

# **ACOUSTIC EMISSION DETECTION OF IMPACT DAMAGE ON SPACE SHUTTLE STRUCTURES**

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## ABSTRACT

The loss of the Space Shuttle Columbia as a result of impact damage from foam debris during ascent has led NASA to investigate the feasibility of on-board impact detection technologies. AE sensing has been utilized to monitor a wide variety of impact conditions on Space Shuttle components ranging from insulating foam and ablator materials, and ice at ascent velocities to simulated hypervelocity micrometeoroid and orbital debris impacts. Impact testing has been performed on both reinforced carbon composite leading edge materials as well as Shuttle tile materials on representative aluminum wing structures. Results of these impact tests will be presented with a focus on the acoustic emission sensor responses to these impact conditions. These tests have demonstrated the potential of employing an on-board Shuttle impact detection system. We will describe the present plans for implementation of an initial, very low frequency acoustic impact sensing system using pre-existing flight qualified hardware. The details of an accompanying flight measurement system to assess the Shuttle's acoustic background noise environment as a function of frequency will be described. The background noise assessment is being performed to optimize the frequency range of sensing for a planned future upgrade to the initial impact sensing system.

## KEY WORDS

Impact detection, Space Shuttle, Thermal Protection System, Reinforced Carbon Carbon

## INTRODUCTION

Damage caused by impact of foam insulation shed from the external tank of the Space Shuttle shortly after launch was suspected as a leading candidate for the cause of the loss of the Space Shuttle Columbia during reentry on February 1, 2003. As a result, an experimental test program was initiated during the accident investigation to reproduce this impact event and determine the resulting damage to the thermal protective systems (TPS) on representative Shuttle wing structures. In addition to reproducing the impact and resulting damage that led to the accident, NASA had the foresight to utilize these impact tests to develop and demonstrate acoustic sensor technology to detect impact damage on future Shuttle flights. Previous testing [1,2] had already demonstrated that such sensors might be used to detect and locate micrometeoroid and orbital debris (MMOD) impact events on spacecraft. Although ascent debris damage was the focus of the Columbia investigation, MMOD has also been identified as a significant potential danger to both the Shuttle and the Space Station [3]. Both low frequency accelerometer and high frequency ultrasonic acoustic emission (AE) sensors were evaluated for this purpose during the accident investigation.

Testing during the investigation successfully validated the capability of these sensors for detecting major catastrophic impact damage. However, additional testing has been necessary to develop this sensing approach for application to the remaining Shuttle fleet as NASA prepares for return to flight. These tests have included the determination of sensor response to a range of energies of foam impact events including those that are near to and below the threshold of damage. Additionally, impact tests have been performed with a number of other potential impact materials that can damage the Shuttle during ascent including ice, ablator, and metal. Also, since it is desirable to have the impact sensing system not only detect ascent debris impacts, but also those of micrometeoroid and orbital debris (MMOD) during orbit, testing has been performed to measure sensor response to hypervelocity impacts. In addition to impact testing on structural test articles, testing was performed on the Shuttle Endeavor to study wave propagation effects and evaluate differences in structural configuration between Columbia and the remaining Shuttle fleet. An overview of these test results is now presented, along with a discussion of the planned implementation for impact sensing on the Shuttle

### COLUMBIA ACCIDENT INVESTIGATION FOAM IMPACT TESTING

At the onset of the Columbia accident investigation, it was not known exactly where the foam debris impacted the Shuttle wing. Video images showed that it struck on the lower surface of the left wing. However, the views and resolution available did not indicate whether it struck the leading edge, which consists of reinforced carbon carbon (RCC), or the lower wing surface, which has thermal protection consisting of tile. Thus, a variety of test specimens were fabricated to investigate the damage caused by foam impacts on these structures. In addition, preliminary testing to calibrate the foam impact gun performance as well as test instrumentation configuration was performed using aluminum plate targets. Accelerometers and acoustic emission sensors were included on all of these tests and successfully detected the impacts in all cases.

