THE PRESENT STATUS OF MAGNETO-OPTIC EDDY CURRENT IMAGING TECHNOLOGY

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INTRODUCTION AND BACKGROUND

This paper provides a description of the basic working principles underlying a new kind of eddy current-based inspection technology called magneto-optic/eddy current imaging [1-4]. By combining magneto-optic imaging and eddy current excitation in an unconventional manner, it is now possible to obtain real-time eddy current images of fatigue cracks and areas of hidden corrosion in structures such as the fuselage of an aging aircraft. The paper begins with a description of working principles, then turns to specific examples of inspections performed on representative samples of commonly encountered airframe components, areas for potential improvement of the technology, and finally, new applications.

GENERAL MAGNETO-OPTIC IMAGING TECHNIQUES

The magneto-optic sensors we employ consist of a thin film of bismuth-doped iron garnet (Bi,Th)$_3$(Fe,Ga)$_5$O$_{12}$ grown on 3-inch diameter, 0.020 inch thick substrate of gadolinium gallium garnet (GGG) [5-7]. These films exhibit three physical properties that are crucial for a practical magneto-optic/eddy current imaging device. First, they exhibit an important property called magnetic anisotropy, that is, they have an easy axis of magnetization normal to the sensor surface. Second, if the magnetic fields along the easy axis of magnetization are removed, the magneto-optic film will retain most of its established magnetization, i.e., it has a memory. Third, these films possess a very large specific Faraday rotation, $\theta_f$ up to 30,000 degrees/cm of thickness.
If normally incident, linearly polarized light is transmitted through such a magneto-optic sensor, the plane of polarization of the light will be rotated by an angle called the Faraday rotation which is proportional to $\theta = \theta_F \mathbf{k} \cdot \mathbf{M}$, where $\mathbf{k}$ is the wave vector of the incident light, and $\mathbf{M}$ is the local time dependent magnetization of the film at the point or region where light is transmitted [5]. Note that $\mathbf{M}$ is always directed, up or down, along the easy axis of magnetization. Because the angle between $\mathbf{k}$ and $\mathbf{M}$ completely determines the sign of the scalar product $\mathbf{k} \cdot \mathbf{M}$, the sense of the Faraday rotation for a given state of magnetization $\mathbf{M}$ does not depend on the sign of $\mathbf{k}$, i.e., the direction in which the light is being propagated through the sensor. Thus, the Faraday rotation will be doubled if the light is first transmitted through, and then reflected back though the sensor again, thereby enhancing sensitivity.

By properly viewing this reflected light through an analyzer, as illustrated in Figure 1, the local state of magnetization of any region in the sensor can be seen as a high contrast dark or light area depending only on the direction of the magnetization $\mathbf{M}$ and the setting of the analyzer. This is the basic property that allows the sensor to create images of the normal-component magnetic fields associated with eddy currents.

THEORETICAL BACKGROUND—EDDY CURRENTS

Faraday’s law of induction in differential form [8,9]

$$\mathbf{V} \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t},$$

(1)

shows that a time varying magnetic field, $\mathbf{B}$, in the vicinity of any electrical conductor will induce a time varying electric field, $\mathbf{E}$, and thus a time varying conduction current $\mathbf{J} = \sigma \mathbf{E}$, in the same conductor. By Lenz’s law, these source-free induced currents, or "eddy" currents, are always opposed in direction to the external currents which produce $\mathbf{B}$.

