EDDY CURRENT TESTING - ARE WE AT THE LIMITS?

S. Udpa and L. Udpa
Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI USA

Abstract: Eddy current methods have evolved over the years both in terms of sophistication as well the range of applications ever since D. E. Hughes demonstrated the merit of the approach in 1879. Rapid advances in our capacity to model the underlying physical process have given us the ability to design probes that offer unprecedented levels of sensitivity and resolution. These advances have been accompanied by developments in the area of signal processing that have resulted in tools capable of characterizing flaws accurately. It would seem, therefore, that the field has matured to a point where further improvements are unlikely. This paper argues that this is not the case and that much can be done to improve the state of the art. The paper discusses the history of the method, covers some of the more intriguing developments in the field in recent years and finally, attempts to prognosticate areas where advances are likely to be seen in the next few years.

Introduction: Eddy current methods of nondestructive evaluation have come a long way since D. E. Hughes [1] demonstrated that such methods can be used to compare and sort materials on the basis of differences in electrical parameters such as conductivity and permeability. Hughes not only showed that the principle of electromagnetic induction can be used as a basis for measuring material properties but also demonstrated the utility of differential measurements for enhancing sensitivity. Although the transducer used by him (a telephone) would seem quaint and out of place in the modern world, the concepts are used to this day in a number of industries to establish the integrity of a wide variety of components and structures. The methods have grown in sophistication as revolutions in the fields of sensors, microelectronics and computers have had their impact on instrumentation. Rapid advances in our ability to model the underlying physical process have given us both the ability to design probes that offer unprecedented levels of sensitivity and resolution as well as examine new ways of interrogating the test specimen. These advances have been accompanied by developments in the area of signal processing that promise significant improvement in our ability to interpret data accurately. The paper will discuss some of the more intriguing developments in the field in recent years and finally, attempt to prognosticate areas where improvements are likely to be seen in the next few years.

Progress in the field has been contributed by developments in a number of other disciplines. Although these developments are largely interconnected, we will attempt to cover these under separate areas leaving the reader to deduce the underlying connections.

Instrumentation: Although primitive by today's standards, many of the early industrial applications of the induction phenomenon were remarkable examples of creativity. They very vividly demonstrate how technologies of the time were put to good use for meeting inspection objectives. Figure 1 shows the schematic diagram of a system developed by Förster [2] in 1937 for sorting parts. The test and reference specimens are excited by a pair of coils. The differential signal (measured through a pair of pick-up coils) is applied to a galvanometer whose needle interrupts a light beam incident on a photocell. An imbalance, resulting from differences in the material properties of the test and reference specimens, causes the galvanometer to deflect allowing the light beam to strike the photocell. The increased conductance of the light cell results in the activation of a solenoid which operates a chute causing parts with flaws to drop into a

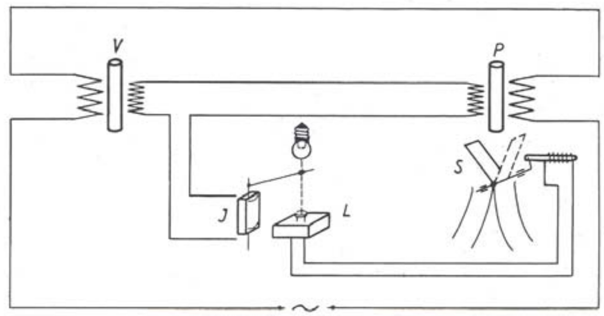

Figure 1: Schematic Diagram of an Early Eddy Current System Developed by Förster [2]

separate bin. Förster continued to make significant contributions to the field including the development of the forerunner of the modern eddyscope. He pioneered the display of information via what are often referred to as "comma curves" in the early 1940s. A more complete list of Dr. Förster's contributions are summarized in an article published in the first edition of the NDT Handbook [3] and a paper that appeared subsequently in 1983 [2].

