CROSS CORRELATION OF EDDY CURRENT IMAGES FOR DETECTION OF FATIGUE CRACK PROPAGATION

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INTRODUCTION

There is a need within the NDE industry to evaluate the growth of damage such as fatigue cracking and plastic deformation over the life of a structure. To accomplish this aim, data collected over a period of time must be compared spatially while quantitative measures must be developed to determine the extent of crack propagation in a damaged region. To facilitate automated inspection and characterization of defects in metals, the application of cross-correlation techniques and frequency mixing to sequential eddy current images of fatigued welds and fatigue cracks in compact tension and reduced section specimens has been investigated. Results indicate that cross-correlation techniques can be used to align scan images to provide a history of damage development and that frequency mixing can enhance the signal-to-noise ratios of fatigue cracks in welded steel. Localized damage was detected by segmenting the images into smaller cross-correlation regions for improved resolution. The technique may be used to examine magnetic eddy current data from ferrous welds and seams and to identify cracks or regions of cold working in transportation and energy-generation systems.

CROSS-CORRELATION DETECTION OF CRACK PROPAGATION

Automated nondestructive inspection of materials over repetitive time intervals requires accurate positioning of the inspection instrument and objective measures for assessing damage progression. The cross correlation between scanned images provides information concerning alignment of scans taken at different service intervals and provides a quantitative measure of changes in material properties caused by damage, corrosion or crack growth. The cross-correlation image is an image of correlation levels, where the location of the absolute peak is the estimated amount that the original two images need

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to be shifted. The peak value of the image is unity if the images correlate exactly, and zero if no correlation is found. Thus, the cross-correlation technique is used to align the images and to provide a measure of similarity between two images.

The correlation between two functions g and h is:

$$\mathrm{Corr}(g, h) = \int_{-\infty}^{\infty} g(T + t)\, h(T)\, dT \qquad (1)$$

The discrete form is:

$$\mathrm{Corr}(g, h)_j = \sum_{k=0}^{n-1} g(j + k)\, h(k) \qquad (2)$$

The expected result of the cross-correlation investigation is that damage growth will alter the characteristics of the images by reducing the correlation value. To test this hypothesis, eddy current images of a growing fatigue crack were obtained from welded A36 steel compact tension (CT) specimens subjected to cyclic loading using an MTS 880 load frame. Eddy current nondestructive inspection techniques are sensitive to several effects in materials, including notches, welds and cracks. The samples were repeatedly fatigued, unloaded, scanned using eddy currents and reloaded for fatigue to observe the crack growth.

Figure 1 shows the eddy current scanned image of a CT specimen before fatigue testing. Figure 2 corresponds to the same specimen after repeated cycling during which a fatigue crack has grown nearly 12 mm and significant plastic deformation has occurred. The fatigue crack and plastic zone growth cause a reduction in the cross-correlation value over time as shown in Figure 3. The final correlation value of 0.5 indicates that a significant change has occurred in the sample and that the cross-correlation technique is able to detect changes caused by cracking. However, this decrease in level was sudden and the correlation coefficient decrease was minimal after the initial crack was detected.

To increase the sensitivity of the cross-correlation method, the original image size was segmented into smaller regions, so that those regions which experience the most change would be emphasized. Segmenting was performed both in vertical (perpendicular to crack growth) and horizontal (parallel with crack growth) strips. For the case of the horizontal segments, the cross-correlation value decreased in the segments that were affected by the crack growth. The horizontal segments away from the crack were not affected. For the case of the vertical segments, the cross-correlation value in each segment decreased as the crack and associated plastic zone propagated through the segment.

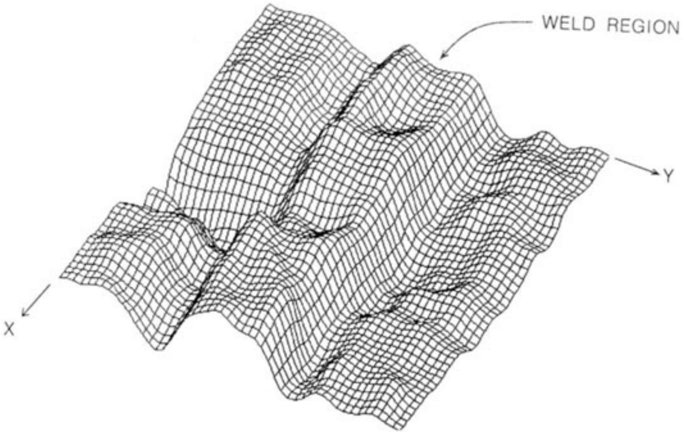

Figure 1. Eddy Current Image of Compact Tension Specimen before Initiation of Crack Growth.

