Magnetostrictive sensor for active health monitoring in structures

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ABSTRACT

A flat magnetostrictive sensor for active health monitoring of a large area of a structure has been developed. The sensor consists of a thin nickel foil and a coil placed over the nickel and, much like a strain gauge, is permanently bonded to the surface of a structure under monitoring. When activated, the sensor generates guided waves in the structure for interrogation and detects signals that are reflected back from the structural geometries and defects in the structure. Since guided waves can travel a long distance in the structure, a large area of the structure can be interrogated and monitored by using the sensor. By periodically acquiring the data and comparing it with the baseline data established at the time of sensor installation, structural changes occurred over that time can be quickly determined for suitable structural management decision. In addition to the ability to actively inspect and monitor a large area of the structure, the sensor is also rugged and inexpensive and therefore has high potential for practical use. As an example of its applicability to aircraft structure, data showing the monitoring of defect growth in fastener holes in a wing structure are presented.

Keywords: structural health monitoring, magnetostrictive sensor, active monitoring, fasteners, aircraft wing

1. INTRODUCTION

1.1 Structural Health Monitoring

There is an increasing need for structural health monitoring (SHM) for diagnostics and prognostics on structural systems to enhance their safety and reliability, minimize their downtime, and reduce operating and maintenance costs. This need exists across various industries including aerospace, defense, marine, oil, gas, petrochemical, bridge, and building. Because of the increasing demand and requirements for SHM, active research and development of SHM technologies is ongoing worldwide.[1]

1.2 Sensor Needs for SHM Applications

Most sensors being considered for SHM are passive such as fiber optics, strain gauges, thermometers, and accelerometers. They detect environmental conditions the structure is subjected to that may be useful to infer the integrity and safety of the structure.

The reliability and confidence of SHM would be significantly improved if active, instead of passive, sensors are used that, when actuated, can inspect critical load-bearing areas of the structure and detect and locate actual damages in the structure such as cracks, debonds, and corrosion wastage.

The primary candidate for active sensors for SHM applications is the guided-wave sensor. The guided waves, such as Lamb waves and shear horizontal (SH) waves in a plate structure and longitudinal waves and torsional waves in a cylindrical structure, can propagate a long distance along the structure and inspect and monitor a large area of the structure for defects and structural conditions from a fixed sensor location.[2-4] The guided-wave sensor therefore would be ideal for SHM of large structures such as aircrafts, spacecrafts, ships, large storage tanks, offshore platforms, pipelines, high-pressure vessels, highway bridges, and high-rise buildings.

1.3 Guided-Wave Sensor Development for Active SHM

For application to active SHM, Southwest Research Institute™ (SwRI™) has recently developed a guided-wave sensor. The sensor, based on the magnetostrictive sensor (MsS) technology developed and patented by SwRI,[5] is inexpensive to build and is flat, lightweight, surface-mounted, and durable, and therefore has high potential for practical applications.

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In this paper, the technical background on the MsS guided-wave sensor for SHM is described in Section 2. As an example of its applicability to SHM of aircraft structures, experimental data showing the monitoring of defect growth in fastener holes in a wing structure are presented in Section 3. Conclusions are given in Section 4, together with recommendations for further work.

2. TECHNICAL BACKGROUND

Figure 1 schematically illustrates the MsS guided-wave sensor designed for SHM of plate-type structural components. The sensor, which is a variation of the MsS plate probe,[3] consists of a thin nickel foil and a coil in thin printed circuit board placed over the nickel. Actual proto-type sensors contain two coils for control of wave propagation direction.

For SHM, the sensor, much like a strain gauge, is permanently bonded to the surface of a structure under monitoring with appropriate adhesive such as epoxy and the nickel substrate is magnetically conditioned. When activated by supplying an rf electrical current pulse to the sensor coils by using the MsS instrument, the coil generates shear-horizontal guided waves in the nickel substrate via the magnetostrictive effects. The generated guided waves, in turn, are coupled to the structure and propagate along the structure for interrogation. The direction of the wave propagation is perpendicular to the length-wise direction of the sensor that acts like a line source (or detector).[6] The sensor then detects signals that are reflected back from the structural geometries and defects, in the same manner used for long-range guided-wave inspection.[2-4]

For SHM, the inspection data are periodically collected and compared to the baseline data established at the time of sensor installation. Because the sensor is remained fixed, the data comparison allows trending of the structural condition changes and a quick detection of damages and their locations that have occurred in the structure over that time for suitable structural management decision. Since guided waves can travel a long distance in the structure, a large area of the structure can be economically interrogated and monitored in this manner.