The arrival of the microprocessor in the 1970's and the availability of inexpensive analog to digital (A/D) converters in recent years have had, perhaps, the most impact on instrumentation. Signals can now be routinely be sampled and quantized with 16 bit precision and as a consequence, bulk of the processing can be performed in discrete-time. Sources of noise introduced in the signal, excluding noise introduced by the transducer, from start (transducer output) to finish (digital output of the instrument) include quantization noise, error introduced due to finite word length and algorithmic errors. The quantization noise is closely related to the number of bits associated with the A/D conversion process. A crude rule of thumb is to assume an improvement of 6 dB in the signal-to-noise ratio (SNR) for every additional bit. Quantization noise is seldom a concern these days with the ready availability of 16 bit converters in the case of conventional eddy current applications. Round-off errors due to finite word length were a matter of concern when microprocessors could not handle fast floating point calculations. The availability of relatively inexpensive 32-bit floating point digital signal processors with cycle time as low as 3.5 ns has rendered this issue moot. The overall SNR of eddy current instruments have leapfrogged as a consequence and most instruments offer performance levels that were simply not possible a few years ago. Ready access to inexpensive computational horsepower with massive amounts of storage within the instrument has also revolutionized our ability to extract and process information in numerous ways. Since most functions are now implemented in software, programmability has become a common place feature. High, low and band pass filters are routinely digital in nature. Features such as rotation, translating and gain and most importantly graphics are all implemented in software. This allows the user to tailor the instrument characteristics to the application far more effectively.

Prognostication in a rapidly changing world is very difficult. However, it is easy to see that spectacular improvements with respect to computation speed and memory will continue to have an impact on the industry. It is more than likely that this will affect the way in which the inspection data is interpreted. Current industrial practice is to rely either on manual interpretation or simple calibration based approaches to estimate the size, shape and location of the flaw. Access to vast amounts of computation power would allow instrument manufacturers to incorporate sophisticated signal interpretation algorithms. A number of three-dimensional defect characterization approaches, both model and system based, have been proposed in recent years. It is relatively safe to assume that such defect characterization algorithms would become an integral part of the instrument menu. In the case of specific geometries, it may even be possible to use the defect profile estimate to calculate its impact on the structural integrity of the test component within the instrument. In short, we will very likely see the migration of activities that have hitherto been performed off-line to the eddy current instrument. The ease with which application specific integrated circuits (ASIC) can be designed and manufactured today as well the emphasis on miniaturization will inevitably result in smaller instrument footprints. The limitation is, of course, the size of the display required to present large amounts of information. This is being addressed through the use of head mounted displays. Such displays are also likely to become commonplace for displaying data in a virtual reality environment. It should routinely be possible in the future to "navigate" through a virtual world allowing the user to examine a defect profile estimate in 3D from any arbitrary perspective using a stereoscopic head display.

Multifrequency eddy current systems have become far more sophisticated as circuit speeds have improved and our ability to build high quality filters and multiplexers/switches have grown. Both time and frequency division multiplexed systems are now routinely available with the latter offering significantly higher eddy current signal bandwidths. This trend is likely to continue into the foreseeable future resulting in much higher inspection speeds. Mixing and other signal processing algorithms for suppressing artefacts are also growing in sophistication and it should be possible to suppress artefacts more effectively in the future.

The availability of high resolution (18 bits and higher) A/D converters will have an impact on pulsed eddy current and remote field eddy current methods. These inspection methods will be able to make use of the large dynamic range and low noise floor of such converters. The circuits preceding the A/D converter (such as the anti-aliasing filter) in the processing scheme will have to be designed very carefully, of course, to ensure full exploitation of their low noise characteristics.

Modeling: Simulation models serve as useful tools, among other things, for gaining an understanding of the underlying physical process, optimizing the design of a probe, selecting an optimum set of test parameters and even calculating the probability of detecting a flaw. Although such models come in several flavors, they can broadly be classified as either analytical or numerical. It must be mentioned that the distinction is somewhat artificial since all analytical models do involve a fair amount of numerical computation and all numerical models in rooted in analytical theory.

