PREDICTIVE MODELS AND RELIABILITY IMPROVEMENT IN ELECTROMAGNETIC NONDESTRUCTIVE EVALUATION

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INTRODUCTION

The role of theory in improving the reliability of electromagnetic NDE is generally the same as with other inspection methods.[1-4] Computational models of the interaction of NDE probes with material flaws can be used to aid in the selection of a method, including details of the probe design, in the verification of the method, by providing data on flaw response, and in the development and analysis of an inspection plan in terms of probability of detection (POD) data. In this paper we will first give examples of how these three aspects of reliability improvement can be accomplished through the use of theoretical models. Then, in the second part of the paper, we will comment on the adequacy of existing models and offer some suggestions for further model development for reliability applications.

Most of the examples used here refer to eddy current applications, specifically to the use of the electric current perturbation[5] (ECP) probe in the inspection of aircraft engine components. However, the basic theory involved in these applications is generally the same as that required for other probe designs and inspection problems. Our conclusions regarding the use of models therefore apply to eddy current testing in general and can even be extended, with some limitations, to other forms of electromagnetic NDE, such as magnetic leakage field inspection of ferromagnetic materials.

SELECTION OF AN INSPECTION METHOD

The first step in the development of an inspection procedure is the selection of an NDE method. Although predictive models might be used to determine the relative merits of different NDE approaches to a particular application, more often than not the choice between, say, eddy current and ultrasonic methods is rather obvious. For our present purpose, therefore, we assume at the outset that an electromagnetic approach has been chosen. The selection of a specific method then involves a decision as to the type of probe to be used, i.e., absolute, differential, ECP, or perhaps some other configuration. One must also choose the excitation waveform, whether single-frequency continuous-wave, multi-frequency, pulsed, etc., and waveform characteristics such as a specific frequency or pulse width.

There is also the question of probe geometry, requiring the selection of winding size and shape best suited to a particular inspection problem. If a sufficiently general computer model of the probe/flaw interaction is available, the optimum choice of these design parameters can be simplified and enhanced by the use of the model to explore various options. There are several examples in the literature of the use of models for such purposes.[6-9] Here we will cite only one to illustrate the idea.

The drawing at the top of Figure 1 is a side view of an ECP differential sensor - two coils wound on a ferrite core and separated by the distance $2\ell_1$. We seek the value of ℓ_1 that maximizes the signal-to-liftoff noise (S/N) ratio for the detection of .25 X .125 mm surface cracks in a low conductivity material such as the titanium alloys commonly used in aircraft engine components. Calculations based on a model described elsewhere[9] give the flaw signal, liftoff noise and S/N ratios shown (on different scales) in the figure. The conclusion we would draw from these results is that, for cracks as small as those of concern here, it is best to keep the ECP sensor coil-to-coil distance as small as possible.

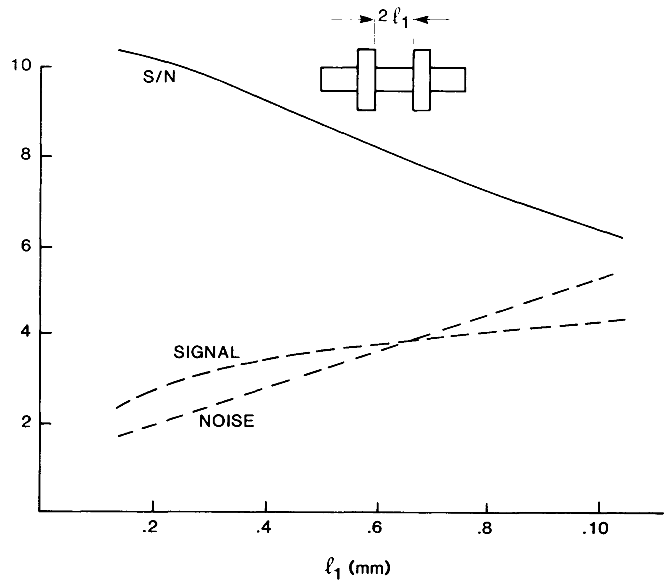

Fig. 1. Optimization of ECP differential coil spacing for small surface crack detection.

VERIFICATION OF THE METHOD

By verification of an NDE method we mean the demonstration, by means of experiment and/or calculations, that adequate S/N ratios are realized for all flaw types and sizes, and all probe-to-flaw distances expected in the actual inspection. In effect, this means to provide all of the flaw sensitivity data one would need, along with adequate noise statistics, to design an inspection system with adequate POD. The main point we wish to make here is that, given the large number of parameters that enter the definition of an inspection system, it is hardly ever possible to provide an adequate data base from experimental results alone. This, then, is the principal role of predictive models in reliability improvement - to extend,interpolate,and extrapolate experimental data to generate a data base adequate for a POD analysis. We will return to this point in the next section.

