AUTOMATIC EDDY CURRENT INSPECTION OF ANTIROTATION WINDOWS IN F100 ENGINE COMPRESSOR AIR SEALS

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INTRODUCTION

In an effort to apply many NDE techniques to real inspections as in an automated inspection system, one often encounters situations less than ideal. These nonideal conditions frequently cause modification of existing techniques, and in some cases may even force the development of new methods. One factor which commonly causes reconsideration of NDE techniques is the geometry of the area to be inspected, since this will vary from application to application in an unpredictable way. This is true in eddy current inspection methods, which are sensitive to surface and conductivity discontinuities and liftoff variations, [1], and therefore are highly geometry dependent. One example, which is the focus of this paper, is the eddy current inspection of a rectangular opening in a surface, such as an antirotation window in aircraft engine airseals. In this situation, an eddy current inspection technique was sought which would allow detection of surface flaws connected to the window. This paper discusses three conventional methods and one novel method of extracting flaw information from the inspection signal. Experimental data are also presented.

EXPERIMENTAL SET-UP

The experimental set-up consisted of a differential eddy current surface probe scanning across or near a window, as shown in Figure 1. The probe liftoff was varied in the experiment, although the effect of liftoff variation was not directly studied. The probe was scanned at a surface speed of 8.1 cm/sec (3.2 inches/sec). The scan path brought the probe just to one side of the rectangular window. The signal generated by rapidly scanning by the window was composed of both a strong geometry signal and a weak signal generated by notches placed near the the windows. This was true regardless of the direction of liftoff response in the impedance plane. For this reason the rotation angle was chosen so that the notch signal was primarily in the vertical direction of the impedance plane. From earlier tests on electrical discharge machine (EDM) notches on flat surfaces, both high pass and low pass filters were selected to eliminate low frequency components of the geometry signal and high

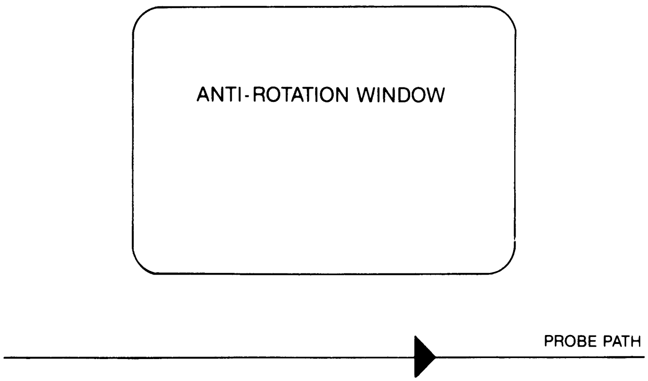


Fig. 1. Experimental set-up, showing path of differential probe.

frequency electronic and mechanical noise, while passing the notch signal. All data presented in this paper were derived from one probe as it scanned one aircraft engine airseal containing six antirotation windows, three of which contained EDM notches. The notches ranged in size from 0.02 to 0.03 inches in length, 0.010 to 0.02 inches in depth, and 0.004 inches wide.

All data were taken using a Nortec NDT-25L Eddy Scope. The study was conducted at a driving frequency of 1 MHz. Qualitative comparisons were made at several other frequencies. The probe was a Nortec 1 MHz, differential pencil probe. The instrument settings were as follows: gain of 100, phase angle of 48 degrees, high pass filter of 20 Hz, and low pass filter of 30 Hz. The data were recorded by a Tektronix 7D20 Programmable Digitizer. Channel 1 digitized the vertical output of the NDT-25L, while channel 2 digitized the horizontal output. With a sweep rate of 20 msec/div of the digitizer, 1024 data points were collected over 0.2 seconds. The frequency of the signals produced by scanning by a window, whether or not it contained a notch, allowed the use of only every tenth data point during signal processing without adversely affecting the results.

