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AIRCRAFT FASTENER DEFECT DETECTION THROUGH POLAR-WAVENUMBER FILTERING OF FULL-FIELD GUIDED WAVE DATA

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ABSTRACT

Scanning laser systems are a class of ultrasonic guided wave systems that have shown great promise for the inspection of complex structures because of the high spatial resolution of their resulting data. Such resolution allows the application of full-field processing techniques with accuracy and speed that has been previously impossible. In this study, the focus is on applying full-field signal processing techniques to automatically detect and characterize fastener damage in aircraft components with realistic structural complexity. The particular testbed being considered is a composite tail section with several rivet lines. Artificial damage was introduced into several of the rivets with different magnitudes and orientations. The ultrasonic waves generated by the scanning laser interact with the damage and reflect differently from undamaged rivets than from damaged ones. While trained users of the laser scanning system can often detect the damage modes by simply viewing the resulting images, a more automated and quantifiable approach is desired to increase the consistency and quantify the confidence of the inspection system. In order to characterize the state of each rivet, a polar wavenumber processing technique is proposed. First, the full-field data is transformed to a new polar coordinate system centered on a particular rivet. A 3D Fourier transform then transforms the data to the frequency-wavenumber domain. Finally, the data is windowed to isolate the waves propagating in the positive radial direction. Analyzing the scattering pattern from each rivet in turn provides information on the health of each rivet. Damage detection may be accomplished either by comparison of the extracted scattering pattern with a model of the expected scattering pattern, or by an absolute reference-free method comparing rivets to one another to identify outliers. The results show that there is the potential to provide quantified damage detection and characterization for fastener damage using laser-excitation guided wave inspection systems.

KEYWORDS : *ultrasonic guided waves, frequency-wavenumber, signal processing*

INTRODUCTION

Ultrasonic guided waves have been the subject of much study in the structural health monitoring (SHM) field due to their desirable properties such as their relatively high range and sensitivity to small damage. Scanning laser-generated ultrasound systems are unique in their ability to rapidly produce a very high spatial density of information [1, 2]. However, with a large volume of data comes even more need for effective signal processing techniques to extract the relevant information for assessing structural integrity. While viewing raw imaging representations of the wave propagation may be sufficient in some limited cases for trained operators of the system to distinguish damage, this work focuses on how more quantifiable and automated techniques may be developed.

In this study, a riveted, composite aircraft specimen is monitored for artificial cracking around the rivets. First, a polar wavenumber processing approach is implemented, similar to approaches used in previous studies [3, 4]. However, in this case the polar wavenumber processing is centered on the feature to be monitored in order to detect changes in the scattering pattern. Next, the potential to use digital image processing techniques to detect the damage is presented. The objective of all of these approaches is to accurately identify and characterize the extent of fastener damage.

1 EXPERIMENTAL PROCEDURE

1.1 Laser-scanning procedure

To collect the full-field guided wave data used in this study, a laser scanning technique has been developed previously [5]. The technique uses a Q-switched pulsed laser to generate guided waves at the point the laser beam impinges on the structure's surface. The beam is directed to different locations on the structure by a two-dimensional scanning mirror. The resulting guided waves are received at a separate, surface-mounted piezoelectric sensor. A complete set of waveforms characterizing the response of that region to guided waves is then obtained by raster scanning the laser over a region of the structure. Elastodynamic reciprocity implies that if the process is linear, the responses collected at a single point from excitation at all of the scanning points are equivalent to the response at each scanning point if the wave had been generated at the receiver. In this way, the guided wave response of the structure can be quickly acquired and intuitively visualized.

1.2 Specimen description

The specimen selected for testing in this study is the tail section of a military aircraft. The material consists of a carbon fiber composite with unknown properties. Several lines of rivets, spaced at 22 mm apart, fix the skin to the substructure. Each rivet has a diameter of approximately 5 mm. An overview of the structure is given in Figure 1.



Figure 1 - Tail section specimen overview

Two of these lines of rivets were chosen for monitoring, with 20 rivets in total considered in the analysis. This area is detailed in Figure 2, which shows the rivet numbering scheme and the

coordinate system. The PZT sensor is mounted on the inside of the specimen at the location denoted by a red circle.

