Eddy current measurements with magneto-resistive sensors: Third-layer flaw detection in a wing-splice structure 25 mm thick

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ABSTRACT

A new eddy-current system based on low-noise magnetoresistive sensors has been developed to detect cracks and corrosion in thick, multi-layer metal structures. The new instrument has detected narrow slots as short as 6.3 mm, in the lowest layer of a stack of three aluminum plates totaling 25 mm in thickness. These flaws were detected through 19 mm of overlying aluminum, in spite of the presence of steel fasteners and the proximity of a plate edge that attenuated the eddy currents impinging on the flaw. This performance was achieved by combining the low-frequency sensitivity of magnetoresistive sensors with a special probe design that minimized background errors due to liftoff, plate-edge effects and the steel fasteners. This new system is potentially useful for inspecting thick, layered structures in aircraft, as well as ferrous metal structures such as pipelines and storage tanks, where the shortness of the skin depth has previously limited the usefulness of eddy-current inspection.

Keywords: Eddy current, NDE, third layer flaw detection, magnetoresistive sensor

1. INTRODUCTION

One of the most difficult problems in nondestructive inspection is detecting flaws in the lower layers of a multi-layered structure made up of thick slabs of metal. Such structures are difficult to inspect by ultrasound, because the sound waves are attenuated by the gaps between the layers. Eddy-current methods have no trouble seeing through the gaps between layers, but most existing eddy-current systems have difficulty seeing more than a few millimeters below the surface of the metal. To see deeper with eddy-currents, we need to work at lower frequencies where the skin depth, or characteristic penetration depth of the electromagnetic fields, is long. To work effectively at lower frequencies, we need new methods to detect the oscillating magnetic field produced by the eddy currents in the sample.

Conventional eddy-current systems detect the magnetic field by measuring the voltage induced in a coil of wire. This method gives poor signal-to-noise ratios at low frequencies, because the induced signal voltage is proportional to the rate of change of the magnetic field. To some extent, we can compensate for this loss of signal by increasing the diameter of the detection coil. However, too large a coil impairs the spatial resolution of the eddy-current measurements. Consequently, to achieve adequate signal-to-noise ratios and spatial resolution, most existing eddy-current systems work at frequencies of at least a few hundred hertz.

We can make more effective eddy-current measurements at much lower frequencies by using the small, cheap, highly sensitive magnetoresistive sensors recently developed by companies such as Kodak, Honeywell, and Phillips. Such sensors have noise levels as low as 20 $pT/Hz^{1/2}$ at frequencies of a few tens of hertz and higher, with a 1/f noise spectrum at lower frequencies. This noise is far lower than that of conventional detection coils, or the Hall sensors used in some eddy-current systems. In addition, the active sensing elements in these magnetoresistive sensors are very small, fitting onto thin-film substrates only a millimeter or two on a side. Thus, these new magnetoresistive sensors combine high spatial resolution with high signal-to-noise ratios, over a frequency range extending essentially to zero frequency.

In a project funded by the U.S. Air Force, I have developed a new eddy-current technique that detects deeply buried flaws in thick, multilayer metal structures. The new instrument has detected thin slots as short as 6.3 mm, in the bottom-most 6.3-mm layer of a stack of aluminum plates totaling 25 mm in thickness. These flaws were detected in spite of the large background signals from nearby steel fasteners, next to a plate edge that was oriented in such a way as to reduce the eddy-current density impinging on the flaw. These results were achieved by combining magnetoresistive sensors with a special probe geometry that increased the eddy-current density deep in the sample, while minimizing interfering signals due to liftoff, steel fasteners, and nearby plate edges.

2. APPARATUS AND METHODS

2.1 Inspection Problem: Wing-Station 405 of the C-141 Aircraft

This work was motivated by an inspection problem of interest to the Air Force: the detection of third-layer cracks in the wing-station 405 lap splice in the C-141 transport aircraft. This problem embodies many of the features that make the inspection of thick, multilayer structures so difficult. As shown in Fig. 1, the lap splice consists of two butted plates 0.5" (12.7 mm) thick, with two aluminum doubler plates .25" (6.3 mm) thick, overlapping the butted plates above and below. This stack of plates is held together by steel taper-lock fasteners.

