AUTOMATIC EDDY CURRENT HOLE CENTERING FOR AIRCRAFT ENGINE COMPONENTS

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INTRODUCTION

The inspection design for the Air Force's Retirement For Cause (RFC) program uses automated eddy current and ultrasonic inspection systems to detect flaws in the compressor and turbine components of the F100 engine. The requirements of the program include the inspection of bolt holes, cooling holes, and oil drain holes in the various engine components. The hole diameters range from 0.060" to 0.600" with many of the components having 60 to 70 holes of a given size. The spacing between holes is fairly accurate; in general, variations are less than 0.010". Since the initial system accomodates approximately 20 different engine components, the only practical method of clamping the components to the systems' turntable utilizes a set of jaws that clamp outwards on a component's bore or rim. This method requires the operator to first align the part on the turntable. Accuracies on the order of 1 to 2 degrees are expected (0.200" at a 7" radius). The inspection of holes is accomplished using rotating eddy current probes having a diameter 0.010" less than the hole diameter. For a reliable inspection, the probe must be centered in the hole to within 0.001" of true center. As stated above, initial probe placement may be 0.200" off center for the first hole and up to 0.010" off center for succeeding holes (see Figure 1). This means that centering must occur while the probe is outside of the hole. The resulting requirements for a hole centering algorithm are:

1) Centering must be accomplished over a wide range of off center distances,

2) The probe must center accurately to within 0.001" of true center,

3) The centering process must be fast - 2 to 4 seconds per hole, and

4) Centering must occur <u>before</u> the probe enters the hole.

Previous work [1] conducted on hole centering has shown that it is feasible to use the inspection eddy current probe for the centering process. This results in substantial benefits in time as it eliminates the

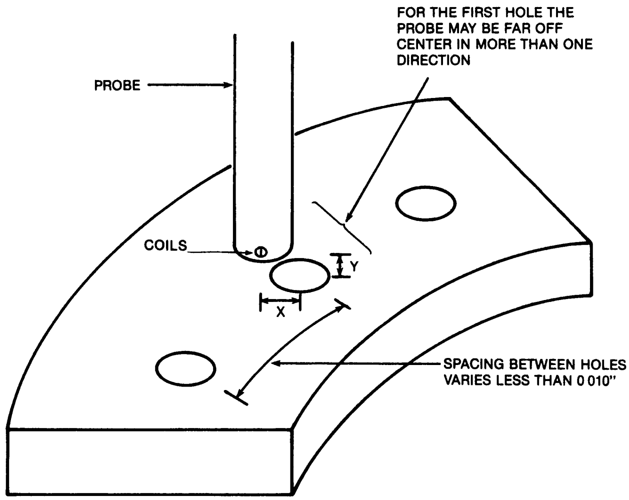

Fig. 1. Section of engine part showing possible initial positioning of probe.

need to pick up a separate probe for centering. For a probe having a diameter near that of a hole and rotating inside the hole, the distance between the wall of the hole and the eddy current coils can be expressed as [2]

$$X = R_h - L\cos(\theta-\theta_o) + [R_p^{\,2} - L^2 \sin^2(\theta-\theta_o)]^{1/2} \qquad (1)$$

where X = coil to wall distance,

R_h = hole diameter,

L = distance off center,

R_p = probe diameter,

and θ = off center angle.

The eddy current probe sees the distance X as a varying liftoff and the resulting liftoff signal is continuous and periodic. Neglecting the constant $(R_h - R_p)$ and taking a first order approximation in L, the liftoff theoretically is

$$X = L\cos(\theta-\theta_o) \qquad (2)$$

and, indeed, this is seen experimentally for a rotating probe inside a hole. For an absolute probe the eddy current liftoff signal is due to the distance X as a function of θ. A differential probe's signal is the derivative of the absolute probe's signal with respect to θ. For any case, including a combination of the two (as in the case of non-ideal differential probes), for small L the response is sinusoidal in form with a period equal to that of the rotating probe. Thus, by proper calibration the distance off center, L, theoretically can be calculated for a probe inside a hole.

