APPLICATION OF SELF-NULLING EDDY CURRENT PROBE AND SPIN-OFF SENSOR TECHNOLOGIES TO AIRLINE INDUSTRIES AND BEYOND

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INTRODUCTION

As the existing commercial air fleet of the airline industry ages, the major demand on the NDE community is to develop simple, cost effective methodologies of higher detectability and reliability. To satisfy such a demand a focused R&D effort has been performed for the past several years through NASA Airframe Structural Integrity Program (NASIP). This particular program concentrates on the development of methodologies applicable to NDI of aircraft fuselage, which, being a thin metallic structure, is best suited for inspection by various electromagnetic techniques. Such is the direct motivation for the development of the self-nulling eddy current probe technology.

The probe operates mainly in two different modes depending on the application purpose; self-nulling mode for the detection of cracks with the operating frequency above 50 kHz, and isolated field mode for the detection of corrosion with the frequency below 15 kHz. The unique characteristic of the probe is that all the flaw information is obtained by measuring the amplitude of output signal resulting in simple instrumentation. The instrument being simple, in turn, significantly reduces, or completely eliminates, the needs of user training and data interpretation. In addition, the measured probe output amplitude can be readily quantified based on a straightforward calibration procedure.

Numerous articles have been published recently on these subjects describing technical details of specific applications [1-7]. As the technology matures, however, an article summarizing up-to-date aspects of the subject is necessary and the present paper is intended to serve this purpose.

BASIC CONFIGURATION

Fig.1.a shows the schematic of the probe which consists of outer (drive) and inner (pickup) coils positioned concentrically. These two coils are separated by a thin-walled cylindrical tube made of a ferromagnet. Shown in Fig. 1.b is an oscilloscope trace that is practically nulled by positioning the probe in a region of an aluminum plate that is free of crack. Such is accomplished by the probe itself without being aided by any electronic circuit or software. Through experiments first and numerical simulation later, it was confirmed that the thin-walled tube has to be magnetically permeable and electrically conducting, with

the magnetic permeability being the dominant factor. It turned out to be that, by effectively countering the applied magnetic field, the concentrated eddy current distribution formed by the ferromagnetic tube is one of the main factors contributing to the self-nulling effect [2]. For this reason, the thin-walled tube is called the "flux-focusing lens". Another critical contribution of the lens is to repel the magnetic flux lines from the drive coil which tend to penetrate through the wall reducing the possibility of flux linkage through the pickup coil.

Shown in Fig. 1.c is the oscilloscope trace of unmistakable sinusoidal output of 100 kHz obtained by placing the probe on top of a fatigue crack with its length about twice larger than the probe diameter and its surface extending through out the entire thickness of a thin aluminum plate. The presence of a crack disturbs the eddy current flow pattern breaking the delicate balance among the factors required by the self-nulling condition.

Fig. 2 shows the typical results of C-scan over an aluminum plate having EDM notches of various length. One can easily see two clear trends in these results, first, the probe output for a given notch has a peak at each tip and, second, the maximum probe output is roughly proportional to the length of the notches. The first is easy to explain. As shown in Fig. 3, the induced eddy current has to flow around the tip creating a magnetic field component which is in the direction of the applied magnetic field causing larger probe output. Based on this, one can readily show that the distance between these maxima is the crack length if it is larger than the probe diameter, and this distance equals the probe diameter if it is smaller than the length of crack. The presence of such local maxima at crack tips provides an interesting application capability which will be presented in the following section. The reason for the sencond trend is given in Ref. 3.