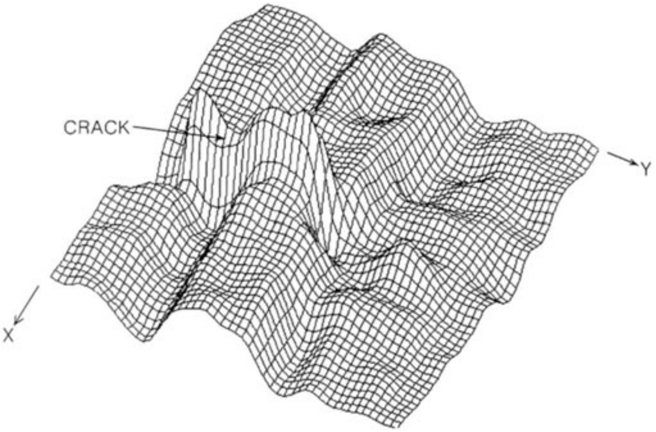

Figure 2. Eddy Current Image of Compact Tension Specimen after Fatigue Crack Growth.

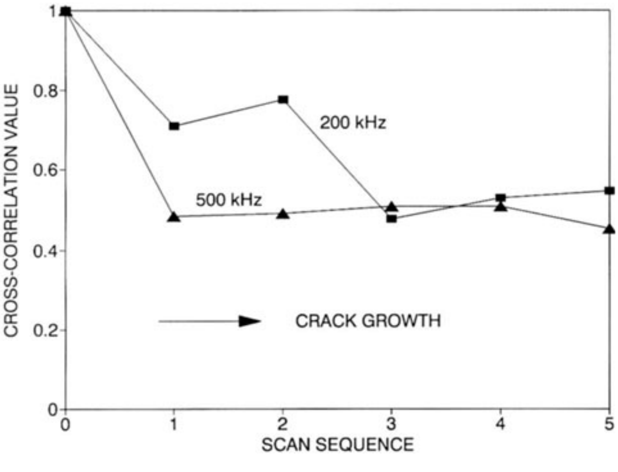

Figure 3. Cross Correlation of Sequential Eddy Current Images of Crack.

CROSS-CORRELATION DETECTION OF PLASTICITY

The cross-correlation technique may also be applied to detection of plastic deformation in metal associated with low cycle fatigue. Welded reduced-section tension specimens of A36 steel were subjected to cyclic stress levels of 350 MPa for up to one-half million cycles using an MTS 880 load frame. The samples were repeatedly fatigued, unloaded, scanned using eddy currents and reloaded for fatigue to observe the growth of the damage regions. For the reduced-section specimens, the large fatigue stress and strain levels required for the ultimate failure of the specimens caused a large initial amount of plastic deformation. Thus, the first cross correlation showed a large initial decrease. This observation shows the sensitivity of the technique for detecting plastic deformation.

Figure 4 shows the cross correlation of the images taken from a reduced-section sample. As expected, the cross-correlation coefficient decreased after the first inspection due to significant plastic deformation in the first fatigue cycle. Further decreases were relatively small. To increase the sensitivity and to discriminate further damage, segmenting was performed on these images. Since a large plastic zone was induced in the specimen within the first fatigue cycle, all correlations were performed relative to the first scan after plastic deformation, scan 1. For the first specimen, the image was segmented into three regions; i.e. below, containing and above the weld. The cross-correlation coefficient decreased as is shown in Figure 5. The final failure occurred in the heat affected zone between the weld region and the region below the weld. As shown in Figure 5, these regions had low values of cross correlation, so the technique succeeded in detecting the region of critical damage prior to failure.

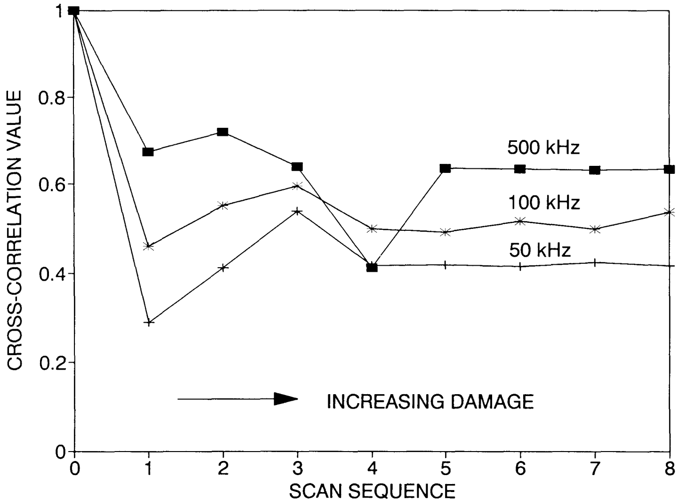

Figure 4. Effect of Damage Progression on Cross-Correlation Value for Reduced-Section Specimen.