It is important at this point to explain the method used to calculate the frequency components of all signals discussed in the following section. Assuming that the notches would be found near the corners of the windows, as was the case for all windows examined, all time domain signals were gated to eliminate either the first or the second half of the signal from the window. The portion of the digitized signal that was kept was then padded with a number of zeros which was at least as great as the number of data points in the gated signal. An FFT algorithm was then applied to this gated and zero padded signal. All signal processing was done using a Hewlett Packard 9836 desktop computer and the Hewlett Packard Waveform Analysis package, 98827A.

OBSERVATIONS AND RESULTS

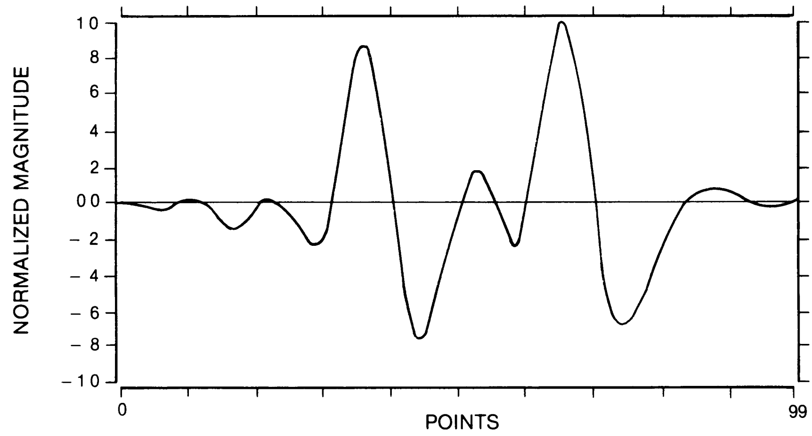
Initially, three possible methods can be considered to separate the notch signal from the geometry signal which remains after filtering. The first method is to determine the geometry signal by scanning good windows, and then subtracting this in the time domain from the inspection signal to reveal any notch signal that might be present. The second method, similar to the first, determines the notch signal by again subtracting the geometry signal from the inspection signal, but, in this case, in the frequency domain. The third method filters the data using either an analog or digital filter which is designed to best filter out the window signal.

The application of these methods to the specific case of detecting notches near antirotation windows proves to be difficult and is perhaps impossible. There are two primary reasons for this: (1) The geometry signal has been observed to vary to such a degree from window to window to make subtraction in either the time domain or the frequency domain undesirable. Example signals are shown in Figures 2 and 3, where typical variations in signals from window to window are seen. These variations produce artificial flaw indications. (2) The difference in frequency between the notch and the geometry signals is small. The notch signal is expected to occur at a frequency in the range of 25 Hz to 40 Hz. As can be seen from Figure 4, not only is this true, but the notch signal for this particular window is fairly large. And yet, by comparing the frequency of the notch signal to that of the good window signal shown in Figure 3, it becomes apparent that an effort to filter out the geometry signal leaving the notch signal would be difficult, if not impossible. Although the method of filtering is not completely ruled out, it would require a filter with a high number of poles to remove the geometry signal, and this would possibly result in "ringing" of the notch signal in the time domain. Further research needs to be conducted in this area to determine whether the constraints on this method will allow application to the antirotation window problem.

As the study of the application of these methods mentioned above progressed, an important observation was made. With the notch signal isolated to the vertical component of the impedance plane, a difference between the vertical component and the horizontal component verses time is observed. This striking difference is not observed in good window signals. To be more specific, the geometry signal appears in both the horizontal and vertical components. In good windows, these two components have marked similarities, even though the pattern varies from window to window. This can be seen in Figure 5, which shows the horizontal and vertical components in the time and frequency domains. In notched windows, the two components have significant differences, as seen in Figure 6. This figure shows the horizontal and vertical components of a notched window in both the time and frequency domains. Initially, these differences in the notched window signals, like the similarities in the good window signals, were qualitative and visual.