As the investigation progressed, sensor data from Columbia and forensics of debris provided indications that the damage had occurred on the leading edge, specifically on RCC panel 8. The focus of the impact testing turned toward foam impacts on leading edge panels mounted on a leading edge support structure (LESS) as shown in Figure 1. This test article consisted of a section of leading edge spar using the honeycomb structural configuration from Columbia, to which leading edge panels 5-10 were attached. Because of the enormous expense and limited availability of RCC panels, initial testing was performed using fiberglass replicas of the leading edge panels, with final testing performed on flight RCC panels. An array of 8 AE sensors (Digital Wave Corporation model B225-5) was attached on the interior side of the spar. The bandwidth of these transducers was specified by the manufacturer to be 30 KHz to 300 KHz. However responses well below 10 KHz were measured. Initial testing with the sensors arrayed close to the impact point demonstrated that signals of significant amplitude were produced and that these signals propagated through the attach fittings into the spar. For later testing, the sensors were arrayed along the length of the spar as shown in Figure 1 to determine how well the signals propagated along the spar, and thus how remote the sensors could be located and detect the impact. As the foam impacts and the attenuation of the complicated structure resulted in very low AE frequency signal content, the AE data was acquired at a sampling frequency of only 500 kHz with a total of 32 Kpoints acquired for each sensor.

For the defining test of the investigation, a foam block weighing 1.67 lbs. was launched at a velocity of 237 m/sec, striking panel 8 as indicated in Figure 1. This impact produced a significant hole in the RCC panel providing conclusive evidence for the Columbia Accident Investigation Board in determining the cause of the accident [4]. The AE signals that were detected from this foam impact event are shown in Figure 2. Only 6 dB of gain was applied to the signals from the AE sensors. As would be expected, the largest signal, arriving earliest in time was that from sensor 5, which was nearest the impact site. Decreasing arrival times and amplitudes of signals from sensors located further away from the impact point were observed. Although not noticeable in this figure as all signals are plotted on the same scale, signals were detected all the way down to the location of sensor 1, suggesting that impact events can be detected by sensors mounted several RCC panels away, a distance of more than 1 m. Examination of the arrival times for signals from sensors 7 and

8 showed that the impact site could be localized with respect to the upper and lower surface of the leading edge.