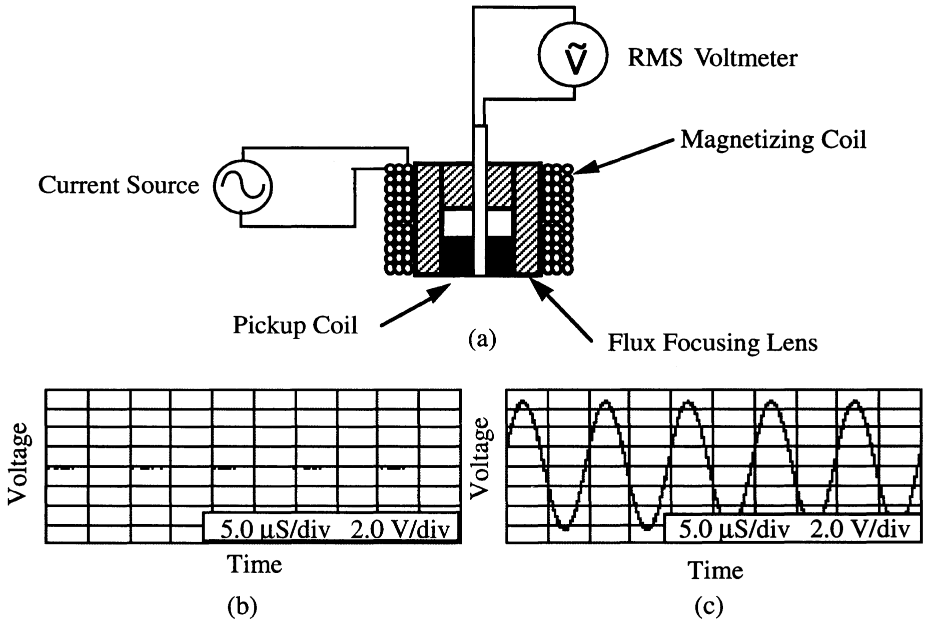


Fig. 1. (a) Schematic arrangement of self-nulling probe, (b) pickup coil signal obtained by placing the probe in a flaw-free region and (c) that obtained by placing the probe on a fatigue crack in an aluminum plate (from Ref. 1).

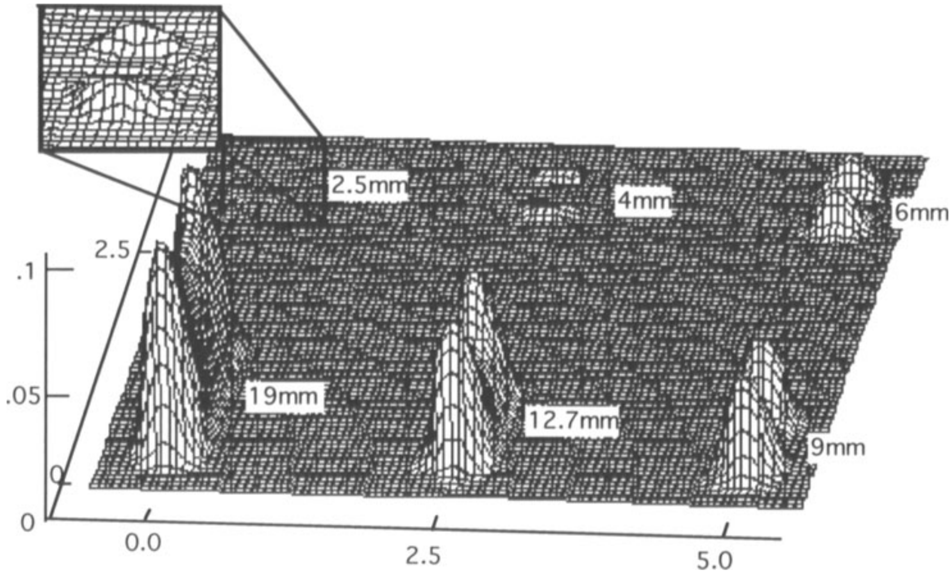
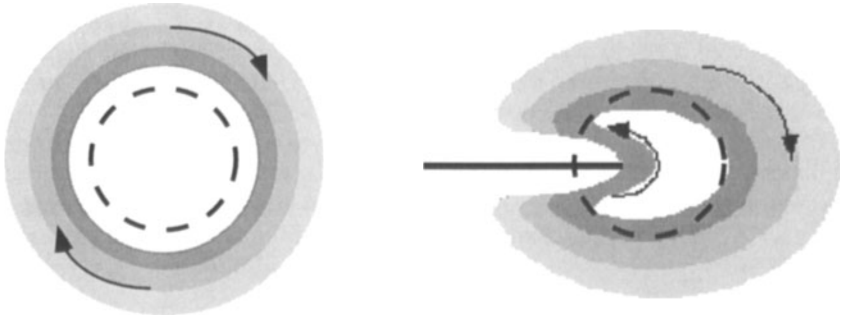