WINDOW 2 — GOOD

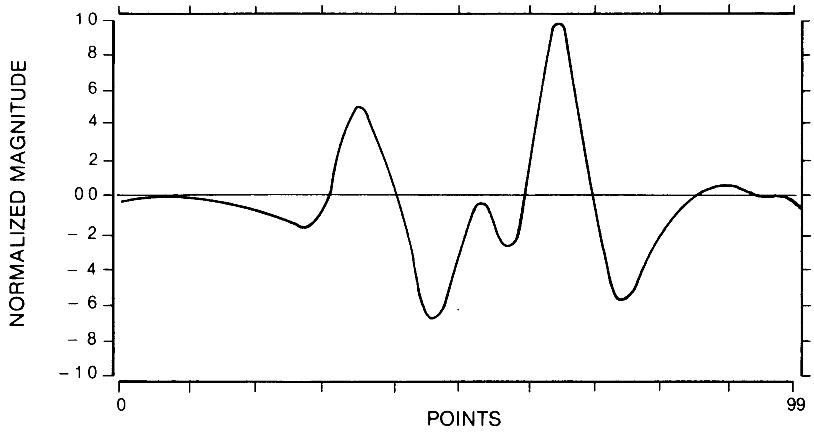
TIME DOMAIN DATA



NORMALIZED MAGNITUDE 1 = 45 VOLTS
SAMPLING PERIOD = 1 95 E - 03 SEC

WINDOW 5 — GOOD

TIME DOMAIN DATA

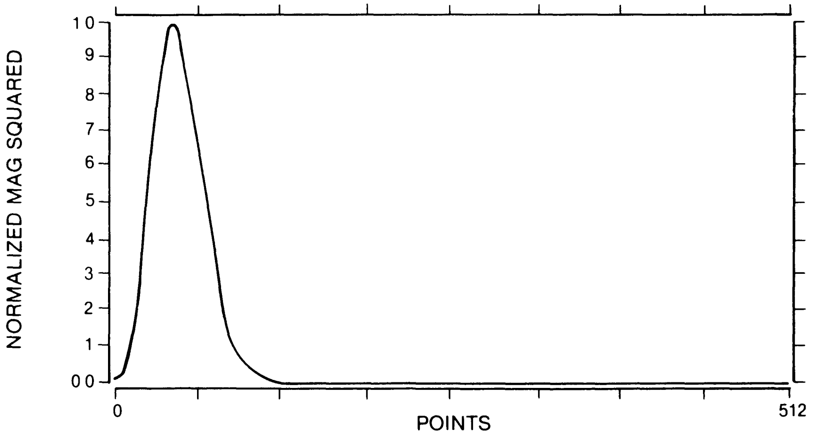


NORMALIZED MAGNITUDE 1 = 52 VOLTS
SAMPLING PERIOD = 1 95 E - 03 SEC

Fig. 2. Sample data showing variations in the time domain signals from window to window for good windows.

WINDOW 5B — GOOD

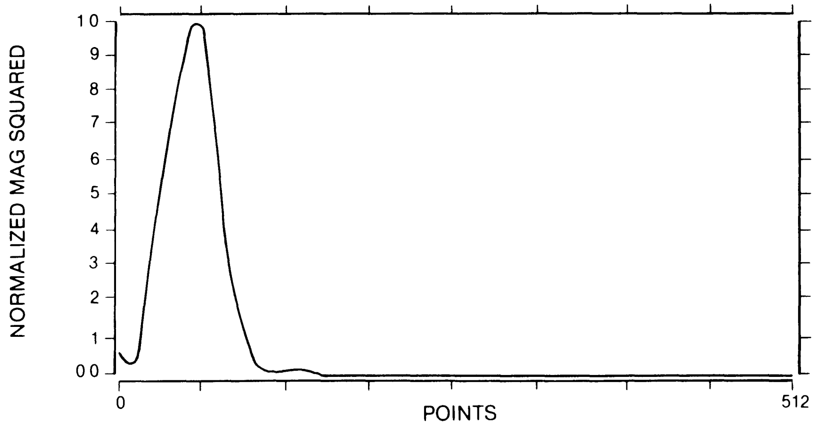
FREQUENCY DOMAIN MAG SQUARED DATA



NORMALIZED MAG SQUARED 1 = 46 VOLTS^2 – SEC^2
FREQUENCY RESOLUTION = 5 01 E – 01 Hz
FOLDOVER FREQUENCY = 2 56 E + 02 Hz = POINT 512