![Figure 1. This figure is a schematic representation of the basic reflection mode geometry for imaging devices employing magneto-optic garnet films.](image)

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LINEAR SHEET CURRENT EXCITATION

Practical magneto-optic/eddy current imaging devices involving large 3-inch diameter sensors must provide a means to excite uniform, linear, sheet-type eddy currents in the test piece. Figure 2 illustrates a step-down transformer arrangement that accomplishes this task. The transformer consists of a primary winding on a ferrite, soft iron, or similar core material and a single turn secondary winding which includes a thin copper foil. This foil is the current element that induces the desired linear sheet-type eddy currents. The multiple turn primary of the transformer is connected to a relatively high voltage, low current source which is designed to deliver the appropriate voltage and current at frequencies of 1.6, 3.2, 6.4, 12.8, 25.6, 51.2, and 102.4 KHz. The relatively large current in the copper foil induces eddy current loops in a nearby electrically conducting test piece as shown. These current loops join in a common area to produce a region of linear sheet currents located just below the magneto-optic sensor. It is of great practical significance that the magnetic fields associated with such sheet currents generally lie parallel to the hard axis of magnetization of the sensor, which means that in the absence of cracks or corrosion in the test piece, the magnetic fields exciting the eddy currents have no effect on the state of magnetization of the sensor.

THE HYBRID MAGNETO-OPTIC/EDDY CURRENT IMAGING TECHNOLOGY

Figure 3 illustrates schematically how the linear sheet-current excitation method is combined with the reflection-mode magneto-optic imaging technique to produce a magneto-optic/eddy current image. In this figure the current paths in both the foil and a test piece are illustrated. Currents in the first half cycle of a full current cycle are indicated as solid lines, while currents in the second half cycle are...
Figure 3. This figure illustrates how a magneto-optic sensor must be modulated in order to obtain a useful magneto-optic image using the linear induction technique.

indicated by dotted lines. Distortions in induced eddy currents due to discontinuities in a test piece, such as a hole, a rivet, or a crack, generally produce detectible magnetic fields normal to the surface of the test piece. Note that these are the only fields detected by the sensor since it is only these magnetic fields which lie parallel to the sensor’s easy axis of magnetization. Solid and dotted lines and curves in Figure 3 also show the normal component magnetic fields corresponding respectively to eddy currents induced in the test piece during the first and second half cycles. These time varying magnetic fields, which are generally associated with cracks or corrosion (a rivet or hole is illustrated), are able to affect the state of magnetization of the sensor because these fields easily penetrate the thin copper foil at the frequencies the device generates.

In addition to the application of information-carrying magnetic fields at the eddy current excitation frequency, a relatively low frequency bias magnetic field is applied to the magneto-optic sensor by a surrounding current-carrying coil (see Figure 1). The resultant total magnetic field applied to the magneto-optic sensor, the modulation field, is the sum of these two fields and results in an image of the type illustrated schematically in Figure 3.
The actual sequence of events in forming an image is illustrated in Figure 4, where an additional "erase" pulse magnetic field, produced by a current flowing in the bias coil, is now included as part of the sensor modulation. First, the sensor is cleared of all images by the erase pulse and set to appear uniformly bright. Then a magnetic bias field from the bias coil, along with the current in the foil are both established as indicated. During the time period alternating currents in the foil and the static bias fields are active, a sequence of images of the type shown in Figure 3 are produced. Finally, the sheet current excitation is turned off. Since the magneto-optic sensor has a memory, the image produced remains until the start of the next current generation cycle. Images are erased and refreshed about 26 times per second. The sheet current induction is only applied with about a 20 percent duty cycle, significantly reducing heating of the thin copper foil.

The successful operation of such a magneto-optic/eddy current imaging device depends on the fact that the instrument produces very large currents in both the conducting foil and the test piece. When the foil is far removed from an electrically conducting test piece, Lorentz forces cause an undesirable bunching of current near the center line of the foil; the larger the current, the greater the bunching. However, these same Lorentz forces ensure that when the conducting foil is placed near the test piece, the currents in the foil will repel the oppositely directed (by Lenz’s law) induced currents in the test piece. This repulsive force has the desirable effect of causing the sheet currents in both the test piece and the foil to be uniform, as desired. Experiments show that this situation of uniform induced eddy currents can be established over a wide range of eddy current frequencies provided only that the thickness of the test piece is not significantly less than the skin depth of the eddy currents in the test piece.
Figure 5. a) illustrates EDM notch images at 102.4 KHz in a 0.060 inch thick plate of aluminum with 0.25 inch diameter holes. Notches beginning at the upper left hole and proceeding counter clockwise, are 0.020, 0.040, 0.060 and 0.080 inches in length. b) illustrates fatigue cracks in a simulated lap joint sample at 51.2 KHz. c) illustrates a corroded region in a panel removed from an aging commercial airplane. Note that the image made at 6.4 KHz and illustrated in d) is "bookmatched" with the sample since it was taken from the side opposite the corrosion.

