of crack fields and single cracks. The signal in the first quadrant at No. 3 is caused by an outer surface crack.

CONCLUSION

It has been demonstrated for special applications that the multi-multi-frequency procedure allows suppression of unwanted influences and characterizes different defect types by their phase angle in a plane constructed by the read-out values. A second step to invert the eddy current signals is the implementation of the signal dynamic of the defects in the evaluation procedure. For such specimens which can be inspected in several traces, the information content of close traces is correlated. The information of these
DEFECT CHARACTERIZATION OF MULTIFREQUENCY EC SYSTEM

Fig. 15. Multi-multi-frequency testing of a SCC-damaged austenitic plate.

signals is evaluated in a computer in order to indicate type, shape and depth of the defects. The potential of the method and its limits have been outlined for the inspection of steam-generator tubes and austenitic tanks.

REFERENCES


DISCUSSION

D.T. Mih (Northrop): I don't understand your past frequency mixing. Are you thinking of products of test frequencies?

K. Betzold (Fraunhofer Institute): No, that's not a product. That's only a combination of the signals that you get at different measuring points in the impedance plane. That means you are working at a well-defined point in the impedance plane, and while you are looking at the variations due to the disturbing effects and the defects at this certain frequency, you combine them according to a multifrequency projection method. That means for the calibration step we are using only amplitude and phase angle information at different frequencies. In this case, we have two frequencies in order to suppress three effects. That's what we have done here.

S.R. Satish (Colorado State University): Each time you knock off a certain component, you lose a certain amount of amplitude, right?

K. Betzold: The more projection you are doing, because it is a projection, the more amplitude you are losing. So we want to have only a few projections. You could imagine that you can have a procedure with a lot of readout channels, and each readout channel should give you only information about one special defect type, but then you have to give three disturbing effects and five other defect types in your calibration steps, so you have eight effects for your projection. So it could happen that you have no readout value at the end because you have projected eight times.