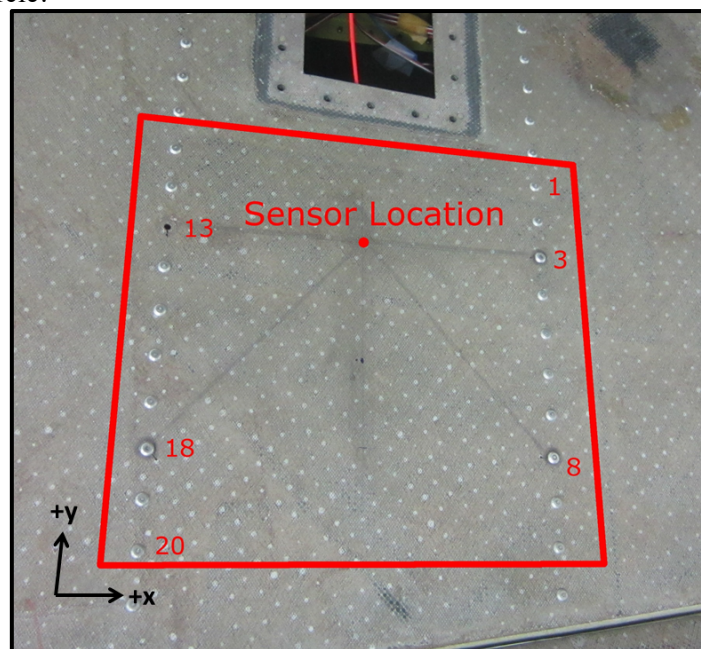


Figure 2 – Approximate scan area with rivet numbering and coordinate system noted

Damage had been introduced artificially to four rivets, which were designated as rivets 3, 8, 13, and 18, before any data acquisition was initiated.. Rivet 13 was completely removed, and each of the four had a simulated crack machined in various directions and lengths. One surface crack was also introduced separately from any rivet-related damage, but this damage mode is not considered here.

1.3 Data acquisition parameters

In order to monitor the two rivet lines of interest, a region of 300 x 240 mm was established as the scan area. The region of interest was scanned by the laser with a repetition rate of 500 Hz and a grid spacing of 0.5 mm. At each scan point, the sensor recorded 2000 data points over 250 μ s. The data were then band-pass filtered from 40-150 kHz to reduce the noise not associated with the guided wave propagation.

2 POLAR-WAVENUMBER PROCESSING METHODOLOGY

Because radially-symmetric PZT sensors are common and they generate radially-propagating wavefields, it is natural to consider a polar coordinate system in processing the full-field data. In addition, many small defects or geometrical features (like rivets) are also characterized by radial scattering patterns. In order to estimate the pattern of waves scattered from each rivet, a polar-wavenumber processing method is proposed. Rather than (or in addition to) removing the incident wavefield through either time- or wavenumber-domain processing [3], each rivet is considered to be the center of a polar coordinate system. A 3D Fourier transform yields the frequency wavenumber data: $U(k_r, k_\theta, \omega)$. A 3D window is then applied that passes only positive (outgoing) radial wavenumbers, effectively isolating waves emanating from the rivet. An inverse Fourier transform may then be applied to return the data to the space-time domain.

3 RESULTS

Figure 1 gives an overview of the global wave propagation. At this specific time, the faster-propagating S0 mode has interacted with all of the rivets and begun to scatter. The slower but higher-amplitude A0 mode can readily be observed as well.