Fig. 2. Results of C-scan over an aluminum plate containing EDM notches of various length (from Ref. 1).



(a) (b)

Fig. 3. Schematic representation of eddy current flow (a) in a flaw-free material and (b) near a crack tip where eddy currents flow with an opposite rotational component (from Ref. 3).

Lowering the operating frequency of the probe extends the range of magnetic field penetration and eddy current distribution into a conducting sample. The probe output does not self-null with the operating frequency below 30 kHz on the surface of a bulk aluminum specimen indicating a slight nonlinearity involved in the process. For a relatively thin sample, the total amount of eddy current, which affects the probe output, depends on its thickness as clearly seen in Fig. 4. All the curves in Fig. 4 begin to increase initially as the intensity of eddy current and pickup coil output increase with the operating frequency. The further increase in frequency reduces the probe output as the process begins to approach the self-nulling situation, hence forming a peak in each curve generated by sweeping the frequency. The position of each curve depends on the sample thickness and the separation becomes larger and the measurement accuracy significantly enhances as the sample thickness decreases providing the detection capability unavailable by ultrasonic methods. A

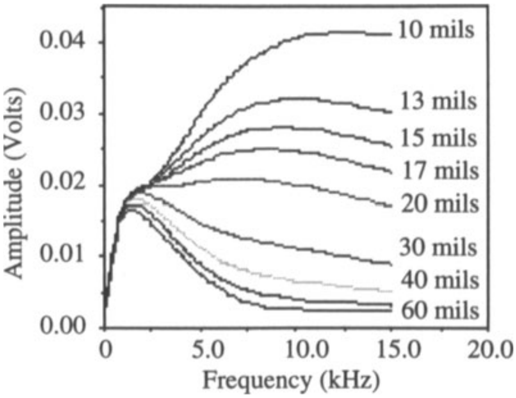


Fig. 4. Aluminum plate thickness dependence of probe output curves generated by frequency sweeping (from Ref.4).

simple algebraic treatment using the results in Fig. 4 enables a two-point calibration for accurate, quantitative thickness gauging of thin conducting plates.

ADVANCED CONFIGURATION FOR PRACTICAL APPLICATION

Prototype devices utilizing the results of Fig. 2 and 4 have been constructed to demonstrate the versatility of the technology. For specific application purpose of aircraft NDI, however, more specialized instruments were needed. One example is the rotating self-nulling probe which is designed to detect fatigue cracks hidden under rivet heads. The basic scheme is to rotate the whole probe around the rivet head to record the probe output as a function of angular position. It was soon discovered that the centers of the circular path of probe motion and the rivet head seldom coincide creating background noise with its maximum amplitude comparable to that of the crack signal. It easy to show that background noise due to misalignment has an angular frequency which is considerably lower than that due to the crack, and they can be separated easily through a simple numerical processing technique.

Fig. 5. a shows the original data of probe output as a function of angular position which result in the spectrum of Fig. 5. b through fast-fourier transform. The frequency space spectrum is bandpass-filtered, as shown in Fig. 5.c, which is then inverse fast fourier transformed to result in the spectrum of Fig. 5. d. The angular position of the peak in the final figure is exactly the orientation of the crack. The test results obtained by using a prototype instrument on the samples available at the FAA's Sandia NDI Validation Center and the details of POD curve based on the results are reported by Wincheski et al. in this conference [8].