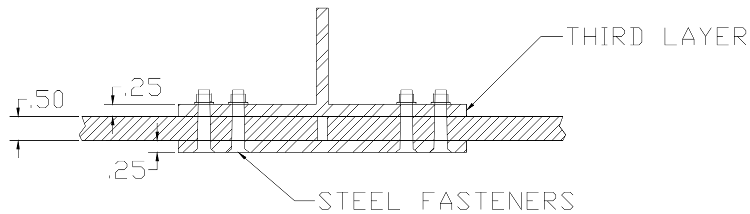

Fig. 1. Layered structure of wing-station 405. Plate thicknesses are given in inches.

The stresses of flight produce fatigue cracks that start from the fastener holes and run parallel to the long edges of the doubler plates (Fig. 2). Cracks can occur in each of the three overlapped plates, but the most difficult cracks to detect are the ones in the third layer, the 6.3-mm aluminum plate farthest from the exposed bottom surface of the wing.

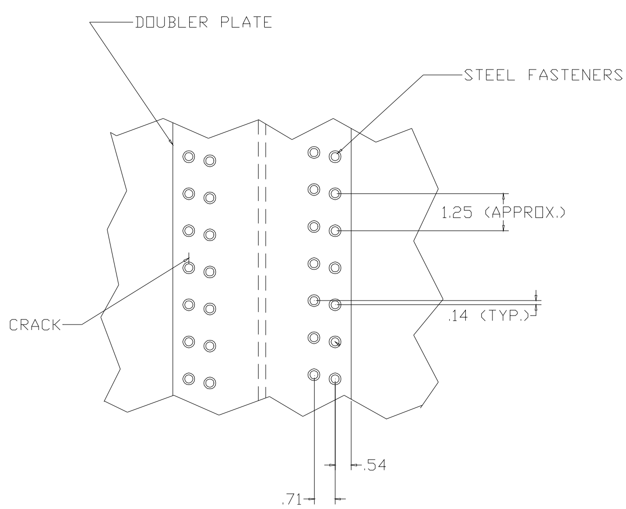

Fig. 2. Location and orientation of fatigue cracks in wing-station 405. (Dimensions in inches.)

At present, the only way to detect such third-layer cracks is to remove each fastener and insert a bolt-hole eddy-current probe. This task is cumbersome, time consuming, and expensive. The fuel must first be drained from the wing, so that someone can crawl inside. Then, two people, one inside the wing and one outside, must work together to remove the fasteners. Only a third of the fasteners can be removed at one time, so that it is necessary to repeat three times the entire process of removing fasteners, performing inspections and replacing fasteners. All of these steps take time, create scheduling problems, and increase costs. Wing-station 405 could be inspected more frequently, at lower cost, if third-layer cracks could be detected by looking through the outer surface of the wing.

Wing-station 405 contains several features that make it a challenge to inspect. The thickness of the aluminum makes it difficult for existing eddy-current systems to penetrate to the third layer. The difficulty is compounded because some of the cracks of interest lie within 14 mm of the edge of the doubler plate. The plate edge itself produces a huge eddy-current signature, which can potentially obscure the small signature of a third-layer crack. In addition, since the plate edge is parallel to the cracks of interest, it tends to block eddy currents flowing perpendicular to the face of the crack. This effect reduces the eddy-current signature of the crack by roughly a factor of three. The greatest problem in inspecting this structure is the presence of steel fasteners. The fasteners produce eddy-current signals that can be 100 times the signal produced by a crack in the third layer. The variability of this fastener signal is the biggest source of background noise in the eddy-current measurements.

2.2 Design of the Eddy-Current Probe

To detect third-layer cracks in this structure, the eddy-current probe was designed to minimize the liftoff effects, maximize the eddy-currents deep in the sample, cancel the signal due to nearby plate edges and minimize the background signals produced by the presence of steel fasteners. The key elements in this design were the layout of the applied-field coil and the placement of the magnetoresistive sensor with respect to the coil.

The applied-field coil consisted of thin, flat strips of copper, laid out on a fiberglass printed-circuit board 19 cm wide and 19 cm long.[1,2] In the central portion of the printed-circuit board, the current paths were arranged in a set of parallel stripes, to approximate a uniform sheet of current. To complete the electric circuit, the current paths returned along the outer edges of the printed-circuit board, forming a rectangular double spiral, shown schematically in Fig. 3.

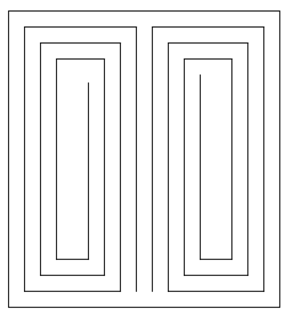

Fig. 3. Double-spiral design of applied-field coil approximating the effect of a uniform sheet of current.

