Historical Development of Eddy Current Testing in Aircraft Maintenance*

by Robert D. Shaffer†

The basic principles of eddy current testing have been known for many years. Even so, industrial applications of the method itself have developed quite slowly. The focus of this paper will be investigations into the application of the eddy current method in the field of aircraft maintenance testing.

The author intends to give the reader insight into past and present application problems and resulting instrumentation designs. In doing so, the hope is to construct an approximate timetable of significant application and instrumentation milestones. A brief look into the future, based on current development work and concepts, is also presented.

There is no intent to establish the credibility of any person, company, or instrument through references in this paper. The objective is to create a brief synopsis of the general instrumentation, applications, and personal contributions that have established the history of today's eddy current testing in aircraft maintenance.

Historical Development Before 1900

Investigations of the electromagnetic test method preceded the development of nearly every other modern technique of nondestructive testing (NDT). In fact, documented use of electromagnetic waves for the NDT of metals predates the experimental proof of the reality of the waves themselves. As early as 1879, roughly eight years before Hertz demonstrated the existence of electromagnetic waves, D. E. Hughes utilized eddy currents to perform simple sorts between different metals and alloys.[1] The results of his experiments were published in the UK in the *Philosophical Magazine* of that year. One of the comments attributed to Hughes had to do with the "exceeding sensitivity" of eddy currents to many different types of material and test variables. This is certainly true and has been the source of the greatest difficulty in accomplishing successful eddy current tests. Eddy current, like other NDT methods, is often sensitive to many variables other than the one being studied. One result is that, historically, eddy current tests were of a nature that provided qualitative and not quantitative results. The move toward obtaining quantitative results is ongoing, and research and development efforts today are directed toward improvement on this end.

False and missed indications were a serious inspection problem.

Modern History (1900–1991)

There was little industrial application of eddy current testing prior to 1925. Between 1925 and the end of World War II in 1945, however, a number of comparator tests were developed and reported in literature. In nearly all cases, quantitative analysis of test object properties or discontinuities was not possible. These comparator systems, which simply evaluated the amplitude of the eddy current signal, received little acceptance in industry and soon passed. However, a few of the developments sponsored by major industries or dedicated inventors survived. Examples of such work performed during this period were significant contributions made by Horace G. Knerr, Cecil Farrow, and Alfred R. Sharples at the then Republic Steel Company, and by Charles W. Burrows, Carl Kinsley, and Theodore W. Zuschlag at Magnetic Analysis Corp.[2] There were, of course, other companies and individuals with significant achievements. These developments, in evolved and modernized forms, are used in industry today. Rapid advances in technologies and electronics slightly before and during World War II created an increased demand for NDT and laid the foundation for the development of advanced test instrumentation.

The aerospace and nuclear power industries were developing rapidly in the late 1940s and early 1950s. These industries and the governmental agencies related to them made a major contribution to the general advance of NDT. Additionally, the introduction of stable, quantitative test instrumentation developed and manufactured by Friedrich Förster of Germany began a rapid development and acceptance of eddy current testing in the USA between 1950 and 1965.

Förster is generally recognized as the pioneer of modern eddy current testing.[3] His early development work, beginning around 1939, had significant impact on the future directions of eddy current testing. His instrumentation was among the first commercially available that provided practical methods for analysis of eddy current signals on the complex plane. Other significant work was accomplished in the United States at