Fig. 6 shows the test results of realtime crack tip tracing operation using the self-nulling probe. The operation is based on the presence of the local maximum probe output at the tip as explained in Fig. 3, which is a unique characteristic of this probe. A computer controlled mechanical scanner continuously oscillates in a region near the tip to find the peak using the gradient search method and keeps updating the peak position as the crack tip moves. Such a capability provides distinct advantages, i. e., all the parameters related to crack growth are immediately available for on-site analysis, and the results can be used to update these parameters to automatically control the fatigue cycles eliminating the need of

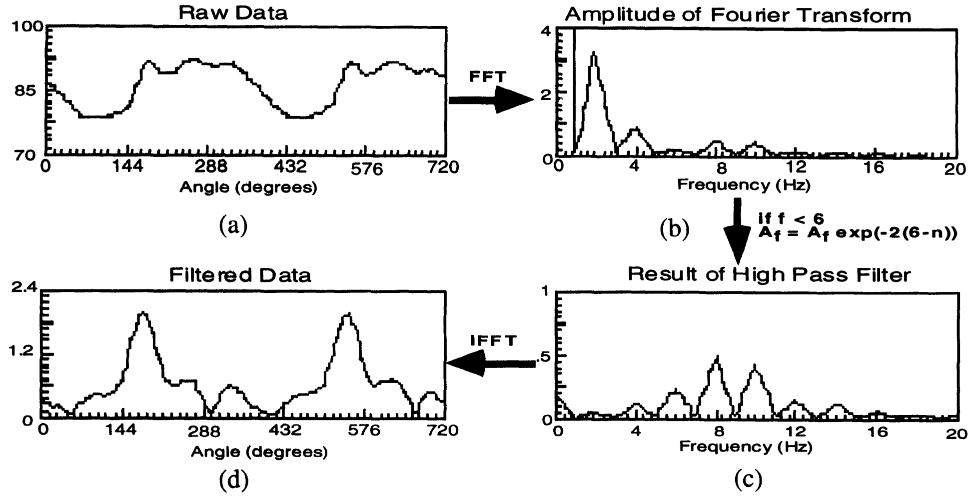


Fig. 5. Sequential steps describing the numerical processing of rotating probe technique to eliminate background noise due to probe artifacts involved in actual tests (from Ref. 7).

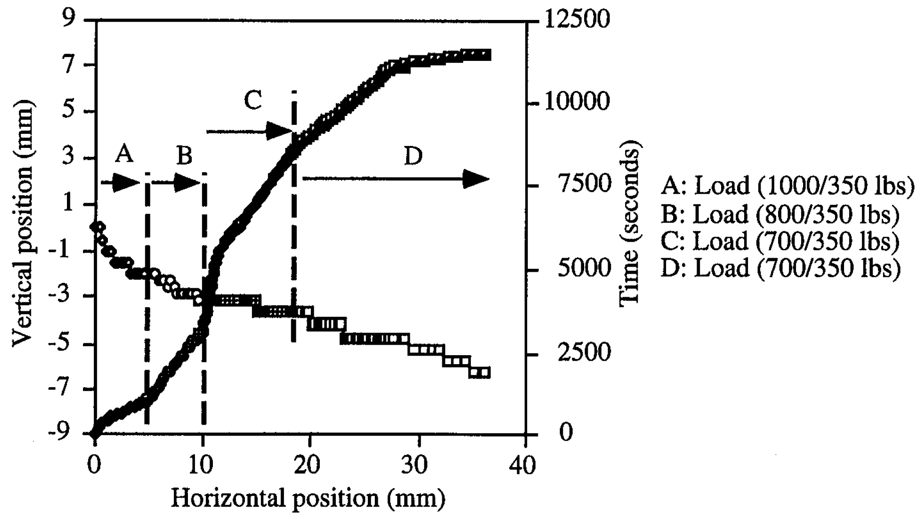


Fig. 6. Results of realtime crack tip tracing during fatigue load cycles applied to an aluminum compact tension specimen. The curve starting in the middle of left vertical axis shows the two-dimensional trajectory of crack tip movement and the other curve shows the elapsed time for the crack tip to reach particular locations (from Ref. 9).

continuous presence of an operator.