Förster [4] was among the first to develop analytical tools to corroborate experimental findings and for predicting the effects of test specimen material properties on measurements. The most important contribution to the field was made by Dodd and Deeds who derived closed form integral expressions in the late 1960's for the impedance of a coil above a layered half-space conducting medium as well as the impedance of a finite length coil encircling a conducting rod. Although these models continue to be used extensively to this day, a number of extensions have been proposed in recent years. Bowler [5], for example, employs the integral expression to compute the pulsed eddy current response using a Fourier series expansion of the input pulse. A number of other alternate approaches for computing the pulsed eddy current response have also been proposed in recent years [6, 7]. Notably, Theodoulidis [8] has developed an analytical model for predicting the fields generated by coils with ferrite cores. Work in the field of analytical model development will continue and provide users with a quick and computationally inexpensive vehicle for calculating probe responses to simple test and flaw geometries.

Developments in computer technology since the 1960's have had a dramatic impact on numerical approaches to simulation. Starting with the first attempts using finite difference methods, numerical approaches to solving partial differential equations that characterize NDE phenomena have blossomed with the ready availability of computational platforms. A number of commercial finite element [9] and volume integral codes [10] capable of simulating arbitrary shaped defects and test geometries are currently available. These codes play a significant role in the design of new probes and the optimization of test conditions. An interesting variation of the finite element method that relies on the underlying mesh and element-node connectivity is the class of meshless methods which discretizes the domain by a set of nodes alone [11]. These methods are inherently more accurate and are particularly useful for representing tight cracks and moving boundaries. Numerical codes have been used with success to gain an understanding of the physical processes associated with NDE methods. One of the well known success stories involves the use of finite element methods to gain insight into the remote field phenomenon by Lord et al. [12].

A dramatic example of the use of numerical models was provided recently by Sun et al. who used finite element techniques tools to design remote field eddy current probes that are capable of detecting defects at depths far greater than the skin depth. It has been argued for many years that it is extremely difficult to detect flaws that are embedded deep in materials using eddy current methods and that such methods are mainly suitable for detecting surface breaking cracks or flaws that are close to the inspection surface. Sun demonstrated that with the clever use of shields within the probe, it is possible to direct energy flow in a manner that facilitates the detection of relatively small flaws at a depth of as much as 20 mm in aluminium [13]. He has also demonstrated that it is possible to detect cracks around rivet holes in the second and third layers of multilayered aircraft structures. Figure 2 shows photographs of a few probes that seem to be able to "violate" the rule of thumb associated with skin depth.

Figure 2: Remote field probes with very high sensitivity [12]

One of the more interesting applications involves the use of numerical models for calculating the probability of detection and the generation of receiver operating characteristics for a given set of test conditions [14]. Although such POD models cannot account for human factors, they are very useful for isolating physical factors that contribute to variations in test results and the impact of such variations on detectability. It is more than likely that such models will become more commonplace as industry begins to embrace the concept of design for testability and life cycle management in the future.

Simulation models are increasingly being used as a basis for solving inverse problems. The most straight forward method is to use an iterative scheme where we use an appropriate norm of the difference (error) between the output of a simulation model and the test signal to adjust the material parameters until agreement between the signals is obtained. A number of schemes to reduce the computational effort ranging from table look-up schemes to methods that improve the convergence rate have been proposed [15-18]. The principal disadvantage lies in the computational burden associated with the implementation of these inversion schemes although some of the newer methods appear to be successful in overcoming this problem. These model based inversion schemes will become more popular as computational power becomes less expensive. Such inversion schemes offer the obvious advantage of not requiring any training data unlike system based approaches which typically need substantial amounts of data. Model based inversion schemes may be the only choice in situations where training data is either scarce or not of the quality required to design robust defect characterization systems.