WINDOW 6A — GOOD

FREQUENCY DOMAIN MAG SQUARED DATA



NORMALIZED MAG SQUARED 1 = 41 VOLTS^2 – SEC^2
FREQUENCY RESOLUTION = 5 01 E – 01 Hz
FOLDOVER FREQUENCY = 2 56 E + 02 Hz = POINT 512

Fig. 3. Sample data showing the variations in the frequency domain signal from window to window for good windows.

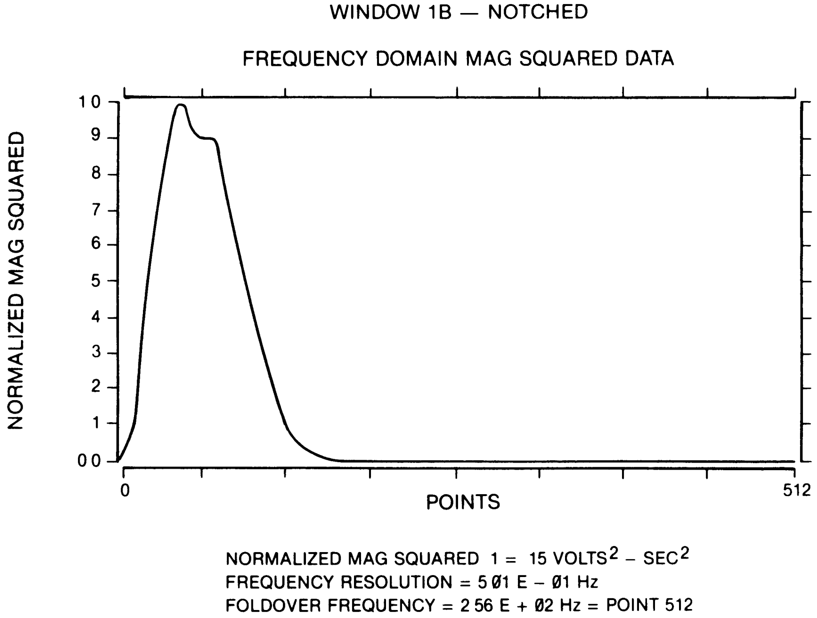


Fig. 4. Sample data showing the frequency domain signal of a window containing an EDM notch.

To make the above observations quantitative, the mean frequency of the horizontal and vertical components can be calculated. As seen in Figure 7, there is a shift in mean frequency from horizontal to vertical components for good windows, but an even larger shift for notched windows. A further observation is the correlation in the scatter between horizontal and vertical components for good windows. This correlation will be dealt with again.

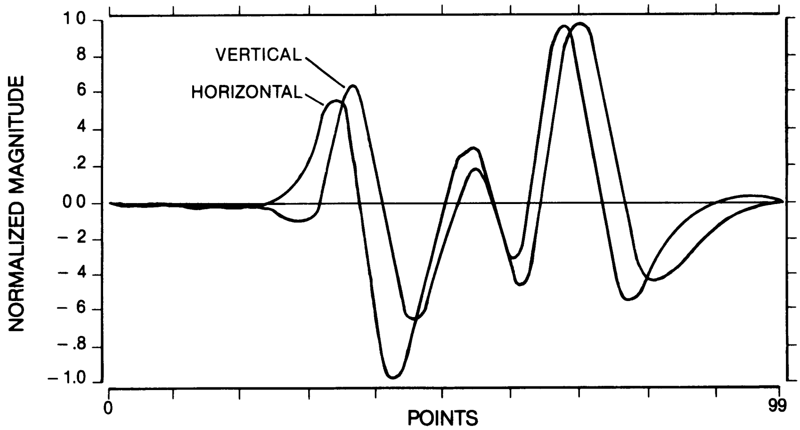
A series of statistics can be calculated. Using the data from the good windows only, the mean of the mean frequencies and the standard deviation of the mean frequencies for both the horizontal and the vertical signals are determined. Using these values the correlation coefficient between horizontal and vertical signals is calculated. All of these values are tabulated in Table 1. Again, a large correlation between horizontal and vertical components is apparent.