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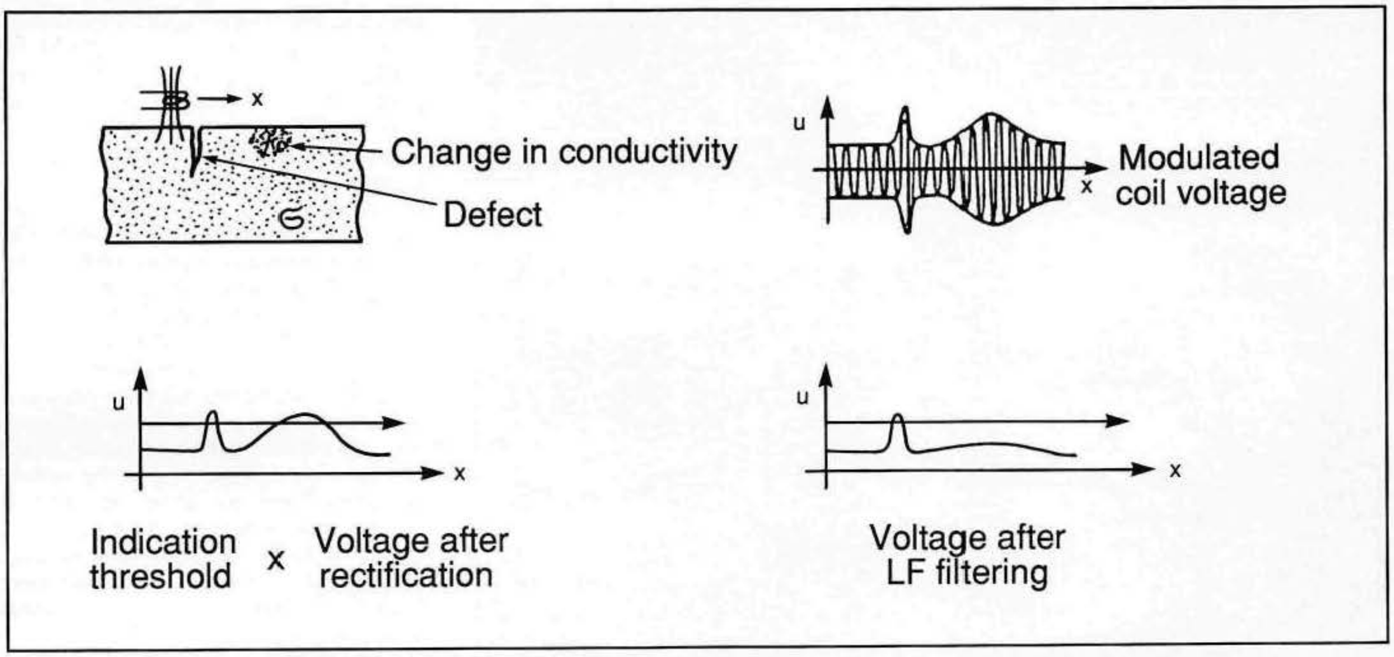

Figure 1—Different modulation frequencies of defect and noise signals.

Oak Ridge, TN, and Hanford, WA, where extensive research was conducted on new concepts and instrumentation. Hugo Libby and others at Hanford, as well as Robert Oliver, Robert McClung, C. V. Dodd, J. A. Deeds, and others at Oak Ridge, all contributed creative work that advanced the method during this time period.

Eddy current testing began in general to be more widely used—a trend that started in the early 1950s and continues today. The method has experienced many changes in instrumentation and transducer design and has become an accepted method of NDT. It is being used on an increasing number of applications in a variety of industries; one

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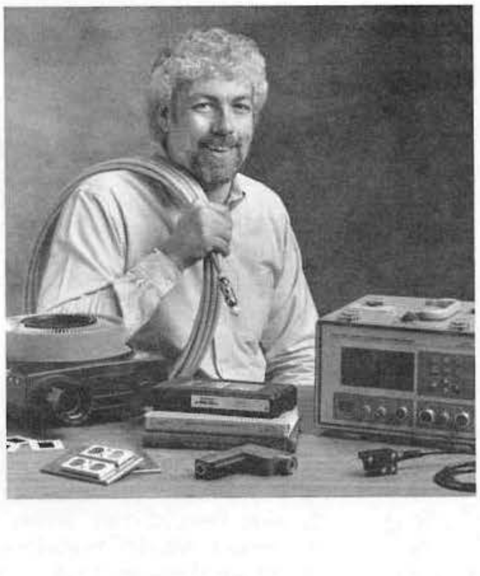

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Figure 2—The Foerster Circograph, in use, 1971.

such industry is aircraft maintenance. The remainder of this paper will be an investigation into the application of the eddy current method in this field.

