ULTRASONIC SENSING AND LIFE PREDICTION FOR THE DARPA STRUCTURAL INTEGRITY PROGNOSIS SYSTEM

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ABSTRACT. The overall objective of the DARPA Structural Integrity Prognosis System (SIPS) program is to develop technologies to advance material damage state condition assessment with limited or no dedicated maintenance action. As a part of the sensors thrust area, an in situ ultrasonic sensing method was developed and demonstrated to detect cracks initiating from fastener holes and provide an estimate of total crack area. Crack area estimates were combined with load history data, projected future loads, and life prediction models to determine a probability density function for time-to-failure. The ultrasonic method utilizes two shear wave angle beam transducers operating in through transmission mode which are mounted on either side of the hole. The transmitted wave travels through the area of expected cracking, and the presence of cracks around the fastener holes decreases the amount of acoustic energy that is received. Furthermore, as cracks open and close during the fatigue process, the received energy is modulated, i.e., decreased when the cracks are open versus closed, and this non-linear behavior is the basis of algorithms developed to detect and size fastener holes cracks. The ultrasonic method was demonstrated as part of an integrated SIPS demonstration whereby aircraft-grade aluminum subcomponents were fatigued to failure. Results are presented from both the ultrasonic measurements and the integrated life prediction software.

Keywords: Ultrasonics, Crack Detection and Sizing, Structural Health Monitoring
PACS: 43.25.Zx, 43.35.Yb, 43.25.Dc, 43.35.Cg

INTRODUCTION

The long range vision of the DARPA Structural Integrity Prognosis System (SIPS) program is to develop a prognostic system to provide military commanders with the data and quantitative performance predictions to adaptively manage, deploy, and use individual combat systems to the limit of their current capability. The objective of the program is to create a tool for predicting near-term system capability, including imminent failure, without the need for any inspection or maintenance action. Sensors provide an “awareness” of the state of the structure and, when defects are present, provide information about defect location and size. By comparing data between subsequent interrogations, the progression of damage in the structure can be determined. This sensor information is required to provide a real-time assessment of the state of the structure, and is a necessary input to life prediction computations if meaningful results are to be expected from the program.
One aspect of the SIPS program for the Phase I effort was to develop and demonstrate a prognosis tool for detecting and sizing cracks emanating from fastener holes in 7075-T651 aluminum during metal fatigue. Described here is the ultrasonic sensing method which was developed and demonstrated for \textit{in situ} crack detection and sizing.

For the problem of nondestructively detecting fastener holes cracks, accepted practice is to use an external angle beam transducer or transducer array to interrogate the region of expected cracking [1,2]. Articulation or scanning of the transducer or array is necessary to discriminate crack signals from hole reflections. The feasibility of using guided waves to detect fastener hole cracks has been investigated [3], but the sensitivity is not as good as for angle beam methods. Regardless of the method, it is well known that closed cracks are much more difficult to detect than open cracks, and that applying an external load to open cracks improves their ability to be detected. Surface wave methods have been developed where a variable load opens and closes cracks and thereby modulates the received ultrasonic signal [4]. The angle beam method developed for the SIPS program utilizes a similar methodology; many of the details of this ultrasonic method are described in [5,6].

\textbf{ULTRASONIC METHOD}

Detection of small fatigue cracks originating from fastener holes is a very challenging problem, even for inspections where ultrasonic transducers can be articulated to optimize the response from a crack. Even under these optimum conditions, it is difficult to detect cracks smaller than about 1 mm in length. The \textit{in situ} environment presents additional challenges, the most serious one being that the transducers cannot be moved to optimize the response to cracks of different shapes, locations and orientations.

For the SIPS program, an ultrasonic method was developed utilizing two 10 MHz, 70° shear wave angle beam transducers mounted on either side of a fastener hole as shown in Figure 1(a). The incident ultrasound generates spiral creeping waves [7] on the surface of the fastener hole, permitting simultaneously monitoring of both sides of the hole over the entire thickness. Figure 1(b) illustrates a top view of one hole, showing that the hole essentially blocks the direct arrival. Some of the incident energy is mode converted to creeping waves which spiral around the hole in both directions, which then mode convert back to shear waves and propagate to the receiver. For the case of a hole with a counterbore and a countersink, arrivals corresponding to a single V echo reflecting from the bottom surface and two double V echoes reflecting from the counterbore and the top surface can be identified as illustrated in Figure 1(c).

![Illustration of ultrasonic monitoring method](image-url)
As cracks initiate and grow, the primary effect is for the cracks to partially block the creeping wave traveling around the hole and thus reduce the received energy. This effect is enhanced as cracks open under load, and the loading also causes a time shift of the received signals due to both elongation of the beam path and the acoustoelastic effect. Figure 2(a) shows a series of waveforms recorded from an uncracked specimen as a function of load, and the time shifts of the various echoes are clearly evident. Figure 2(b) shows a plot of load vs. the measured time shift, and this linear relationship agrees well with theory [5].