Table 1. Statistics on Good Windows

	Vertical	Horizontal
Mean of Mean Frequencies	25.6 Hz	22.5 Hz
Standard Deviation of Mean Frequencies	2 Hz	1.1 Hz
Correlation Between Horizontal and Vertical	0.88 => Highly Correlated	

WINDOW 3 — GOOD

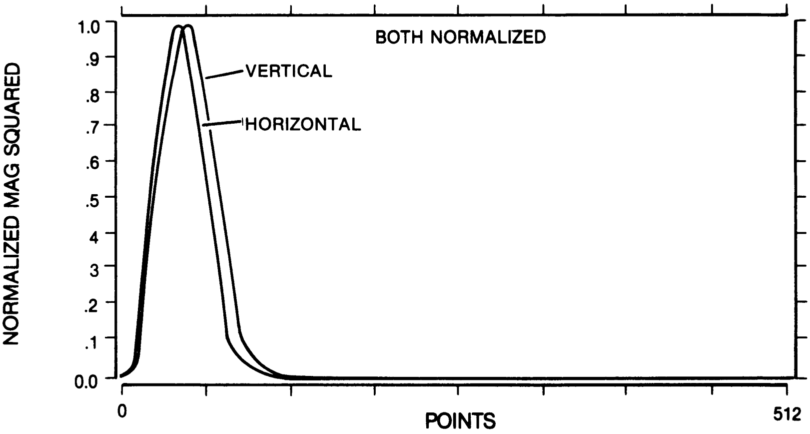
TIME DOMAIN DATA



NORMALIZED MAGNITUDE: 1 = HOR: .8 VOLTS, VERT 7 VOLTS
SAMPLING PERIOD = 1 95 E – 03 SEC

WINDOW 3B — GOOD

FREQUENCY DOMAIN MAG SQUARED DATA

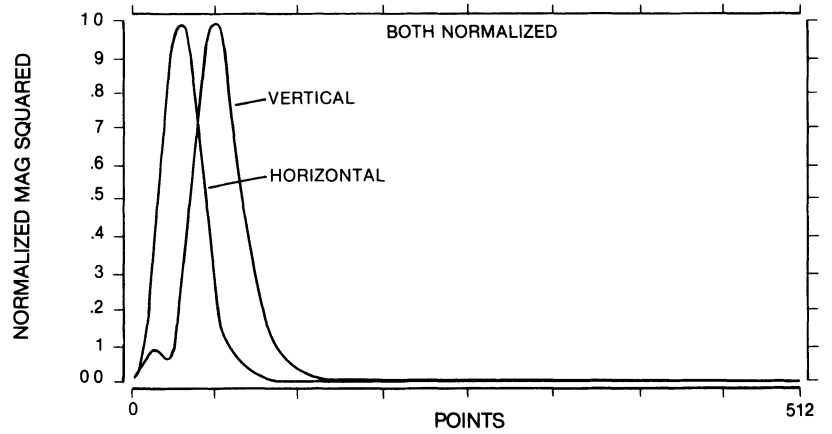


NORMALIZED MAG SQUARED: 1 = HOR: 1.4 VOLTS^2 – SEC^2, VERT: 0.86 VOLTS^2 – SEC^2
FREQUENCY RESOLUTION = 5.01 E – 01 Hz
FOLDOVER FREQUENCY = 2.56 E + 02 Hz = POINT 512

Fig. 5. Comparison of vertical and horizontal signals in both the time and frequency domains. These are good window signals.