Primary Aircraft Maintenance Applications

In the late 1950s and early 1960s, eddy current began to be applied to problems encountered in the aircraft industry. The two earliest applications were the measurement of conductivity of materials and the detection of surface cracks. Both of these applications are still commonly used with eddy current testing. These uses of eddy current led to other uses and to the development of a variety of instrumentation suited to different testing requirements. Examples include instrumentation and probes designed for specific applications, such as bolt or rivet hole inspection, coating or cladding thickness measurement, aircraft wheel testing, and turbine blade inspection.

Currently, the variety of eddy current instrumentation available and the number of applications to which it is applied is very broad. However, a high percentage of all applications falls into one of three major application categories: conductivity measurement, detection of surface cracks, or detection of subsurface cracks and corrosion.[4]

Conductivity Measurement

It is difficult to say whether conductivity measurement or surface crack detection was the first aircraft maintenance application of eddy current. Both applications came into practical use in the late 1950s. Conductivity measurement can be used to solve a variety of application problems; three major applications would be the sorting of mixed metals, determination of heat treatment of aluminum alloys, and determination of overheating or fire damage to aluminum structure. The conductivity of common aluminum alloys varies roughly in the range of 20–65 percent of the International Annealed Copper Standard (IACS). Specific alloys can vary significantly in different temper conditions. An example would be 2014, which varies from approximately 34 percent IACS (at 20° C) in the T4 condition to approximately 39.5 percent IACS (at 20° C) in the T6 condition. These variances in conductivity allow us to sort mixed materials such as fasteners on the basis of conductivity measurement. Such measurements can just as easily verify that fasteners made of the proper material are in fact used in the aircraft structure. Heat damage, which results in conductivity changes, can also be monitored. The use of eddy current devices to monitor conductivity on aluminum alloys has been well documented in published papers by Rummel[5] and Hagemaier.[6] These papers and others have established that heat damage assessment is possible; a direct relationship has been established between conductivity, hardness, and mechanical properties of various aluminum alloys.

The first commercially available conductivity measurement instruments were those manufactured by Foerster and Magnaflux. These were the Foerster Sigmatest 2.067, Magnaflux FM 110, and later FM 120. The early units had meter displays that supplied conductivity readings in percent of IACS. These first instruments were very basic. There are a number of instruments on the market today with features that were required to meet increasing application needs. Most instruments provide digital readout of the conductivity value and allow automatic correction for probe liftoff (as one might encounter on a painted surface). Some instruments have multiple frequencies, allowing for measurement on an increased range of material thicknesses. Others allow for automatic correction of the conductivity reading on curved surfaces and/or correction of the conductivity with respect to the materials temperature coefficient and temperature at time of measurement. Nearly all of the features available in a modern conductivity measurement instrument have been driven by application needs that have presented themselves over the last 30 years. The accuracy provided by today's instruments is on the order of 1 percent IACS, with good repeatability.

Surface Crack Detection

Detection of surface cracks on aircraft structures and engines began as one of the earliest eddy current applications and is probably the most common application of the eddy current method in aircraft maintenance today. The first instruments commercially available for this application, the Förster Defectometer 2.154 and Magnaflux ED-500, were introduced in the late 1950s. These instruments worked with simple single-winding probes that were part of a tuned oscillator circuit. Changes in probe impedance caused by the eddy current flow in the part with which the probe was in contact caused the oscillator output to vary in amplitude. These amplitude changes were observed by the operator or inspector on a meter built into the instrument. Presence of surface cracks would cause a meter deflection, alerting the operator or inspector. This method of surface crack detection, while very basic, proved effective for many different surface crack inspections. It was widely used for inspection of aircraft wheels, engine parts (i.e., turbine blades), and bolt and rivet holes. Instrumentation of this type has been modernized by different equipment manufacturers and is still used today for a variety of surface crack applications.

One of the weaknesses of this technique in some applications is that parts are often rejected that, when subjected to a critical visual or metallographic examination, show no defect. This is due in part to the fact that instruments based on this technique are not phase-sensitive. A valuable part of the information supplied by an eddy current test signal is not evaluated. It is well known that the amplitude of the eddy current signal is affected by many factors, including part thickness, conductivity, temperature, and permeability. Any of these variables could result in amplitude variations on the meter that could be misinterpreted as surface cracks.