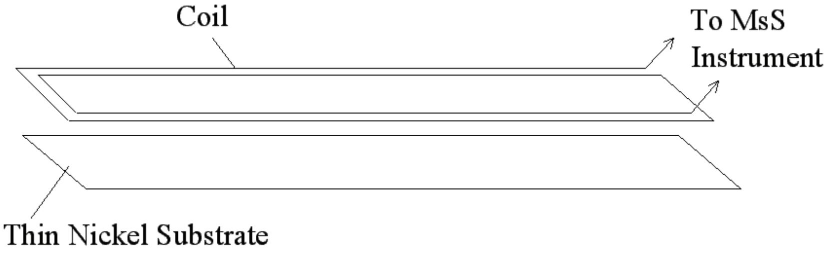

Fig. 1. Illustration of the flat MsS guided-wave probe for structural health monitoring.
The coil is placed directly on the nickel layer.

3. EXAMPLE OF APPLICATION–SHM OF FASTENER HOLES IN A WING STRUCTURE

3.1 Objective

Aircraft structures such as fuselage and wing skins are assembled together with fasteners. Corrosion and cracking that occur around and under fasteners are major concerns for assuring structural safety of the aircraft. Because of the complicated geometry of the fastened structure and the large number of fasteners, inspection of such structures is time consuming and difficult. Cost-effective and economical maintenance of fastened aircraft structures could be achieved by applying a suitable SHM method.

The experimental investigation described in this section was conducted to determine the feasibility of active SHM of a large area of a fastener structure by using the MsS guided-wave sensor and, if feasible, its capability.

3.2 Experimental Arrangement and Procedures

Figure 2 illustrates the configuration of a test panel and the MsS guided-wave sensor (called MsS probe in the figure). The test panel was a 1/4-inch-thick, 3- x 4-foot aluminum plate and had 1/4-inch-diameter tapered fastener holes along two edges of the plate. The center of each hole was located at approximately 1 inch from the edge of the plate, and the distance between the centers of the adjacent holes was approximately 3 inches.

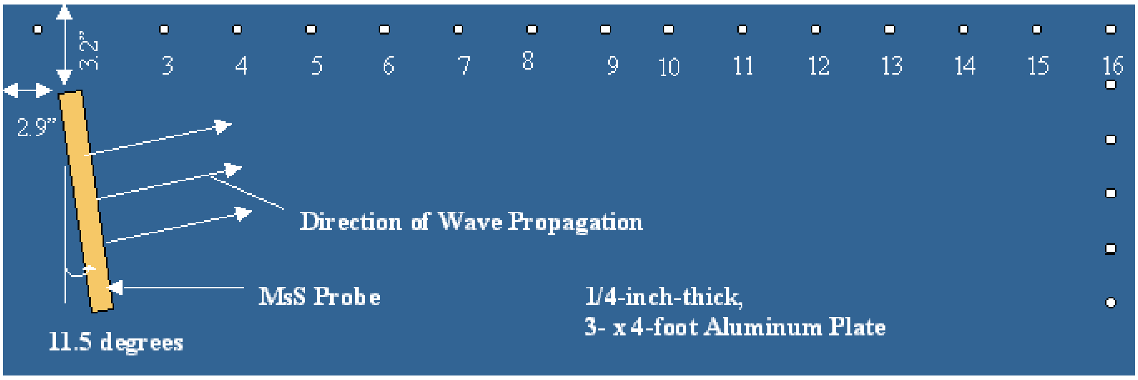

Fig. 2. Configuration of test panel and MsS probe

An approximately 8-inch-long MsS probe was placed at a slanting angle so that the probe could interrogate multiple fastener holes (numbered 3 to 16) simultaneously.