This flat-sheet produced a magnetic field that reached deep into the sample, increasing the signal from a third-layer flaw. In addition, the flat-sheet coil greatly reduced liftoff effects. This advantage was very useful in third-layer flaw detection. Most eddy-current probes use ac field coils with relatively small diameters. With such coils, the eddy-current signal is sensitive to small variations in the distance between the coil and the sample surface. The resulting background noise can easily be much larger than the response due to flaws in the sample. To cancel out this effect, the common practice is to measure the magnetic-field response 90 degrees out of phase with the signal due to liftoff. However, when the applied field is produced by a wide, uniform sheet of current, the field at the sample surface does not depend so strongly on the distance between the surface and the current sheet. As a result, the liftoff effect is greatly reduced, and it is possible to choose the phase to eliminate other background effects. I used this phase adjustment to minimize the largest background signal, that produced by the steel fasteners.

For most of the eddy-current measurements, a single magnetoresistive sensor was mounted at the center of the applied-field coil, oriented so as to detect the component of magnetic field perpendicular to the plane of the coil. Measuring the perpendicular field component reduced the background signal due to the steel fasteners. It also helped to cancel out background signals due to the nearby edges of aluminum sample plates, as described in Sec. 2.3 below.

The magnetoresistive sensors used in this work were developed by Kodak, Inc..[3] The sensors were purchased from Quantum Magnetics, Inc., which provided the sensors under a marketing agreement with Kodak. The sensors were operated using feedback electronics, which provided a current to a feedback coil, maintaining a constant magnetic field at the sensor.[1]

During eddy-current measurements, an oscillating (ac) current was supplied to the applied-field coil from a standard function generator (Hewlett-Packard 33120A). A lockin amplifier (Stanford Research SR530) was used to measure the components of the magnetoresistive sensor output in phase and out of phase with the current in the applied-field coil.

2.3 Test Specimen and Measurement Geometry

The eddy-current measurements were done using a specimen that simulated the key features of the wing-station 405 lap splice, including the thickness of the aluminum plates, the steel fasteners, and the proximity of cracks to the edges of the plates. As shown in Fig. 4, the sample consisted of three aluminum plates stacked together. The middle plate, 0.5" (12.7 mm) thick, was sandwiched between upper and lower plates .25" (6.3 mm) thick. The middle plate was offset from the other two, so that one of its long edges extended 1" (25.4 mm) beyond the edges of the top and bottom plates. The plates contained two rows of fastener holes, which ran parallel to the plate edges. The first row was .54" (13.7 mm) from the nearest edge of the top plate, and the second row was .71" (18 mm) from the first row. The fastener holes in each row were separated by 1.25" (31.7 mm), and the fasteners in the second row were offset from the holes in the first row by .14" (3.6 mm) in the direction parallel to the rows. The holes in the top plate were countersunk to accommodate steel taper-lock fasteners of the type used in wing-station 405.

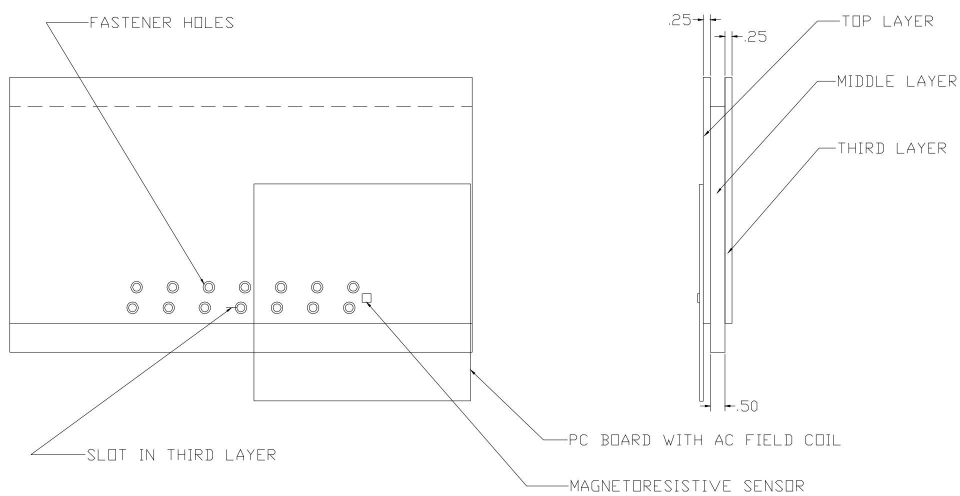

Fig. 4. Specimen simulating key features of wing-station 405. (Dimensions in inches.)

