OPTIMIZING THE DESIGN OF MULTILAYER EDDY CURRENT PROBES - A THEORETICAL AND EXPERIMENTAL STUDY

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INTRODUCTION

General Electric developed a new eddy current probe technology in the early '90's to address critical NDE needs in the aerospace industry. The technology utilizes lasers to trace out precise, multiple turn coils on a flexible substrate. The result is an eddy current probe that is capable of conforming to complex geometries and inspecting with a very high detection sensitivity. To cover large areas quickly, arrays of these coils were also fabricated and are currently in use with great success at GE inspection facilities. The newly developed probes, however, raised some unique questions and problems that needed to be addressed in order to determine the "best" probe configuration. In this paper we summarize these issues and through a combination of experimental and finite element results, we show how the design of the probe is "optimized" for various applications. Further details on the development of the technology are provided in a companion paper in these proceedings[1].

The flexible probes were originally developed to improve sensitivity and speed for inspecting newly manufactured aircraft engine parts with complex geometries[2]. Having accomplished this, the focus is now on improving upon these aspects and in extending the probes applicability to field-service inspections. In-service inspections require further improvements in the robustness and inspection time of the technique. Thus, we are studying ways to optimize the performance of the probe with respect to its geometry and operating frequency to perform tests quickly and with a high degree of detection sensitivity.

BASIC COIL DESIGN

The coils are fabricated using a proprietary technology developed at GE Corporate Research and Development Center. A photolithographic fabrication process produces perfectly repeatable coils with multiple turns and multiple layers. The elements are encapsulated on a thin flexible dielectric for a total thickness of about 0.004 inches (0.1mm). Although almost any shape coil is possible, it was decided early on to fabricate rectangular coils. Alternative coil designs have been fabricated, however, in this analysis only rectangular shaped coils will be considered. To further narrow the scope of the analysis we limit our results to driver-sense type probes where the sense coils are differentially wound. A conceptual schematic of the flexible probe layout is shown in Fig. 1 below. The filled and unfilled rectangles represent possible locations of drive and sense lines respectively.

A typical coil can contain several layers. There are, however, practical limits on how many layers are possible before the probe becomes too stiff. As a result, the number of turns is limited and the impedance of the coils is quite low. This impacts on the range of frequencies at which the coils can operate, the flaws they can detect and also on their susceptibility to noise. A variety of other factors and parameters need to be considered when designing coils to make the "best" probe. For convenience, the relevant parameters with their associated issues and constraints are summarized in Table I. The effects of these parameters will be detailed further while explaining the operational characteristics of the probe in the next section.

COIL CHARACTERISTICS

In conventional probe design, the number of turns on a coil is governed by the desired frequency of operation. The frequency of operation is dictated by the size of the flaw and the type of material being inspected. In general, the probe is optimized for crack detection if it operates near the knee of the normalized impedance curve as shown in Fig. 2 (a) below. In this region we obtain the best separation between lift-off, crack indications and conductivity variations. Operating too close to the resonant frequency of the coil, however, causes significant electronic noise that can mask the crack signal. This effect is highlighted in Fig.3 (a). Here scan images of a conventional 1/8" split-core differential probe with a resonant frequency of 5.5 MHz are presented. The probe was scanned over an inconel test block containing manufactured defects. The indications from left to right in the scan images are EDM notches with dimensions of 30x15 mils, 12x6 mils and 6x3 mils respectively. The final defect is a 4x20 mil Cylindrical EDM hole. There is a significant increase in the background noise level as shown in the 5 MHz plot. Operating the probe at a frequency on either side of the resonant frequency yields good detection results.

Flexible coils, on the other hand, have a much lower impedance and, as a result, a much higher resonant frequency. A typical coil may resonate anywhere from between 30 and 50 MHz. Thus, it is not possible to operate the coils in the knee of the normalized impedance curve. The probes are run far below resonance as shown in Fig. 2 (b). The