Using the MsS probe and MsS instrument (Model 2020),[7] 128-kHz shear horizontal guided waves were launched toward the numbered fastener holes, and the resulting signals reflected from them were detected.

In simulation of SHM, baseline data were first acquired from the test panel. Then data were acquired periodically after placing a notch initiating from Hole 10 along the direction perpendicular to the panel edge while increasing its size – equivalent to the area of approximately 0.05, 0.10, 0.15, and 0.20-inch-long-side, isosceles right triangles or approximately 0.0013, 0.005, 0.011 and 0.020 inch^2 in cross-sectional areas. Afterwards, another notch initiating from Hole 12 in the direction parallel to the panel edge was placed and its length incrementally increased in the same manner, and the periodic data acquisition was repeated. Finally, a corrosion area initiating from Hole 13 in the direction perpendicular to the panel edge was placed and the same test was repeated. Figure 3 shows a photo of the fastener hole with no defect and those with simulated defect in holes 10, 12, and 13, respectively.

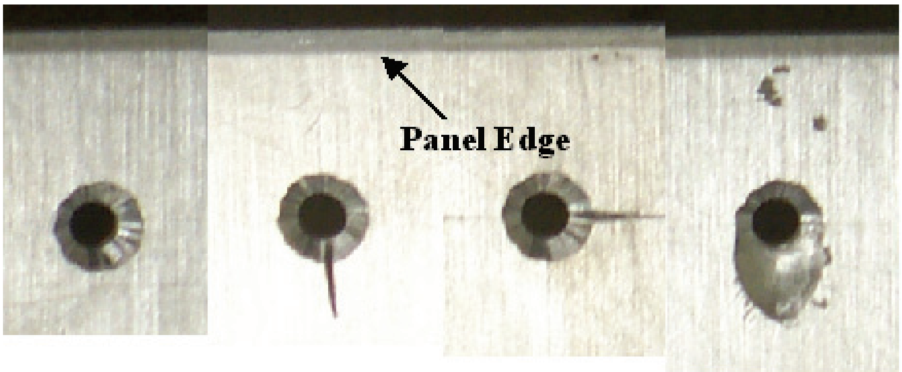

Fig.3. Photo of fastener holes and simulated defects used in this test (from left to right, fastener hole with no defect, notch from Hole 10, notch from Hole 12, and corrosion area from Hole 13)

The periodically acquired data were then compared with the baseline data (which are the data acquired before placing a defect in each hole) by using a signal differential algorithm developed by SwRI.

3.3 Experimental Results and Discussion

Figure 4 shows the data obtained from the test panel before placing any defect in the fastener holes. The data showed signals reflected from holes 5 through 16 together with the signal reflected from the corner of the test panel, as indicated in the figure. As might be expected, the corner signal was the largest in the amplitude. Signals from holes 9 to 14, which were situated near the central axis of the propagated guided-wave beam, were somewhat larger than those from other holes. Because of the dead zone associated with the initial pulse, signals from the nearby holes 3 and 4 were not detectable. The data in Figure 4 suggested that, using the sensor setup, holes 5 to 16 could be surveyed and interrogated for SHM.

Figure 5 shows a series of periodically acquired data while the notch from the Fastener Hole 10 was increased in size. In the figure, X represents the side of isosceles right triangle. The changes in the Hole 10 signal that would have occurred due to the presence of the notch were difficult to recognize in this figure, reconfirming the well-known difficulty of detecting defects in structures with complicated geometries from guided-wave inspection data.

However, when the data in Figure 5 were processed in the monitoring mode by subtracting the baseline data (in Figure 4) from them, the changes that occurred in the data were detectable, as shown in Figure 6. In these differential data, the change in the Fastener Hole 10 signal was observable when the notch size was equivalent to X = 0.10 inch or larger, and its amplitude increased with the notch size. The results shown in Figure 6 clearly showed the ability to detect and locate a defect and its growth in a fastener structure with the active monitoring approach.

The series of periodically acquired data while the defects from Fastener Holes 12 and 13 were incrementally increased were similar to those shown in Figure 5. As in Figure 5, the changes in the signal caused by the defects were difficult to identify from the acquired data.