A number of interchangeable plates were used in the third layer of the sample. To simulate cracks in the third layer, these plates had slots of varying length, radiating from one of the fastener holes in a direction parallel to the nearby edge of the plate. The slots were produced by electrical discharge machining (EDM). Each EDM slot was approximately 0.25 mm wide, and ran through the full 6.3-mm thickness of the third-layer plate.

During eddy-current measurements, the eddy-current probe, consisting of the magnetoresistive sensor and applied-field coil, was placed flat on the sample surface as shown in Fig. 4. The applied-field coil was oriented so that the current sheet in the central region of the printed-circuit board ran perpendicular to the long edges of the sample plates. This arrangement produced eddy currents that were perpendicular to the surface of the slot in the third layer. The single magnetoresistive sensor was mounted at the center of the applied-field coil, and was oriented to detect the magnetic field perpendicular to the sample surface.

When the applied-field coil was placed on the specimen in this orientation, the resulting eddy-current distribution had a special symmetry that considerably reduced the background signals due to the nearby edges of the specimen. The applied-field coil shown in Fig. 3 has a plane of mirror symmetry that bisects the coil along a line parallel to the current paths in the central portion of the circuit board. When the coil was placed flat on the surface of the specimen, with the central current sheet perpendicular to the edges of the specimen plates, the eddy currents in the specimen took on approximately the same mirror symmetry as the current distribution in the coil itself. (This symmetry was disturbed only by the effects of the ends of the specimen, and by the local perturbations caused by fasteners, EDM slots and other nonuniformities.) With this symmetrical current distribution, the magnetic field in the mirror plane had no component in the direction perpendicular to the sample surface. Consequently, when the magnetoresistive sensor was placed at the center of the coil and oriented to detect the perpendicular component of the magnetic field, there was approximately no magnetic signal due to the flow of eddy currents near the plate edges. This symmetry minimized any background signal variations due to changes in the position of the eddy-current probe with respect to the plate edges.

3. RESULTS

Third-layer flaws were detected both by scanning the eddy-current probe parallel to the edge of the specimen, and by scanning the probe in two dimensions over the top surface of the specimen. Results from both types of measurements are described below.