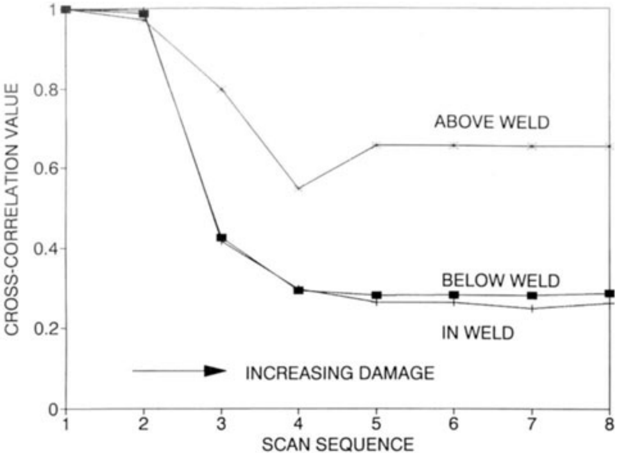

Figure 5. Effect of Damage Progression on Cross-Correlation Value for Segmented Image of Reduced-Section Specimen

FREQUENCY MIXING FOR NOISE SUPPRESSION

Although eddy current nondestructive evaluation techniques are effective tools for monitoring damage conditions in structural components, signal interpretation is a major obstacle to be overcome, especially in the presence of complex geometries. The fact that cracks often emanate from highly stressed regions, which have strong geometrical changes, causes difficulty in the interpretation of eddy current signals. For example, cracks often form at fastener holes and at corners. Highly stressed regions are often reinforced and the eddy current probe will pick up the reinforcement in addition to the crack signal. The objective of frequency mixing is to remove the unwanted effects of geometry and material property changes in weld regions.

Implementation of frequency mixing techniques requires the determination of the relationship between eddy current response and frequency for each unwanted effect. For weld inspection, one could suppress the effect of the weld region on eddy current response and leave the response from other objects, such as cracks. The key to success of this technique is that the wanted and unwanted effects vary differently as functions of frequency.

The effect of frequency on eddy current response was obtained by scanning a sample at two different frequencies, 200 and 500 kHz. The images were viewed and the region to suppress was identified as to its location and size. The two images were scaled and summed to result in a single image that does not suffer from the large undesirable background effects. The scaling parameters were determined to minimize the power (H^2+V^2) in the suppressed region. For mixing two images, the format is as follows:

$$\begin{bmatrix} H_3 \\ V_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} H_1 \\ V_1 \end{bmatrix} + \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} H_2 \\ V_2 \end{bmatrix} \qquad (3)$$

where

H is the horizontal eddy current response,
V is the vertical eddy current response,
1, 2 and 3 are the first, second and resulting images, respectively, and
a_{11}, a_{12}, a_{21} and a_{22} are the mixing coefficients.

The resultant image is comprised of the weighted sum of the resultant vectors at each spatial point. The mixing coefficients a_{11}, a_{12}, a_{21} and a_{22} are determined by minimizing the power over the mixing region. Once these coefficients are determined, the mixing is performed over the entire image. Previous experience has shown that a two-frequency mix results in the best suppression of the undesired effect. The use of three or more frequencies tends to add noise to the images rather than suppress noise. These mixing coefficients are used to combine the two original images over their entire areas, not just the mix region. The method succeeds if the response from the crack changes differently with frequency than does the response from the weld region. Once computed, these mixing coefficients may be stored for mixing other images.

Frequency mixing was applied to the compact tension specimens to increase the signal-to-noise ratio of the crack signals in the weld region. A typical eddy current image of a CT specimen containing a weld and crack is shown in Figure 6. Regions of interest include the machined notch in the CT specimen, the base material, the crack and the weld region. The eddy current response level of the weld and crack regions are higher than those of the surrounding regions. This fact demonstrates the effectiveness of the eddy current technique in detecting cracks and welded regions, but reveals a difficulty. If defects are detected based on amplitude, then false alarms will occur more often in the weld region. This problem is alleviated when frequency mixing is used to reduce the eddy current response to weld regions.