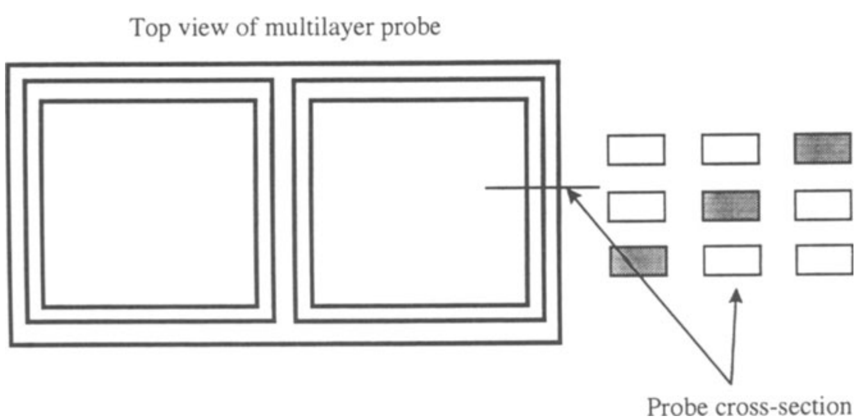


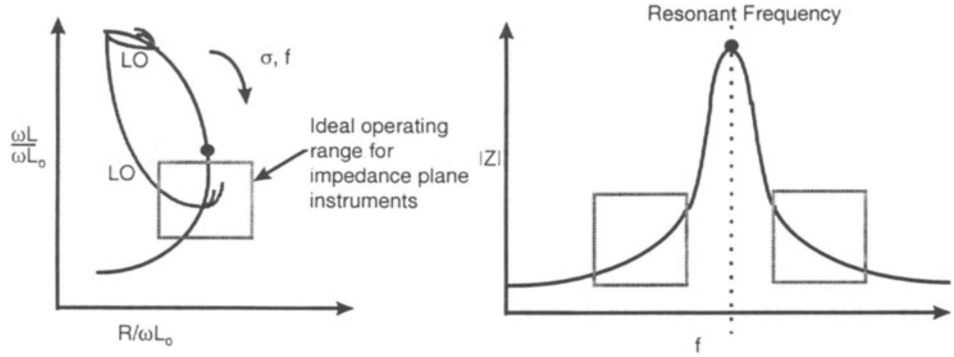
Fig. 1 Conceptual schematic of typical probe layout.

Table I. Optimization Considerations for the Flexible Probe

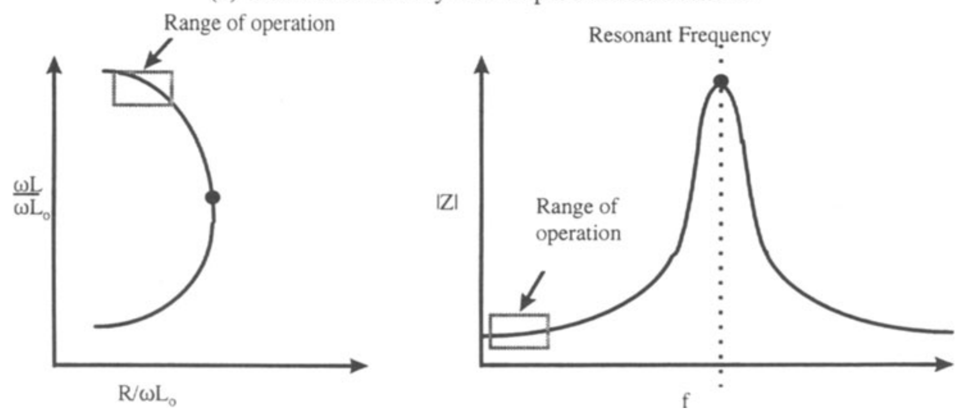
Parameter	Issues	Constraints
Coil Size	Impact on minimum detectable flaw? Impact on depth of penetration?	Larger coils have reduced S/N. Penetration depth.
Coil Shape	Surface coverage versus flaw detection	
Drive Coil		
Number of layers	Impact on flaw detection?	Practical limits. Stiffer probes.
Number of turns	Will increasing turns improve flaw detection?	Practical limits.
Sense Coil		
Number of layers	Impact on flaw detection?	Practical limits. Stiffer probes.
Number of turns	Will increasing turns improve flaw detection?	Geometric limits. Surface extent.
Frequency	Detection requirements versus probe requirements.	Coils are low impedance and are negatively impacted by noise at low frequencies.
Excitation Current	How does it impact on S/N?	Circuits have a practical upper limit of possible applied current.
Gain	How much, and where should it be introduced?	
Physical Inspection angle	Maximum coverage versus flaw detectibility.	
Drive and sense lead geometrical constraints	What drive-sense configurations are geometrically possible?	Certain configurations are not possible.
Location of windings	Proximity and relative location of drive and sense leads and how do they impact on flaw detection?	