3.1. Eddy-Current Scans in One Dimension

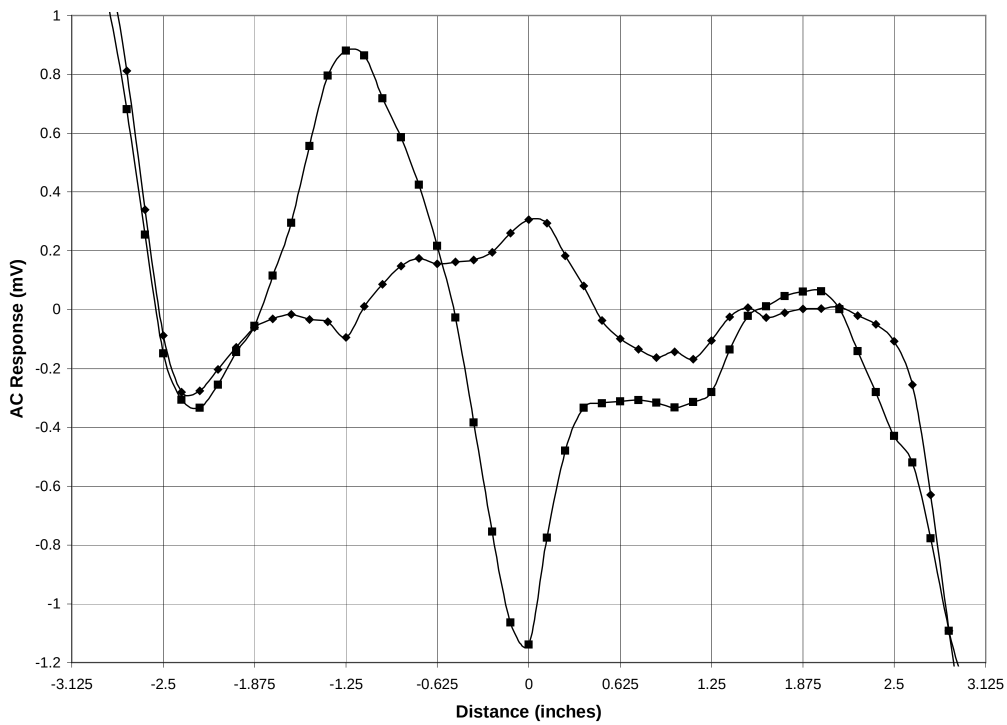

Fig. 5. Eddy-current response of a specimen simulating wing-station 405 of the C-141 aircraft. Squares indicate the response with a slot 9.5 mm long, radiating from a fastener hole in the third layer of a stack of plates 25.4 mm thick. Diamonds indicate the response obtained without the third-layer flaw.

In one set of eddy-current measurements, the sensor unit was scanned parallel to the long edges of the specimen, so that the magnetoresistive sensor passed approximately midway between the two rows of fasteners in the specimen. Fig. 5 shows the results of one such experiment. The figure shows the eddy-current signal in arbitrary units, as a function of sample position in inches. The squares in the figure indicate the signal obtained with an EDM slot 9.5 mm long, radiating from one of the fastener holes in the third layer of the specimen, at the center of the row of fasteners nearest the edge of the sample plate. The diamonds in the figure show the eddy-current response in the absence of the third-layer flaw. With the flaw, the eddy-current signal shows a negative peak at a location corresponding to the fastener hole containing the EDM slot, with a somewhat broader positive peak at the position corresponding to the adjacent fastener.

This two-peaked signature, and particularly the locations of the peaks, suggests that the magnetic field due to the third-layer flaw was channeled along one fastener toward the sample surface, and then back into the specimen along the adjacent fastener. This interpretation is supported by other eddy-current measurements, in which the magnetoresistive sensor was oriented parallel to the rows of fasteners. These measurements indicated a broad peak in the parallel component of the magnetic field, in the region between the two fasteners.

The data in Fig. 5 turn sharply upward at the negative end of the distance scale and sharply downward at the positive end. These trends are due to the influence of the ends of the specimen.

The results above were obtained at a frequency of 35 Hz, at a phase shift of 73 degrees with respect to the current in the applied-field coil. This frequency, much lower than that used in most eddy-current measurements, was chosen to optimize the eddy-current signal penetrating the thick layers of aluminum. The phase shift was chosen to minimize the eddy-current signal due to the steel fasteners in the specimen. As noted in Sec. 2.2, this choice of phase shift was possible in part because the applied-field coil was designed to minimize liftoff errors.

The 73-degree phase shift eliminated most, but not all, of the signal due to the fasteners. Most of the remaining fastener signal was removed by subtracting from the data a periodic background signal representing the average behavior of the steel fasteners. The resulting signal contained a slight background variation, reflecting the differences in response among the individual fasteners. This variable fastener response was the dominant source of background noise in the eddy-current measurements.

Fig. 6 below shows the eddy-current response obtained with a third-layer slot 6.3 mm long. Here, a periodic fastener correction and a quadratic background trend have been subtracted from the data. The eddy-current response with the 6.3-mm flaw (diamonds) show a negative peak at sensor position of 0", corresponding to the location of the fastener hole that contained the flaw. This peak falls outside the range of variation in the background signal obtained without the flaw. This result suggests that third-layer cracks as short as 6.2 mm are marginally detectable with present techniques. Smaller flaws may be detected in the future, by optimizing the applied-field coil and statistically characterizing the background response of the steel fasteners.