The success of any eddy current test will depend on the test instrument's ability to respond to the condition of interest while suppressing responses to unwanted variables. Two important developments that would increase the success of eddy current testing occurred shortly after the instrumentation previously described was introduced into aircraft maintenance. These developments were the introduction of phase-sensitive instrumentation and the use of the modulation analysis technique by test instruments to separate desired and undesired test variables.

Portable phase-sensitive instrumentation came about in part due to research at the Oak Ridge National Laboratory by C. V. Dodd.[7] Shortly after the publication of his work in the early 1970s, a number of instruments began to appear on the commercial market, including the Phasemaster, the Nortec NDT-3, and the Zetec MIZ-10. These instruments, which incorporated meters, had restrictive displays; instrumentation with cathode-ray tube displays soon followed. The introduction of portable cathode-ray tube impedance-plane analysis instruments in the late 1970s and early 1980s has provided the most significant advancement of eddy current testing in aircraft maintenance to date. This instrumentation has promoted inspection confidence and reliability, and has permitted eddy current testing to be applied to a variety of applications in the past 10 years. Examples would include surface cracks, subsurface crack detection, corrosion thinning, metal spacing, and material thickness. The principles and applications of eddy current impedance-plane testing are well described in articles by Hagemaier and are not within the scope of this paper.[8] In general, this type of instrumentation makes it easier to optimize the eddy current test for the specific application.

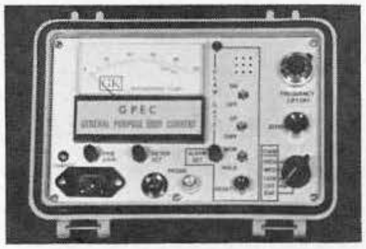
The modulation analysis technique is used extensively in surface crack detection. The principles of this technique are illustrated in Figure 1.[9] Modulation analysis is often used for crack detection applications and, in particular, for bolt and rivet hole inspection. Early methods of hole inspection utilized absolute probes connected to simple amplitude-evaluation instruments. The operator manually rotated the bolt hole probe 360 degrees inside the hole, indexed down further into the hole, and repeated the procedure for the entire hole depth. False and missed indications were a serious inspection problem. Instrumentation utilizing modulation analysis techniques have contributed to the development of high–rotational-speed mechanical scanners that, in some cases, index into the hole automatically. This has resulted in faster and more reliable inspection of rivet and bolt holes. One of the earliest commercially available mechanical scanners for bolt hole inspection was the Foerster Circograph (Figure 2), in practical use around 1971. These early systems were heavy and cumbersome to use. Today, a number of portable, high-speed, and high-performance bolt hole inspection systems are available.

Eddy current probe development and design have also played a major role in the improved capability and reliability of eddy current inspection for surface cracks. Over the years, a better understanding of aircraft applications and impedance plane principles has led to a variety of special probe designs and configurations. Although they will not be discussed in detail here, some developments, such as the introduction of shielded probes that contain the electromagnetic field, have had a significant impact on the use and success of eddy current testing for particular applications. The basic construction and characteristics of a typical shielded probe are illustrated in Figure 3.

Subsurface Crack and Corrosion Detection

Reliable inspection for subsurface cracks and corrosion with eddy current requires instruments that are not only phase-sensitive but also capable of operating at low test frequencies. The introduction of phase-sensitive eddy current test instruments in the early to mid-1970s led to the use of eddy current testing in subsurface crack and corrosion detection. Earlier instrumentation had two disadvantages for this field of application: lack of phase sensitivity and high operating frequencies. Surface crack detection procedures often require operating frequencies in the range of 1 kHz to 1 MHz. As a result, most of the early commercially available eddy current equipment operated in this frequency range. Modern instrumentation that met the previously mentioned requirements became readily available in the late 1970s and early 1980s. This type of instrument usually incorporates a cathode-ray tube impedance-plane display and provides a wide test frequency range. A range of test frequencies from 100 Hz to 10 MHz is now commonly available. The addition of lower test frequencies has made these instruments very useful in subsurface inspections. Some typical applications for low-frequency eddy current inspection are shown in Figure 4. Subsurface applications of eddy current testing probably grew more than any other aircraft maintenance method in the 1980s.