Sensors: Eddy current methods have traditionally relied on coils and in some instances Hall Effect devices to measure fields. Coil type transducers offer the advantages of being very accurate, robust and simple to construct. The measurements are somewhat noisy since the output voltage is related to the time-derivative of the field. However, this is seldom a concern in the case of conventional single frequency eddy current methods since the coherent detection scheme employed in most eddy current instruments has excellent noise rejection characteristics. Its low sensitivity can, however, be a drawback when the field levels are very low. A number of devices are currently being used in situations where the field levels are low. Two of the more recent entries into the field are the giant magnetostrictive (GMR) probes [19] and fluxset sensors [20]. GMR probes are being studied extensively and it is more than likely that the device would find widespread application in the near future as the drive towards higher sensitivity picks up steam.

The most sensitive eddy current transducers continue to be superconducting quantum interference devices (SQUID) [21]. These devices are capable of measuring field levels several orders of magnitudes less than conventional Hall Effect sensors. It should be possible to see portable versions of the device routinely in the future.

Another relatively new device using bubble memory technology is the magneto-optic sensor that produces real-time analogue images of the magnetic flux associated with the induced eddy currents [22]. This technique is gaining acceptance in the aviation industry due to its easy-to-interpret imaging capability for detecting cracks and corrosion in multilayer airframe structures.

Signal Processing: Signal processing techniques represent a powerful approach for improving the probability of detection. Such techniques are also very often used to enhance the quality of the signal by reducing noise and other artefacts that detract from our ability to detect and characterize the flaw. Signal enhancement procedures are of interest in situations where the signal is interpreted manually as well as in cases where it is analyzed using an automatic system.

Signal quality can be enhanced in a variety of ways ranging from simple filtering schemes to those that adapt with noise statistics. The latter are particularly useful when the noise is highly correlated with the signal. Figure 3 shows the result of applying an adaptive filter to magnetic flux leakage signals obtained during the inspection of natural gas transmission pipelines. The signal is corrupted by noise that is generated as a result of helical variations in the grain orientation introduced during the manufacturing process [23]. Although the signal is a magnetic flux leakage (MFL) signal, the procedure can be applied with equal effectiveness to eddy current signals.

A number of new approaches have been proposed in recent years for the classification of defect signals. A variety of pattern recognition techniques based on statistical as well as trainable approaches have shown promise [24-25]. Prominent among the latter category are those that make use of neural networks. Equally interesting developments are occurring with regard to the development of systems based methods for estimating defect profiles. Figure 4 demonstrates the use of wavelet basis functions for reconstructing flaw profiles from MFL signals.