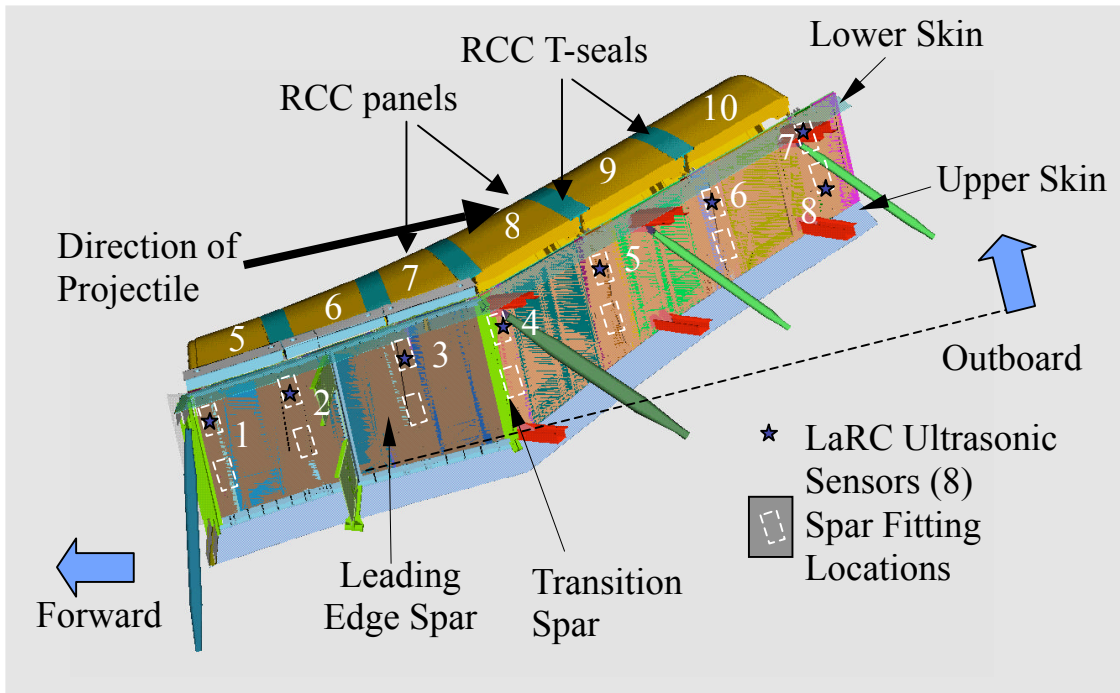


Figure 1. Leading Edge Support Structure with RCC panels 5-10 and T-seals shown. The locations of the AE sensors 1 through 8 are indicated with black stars.

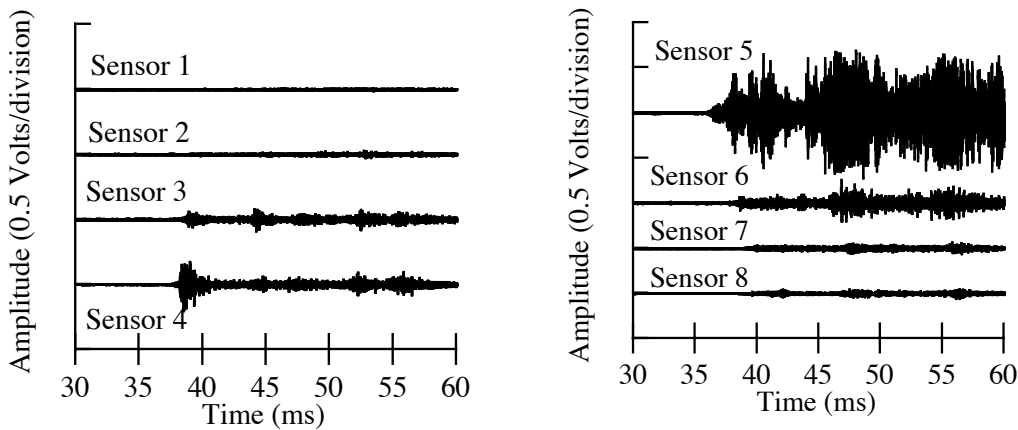


Figure 2. AE signals from foam impact on Shuttle RCC wing leading edge.

### RETURN TO FLIGHT TESTING

At the completion of the accident investigation, a number of questions remained regarding the capability of acoustic impact sensing on the Shuttle. These included the detectability of much smaller foam impacts including those near or below the threshold of damage, the characteristics of signals caused by other potential impact source materials including ice, ablator, and metal at ascent velocities as well as hypervelocity impacts to simulate orbital impacts. These effects needed to be assessed for impacts on both the leading edge as well as on the tile protected lower wing surface including the main landing gear door. Another issue was that the construction of the wing spar on the remaining Shuttle fleet varied considerably from that of Columbia and the effects of this

difference on acoustic wave propagation had to be investigated. Thus, a comprehensive test program was initiated to address these questions. As it is impossible, as well as expensive, to test all possible combinations of impact parameters, a simultaneous modeling effort was initiated to develop capabilities to model impact events on Shuttle wing structures. One key experimental piece of data required for these models was the measurement of the transfer function of the acoustic signals from the RCC leading edge to the spar where sensors are located. Additional experiments were performed to acquire this critical data.