Figure 2 illustrates the type of data we need for reliability analysis. In this case the plots are flux leakage maps for spheroidal voids in a ferromagnetic material; however, given a suitable computer model, similar maps can also be generated for eddy current probe response. We can use such maps, along with empirical data on background noise, to determine how the S/N ratio varies with flaw size and other inspection parameters, thus providing a preliminary assessment of the performance of the system. Such data are also useful in making tentative choices of inspection parameters such as probe size and scan track spacing, prior to an analysis of probability of detection.

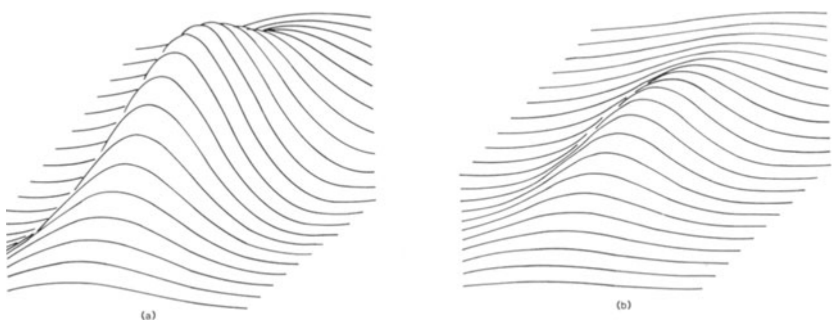

Fig. 2. Flux leakage fields for spheroidal voids in a magnetic material. Major and minor axes are 1.3 and 1.0 cm, respectively, in (a) and 0.6 and 0.5 cm in (b).

DEVELOPMENT OF AN INSPECTION PLAN

As was noted earlier, the primary role of predictive models in reliability improvement is to provide whatever flaw response data are needed to determine the probability of flaw detection as a function of inspection parameters. The development of an inspection plan is the process in which we choose a set of inspection parameters, calculate probabilities of detection and false alarm, and then, if necessary, change one or more parameters and repeat the process until satisfactory probabilities are achieved.

To illustrate, we will make use of experimental ECP data[10,11] for small surface flaws in a blade slot of an F100 first stage fan disk. From scans like those shown in Figure 3 we obtain the background and signal distributions shown in Figure 4, if flaw signal amplitudes are taken from scans directly over the flaw. This, however, is a rather unrealistic situation because in an actual inspection the flaw can be anywhere between adjacent scan tracks. To obtain a more useful signal distribution it was therefore necessary to make additional scans at various distances from the flaw, resulting in a broader signal distribution than that shown in Figure 4. A schematic illustration of the result for a fixed flaw size and scan track spacing is shown in Figure 5 (actual data are presented in references 10 and 11). Once this was done, probabilities of detection and false alarm were determined by calculating the appropriate shaded areas shown in the figure.

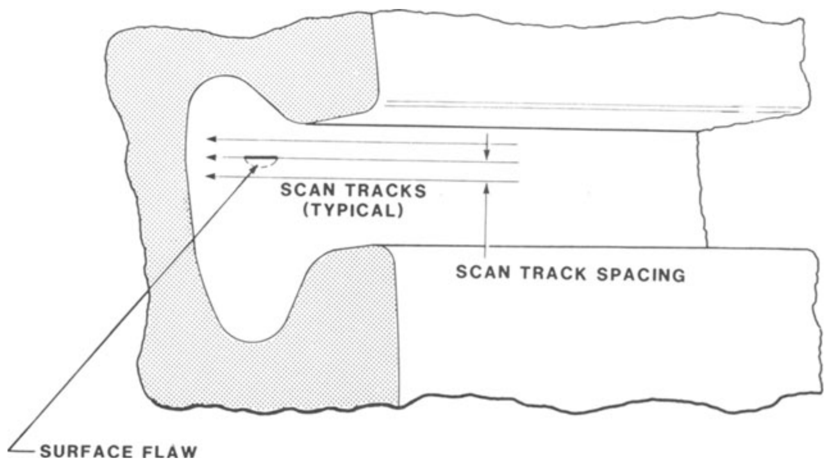

Fig. 3. Scan pattern for the inspection of blade slots in a fan disk.