As with surface crack applications,



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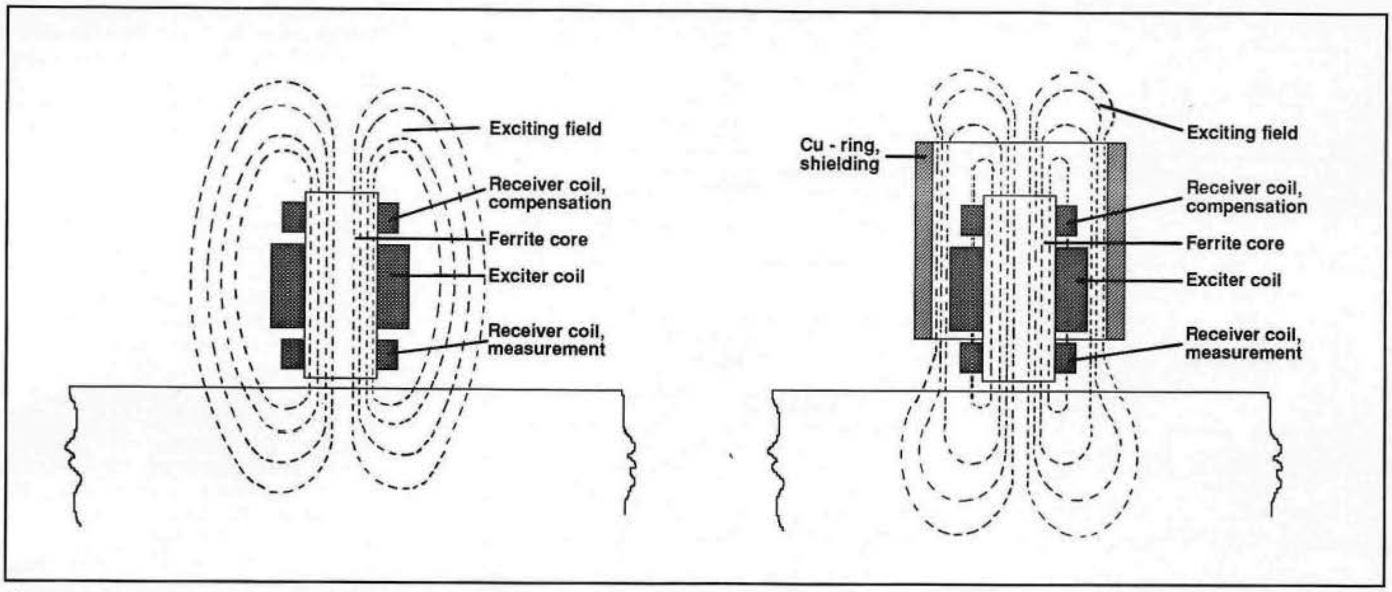

Figure 3—Basic construction and characteristics of a typical shielded probe.

the development of new and improved eddy current probes further advanced the implementation of subsurface inspections. One example would be the introduction of the "ring" or "donut" probe in the early 1970s. G. Ansley and R. Neufeld have conducted and reported on investigations using such probes for low frequency inspection around fasteners.[10] Another application would be a version of the "sliding" probe for improved fastener hole inspection, as developed by Jim Pellicer.[11] The sliding probe concept is illustrated in Figure 5. These improvements in probe design contributed significantly to the increased utilization, reliability, and effectiveness of eddy current for subsurface applications during the 1980s.