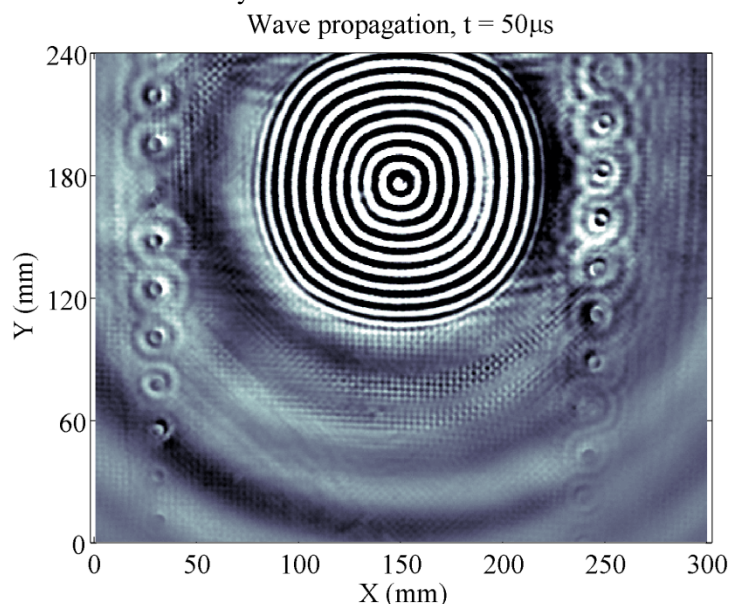


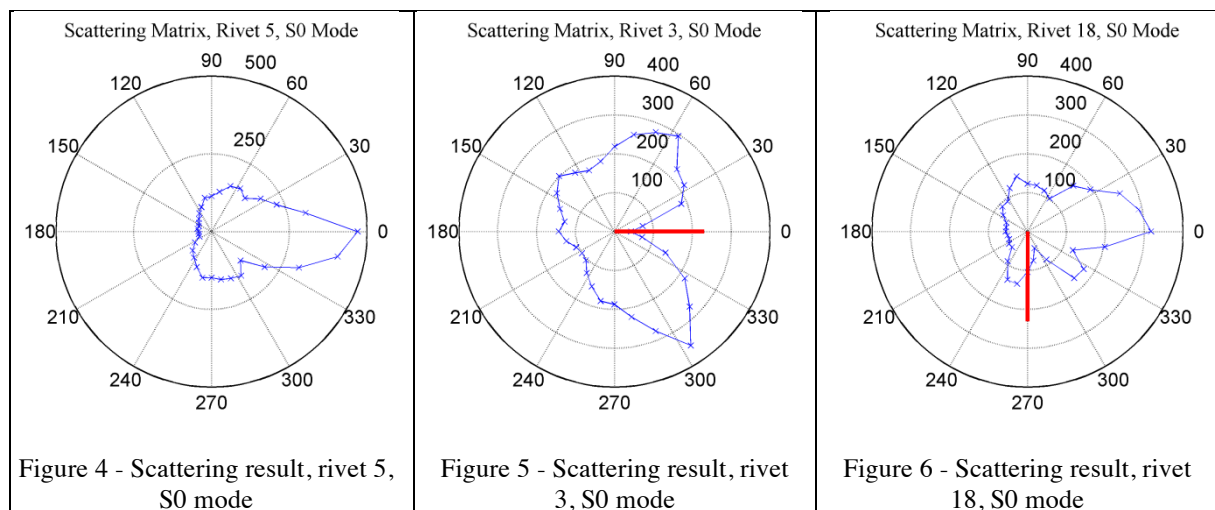
Figure 3 - Snapshot of full-field data showing S0 mode interaction with rivets

3.1 Scattering matrix reconstructions

The scattering pattern of each rivet is determined by establishing a spatial window of 40 mm x 40 mm centered on the rivet. After implementing the polar wavenumber transformation on the data in that window, a fixed radius of 4 mm is used to extract the scattering pattern. The resulting representations are therefore rather near-field, at almost twice the rivet radius, but this parameter could be adjusted depending on the application. The data is re-interpolated on that circumference and the energy of the wavefield is calculated over a specific time window corresponding to the arrival window of the first scattered waves from the rivet.

Note that the “scattering matrices” presented here are really a slice of a higher order tensor, because they are sampled at only one incident wave direction. The most general description of the scattering of a feature would be a function of incident angle, reflected angle, wave mode, and even possibly the radius at which the response is measured. For this study, the S0 mode was chosen as the focus because it is the first to arrive, whereas the A0 arrival is superimposed with the S0 waves as well. However, it is feasible to use both modes if such an approach is warranted by the application.

The scattering pattern of a few rivets is presented for reference. Each has been rotated such that the incident wave approaches the rivet from the 0-degree direction. Figure 4 shows the response of rivet 5 as an example of a typical undamaged rivet. For the S0 mode, the backscatter from the hole is dominant. Rivet 3 shows a much different response in Figure 5, however, due to the crack that extends in the same direction. The results for rivet 18, shown in Figure 6, are more difficult for visually distinguishing the presence of damage. There is a lower amplitude notch near the direction of the crack, which may be assumed to be a result of the crack.