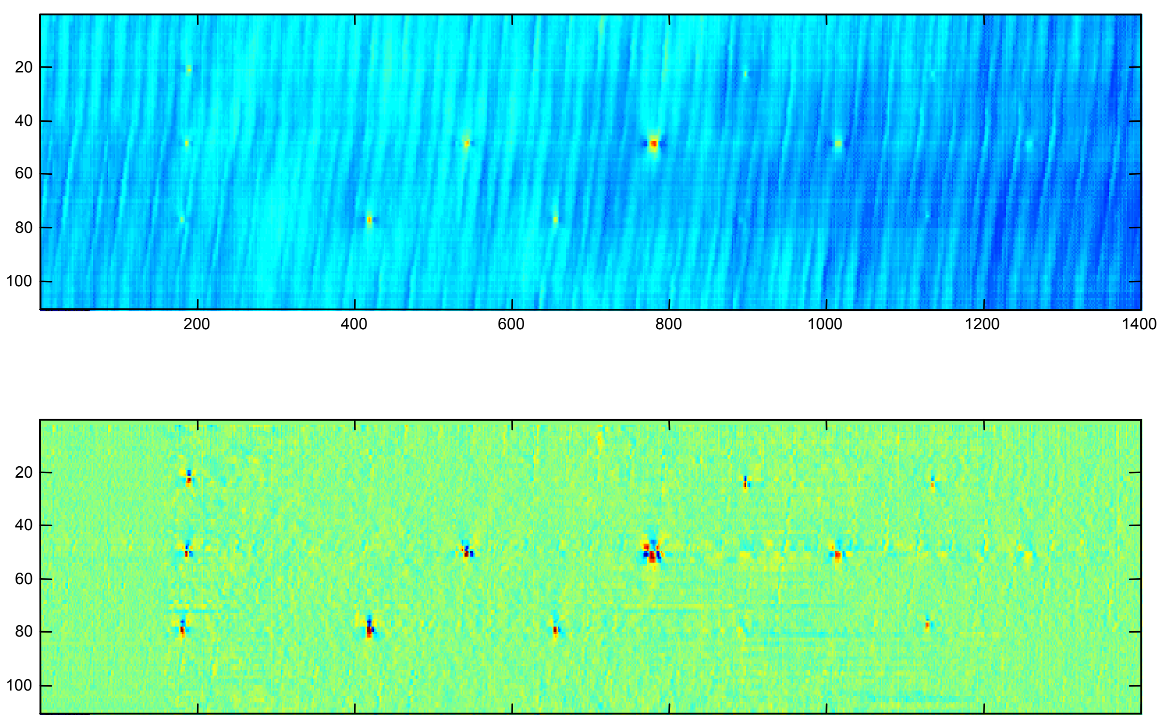

Figure 3: Original (top) and Filtered Magnetic Flux Leakage Images.

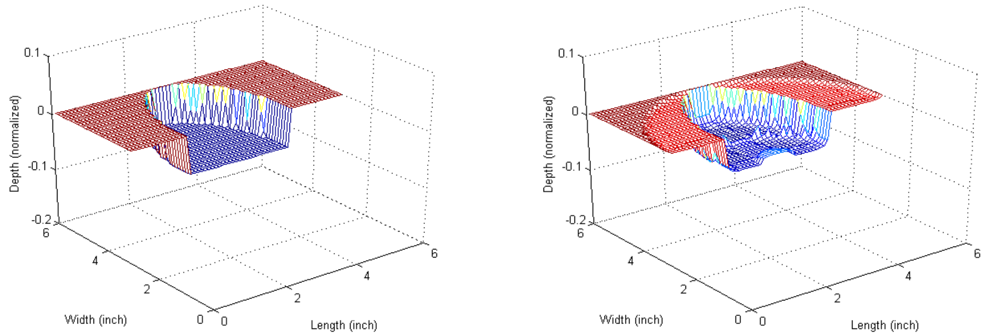

Figure 4: True and Reconstructed Defect Profiles Obtained From Magnetic Flux Leakage Signals Using Wavelet Functions

One of the more exciting developments in the field involves the concept of data fusion [26, 27]. The basic premise is that it is possible to garner additional information concerning the state of the specimen by combining information from multiple sensors. Sensors could be of the same type (operating at different positions and/or excitation frequency) or they could be entirely different from each other (heterogeneous environment). Although the subject matter is in its infancy, it is, perhaps, safe to predict that data fusion methods will be receiving a lot more attention in the future.

Space considerations preclude a more detailed discussion of some of these exciting developments in the field of signal processing. It is a safe bet to assume, though, as we begin to reach the physical limits of some the methods and signal-to-noise ratios begin to plummet, we will have to turn to such methods to extract as much information as is feasible to make any headway.

Conclusions: It is impossible for a paper such as this to capture the essence of all that has been done in a field that is over a hundred years old. However, it is safe to say that some of the most exciting developments are ahead of us. A confluence of developments in the fields of electronics, computer technology, simulation tools and signal processing is contributing to the excitement and fuelling some of the most compelling advances. Technology is indeed breathing new life into the field and there is much to look forward to in this important scientific endeavour!

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