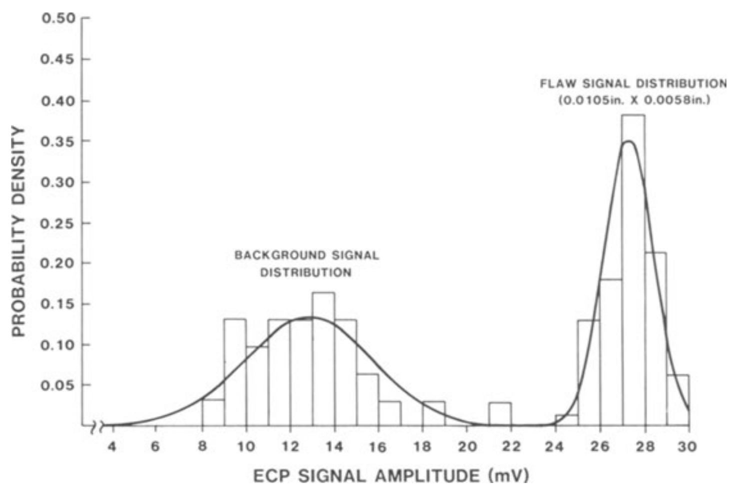

Fig. 4. Signal and background probability density functions for blade slot inspection.

It is important to note that this exercise, which was based on approximately 100 ECP data scans to obtain flaw signal distributions, allowed us to determine the POD as a function of false alarm rate for only one flaw size and one scan configuration. To obtain POD estimates for flaw sizes other than the one studied experimentally, it was necessary to make certain assumptions regarding the shape and mean amplitude of the signal distribution as a function of flaw size. A description of the procedure used and the resulting POD data are presented elsewhere.[10,11]

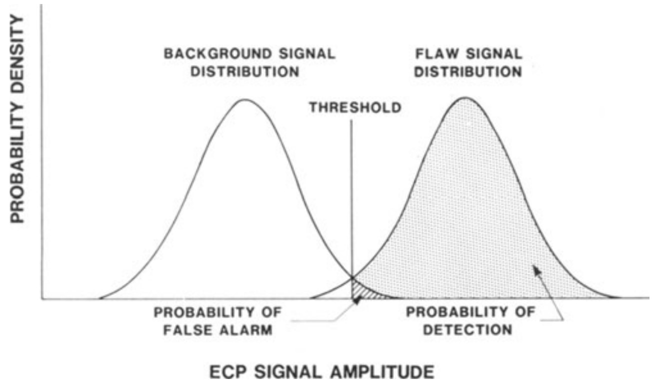

Fig. 5. Schematic probability density functions and their relationship to probabilities of detection and false alarm.

The main point we wish to make here is that if the ECP computer model we now have available had been operational at the time, we could have used the model to extend the data base to other flaw sizes, scan track spacings, and even different probe configurations or operating frequencies, if desired.

In terms of reliability improvement, this, then, is the payoff to the development of predictive models. Once we have completed the theoretical development, verified our results by comparison with experiment, and written the necessary computer programs, we can very easily test the adequacy of an inspection by using the model to extend the experimental data base and predict POD data. If the inspection system does not perform as expected, it is also very easy to change one parameter or another and try again. To do such studies by purely experimental methods would almost always involve prohibitive time and cost expenditures, and it would seem, therefore, that the use of predictive models offers the only hope for a thorough analysis of inspection reliability.

MODEL DEVELOPMENT

We will now leave the subject of model applications to offer some opinions on the suitability of existing models and prospects for their adaptation to reliability problems. Thus, the question we address here is to what extent we can use available theory, and models that might be developed, to examine realistic inspection problems.

We must distinguish between two different types of models - those based on analytic solutions and those, such as the finite element method[12], which are essentially numerical simulations of the behavior of electromagnetic fields. Analytic solutions offer the advantage of simplicity, which translates into speed of computer execution and the possibility of generating an abundance of data in a very short time. Exact analytic solutions are, however, limited to a few simple geometries and one is therefore forced to use approximate solutions in almost all applications to NDE. Numerical simulation methods are potentially capable of handling very complex geometries, but tend to place much greater demands on computer time and memory.[13] Because most reliability applications require the solution of a very large number of problems, models based on analytic solutions seem to be the only choice at the present time, despite their known deficiencies and limitations. The comments that follow therefore refer to such analytic models except where noted.

Predictions of the effects of probe geometry and frequency on flaw response can now be treated for non-symmetric[14] as well as axisymmetric[15] air-core coils. Ferrite core effects are usually approximated by a simple amplification factor; the influence of this approximation on flaw response calculations has not yet been investigated.