problem with operating the probe in this region is that unless the frequency is quite high you do not get a measurable probe output. A fairly large gain is required to use the coils effectively. Gains on the order of 60-80 dB are usually required to obtain detectible results. Increasing the gain has the detrimental effect of increasing both the signal and the noise (unwanted signals). To enhance signal-to-noise (s/n) a small preamplifier is added as close to the coils as possible. This amplifies the signal to a reasonable level before it can pick up additional noise as it travels through the cables to the instrument. This improves s/n by 10% or more, depending on the size of the coil. Details on the pre-amplification of the flexible coils are given in a companion paper in these proceedings[3].

Incorporating these findings into the design of the probe results in a very broad-banded probe with excellent detection capabilities. Results for a rectangular shaped, multiple layer flexible probe with approximately the same cross-sectional area as the 1/8"



(a) Conventional eddy current probe characteristics



(b) Flexible multiple layer probe characteristics

Fig. 2. Impedance and flaw detection characteristics of conventional and flexible probes.

multiple layer flexible probe with approximately the same cross-sectional area as the 1/8"conventional probe are presented in Fig. 3 (b). This figure highlights what we mean by broad-banded. The probe has excellent detection capabilities from 2.5-20 MHz. Signal-to-noise for the conventional probe, on the other hand, is considerably reduced when operating above 8MHz. We should also point out that larger flexible probes have been fabricated and used to detect defects in magnetic steel while operating as low as 100 kHz.

Other factors which play a major role in the performance of the coils are related to the geometry of the coil and how variations in the geometry impact on flaw detection. To study this further a finite element analysis was performed to aid in optimizing the most important features related to flaw detection. Finite element results showing the amplitude of eddy currents induced by a rectangular coil into an electrically conductive sample are presented in Fig. 4. It is interesting to note that the streamlines of the eddy currents closely follow the shape of the coil. The density of the eddy currents directly beneath the wire is several times larger than the surrounding area. This suggests that crack detection is more a function of the location of the coil winding with respect to a crack and not the area of the coil. Consequently, a long and narrow rectangular coil should have detection characteristics similar to a circular coil having a circumference the same length as the perimeter of the rectangular coil.