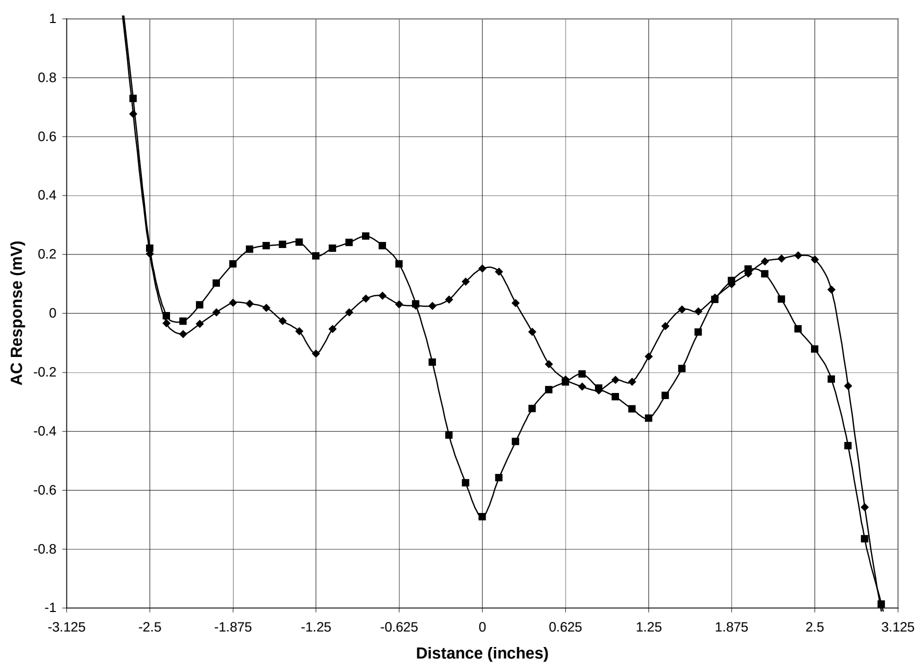

Fig. 6. Eddy-current data with and without a 6.2-mm slot in the third layer of the specimen. Squares indicate the signal with the third-layer flaw. Diamonds indicate the signal without the flaw.

3.2. Two-Dimensional Eddy-Current Images

Fig. 7 below shows an image obtained by scanning the eddy-current probe in two dimensions over the top surface of the specimen. In this example, there is an EDM slot 9.5 mm long, in the third layer of the specimen. The gray scale in the image indicates the amplitude of the eddy-current response at 45 Hz, at a phase of 79 degrees with respect to the applied ac field. This phase was chosen to eliminate as much as possible of the signal due to the steel fasteners.

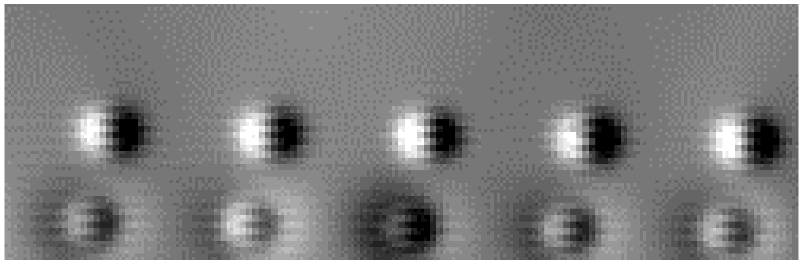

Fig. 7. Eddy-current image obtained with a third-layer slot 9.5 mm long, extending to the left from the fastener hole at the center of the row nearest the lower edge of the image.

The image in Fig. 7 spans two rows of five fasteners. Each fastener appears in the image as a circular feature, with its left half lighter, and its right half darker than the background. The third-layer slot extends to the left from the fastener hole at the center of the lower row of fasteners. This flaw appears as a darkening of the eddy-current image in a roughly circular region slightly offset from the central fastener. There is also slight lightening of the image in region near the adjacent fastener to the left of the central fastener. This intensity distribution is consistent with the one-dimensional scans described in Sec. 3.1, where a negative peak was observed next to the fastener hole containing the flaw and a positive peak was observed at the adjacent fastener.

4. CONCLUSIONS

This work shows that low-frequency eddy-current measurements, using small, inexpensive magnetoresistive sensors, can detect sublayer flaws in very thick, multilayer metal structures. The results to date indicate that EDM slots 9.5 mm long are clearly detectable in the third layer, beneath 19 mm of overlying aluminum, while slots as short as 6.2 mm produce signatures just above the background signal due to variations in the response of steel fasteners in the specimen.

This work also indicates that the main source of background noise in these low-frequency eddy-current measurements is not the magnetoresistive sensors, but variations in the response of the specimen itself. Consequently, the sensitivity of the magnetoresistive sensors appears more than adequate for any practical applications in eddy-current NDE of thick metal structures.

This new eddy-current system is potentially useful for inspecting aircraft structures involving thick layers of aluminum, including critical wing splices in some transport aircraft, thick wing skins in some fighter aircraft and other thick-section structures such as wheel rims. The new system may also be useful for inspecting steel structures such as pipelines and storage tanks, since the use of low frequencies can compensate for the high magnetic permeability of steel, allowing eddy-current measurements to see much deeper into the metal.

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