The differential data processed in the monitoring mode are shown in Figures 7 and 8 for the notch from Hole 12 and the corrosion area from Hole 13, respectively. For the differential data in Figure 7, the data acquired with the X = 0.20-inch-size notch from Hole10 (lowest trace in Figure 5) were used as the baseline data. For those in Figure 8, the data acquired with the X = 0.2-inch-size notches from Holes 10 and 12 were used as the reference.

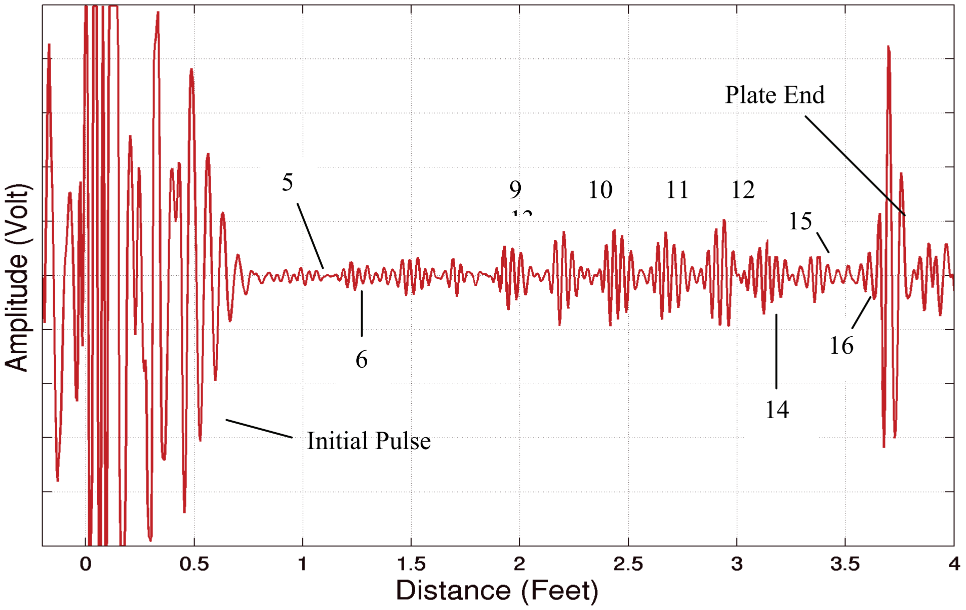

Fig. 4. Example of test data obtained from the test panel before placing simulated defects

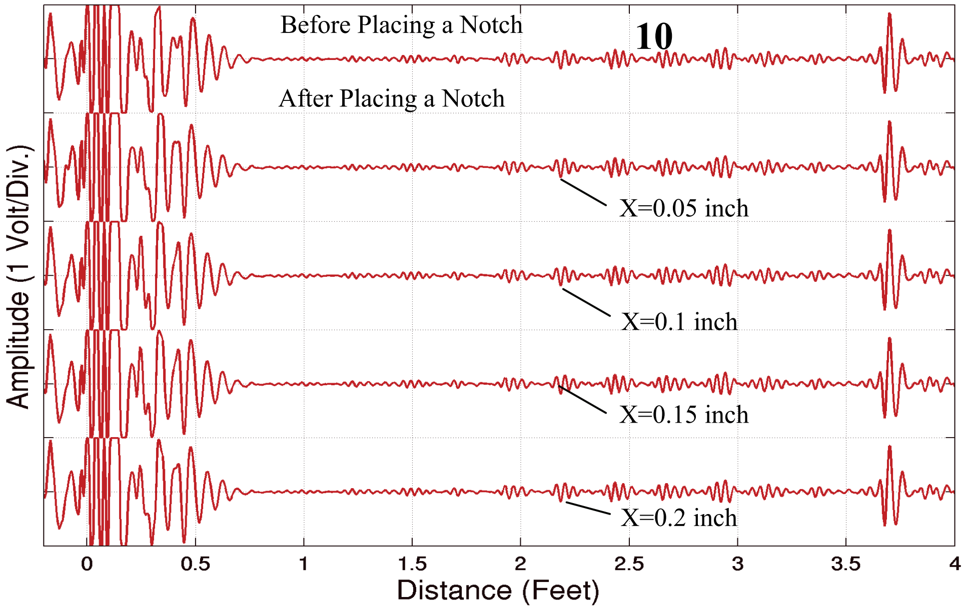

Fig. 5. Series of periodically acquired data while the notch from Fastener Hole 10 was increased in size that was equivalent to the area of isosceles right triangle with approximately 0.05, 0.10, 0.15, and 0.20-inch-long side (=X).

