ANALYSIS OF GLOBAL ULTRASONIC SENSOR DATA FROM A FULL SCALE WING PANEL TEST

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ABSTRACT. A full scale wing panel fatigue test was undertaken in 2007 as a part of the DARPA Structural Integrity Prognosis System (SIPS) program. Both local and global ultrasonic sensors were installed on the wing panel and data were recorded periodically over a period of about seven weeks. The local ultrasonic sensors interrogated a small number of selected fastener holes, and the global ultrasonic sensors were arranged in a spatially distributed array surrounding an area encompassing multiple fastener holes of interest. The global ultrasonic sensor data is the focus of the work reported here. Waveforms were recorded from all pitch-catch sensor pairs as a function of static load while fatiguing was paused. The time windows over which the waveforms were recorded were long enough to include most of the reverberating energy. Partway through the test simulated defects were temporarily introduced by gluing masses onto the surface of the wing panel, and waveforms were recorded immediately before their attachment and after their removal. The overall fatigue test was terminated while cracks originating from the fastener holes were still relatively small and before they reached the surface of the wing panel. Both detection and localization results are shown for the artificial damage, and the overall repeatability and stability of the signals are analyzed. Also shown is an analysis of how the reverberating signals change as a function of applied load. The fastener hole fatigue cracks were not detected by the global transducer array, which is not surprising given the final sizes of the cracks as determined by later destructive analysis. However, signals were stable throughout the entire fatigue test, and effects of load on the received signals were significant, both in the short-time and long-time signal regimes.

Keywords: Structural Health Monitoring, Sparse Ultrasonic Array, Change Detection, Ultrasonic Imaging, Acoustoelasticity

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INTRODUCTION

Prognosis of remaining structural life has been the focus of the DARPA Structural Integrity Prognosis System (SIPS) program, initiated in 2004 with Northrop Grumman Corporation as the prime contractor. One of the target structures for the project is an aircraft wing panel where the known critical sites for fatigue crack initiation and growth are fastener holes. A number of sensor systems have been considered for local detection and sizing of very small fatigue cracks [1], and these have been extensively tested both in the laboratory and as a part of full scale fatigue tests [2-4]. However, during an earlier full scale wing panel test, cracking occurred in an unexpected location, and a large area sensing...
method was thought to be desirable. As a result, during the second full scale wing panel test, a spatially distributed array of ultrasonic sensors was mounted on the wing panel and data were recorded throughout the test. Prior laboratory work on flat panels, both with and without holes and thickness changes [5,6], suggested that this type of sensor array may be feasible for in situ detection and localization of damage on an actual wing panel structure.

TEST DESCRIPTION

Overview

A schematic of the wing panel is shown in Fig. 1. The line of fastener holes was instrumented with a variety of sensors, both local and global, as shown in the photograph of Fig. 2. The sensors comprising the sparse array are highlighted with numbered circles.

FIGURE 1. Sketch of full scale wing panel fatigue test.

FIGURE 2. Photograph of sensors mounted on the wing panel with the global ultrasonic sensors highlighted by numbered circles.
Fatigue Test

The wing panel was fatigued using a repetitive spectrum loading for a total of 205.5 hours of fatiguing over about 6-1/2 calendar weeks in August and September of 2007. Full load (100%) corresponded to a strain of approximately 0.0025 on the surface near the holes in the principal strain direction. There were a total of 123,299 load cycles during the 25 days of actual testing. Prior to the start of fatiguing, NDI was performed on each of the fastener holes using an ultrasonic phased array system, and no cracks larger than about 0.4 mm in length were detected. After fatiguing was completed, destructive tests showed that the biggest cracks were about 2.8 mm in length and 1.4 mm in depth.

Signals and Preprocessing

Signals were recorded from all 28 pitch-catch transducer pairs at semi-regular intervals (typically twice per day) throughout the fatigue test. A custom spike-mode pulser-receiver and 16 channel multiplexer were used, and waveforms were digitized at 12.5 MHz for a time window of 1000 μs. Each acquired waveform was an average of 20 signals to reduce incoherent noise. Fatiguing was halted prior to data acquisition, which occurred while static loads were applied from 0 to 100% in 10% steps. All 28 waveforms were acquired and stored for each load level, for a total of 308 waveforms.

Prior experience with the transducers has shown that the S0 mode around 200 kHz is dominant. It is also the fastest mode, and its group velocity is estimated from the direct arrivals. Signals from all 28 pairs are shown in Fig. 3(a) after filtering by convolution with a 3 cycle, Hanning windowed, 200 kHz tone burst; times of the first arrivals are also shown. Figure 3(b) shows arrival time vs. distance data, where it is clear that the group velocity is generally consistent for all transducer pairs despite thickness changes and other geometrical complexities. The group velocity, which is the slope of the linear fit, is 5.25 mm/μs. The phase velocity is similar, and the wavelength is about 25 mm.

FIGURE 3. (a) Signals recorded under no load and stacked by transducer number. Automatically detected first arrivals are indicated by the “x” symbols. (b) Group velocity calibration results.
ANALYSIS METHODS

Change Detection

Changes in signals were detected and quantified via the local temporal coherence (LTC), which is based upon the local (short time) cross correlation using a window of width $T$ which slides along both of the signals. The short time cross correlation is normalized by the autocorrelations to obtain the local temporal coherence [7]. Similar to the correlation coefficient, if two signals are identical in shape, the peak coherence at each time step is unity even if the amplitudes are different. Unlike the correlation coefficient, the peak of the absolute value of the local temporal coherence is a function of time, and is a measure of how the shapes of two signals are changing with time, even if there are amplitude differences and small time shifts. The peak coherence, $C(t)$, is the peak value of the LTC for each time window,

$$C(t_n) = \max_{\tau} |\gamma_{xy}(\tau, t_n)|$$

where $\gamma_{xy}$ is the LTC, $\tau$ is the cross correlation lag, and $t_n$ is the time of the center of the $n$th sliding window. This function is a measure of the overall difference in shape between the two signals. More information on the LTC and peak coherence can be found in [7].