In order to interpret the scattering matrices quantitatively, two different metrics were implemented for the damage detection step. The first metric is known as circularity, and it measures how similar the scattering is to a circle. While it is not expected that the scattering pattern should be circular, it does give an effective measure of whether sudden deviations are present (which are observed at the angles corresponding to crack damage). Circularity, which is used in the digital image processing field, is defined according to Equation (1):

$$c = p^2 / A \quad (1)$$

where c is the circularity, p is the perimeter, and A is the area of the shape [6]. Note that for a perfect circle, the value of the circularity would be $c = 4\pi$, with higher values representing less circular objects. Figure 7 shows the results of computing this metric for each rivet. The red diamonds represent the damaged rivets, the blue circles represent healthy rivets, and the dotted black line denotes the separation between the two rivet lines. It is evident that the rivets 13 and 18 are fairly well-detected by this metric, but rivets 3 and 8 are less well-separated.

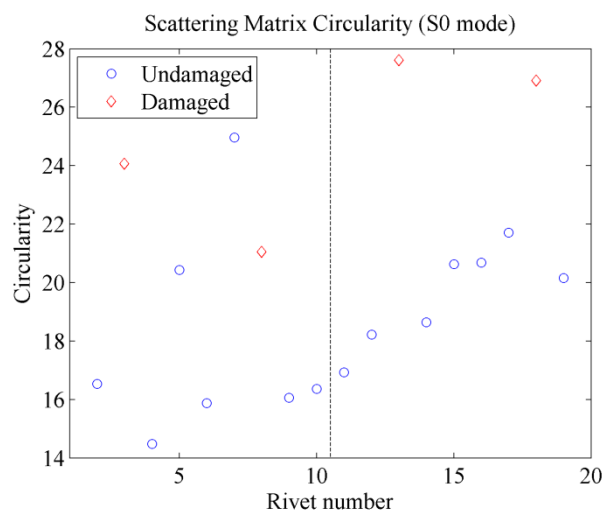


Figure 7 - Circularity of the scattering matrix for each rivet (S0 mode)

A better metric for a kind of self-referencing damage detection paradigm is the average correlation coefficient between a rivet and all of the other rivets being evaluated. Assuming that most of the rivets will be intact for situations where SHM is useful, damaged rivets should have scattering

patterns that are less similar to other, healthy rivets. A comparison of average correlation coefficients for the S0 mode is given in Figure 8.

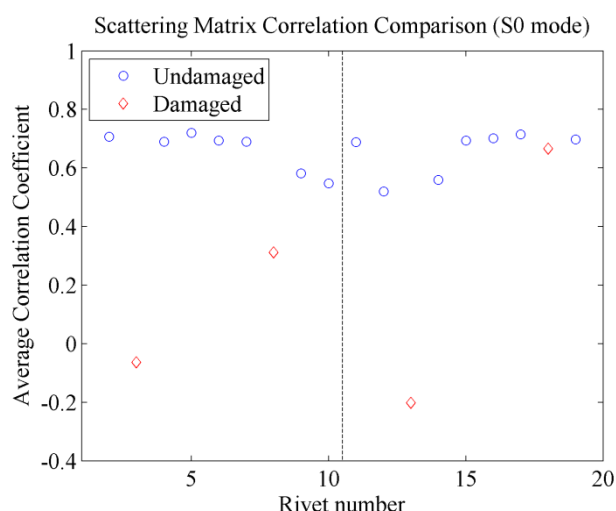


Figure 8 - Average correlation coefficient with all other rivets (S0 mode)

The results of the correlation coefficient comparison are very encouraging. The healthy rivets tend to have scattering matrix correlation coefficients in the range of 0.5-0.75. Rivets 3, 8, and 13 have values significantly lower than that range, indicating that something is wrong with the rivet. Interestingly, however, rivet 18 does not exhibit the expected decrease.

3.2 Digital image processing methods

It is also possible that images of the wavefield could be processed for the detection or characterization of damage by borrowing techniques from the field of digital image processing. This approach would more directly take advantage of the features that are visible in the waveform videos, but has the advantage of using quantifiable metrics like the circularity metric introduced previously. Figure 9, Figure 10, and Figure 11 show frames of the wavefield that highlight rivets 5, 3, and 8, respectively.