The method that produced the results of Fig. 3 was extended for the application to an aircraft lapjoints. Fig.7 show a one-dimensional scan results with a double-layer samples with a non-uniform air gap using two frequencies, 2.5 and 5.0 kHz. The effect of varying air gap in this figure is clearly seen by the background shift along the scan direction. It has been confirmed that a simple numerical processing with an adjustable input parameter, called a

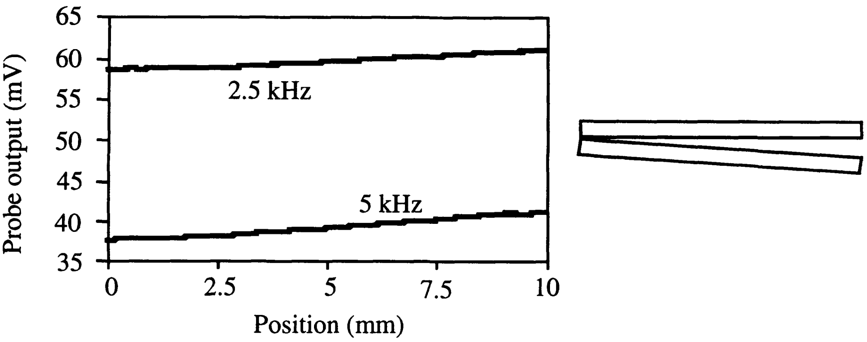


Fig. 7. Results of one-dimensional scan using two operating frequencies over a flaw-free double layer sample with a varying air gap as shown in the schematics. It is apparent that such a gap causes a position-dependent background making point-by-point quantitative measurement impossible (from Ref. 5).

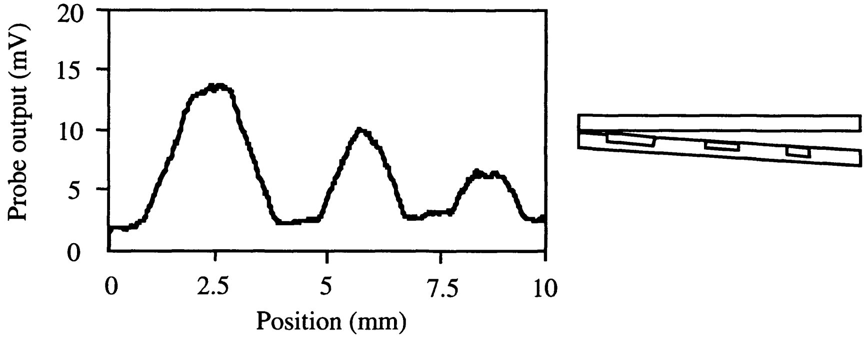
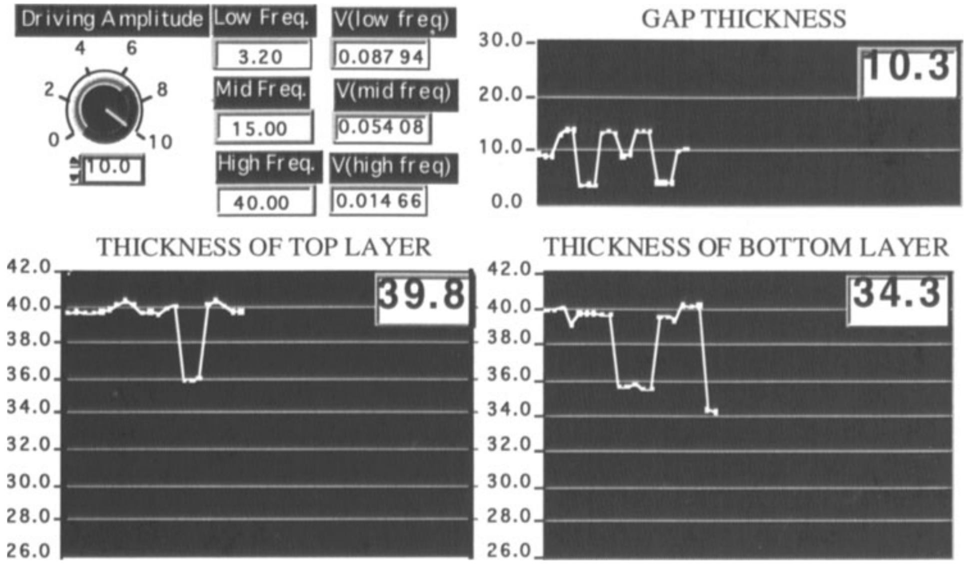