Delay-and-Sum Imaging

Changes in signals are localized by applying a delay-and-sum algorithm to signal differences (i.e., baselines are subtracted from current signals) [6]. The delays are the calculated transit times from the transmitters to the imaging point to the receivers. Images were constructed from the envelope of the differenced signals after preprocessing the raw signals by (1) normalizing the total energy as per the expected $1/r$ decay, (2) filtering by convolution with a 3-cycle, Hanning-windowed, 200 kHz tone burst, and (3) exponential windowing with a decay constant of 15 $\mu$s. The exponential window reduces components of the received signals that are located in time later than the direct arrival, and the resulting images are thus based primarily upon changes in the direct arrival and scattered signals that occur shortly after the direct arrival.

RESULTS AND DISCUSSION

Signal changes as measured by the peak coherence are used to evaluate signal stability, quantify load effects, and detect structural changes. The delay-and-sum imaging algorithm is applied with the goal of localizing structural changes.

Signal Stability

Received signals exhibited excellent long term stability as shown in Fig. 4 for transmitting on sensor #2 and receiving on sensor #3; all signals were recorded at 100% load. Sensors #2 and #3 are separated by approximately 167 mm, and the calculated direct arrival is about 32 $\mu$s. The time window shown in the figure of about 430 $\mu$s corresponds to a travel path of approximately 2.2 m, which includes many reverberations within the wing panel. Note that even small waveform details are consistent over the 7 week time interval.
Signal Comparisons

The most obvious effect of an applied load is to shift the direct arrivals in time, which is caused by both dimensional changes (strains) and velocity changes (acoustoelastic effect). The magnitude and direction of the time shift are a function of the angle of the line connecting the source and the receiver and their separation distance. Figure 5 shows the time shifts and maps them to an angle-dependent wave speed. The angular dependence of the wave speed characterizes the 2D strain tensor of the wing panel.

![Figure 4](image1.png)

**FIGURE 4.** Illustration of signal stability at 100% load for transmitter #2 and receiver #3.

![Figure 5](image2.png)

**FIGURE 5.** Effect of load on direct arrival times. (a) Time shift vs. load for all sensor pairs, (b) time shift vs. angle at 100% load, (c) time shifts normalized by transducer separation, and (d) velocity vs. angle. Note that an angle of zero is transverse to the principal strain direction, and +/-90° is along it.
Applied loads not only shift the first arrival but also influence the entire signal. Each complex waveform can be thought of as the sum of many reflected and scattered echoes, where each echo has propagated along a path composed of multiple segments of various lengths and orientations. Since each path is shifted differently, each waveform changes in a complex manner as a function of travel time. These changes can be quantified by the peak coherence, $C(t)$, as shown in Fig. 6, where signals at zero load are compared to those at 10%, 20%, 50% and 100% loads. It can be seen that for even a modest load of 20%, the signals rapidly lose coherence as a function of travel time. This behavior can be contrasted to that caused by homogeneous temperature variations, where time shifts are proportional to travel time and signal coherence is maintained over reasonable temperature changes [7,8].

Figure 7 shows several other signal comparisons. The top two figures compare signals separated in time by about one week (14,156 cycles) but recorded at the same load levels. As was seen in Fig. 4 for the one transducer pair at 100% load, the signals maintain coherence over the recorded time window; the coherence is slightly better at 100% load as compared to zero load.

The middle two figures compare signals before and after masses were glued to the wing panel surface, and there is a noticeable loss of coherence as compared to the top two figures. Clearly the scattering of the waves by the masses has changed the received signals enough so that the presence of the masses can be detected.

The bottom two figures compare signals recorded after various numbers of fatigue cycles to baselines recorded near the beginning of the fatigue test. Although there is some loss of coherence, it is not as much as was caused by the glued-on masses, and in particular the early time behavior does not indicate a coherence loss as was the case for the masses. If the fastener hole cracks were significantly affecting the signals, at least some of the direct arrivals should be changed and the early time coherence affected. Given that this was not the case, the conclusion is that the cracks were not detected, which is not unexpected given that they were an order of magnitude smaller than the wavelength.

**FIGURE 6.** Effect of load on signal coherence for comparing signals recorded at no load to the corresponding signals at 10%, 20%, 50% and 100%. Signals from all 28 transducer pairs are shown together on each plot.
Localization of Structural Changes

The time-of-arrival imaging algorithm was applied to the differenced signals before and after each of the two masses was glued to the outer surface of the wing panel. The images are shown in Fig. 8 where it can be seen that the first mass is localized reasonably well. The second mass is localized to the general area of the wing, but the image amplitude is significantly less than that of the first mass.
SUMMARY AND CONCLUSIONS

The main contributions of the work presented here are (1) glued-on guided wave sensors can not only survive many thousands of fatigue cycles, they can provide stable and repeatable data, and (2) the effects of loading on the signals are significant and must be considered as part of the data interpretation process. The cracks generated as part of this wing panel test were not large enough to evaluate the efficacy of the sensor array in terms of detecting and localizing damage, although the glued-on masses indicate that the sensor array may have sufficient sensitivity for detecting larger flaws.

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