### Launch Debris Impact Testing

Additional foam impact tests were performed on RCC panels over a range of projectile sizes and impact velocities. These impact tests were performed on different panels on the LESS test article, as well as on the T-35 test article, which represented a more outboard section of the wing. This test article allow impact tests on panels 16 and 17 and further provided the opportunity to evaluate the effect of differing impact locations on measured signals. Signals from small projectiles and/or low impact velocities producing impact energies below the threshold of damage were still readily detected. Variations in the signal amplitude correlated with the impact energy. In addition to sensors on the spar, sensors were also placed on the RCC panel of the T-35 test article to measure the transfer function response from the RCC panel to the spar. The frequency response plots in Figure 3 show the significant loss in high frequency signal content that occurs as the signal propagates from the RCC to the wing spar of Columbia construction. Preliminary testing on test articles with the wing spar construction of the remaining Shuttle fleet suggests that this high frequency attenuation might not be as severe.

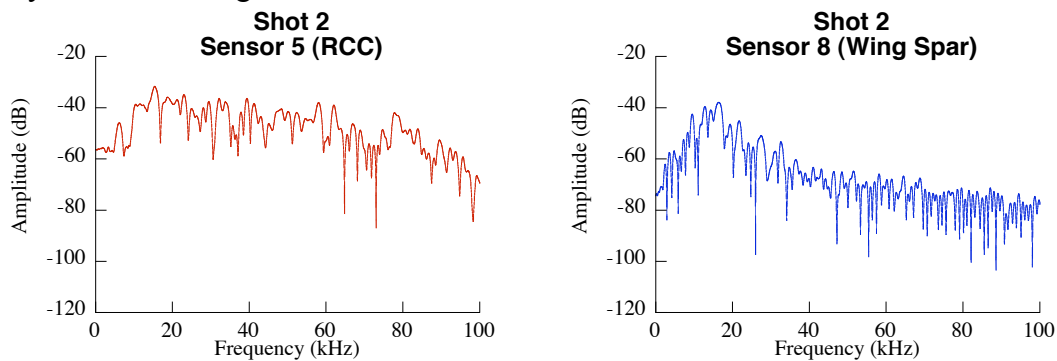


Figure 3. Frequency content of foam impact signals for sensors on RCC panel and wing spar.

Foam impact tests were also performed on lower wing specimens representative of regions on which the thermal protection material is tile. Specimens from this region of the wing also included a main landing gear door. Representative damage for a wing specimen impacted by foam at approximately 259 m/sec is shown in Figure 4 in which a hole formed by a tile that was broken away by the impact can be observed. Signals were again readily detected by AE transducers for all impact conditions studied. Although the signals were very complex due to the complicated nature of the source and the complex structural geometry of the tile and wing specimen, source location could be determined using appropriate frequency filtering to selectively analyze the flexural mode of propagation.

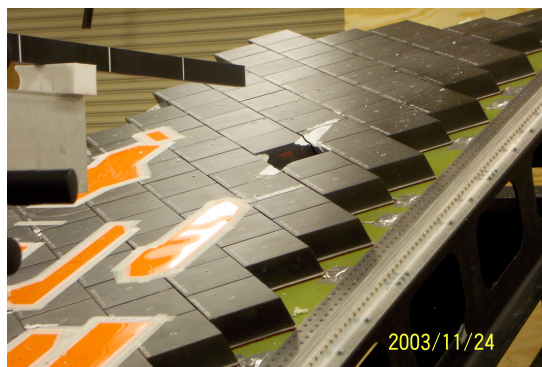


Figure 4. A wing acreage tile test article showing the resulting tile loss due to a foam impact.

Impact testing on RCC and tile specimens was also performed using other types of potential launch debris. These materials included ice, ablator and metal. Again, the impact velocity and energy was varied over a range from below the damage threshold to that causing substantial damage. AE and accelerometer sensor data were obtained for all tests. Preliminary analysis shows that all impacts were successfully detected with both accelerometers and AE sensors, and that again there was a correlation between signal amplitude and energy of impact.