Received signals are recorded dynamically during the loading process without stopping the fatiguing. The instantaneous load for each recorded signal is determined from the time shift based upon the measurements from the undamaged specimen (e.g., as shown in Figure 2(b)). If a set of signals is recorded over an appropriate time interval, then a representative set of loads will be obtained. For each signal, and thus for each load, the energy of the echo of interest can be determined. As cracks grow, they will open and close under load, and the energy will be modulated with load. Thus, the overall response will be reduced as the crack size increases, and the relative energy for different loads will decrease as a function of load. This response is quantified by the ultrasonic energy ratio, which is calculated as the ratio of the energy received when a reference load is applied to that obtained with no load. The total crack area is then estimated from the energy ratio [6]. Figure 3 illustrates this entire process. Note that the energy ratio is first normalized by that of the undamaged specimen, and the entire curve is adjusted by smoothing and trend removal prior to crack area estimation.

Fatigue tests were performed on multiple coupons where fatiguing was terminated early in order to obtain energy ratio versus crack size data for small cracks of interest. Specimens were fractured and the crack surfaces were photographed and analyzed to obtain total crack area, total crack length and maximum crack depth. Ultrasonic energy ratio data were correlated to total crack area for the small crack regime, and an approximately linear relationship was established for countersink/counterbore holes. A simple model based upon reasonable assumptions for the beam profile and crack geometries was implemented to extend the correlation to larger crack sizes [6]. The resulting blended calibration curve is shown in Figure 3(d), which is used to map the energy ratio data of Figure 3(c) to the crack area estimates of Figure 3(e).

![Figure 2](image-url)

**FIGURE 2.** Data from undamaged specimen showing time shift versus applied tensile load. (a) Individual waveforms, and (b) typical curve from a single echo.
FIGURE 3. Illustration of estimating total crack area from ultrasonic data. (a) Loads estimated from a set of 50 waveforms, (b) energy vs. load curve, (c) raw and adjusted energy ratios, (d) crack area calibration curve, and (e) estimated crack areas.

REPRESENTATIVE ULTRASONIC RESULTS

During Phase I of this project fatigue tests were performed on a variety of multi-hole coupons and subcomponents, with over 45 instrumented tests having been performed (more than 90 holes). Figure 4 shows typical energy ratio curves and crack area estimates from a 2-hole coupon with counterbore/countersink holes. Figure 4(c), which shows all of the energy vs. load curves from the fatigue test, illustrates typical changes in behavior before and after cracks begin to grow. Note that early in life the curves are essentially flat, whereas later in life the reduction of energy as cracks open under load is clearly evident.

FIGURE 4. Typical ultrasonic results from a countersink/counterbore hole. (a) Energy ratio as determined from dynamic measurements, (b) estimated crack size, and (c) entire family of energy versus load curves showing effect of load on the ultrasonic response as cracks grow.
A large subcomponent containing 18 holes was fatigued to failure over a period of several days as part of the SIPS Phase I demonstration tests. Ultrasonic energy ratio curves and crack area estimates are shown in Figure 5 for the two holes that were instrumented with ultrasonic sensors. One of these holes, hole #25 in the figures, contained the fatal flaw which eventually caused the subcomponent to fail. Ultrasonic sensors were removed after 36869 cycles when cracks on both sides of hole #25 reached the surface, and the specimen was then fatigued until failure. The crack in hole #25 was detected ultrasonically at about 20,000 cycles, which was less than half of the ultimate fatigue life of 42,367 cycles.

Several estimates of crack length were made visually using a 10X magnifier during the fatigue process. Table 1 compares the ultrasonic area estimates to areas computed from the visual estimates of crack length assuming half-penny shaped cracks; the ultrasonic results are consistent with the visual estimates.

### PROGNOSIS METHODOLOGY AND RESULTS

In the context of structural health management, diagnosis is the classification of a current material damage state and prognosis is the estimate of a future material damage state. The challenge of the SIPS program is to achieve unprecedented levels of uncertainty management in material diagnosis and prognosis so that well informed operational and maintenance decisions can be made. Thus far this has been accomplished in the laboratory by employing state-of-the-art physics of failure models and advanced sensor technology combined with adaptive reasoning/prediction methods. Figure 6 illustrates the fundamental approach to uncertainty management. In Figure 6(a), an estimate of the time to a predefined level of damage is made with a lifing model where the significant variance in the prediction is the aggregate of both reducible and irreducible uncertainties. If a damage estimate is available at some future time, as shown in Figure 6(b), it can be used to “calibrate” some of the model’s random variables and thereby realize a more accurate life prediction that could enable a delay in maintenance action without additional failure risk.