Fig. 8. Results of numerical processing of two frequency data to eliminate the position-dependent background one-dimensional scan over a double layer sample with varying air gap and material loss as shown (from Ref. 5).

two-frequency mixing technique, can eliminate the position-dependent background enabling point-by-point quantitative thickness gauging as shown in Fig. 8. This method, however, is insufficient for truly quantitative thickness gauging since the test results cannot distinguish the material loss at the bottom of the top layer from that at the top of the bottom layer. To obtain further information on a double-layer structure it is necessary to use three operating frequencies providing three equations for three unknowns, i. e., the thickness of top layer, separation between the layers and thickness of bottom layer. The typical test results of three-frequency mixing technique are shown in Fig.9 and the details of the methodology is reported by Fulton et al. in this conference [5].

NON-AEROSPACE APPLICATION POTENTIAL

It has been demonstrated that the self-nulling probe can detect the presence of a weld seam hidden under a layer of paint [10]. This may be a significant impact on the crime prevention effort related to auto theft in European countries where the vehicle identification numbers stamped on the roof are switched among legitimate and illegitimate vehicles by cutting and welding the roof sections. The advantage of the self-nulling probe for this appli-



Driving Amplitude 10.0

Low Freq. 3.20

Mid Freq. 15.00

High Freq. 40.00

V(low freq) 0.087 94

V(mid freq) 0.054 08

V(high freq) 0.014 66

GAP THICKNESS 10.3

THICKNESS OF TOP LAYER 39.8

THICKNESS OF BOTTOM LAYER 34.3

Fig. 9. Typical results of point-by-point measurements using the three-frequency mixing technique for multilayer thickness gauging displayed in a laptop computer screen. The vertical axes of all three figures are in the unit of mils. The data points in each display indicate the results of particular measurements and the number at the right top corner indicates the quantitative thickness value of the latest measurement (from Ref. 5).

cation is that it can be used by any law enforcement officer without receiving any user training.

Billets being produced in a steelmill normally contain surface cracks which are to be milled away. Knowing the maximum depth of the surface cracks in a given region is critical to economically optimized quality assurance of the billets [11]. With its test results being easily quantifiable, the self-nulling probe has a definite advantage. It has been shown that the probe can be used as an alloy sorter for certain range of metallic components. The probe has been also shown to be able to detect cracks the welded joints without being affected by the presence of the weld seam [12].

SUMMARY

This paper briefly reviews the basic characteristics of the self-nulling eddy current probe, capability of prototype instruments configured for specific application to the NDI of aircraft, and potential areas of non-aerospace application. The simplicity and versatility of the technique has been well proven. As the technical concept is less than three years old, the instrument technology is being rapidly developed and new areas of application is being constantly found.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to B. Wincheski for his assistance in providing the figures in this paper.

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