WINDOW 4B — NOTCHED

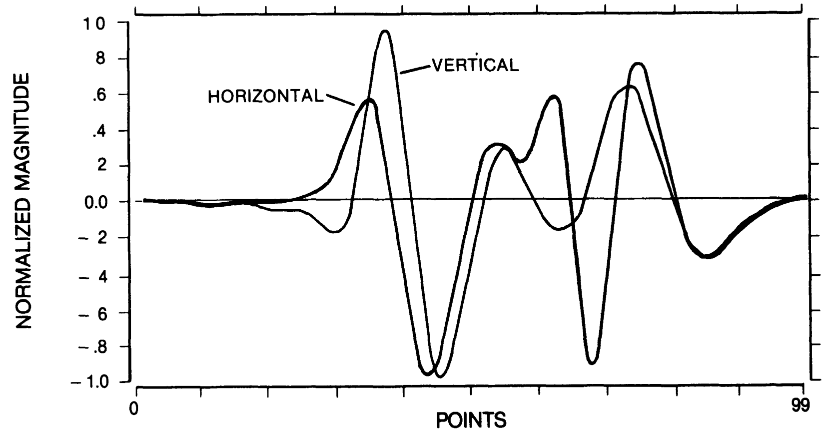
FREQUENCY DOMAIN MAG SQUARED DATA



NORMALIZED MAG SQUARED: 1 = HOR: 65 VOLTS^2 – SEC^2, VERT 43 VOLTS^2 – SEC^2
FREQUENCY RESOLUTION = 5.01 E – 01 Hz
FOLDOVER FREQUENCY = 2.56 E + 02 Hz = POINT 512

WINDOW 4 — NOTCHED

TIME DOMAIN DATA



NORMALIZED MAGNITUDE: 1 = HOR: .86 VOLTS, VERT: .48 VOLTS
SAMPLING PERIOD = 1.95 E – 03 SEC

Fig. 6. Comparison of vertical and horizontal signals in both the time and frequency domains. These are from windows containing EDM notches.

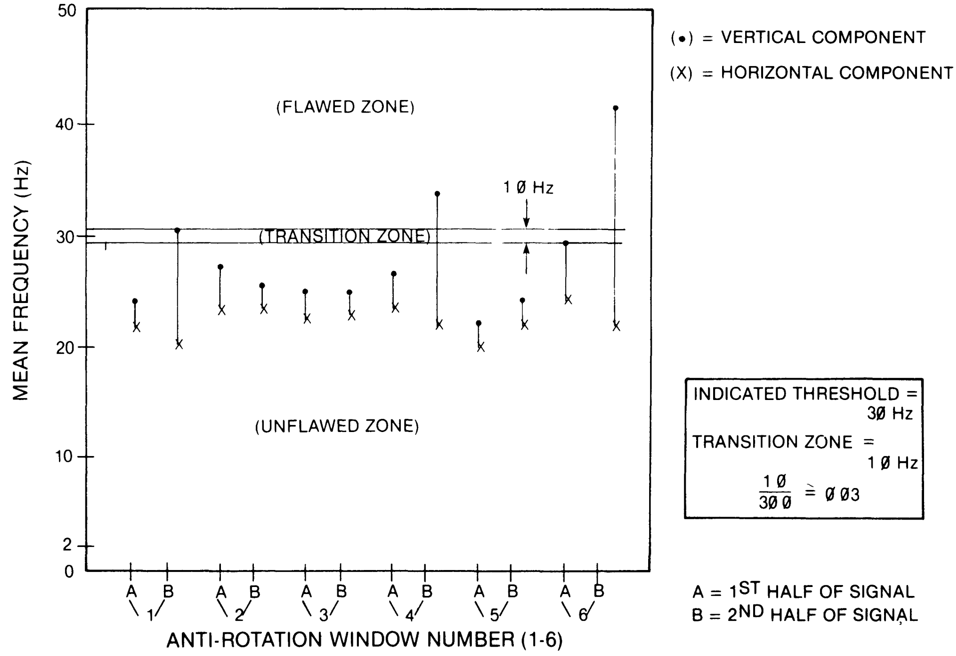


Fig. 7. Plot of mean frequency of vertical and horizontal components for various windows, good and notched. Both notched and unnotched windows are represented.