![Figure 5](image_url)

**FIGURE 5.** Phase I demonstration test results for two fastener holes instrumented with ultrasonic sensors in an 18-hole large subcomponent. (a) Ultrasonic energy ratio curves, and (b) crack area estimates.

**TABLE 1.** Comparison of ultrasonic and visual estimates of crack area.

<table>
<thead>
<tr>
<th>Cycles</th>
<th>Hole #20 Total Area (mm²)</th>
<th>Hole #25 Total Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Visual</td>
<td>Ultrasonic</td>
</tr>
<tr>
<td>28,800</td>
<td>0.7</td>
<td>1.3</td>
</tr>
<tr>
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<td>3.4</td>
<td>2.1</td>
</tr>
<tr>
<td>33,000</td>
<td>3.4</td>
<td>2.6</td>
</tr>
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</table>
For the work presented here, a detection threshold was assigned to the ultrasonic measurement system. This threshold corresponded to the adjusted energy ratio at which there was 95% confidence that a cracked area of greater than 1 mm$^2$ was present with a 5% false alarm rate. Conceptual sketches of probability of detection, $P_D(a)$, and probability of false alarm, $P_{FA}(a)$, are shown in Figure 7(a), where $a_i$ indicates the detection threshold.

A fused probabilistic model, composed of FASTRAN [8] and Multi-Stage Fatigue [9], was used to generate a distribution of the time to a crack of 1 mm$^2$ (the ultrasonic detection threshold) in any given hole. While the details of generating this Probability Density Function (PDF) are beyond the scope of this paper, the result was a non-normal PDF adequately represented by the distribution shown in Figure 7(b), where $t_i$ indicates the time at which the ultrasonic system first detects the crack. When this event happens, a conditional PDF, $f(t|DC)$, is generated, which is the probability of the 1 mm$^2$ crack occurring at $t$ given that a crack was first detected at $t_i$. This PDF, shown in Figure 7(c), is non-zero for $t > t_i$ because of the probability of false alarm associated with the threshold setting. The equations governing the transformation are [10],

$$f(t|DC) = \begin{cases} \frac{f(t)P_D(a_i)}{P(DC)} & t \leq t_i \\ \frac{f(t)P_{FA}(a_i)}{P(DC)} & t > t_i \end{cases}$$

where $P(DC) = P_D(a_i) \int_0^{t_i} f(\tau)d\tau + P_{FA}(a_i) \int_{t_i}^{\infty} f(\tau)d\tau.$

(1)

Here $P(DC)$ is the probability of a detected crack.

FIGURE 7. Detection probability functions. (a) Sensor probability of detection and probability of false alarm, (b) PDF that the crack reaches the minimum detectable size at a particular time, and (c) conditional PDF that the crack reaches the minimum detectable size given that it was detected (perhaps falsely) at time $t_i$. 
Once the model predictions at the current time \( t_1 \) have been calibrated, the model parameters themselves are refined by first finding the constrained set of model random variables that yield the same likelihood at \( t_1 \) and then using this “calibrated” model for future damage state predictions. Figures 8(a) and 8(b) show snapshots of the actual adaptations based on the current state damage estimate provided by the ultrasonic system.

Initially, life predictions for Hole #25 had wide distributions characteristic of fatigue. At the 50% life point, the prognosis system was able to reduce the standard deviation by a factor of two with the correct mean (within 5%), and by the 75% life point, the standard deviation was reduced by about a factor of ten (see Figure 9).

![Figure 8](image1)

**FIGURE 8.** (a) Prognosis after initial adaptation, and (b) prognosis after subsequent adaptations.

![Figure 9](image2)

**FIGURE 9.** Detection and life prediction results over the course of the test. (a) Estimated crack size distributions, and (b) remaining life predictions.
SUMMARY AND CONCLUSIONS

The ultrasonic in situ crack detection and sizing method developed as a part of Phase I of the DARPA Structural Integrity Prognosis System Program has been successfully demonstrated on through hole and countersink/counterbore hole geometries. The overall methodology is suitable for in situ implementation in an on-aircraft environment where loads are variable and data are acquired while loads are changing. The method offers potentially improved sensitivity compared to static inspection methods because it takes advantage of the applied load opening and closing cracks which modulates the ultrasonic response. Furthermore, it has been successfully demonstrated that the ultrasonic crack area estimates can be used as input to reasoning software to provide accurate estimates of remaining life with significant reductions in uncertainty.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the work of all the SIPS team members at Northrop Grumman, Georgia Tech and Impact. This work is sponsored by the Defense Advanced Research Projects Agency (DARPA), Defense Sciences Office, “Structural Integrity Prognosis System” Program, contract No. HR0011-04-0003, to Northrop Grumman, Integrated Systems, and is approved for public release, unlimited distribution.

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