Theoretical models of the influence of flaw geometry on the flaw response signal have received considerable attention in the past few years. Though much remains to be done in this area, recent results for rectangular[16] and ellipsoidal[17] models of normally-entering surface cracks suggest that approximate methods for treating this class of flaws will soon emerge. For more complicated closed-crack configurations the approach suggested by Bowler[18], which might be described as a blend of the analytic and numerical simulation methods, appears promising. At the present time, however, working models are based on the small flaw approximation in which it is assumed that the incident eddy current field is uniform over the face of the flaw. Use of these models should cause no difficulties if the flaw dimensions are indeed small compared to the probe dimensions and the skin depth. Otherwise, one can expect the small flaw model to give a distorted picture of the signal as a function of probe position.

Certain other inspection parameters can be treated without difficulty. Predictions of the effects of scan track spacing or liftoff on the flaw signal distribution are largely a matter of preparing the appropriate computer programs. On the other hand, calculations for general, non-sinusoidal excitation waveforms are a rather recent development[19,20] and are not yet ready for application.

With respect to inspection reliability problems, perhaps the most serious deficiency of existing models is their inability to treat the effects of part geometry on the signal. All models of probe response assume either cylindrical symmetry or an infinite medium bounded by a plane surface. Applications to such important practical problems as inspections for corner cracks, flaws near edges, or flaws in complex geometry pieces, are therefore beyond the capabilities of available theoretical models. Furthermore, there seem to be no immediate prospects for the development of analytic approaches to most such problems. It appears that we must await the further development of numerical simulation methods, and the computer technology to make them affordable, before modeling of complex part geometry can be accomplished.

There is one important exception - the right angle corner. Kahn, et al.,[21] used an image method to develop a reasonably simple eddy current Green's function for this geometry, which, it would seem, could form the basis for further model development. If this can be done it would permit the treatment of corner cracks and other edge effects, thus extending the usefulness of theory to a wider class of inspection problems.

Needless to say, one of our recommendations for further model development is an investigation of the right angle corner problem. There is also a need for improved models of the eddy current/flaw interaction and their extension to more complex defect shapes, perhaps by a boundary integral treatment like that used by Bowler.[18]

Finally, we think it could prove very useful to begin now to construct models of complete inspection systems - including all the details of probe geometry, flaw size and shape, and scan patterns. While all of the theoretical elements that comprise such a calculation may not be developed to our satisfaction at the present time, there are practical inspection situations, such as small flaws near flat surfaces, where existing theory should provide reliable answers. Even a few applications to relatively simple inspection problems could provide not only improved reliability at lower cost for the problems in question, but would also serve as convincing demonstrations of the potential of predictive models in reliability improvement.

ACKNOWLEDGEMENTS

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DISCUSSION

R. B. Thompson (Ames Laboratory): There's something you sort of alluded to, you didn't elaborate on; I want to probe your thoughts further on it. In modeling, as you say, it's straightforward to be able to predict the signal from the flaw, and if you are smart enough and/or have a big enough computer, you can do it. The prediction of noise is a little more difficult in that there are many different possible sources of noise and you have to decide which is important. What do you think of the possibility of determining noise experimentally and having some formalism whereby you combine experimentally-determined noise on the particular kind of part with analytically-predicted signals? Do you think that's a reasonable hybrid approach?

R. E. Beissner: That's really what I was assuming all along as a way of getting a probability of detection. I'm assuming that we have an empirical background distribution, as I called it, and that we hold that fixed and we predict only what happens when another inspection parameter varies and the flaw signal changes. The idea of predicting noise is intriguing but you have to know so much about what's in the material.

R. B. Thompson: I guess I'm thinking if you are talking about far-off design, you want to have a part in which to measure the noise, so you want to have some rough estimates of what the noise would be for the designers. But if you already have the part in hand, maybe you are better off directly measuring it.

R. E. Beissner: I wasn't thinking so much of design, but that's certainly a valid consideration. I haven't addressed that.

A. J. Bahr (SRI International): It seems to me that you need to address the problem of modeling the contributions to the noise in order to optimize your system design. So in listing important problems to be worked on, it's equally important to know the noise process.

R. E. Beissner: I'm assuming something that I didn't state, that we have the part in hand and we can make measurements of noise, but we just don't have the time and the money to make all the other measurements.

A. J. Bahr: But the design of your probe can be affected by the noise.

R. E. Beissner: That's right. You couldn't optimize the probe design without noise information.

A. J. Bahr: It's just a suggestion.

R. E. Beissner: - and a good one. Thank you.