EXPERIMENTAL PROCEDURE

For the RFC System the initial position of the first hole to be inspected is not known accurately enough to allow the probe to move into the hole for centering. In this case centering must occur outside of the hole (see Figure 2). With the probe above the hole and possibly very far off center the above expression for liftoff may no longer apply. The physical situation is similar to the in-hole case, however, it is expected that when the probe is far off center the unfiltered liftoff signal will contain different frequency components. Thus, the initial efforts were aimed at determining whether a first order approximation would remain valid under these conditions. This determination was made empirically. Experimentally a low pass filter can remove the higher order frequency components from the signal leaving only the fundamental frequency component due to the rotating probe. This filtered signal is periodic and represents a first order approximation to the unfiltered signal. It is then necessary to show that this filtered signal is correlated to the probe's off center distance. Extensive testing has empirically confirmed this correlation. The liftoff signal also contains a dc component that may be large, especially when centering with the probe above the hole. Again, the use of filters (high pass) can be implemented to remove the dc component without adversely affecting the accuracy of centering. One additional benefit of filtering is that flaw signals, which may be present, and will affect the accuracy of centering, are eliminated. Using these findings an algorithm has been developed to center the probe over a hole.

As has been stated, an off center eddy current probe rotating above a hole produces a periodic signal with an amplitude that correlates to liftoff. When the probe is centered the liftoff response as a function of O is zero; the unfiltered eddy current signal amplitude is simply a dc re-

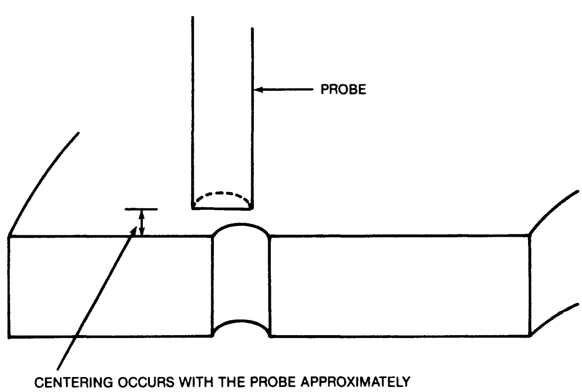

Fig. 2. Cross sectional view showing that the probe is above the surface of the part when centering.

sponse. Figure 3 shows three curves labelled "centered", "off X", and "off Y". The data for Figure 3 was taken using a 0.316" diameter probe manually centered above a 0.330" diameter hole. The probe was spinning at 1500 r.p.m. and the analog signal was sampled and digitized at a rate of 20,000 Hz. A Nortec NDT25-L eddy current instrument was used to take the data. The small amplitude variation in the "centered" curve shows that the probe is slightly off center (0.0009"). The "off X" curve was obtained with the probe 0.010" off center in the +X direction relative to the scanning system's coordinates. The "off Y" curve was obtained with the probe 0.010" in the +Y direction. The abscissa on the graph shows the corresponding sampler channel numbers. From Figure 3 it is seen that a one time calibration can correlate sampler channel numbers to scanning system coordinates for a given probe. In Figure 3 channel #40 is correlated to the + X-axis and channel #260 is correlated to the +Y-axis. The addition of a scaling factor relating amplitude to the distance off center completes the basic centering algorithm:

#1 Sample & digitize the eddy current signal from one rotation of the probe.

#2 Read the appropriate sampler channels; if the amplitudes equal zero, then exit the algorithm.

#3 Multiply the amplitudes by the scaling factor to calculate the distance off center.

#4 Command the mechanical scanning system to move each axis the appropriate distance. Go to #1.

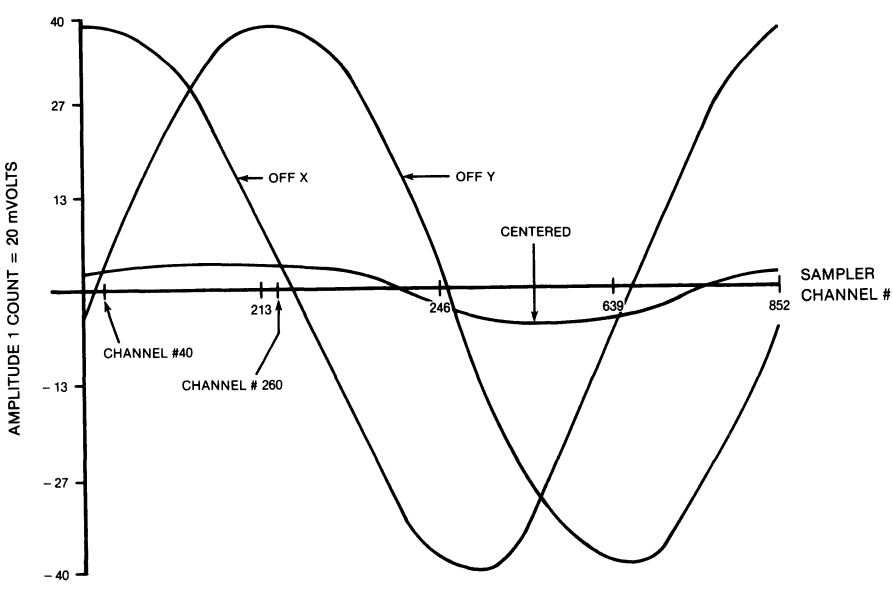

Fig. 3. Three curves of amplitude vs. sampler channel number. "Centered"- the probe is centered over the hole. "Off X" and "Off Y" - the probe is 0.010" off center in the +X and +Y directions.