Based on this correlation a new parameter can be calculated. This new parameter is the difference (vertical minus horizontal) between the mean frequency of the vertical component and the mean frequency of the horizontal component. These data are presented in Figure 8. The mean and standard deviations of this new parameter for good windows are tabulated in Table 2. It is important to note that the standard deviation of this parameter is actually smaller than the standard deviation of the mean frequency of the vertical component, and is only slightly larger than the that of the horizontal component, even though it is derived from these two by a simple subtraction. This is due to the large correlation between the horizontal and vertical signals in good windows. The values of this new parameter, the mean value of the vertical component less the corresponding value of the horizontal component, for the windows which contain notches are included in Figure 8.

Table 2. Additional Statistics on Good Windows

Mean of Difference of Means	3.1 Hz
Standard Deviation in Difference of Means	1.4 Hz

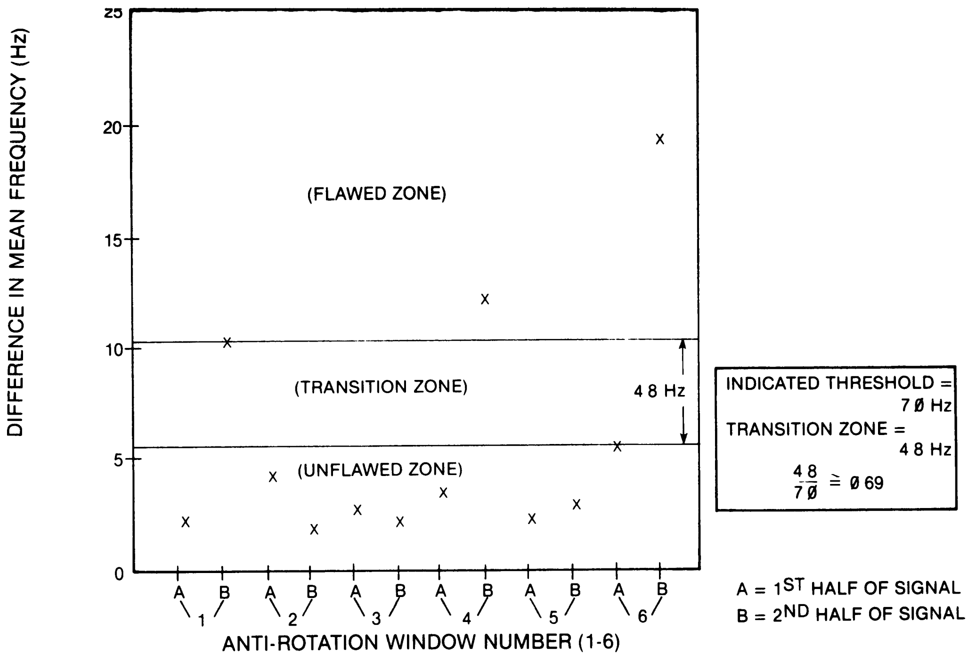


Fig. 8. Plot of the difference, vertical minus horizontal, between the mean frequencies for various antirotation windows. Both notched and unnotched windows are represented.