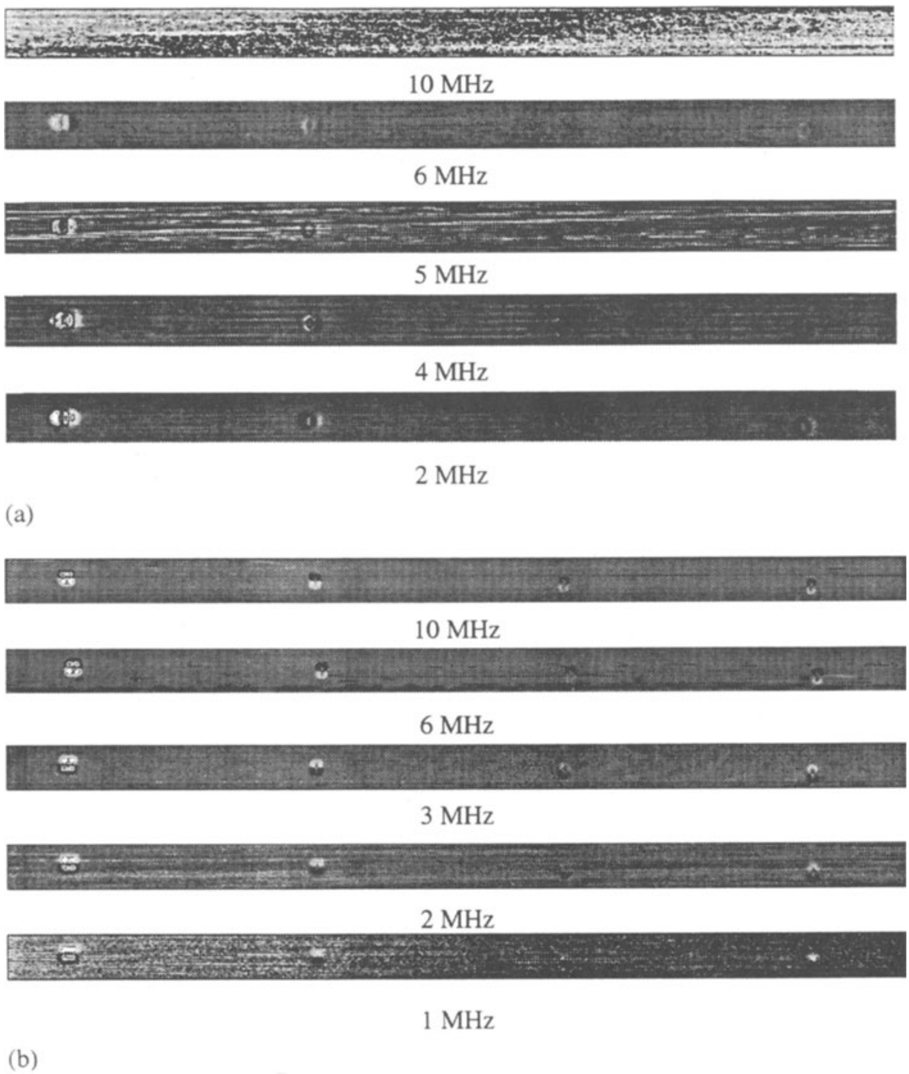


Fig. 3. Scan images using (a) a conventional 1/8" split core differential probe and (b) a rectangular shaped flexible differential probe at various frequencies. Flaws are EDM notches with dimensions in mils (0.001"or 0.025mm) of 30x15, 12x6, 6x3 and a 4 mil diameter hole that is 20 mils deep.

One potential problem that needed to be investigated, was whether the narrow rectangular coil would have a reduced depth of penetration. A series of finite element models were run and the results are presented in Fig. 5. The results clearly show that the shape of the coil does not impact on the depth of penetration into the sample. The only factors that have an effect are the excitation frequency, sample conductivity and the cross-sectional area of the probe. When the area of the probe is held constant, and only the shape is varied the results are the same for all the coils studied. The only difference in the results between the coil we modeled was the magnitude of the density of the eddy currents produced on the surface of the sample. It tended to be slightly larger for the circular coils, but when normalized to the maximum surface density all the coils gave the same depth of penetration curves.

Fig. 4. Finite element results of the induced eddy current density in an electrically conductive sample with and without a crack present.

Another aspect of the probe to consider is where to place the drive coil lines relative to the receive lines to obtain the maximum coupling for enhanced flaw detection. Fig. 4 above clearly indicated that the maximum sensitivity is directly beneath the drive coil line. Thus, this should be an ideal location for the sense lead. The next question is if we have several turns on a layer; Will additional turns in the center of the coil increase sensitivity? To study this further a finite element model of a rectangular coil was developed to see how the flux density varied immediately surrounding the drive line. Fig. 6 shows the magnitude of the flux produced by the drive line. The results are from the cross-section of only one side of the coil and are symmetric for the drive line on the opposite side of the coil. The center of the coil is located to the left in the figure. The results clearly show that the maximum flux is directly beneath the drive line and it decreases rapidly as we move to either side. However, as we move to the outside of the coil, the flux density decreases more quickly than if we move towards the center of the probe. Thus, any extra turns on the coil will be most effective if placed as close to the