As can be seen the simplicity and straight forwardness of this algorithm allows quick execution on an automated system. After the sampler has taken one set of data (corresponding to one rotation of the probe) the system computer checks the X-axis and Y-axis sampler channels. If the amplitudes of these channels differ from zero the computer multiplies the amplitudes by the scaling factors and commands the scanning system to move the appropriate axis the calculated distance. It is important to note that only two channels - one byte per channel - are read to determine the off center distance. This can be done very quickly and offers considerable time savings over processing the total waveform.

The accuracy of centering is a function of the resolution of the A/D convertor and the gain of the eddy current instrument. Typically, the eddy current coils are 0.040" above the surface of a part. Using the maximum gain on the NDT25-L and a sampler resolution of 20mV/bit, a centering accuracy better than 0.0005" is attainable. Also, if a signal is noisy averaging can be used to improve results.

Figure 4 shows a graph of amplitude versus distance off center for a 0.316" diameter probe over a 0.330" diameter hole. The slope of the curve from 0.0" to 0.010" is used to determine the scaling factor. If the probe is reasonably close to center (say within 0.050") the correction can, in theory, be made in one movement. If the probe is between 0.050" and 0.200" off center, two to four moves are usually required to center the probe. An interesting situation occurs when the probe is more than one-half its diameter off center. It is seen that for distances above 0.200", the slope is negative. In this range the algorithm would cause the adjustment of the probe to be less than what is needed. In fact, if the probe is very much off center, say 0.300", the adjustment would be very small (only 0.015"). However, since the algorithm is repeated until the amplitude is less than one sampler amplitude count (20 mV), the computer will continue to take sampler readings and move the probe accordingly. As the amplitude becomes larger the correction step size becomes larger. The probe will eventually be centered. Figure 4 also shows that the probe can be 0.335" off center and the algorithm will center the probe; farther than this results in the probe moving away from the hole. In this case it is worth mentioning that since the algorithm moves the probe towards a "hole" a geometry feature such as a wall will cause the probe to move away from the wall. Thus, even if a probe were placed off center enough so that it moves away from the hole, it would not run into any raised features of the engine part (see Figure 5).

Another advantage of this algorithm results from the addition of an offset for each sampler channel used for centering. For instance if it is found that the sampler channel corresponding to the X-axis has a non-zero value when centered, this value can be entered as an offset and then subtracted from the amplitudes received while centering. This is especially valuable where the engine part has another geometry feature near the hole being scanned or where a hole is drilled obliquely to the part surface. Figure 5 shows a typical example where a wall is situated near a hole. The resulting eddy current signal from a probe centered above the hole is shown in Figure 6. This waveform should be compared with the "Centered" waveform in Figure 3. If this "geometry signal" was not taken into account, the probe would not center correctly. The use of offsets allows this situation to be taken into account and accurate centering to occur.