SELECTED EXAMPLES OF IMAGES OF FATIGUE CRACKS AND CORROSION IN ALUMINUM

Figure 5 illustrates typical magneto-optic/eddy current images produced by fatigue cracks and corrosion.
NEW TECHNICAL DEVELOPMENTS

Many technical developments are presently being evaluated for future applications. These include higher frequency excitation, higher induction currents, the use of surface conforming copper foils, rotating induction currents for improved images, and improved sensors.

Recent improvements in the eddy current induction transformer and in the switching power supply have permitted experiments at frequencies as high as 500 KHz. These frequencies may be useful for achieving higher resolution in images of low conductivity materials, such as titanium and stainless steels.

Advances have also been made in increasing the induced eddy current levels. This may be useful for better detection of second layer corrosion and cracks which normally generate weak magnetic fields in comparison with near surface defects.

Preliminary experiments using imaging heads with conforming foils have been used for inspection of raised welds in typical welded aluminum aerospace components such as fuel and oxidizer tanks.

Technical developments which would result in rotating sheet currents are being pursued. This method could eliminate the "slotted screw" appearance of rivet images produced with linear sheet current excitation (see Figure 5), and obviate the present need for the inspector to rotate the imaging head for a complete inspection of a test piece. This advance could also eliminate unwanted spatial frequencies in images, making it easier to use established image processing and interpretation techniques in automated inspections.

The currently available magneto-optic sensors respond to anomalous magnetic fields as small as 20 milligauss, and provide excellent images for most conventional applications. However, when low frequencies, less than 1.6 KHz, are being used and deep corrosion or multiple layer cracking below 1/8 inch in depth is being investigated, improved sensors would be desirable. Research on sensors for improved sensitivity, temperature dependence, uniformity, and other desirable features is being pursued.

NEW APPLICATIONS

The principal application of the new magneto-optic/eddy current imaging technology has been in the inspection of aluminum lap joints of aging aircraft. However, the device can also work on steel as a replacement for some magnetic particle techniques, on materials such as titanium, and to some extent, on carbon fiber composites. Composite structures containing metallic conducting honeycomb interior components have also been inspected. While these applications are often not optimal for the present device, it is clearly not limited to inspections of aluminum aircraft components.
SUMMARY AND CONCLUSIONS

This paper has described the basic working principles underlying a new magneto-optic/eddy current imaging device. The device has demonstrated the ability to image both cracks and corrosion in typical aluminum aircraft components such as lap joints. The established advantages of the new technology in both laboratory and field inspections involving aging aircraft include: output in the form of direct, real-time images; ease of use; rapid area coverage; removal of paint or decals not required; good sensitivity to both large and small cracks; and complete, low cost documentation of inspections if desired.

Magneto-optic/eddy current imaging technology has been approved by the major airframe manufacturers for use on many commercial models [10-12]. American Airlines, NASA and the U.S. Air Force, to name a few organizations, are currently using the technology.

REFERENCES

4. In September 1990, R&D Magazine selected the Magneto-Optic/Eddy Current Imager for an R&D-100 Award as one of the 100 most significant technical products of the year. Photonics Spectra also selected the Magneto-Optic/Eddy Current Imager for a 1991 Circle of Excellence Award as one of the 25 best new products in the industry.