DISCUSSION

In Table 3, a comparison between the data as represented in Figures 7 and 8 is presented. This table gives the width of the region separating the good windows and the notched windows. It is in this region that a threshold would have to be set to distinguish between notched and unnotched windows for each way of observing the data in an inspection. Also in the table is a value labeled "Deviation from the Mean in Units of Standard Deviation". This value is the smallest separation for notched windows from the good windows' mean in units of one standard deviation. For comparison purposes, assuming a normal distribution, the odds against a good window exceeding one standard deviation from the mean are 2.15:1; two standard deviations, 21:1; three standard deviations, 370:1; four

Table 3. Comparison of two Methods: the Mean Frequency of the Vertical Component and the Difference of Means

	Mean Frequency of Vertical Component	Difference of Means[a]
Separation Region	1.0 Hz	4.8 Hz
Deviation From Mean in Units Of Standard Deviation	2.5	5.2

(a) The mean frequency of the vertical component minus that of the horizontal component.

standard deviations, 16,000:1; and five standard deviations, 1,700,000:1, [2]. In other words, it is very unlikely to find a good window having a value given by the method of DIFFERENCE OF MEANS which is the same as the values observed in notched windows. This is not true for the method which uses only the mean frequency of the vertical component.

At this point a generalization can be made. In general, it may happen that the mean frequency of the vertical and horizontal components are not nearly equal. If, however, they are still correlated for good windows, a function, g(V,H), may be able to be found such that

$$g(V_{good},H_{good}) \neq g(V_{notched},H_{notched}),$$

where V and H are the mean frequencies of the vertical and horizontal signals, the subscript describing the window. The only condition for this generalized technique to be applicable is that the quantity given by

$$g(V_{notched},H_{notched}) - \langle g\rangle_{good}$$

be large (in units of standard deviation of g over good windows), for all notched windows. $\langle g\rangle_{good}$ is the mean value of g over all good windows.

As presented in this paper,

$$g(V,H) = V - H.$$

An improvement, empirically determined, is

$$g(V,H) = V - 1.133 \times H.$$

The factor, 1.133, simply normalizes the horizontal mean frequency to the vertical mean frequency. With this change, the statistics for good windows are as follows: the mean is 0.0 Hz, the standard deviation is 1 Hz, and the deviation of the notched windows from the mean in units of standard deviation is 7.7. This is a significant improvement over what has already been presented.

The technique can be further generalized by allowing V and H to be generalized functions of the vertical and horizontal signals. The technique can then be applied to other geometries. An example is the simple case of an absolute probe over a planar surface. In this case, the geometry signal is the signal due to liftoff variations and V and H become V(t) and H(t), the vertical and horizontal signals in the time domain, respectively. The function g becomes

$$g(V,H) = V(t)\cos(A) - H(t)\sin(A)$$

where A is an appropriate phase angle making g(V,H) equal to zero when no flaws are present. This is commonly done with internal circuitry of most eddy current instruments.

Another example of the use of this generalized technique is the case of a differential probe over a planar surface. In this case, the geometry signal is produced by variations in the angle that the probe makes with the inspection surface. A third example is the inspection of holes which intersect a surface at oblique angles. V, H and g are more difficult to determine in these cases.

SUMMARY AND CONCLUSIONS

In summary, the research to date indicates the possibility of separating the flaw signal from the geometry signal as a differential probe is scanned near an antirotation window, by using the horizontal component of the impedance plane as the signature of the window. The mean frequency of this component can be subtracted from the mean frequency of the vertical component, enhancing the flaw response compared to the window response.

Further experiments need to be conducted to verify this method of processing the signals generated by scanning in the manner described in this experiment. As the data base is increased, it is hoped that the conditions necessary to insure the separation of notch from geometry will be quantified. One class of experiment will vary the notch parameters, such as location, orientation, and size. Additional experiments need to be conducted on fatigue cracks. Another class of experiment will vary the probe parameters, such as liftoff, diameter, impedance, orientation, frequency, high pass filter, low pass filter, and probe scan speed. Another set of experiments may be directed toward improving the technique by using multiple frequencies. Finally, experiments need to be conducted to model the data in order to be able to invert the signals, allowing the flaw size, shape, orientation, and location to be determined. This would include experiments to determine the model and/or model parameters, and to verify this model.

ACKNOWLEDGEMENTS

This work was conducted under contract number F33615-81-C-5002 of the Air Force Wright Aeronautical Laboratories/Materials Laboratory.

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