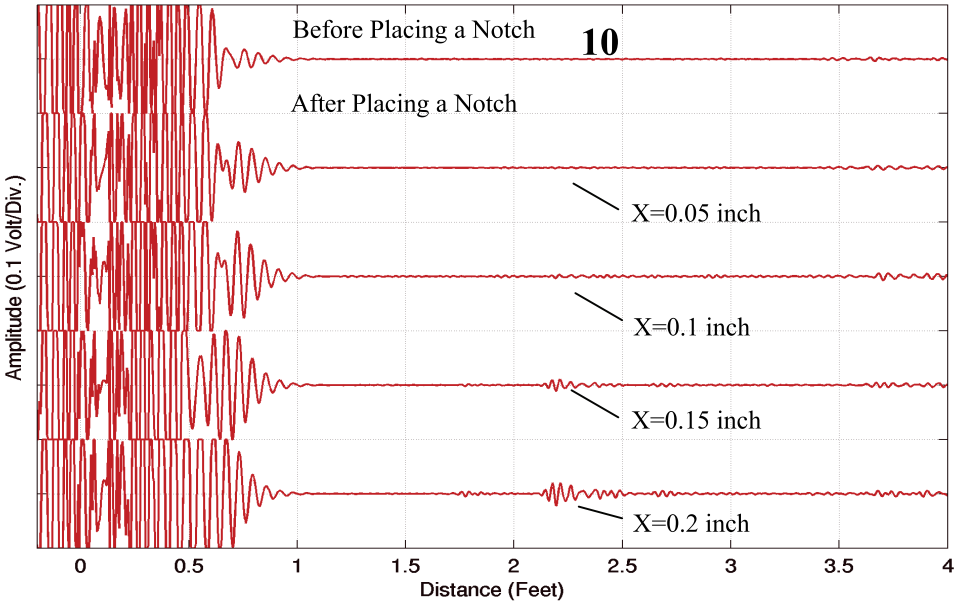

Fig. 6. Differential data of the data in Figure 5 obtained by subtracting the baseline data in Figure 4 from them in the monitoring mode. X represents the side of isosceles right triangle.

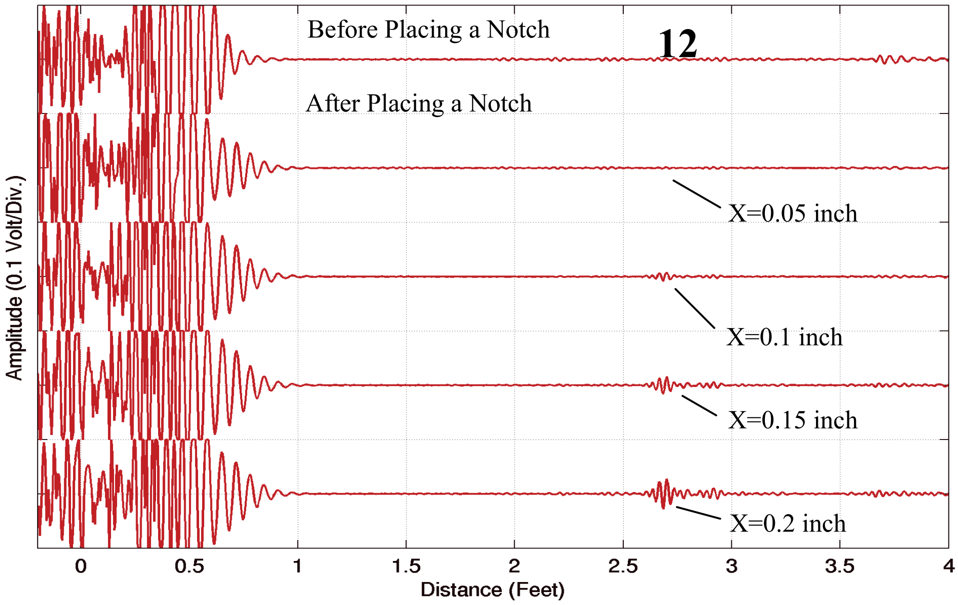

Fig. 7. Differential data for Fastener Hole 12 with a notch of various sizes in the direction parallel to the panel edge. X represents the side of isosceles right triangle.