The number and type of subsurface applications now being performed in practice, while growing, is not the subject of this paper. However, a general overview of subsurface crack detection

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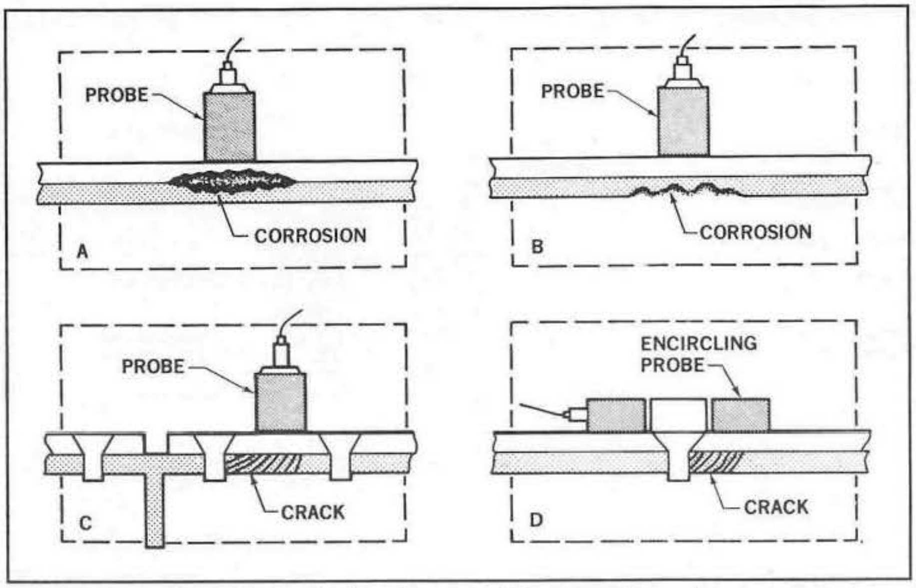

Figure 4—Typical applications for low-frequency eddy current inspection.

can be found in a paper by Hagemaier et al.[12] The same is provided for corrosion applications in a paper by Pellicer.[13] These papers illustrate how extensively eddy current is now being used in this field of application.

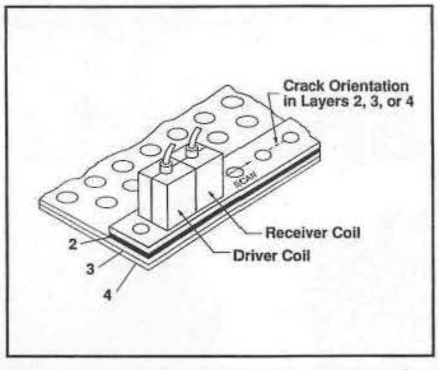

Figure 5—Sliding "driver/receiver" reflection probe.

Future Direction

Over the past 30 years, eddy current has developed into a primary method of crack detection on aircraft structures and engines. Increasing application demands due to new manufacturing materials and aging aircraft will continue to surface. These application requirements will result in a continued increase in the use of eddy current inspection. They will also provide a basis for continued development work to improve existing instrumentation and discover new and better techniques.

In reference to the statement attributed to D. E. Hughes presented earlier in this paper, the "exceeding sensitivity" of eddy current to a variety of material and test variables may well turn out to be the method's greatest strength. Current and future development in computer-aided signal analysis should enhance eddy current applications and increase inspection reliability. Improvements in, and the use of, multifrequency eddy current instruments should further increase reliability and application of the method. Automated inspection systems and defect imaging should come into routine use. In general, innovations that expand the realm of application, increase the reliability of inspection, reduce the operator or inspector involvement (human factor), and increase the speed of inspection should arrive.[14] These are some of the major areas of concern for the user of eddy current equipment. These concerns and needs should provide companies and individuals with the incentive to meet these requirements and further develop the application of eddy current testing in aircraft maintenance in the future.

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Instruments Stolen

Kirk A. Thams, general manager of XRI Testing, Troy, MI, advises *Materials Evaluation* to warn its members about the theft of nondestructive test equipment, particularly portable ultrasonic flaw detectors from XRI's laboratory in Cincinnati, OH.

The instruments stolen were one Nortec NDT-131D, serial number 538B; one Sonic 132, serial number 372B; and one Mitsubishi FD 610, serial number C477869. The cooperation of anyone knowing the whereabouts of these units will be appreciated; call (313) 362-2242.

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