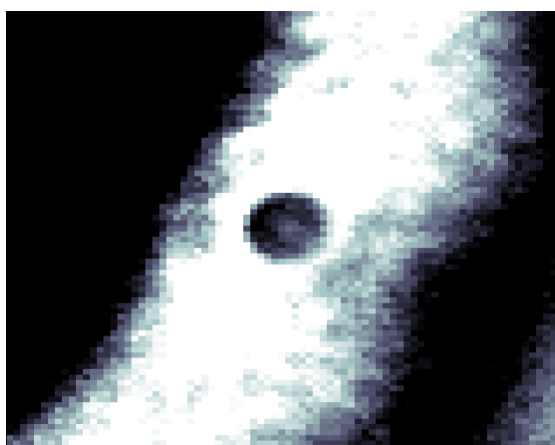


Figure 9 - Wavefield image for rivet 5 (healthy)

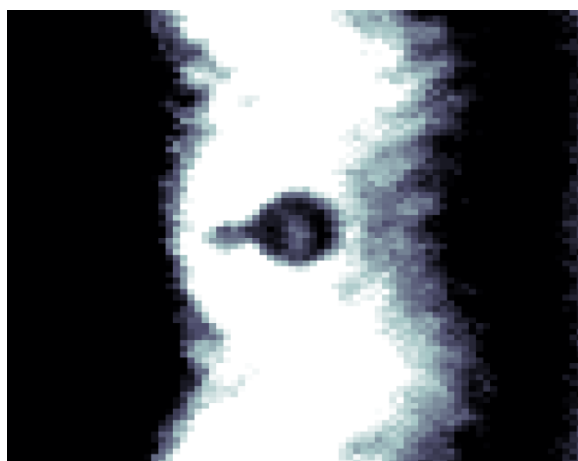


Figure 10 - Wavefield image for rivet 3, with crack evident

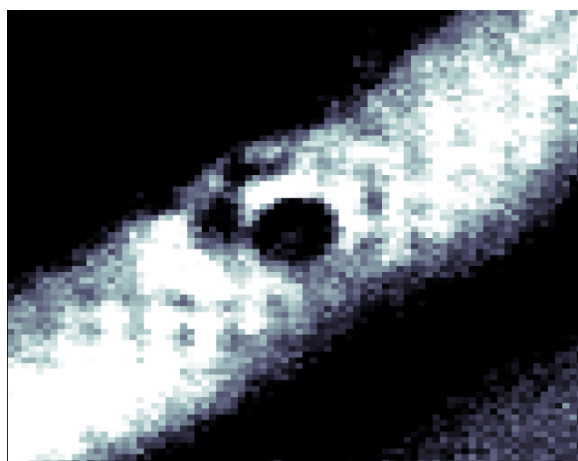


Figure 11 - Wavefield image for rivet 8, with crack evident

For rivets 3 and 8, the cracks are fairly evident as dark protrusions from the hole. Figure 11 shows that the waves from a different incident angle (relative to the damage) interact in a less straightforward manner. As a quick verification of the ability of digital image processing techniques to evaluate the damage, the circularity metric was calculated for these shapes, which are expected to be highly circular due to the circular shape of the rivets. First, the images were thresholded to black and white, and then the area and perimeter of the rivet shapes were calculated (using MATLAB's `bwarea` and `bwboundaries` functions). The resulting circularities are given in Table 1.

Table 1 - Circularity metrics calculated with digital image processing

Rivet #	Rivet 3	Rivet 5	Rivet 8
Circularity	28.1	20.3	39.0

So, having established that healthy rivets are very circular and crack damage causes a significant deviation from that state, a digital image processing approach could be further implemented. In particular, such an approach offers distinct advantages in terms of providing direct, quantitative characterization of the damage (e.g. crack length). It should be noted that perhaps the most significant challenge associated with such analysis is choosing a time frame with sufficient contrast between the rivet and surroundings. While such selection is possible, an automated procedure for contrast selection is a topic for future work.

CONCLUSION

This work presented a new approach to quantitatively evaluating the health of aircraft fasteners from full-field guided wave data. Polar wavenumber filtering was used to isolate waves propagating in the positive radial direction from each of the fasteners individually. From that transformation, determining the scattering pattern of the rivets becomes a natural step, and examples of those scattering patterns for the S0 mode were presented. Further evaluation of the scattering matrices for damage requires comparison with an expected model. Here, the most effective method implemented was to use the average correlation coefficient between the scattering matrices of each of the rivets, which provides a self-referencing approach to assessing the damage. Circularity was also introduced as a metric borrowed from the field of digital image processing, and it was shown to be effective at detecting damage for particular frames of the full-field data, provided the appropriate frames can be selected. In total, this work represents an initial step toward establishing automated methods for quantitatively evaluating full-field guided wave data.

ACKNOWLEDGMENTS

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