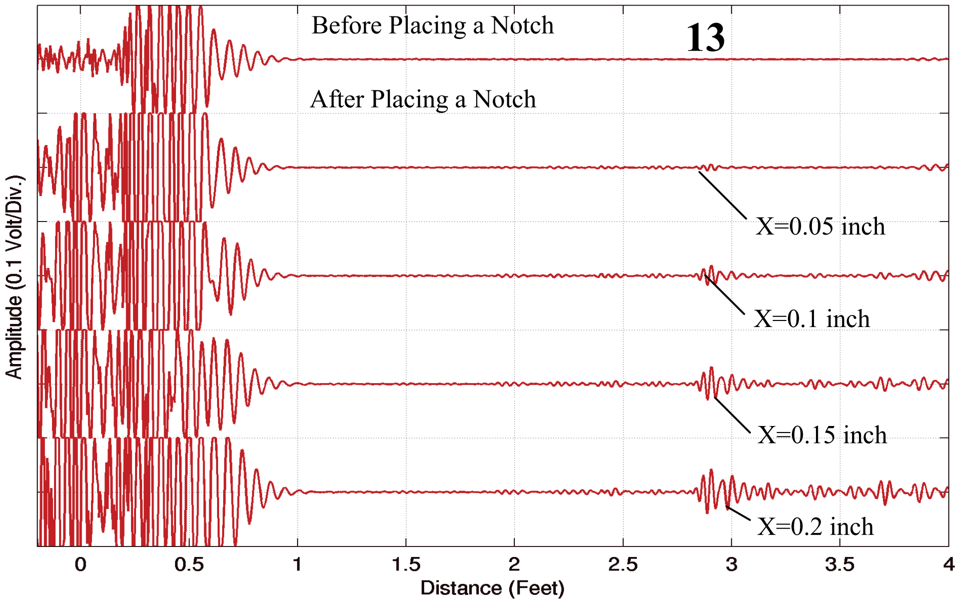

Fig. 8. Differential data for Fastener Hole 13 with a corrosion area of various sizes in the direction perpendicular to the panel edge. X represents the side of isosceles right triangle.

The differential data in Figure 7 showed that, despite the unfavorable orientation of the notch that was almost hidden from the direct view from the MsS probe, the changes in the Fastener Hole 12 signal were detectable when the notch size was equivalent to X = 0.10 inch or larger. The differential data in Figure 8 also showed that the changes in the Fastener Hole 13 signal were detectable even when the cross-section of corrosion area was as small as 0.0013 inch^2 (or equivalently X = 0.05 inch).

The test results described above clearly demonstrated the capability and potential of the MsS for active SHM of a large area (several feet) of fastener structures for detection of defects and their locations and growth with time.

4. CONCLUSIONS

Conclusions that can be drawn from the test results described in this paper include:

(1) Active SHM of a large area (several feet) of fastener structure is feasible by using the flat MsS guided-wave sensor.
(2) Defects such as cracking and corrosion wall-loss area and their growth with time can be detected and monitored by using the active MsS-SHM approach.
(3) The flat MsS guided-wave sensor is low-profiled, light in weight, surface attachable, rugged, and inexpensive, and therefore has high potential for practical use.

For practical implementation of the MsS guided-wave sensor for long-term SHM, further research and development of the sensor are recommended in the following areas:

(1) The long-term stability of the sensor in the operating environment of the structure under monitoring.
(2) The extent of its application—types of structures, monitoring range, and sensitivity of monitoring.
(3) Data processing methods for enhanced monitoring capability.
(4) Procedures for implementation and multiple sensor control.
(5) Field evaluation and test.

5. ACKNOWLEDGEMENTS

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