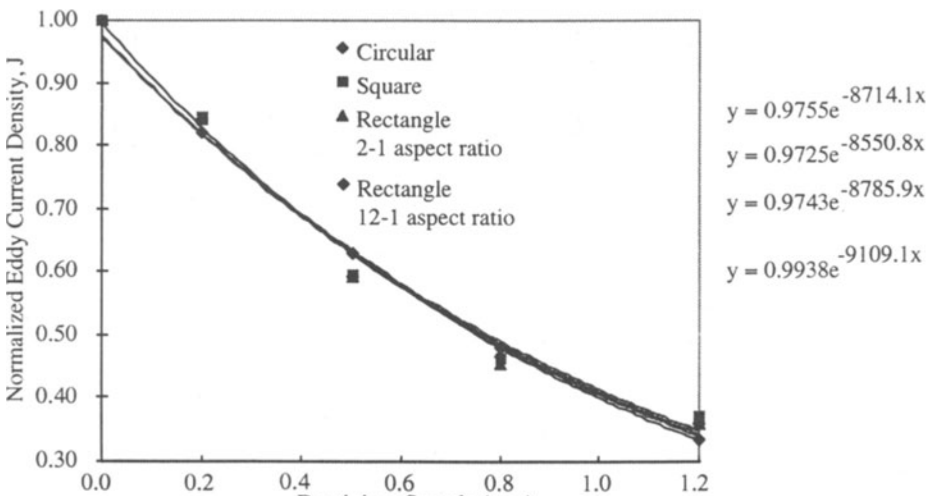


Fig. 5. Finite element results showing depth of penetration as a function of the coil geometry.

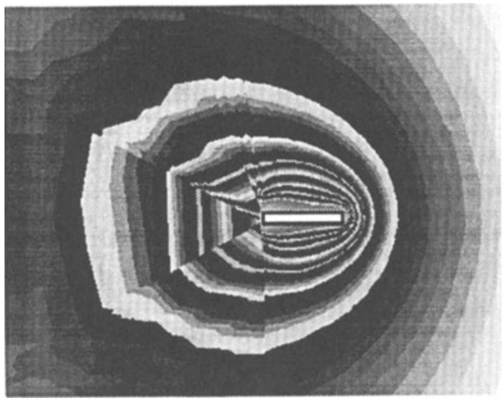


Fig. 6. Magnetic flux density around one lead of a rectangular drive line. This shows a cross-section of the flux perpendicular to the direction of current flow with the center of the coil located to the left of the figure.

drive line as possible. Additional turns beneath and inside of the probe will be more effective than those outside of the drive. In laboratory tests it was found that an increase in the number of turns towards the center of the probe did, as expected, increase the overall probe output. However, there was no noticeable effect on s/n.

The final consideration is the susceptibility of the probe to mechanical noise created during scanning. As with conventional EC probes this is the largest contributor of noise or unwanted signals. However, since the probes are not rigid and can conform to the surface of the sample, we have found that this form of noise is even smaller than that of the conventional probes. This is true provided a sacrificial top layer with a small frictional coefficient is also used to reduce dragging. In addition, a sufficiently compliant and compressible backing material should be used to keep the probe in contact with the sample. Without these additions the probes, being thin and flexible, will vibrate and cause noise problems exceeding that of conventional probes.

SUMMARY

Flexible multiple layer eddy current probes are a unique and useful addition to eddy current inspections. Their ability to conform and operate over a wide frequency range make them a very versatile tool. Their uniqueness also raises new issues which must be considered when designing probes for specific applications. In particular, the low impedance of the coils causes come difficulties with regards to obtaining a sufficient signal above the noise. However, since we have more control over where we can place both the drive and sense leads we can maximize the coupling between the two and, as a result , enhance the s/n. In addition, the placement of a preamplifier as close to the coil as possible also serves to increase the signal-to-noise ratio. Lastly, since a variety of coil geometries are possible, we can vary the shape of the coil to give the "best" detection results.

A large amount has been learned, but further optimization is still possible. Work continues to focus on new and better ways to make and use this new technology and provide a faster, more robust probe with better flaw detection capabilities.

REFERENCES

1. K. Hedengren, J. Fulton, J. Young, T. Patton, and R. Filkins, "Progress in Flexible Eddy Current Array Technology," presented at *1996 Review of Progress in QNDE*, Brunswick, Maine.
2. Hurley, D. C., Hedengren, K.H., Howard, P.J., Kornrumpf, W. P., Sutton, G. E., and Young, J. D., "An Eddy Current System for Aircraft Engine Inspections," Review of Progress in Quantitative NDE, Vol.13A, edited by D. O. Thompson and D. E. Chimenti (Plenum Press, New York, 1994), p. 1111.
3. T. Patton, R Filkins, J. Fulton, K. Hedengren, J. Young, C. Granger and T. Hewton, "Development of a Hand-Held, Flexible Eddy Current Probe for Inspection of Curving Surfaces," presented at *1996 Review of Progress in QNDE*, Brunswick, Maine.