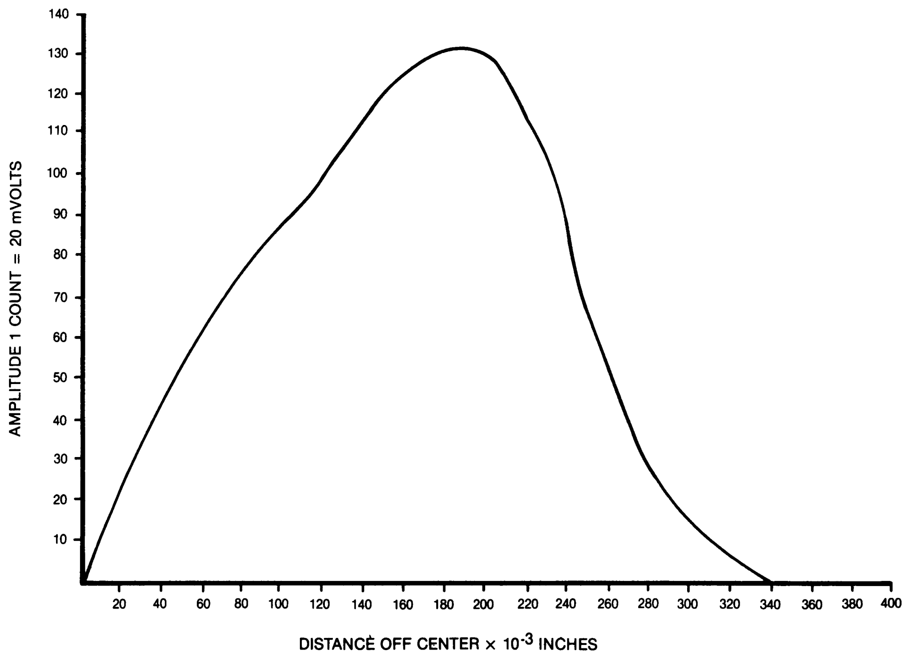

Fig. 4. Amplitude vs. distance off center for a 0.316" probe

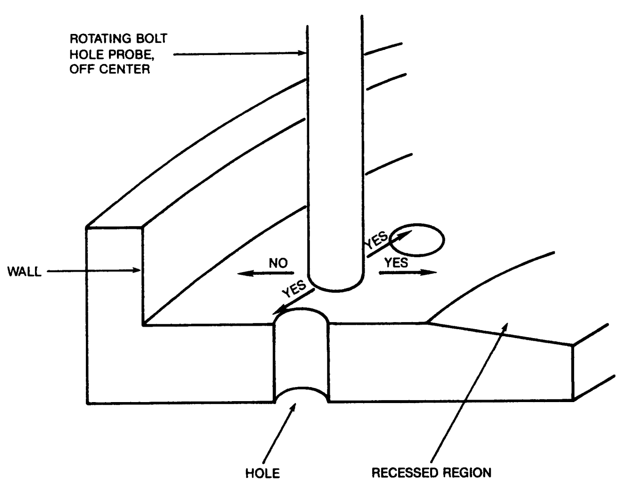

Fig. 5. In this case the probe is positioned too far from the hole for centering to take place. However, due to the nature of the centering algorithm, the probe will move away from raised features, such as the wall, and towards "safe" areas.

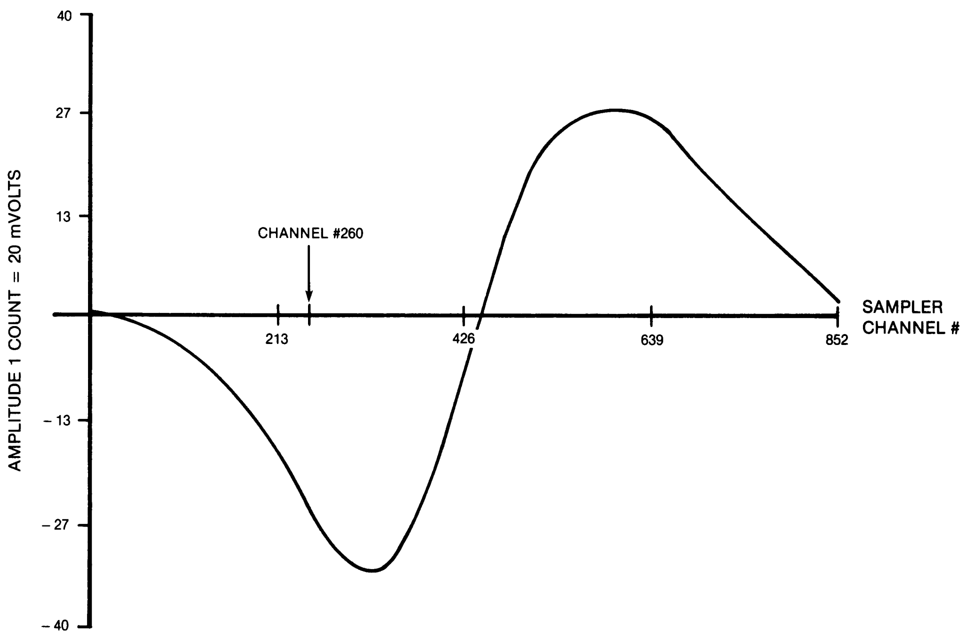

Fig. 6. Geometry signal due to a wall (such as in Figure 5).

SUMMARY

An algorithm for centering a rotating, eddy current, hole probe over a hole is presented. Data gathered to date have shown this algorithm to be fast, accurate, reliable, and flexible for a wide range of probe diameters (0.103" to 0.388"). Preliminary results indicate that centering accuracies better than 0.0005" are attainable. Evidence is presented showing the applicability of this algorithm even to the cases where the probe is off center by more than the probe diameter. Finally, data are presented showing the ability of the algorithm to compensate for nearby geometries that adversely effect the centering procedure.

ACKNOWLEDGEMENT

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