To apply the frequency mixing technique for weld signal suppression, eddy current scans were taken at 200 and 500 kHz. After mixing the images, the weld response was reduced and had a signal of similar strength to the surrounding base region as shown in Figure 7. While the crack signal was visibly enhanced in Figure 7, a side effect of this process was that the notch signal was also enhanced. The notch was not included in the mix determination, so this effect was expected. Mixing may be performed to remove the notch effect as shown in Figure 8. The effect of the notch was reduced, but the crack and weld regions were retained. In the experience of the authors, frequency mixing techniques should prove useful in suppressing background features of eddy current scans which mask the features of interest such as cracking as illustrated in this example.

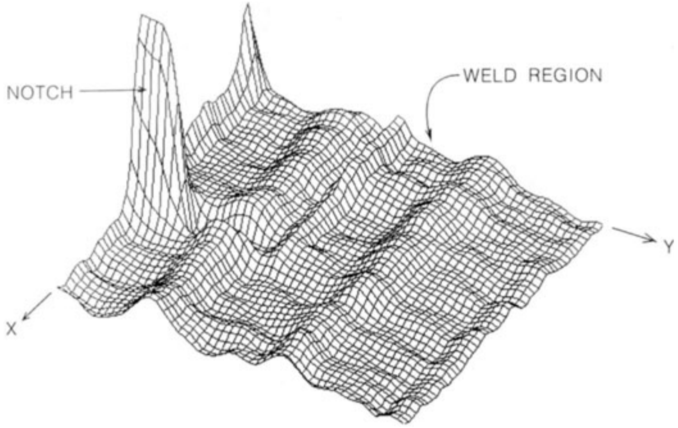

Figure 6. Eddy Current Scan of Compact Tension Specimen.

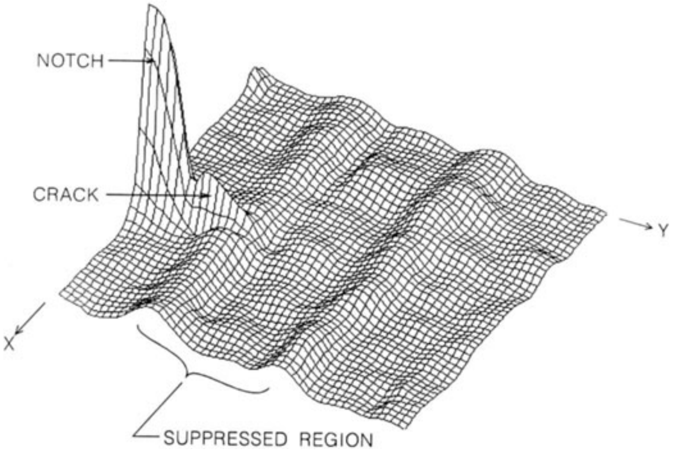

Figure 7. Frequency Mixing for Suppression of Weld Region.

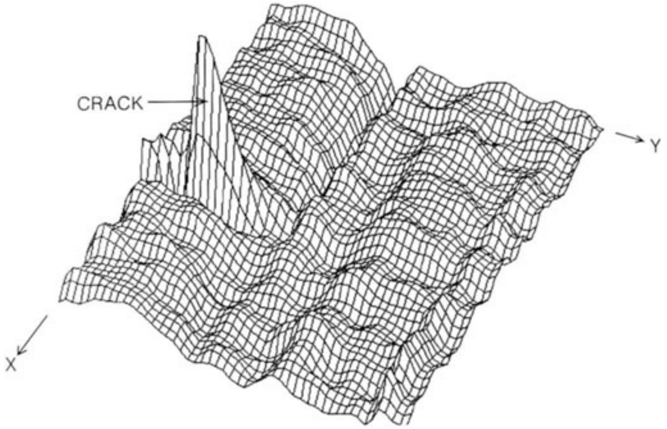

Figure 8. Frequency Mixing for Suppression of Notch Region.

CONCLUSIONS

The cross-correlation technique, when used in conjunction with eddy current inspection, is sensitive to plastic deformation and to the presence of a crack. The cross-correlation technique can be used to align inspection images. After initial plasticity and/or crack growth, the cross-correlation technique is less sensitive to further damage development. In particular, the cross-correlation technique was effective in detecting plastic deformation in reduced-tension specimens, but did not continue to show further damage development. In addition, the technique detected initial crack growth and plastic zones in CT specimens, but was less sensitive to the growth of cracks. Image segmentation increases the sensitivity of the cross-correlation technique and allows a better estimate of damage location.

Frequency mixing can increase the signal-to-noise ratio of cracks in welds because crack signals and notch signals are separable in the frequency domain. Frequency mixing usually suppresses one feature at a time. For most applications, single feature suppression is sufficient.

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