### Hypervelocity Impact Testing

Hypervelocity impact tests are being performed to simulate micrometeoroid and orbital debris (MMOD) damage that can occur once the Shuttle is in orbit. Initial tests were performed on flat metal and fiberglass plates to develop a database to support modeling efforts as well as to determine appropriate instrumentation settings. Figure 5 shows typical damage resulting from two hypervelocity impact events at 6.8 km/s in a fiberglass plate. The smaller impact was created by a 1 mm diameter aluminum projectile while the larger was created by a 2 mm aluminum projectile, which fully penetrated the plate. Contrary to previous hypervelocity impact testing in graphite/epoxy composites plates [1], the AE signals in the fiberglass plates contained only extensional mode components with no flexural mode present. This is shown in the signals of Figure 6a. For comparison a lead break simulated AE signal near the impact site shown in Figure 6b clearly shows the extensional and flexural mode components. It is interesting to note in comparing these signals that there was 64 dB of attenuation applied to the signals from the hypervelocity impact as compared to 47 dB of gain for the lead break signal. There is a tremendous amount of energy in the hypervelocity impacts. Figure 7 shows the raw signal amplitude, after adjustment for the attenuation, from a series of hypervelocity impacts on a fiberglass plate as a function of impact energy. As shown in this figure, the raw signal amplitude increases with corresponding impact energy until it peaks at nearly 80 volts for an impact energy of nearly 100 J. For impacts exceeding 100 J, the projectile penetrates the plate and a decrease in AE signal amplitude is observed. Additional testing is ongoing to further understand this decrease in signal amplitude after penetration as this may be important in determining impact detection thresholds.

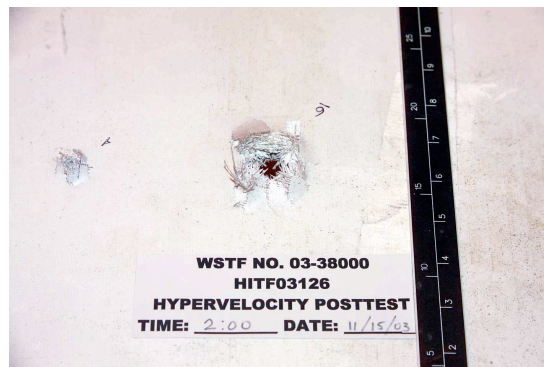


Figure 5. Fiberglass panel showing damage from two hypervelocity impacts.

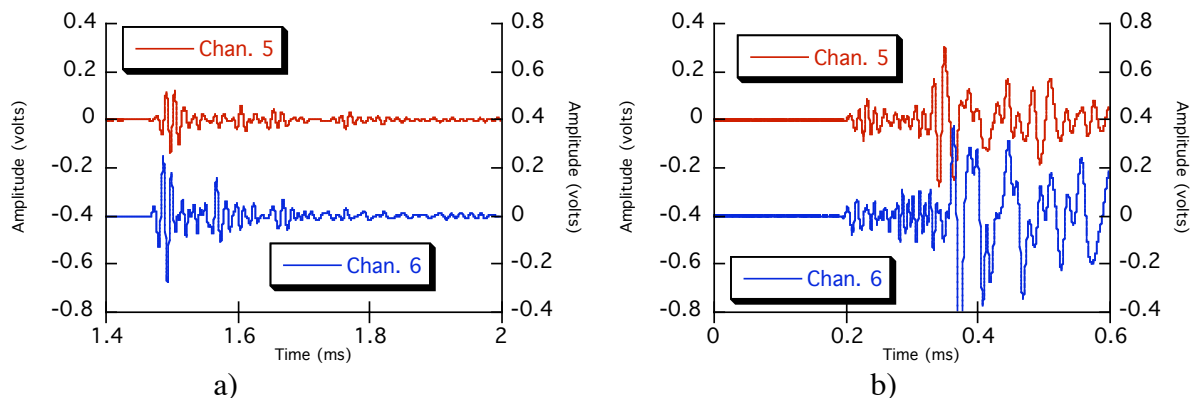


Figure 6. AE signals produced by a) hypervelocity impact and b) pencil lead break.

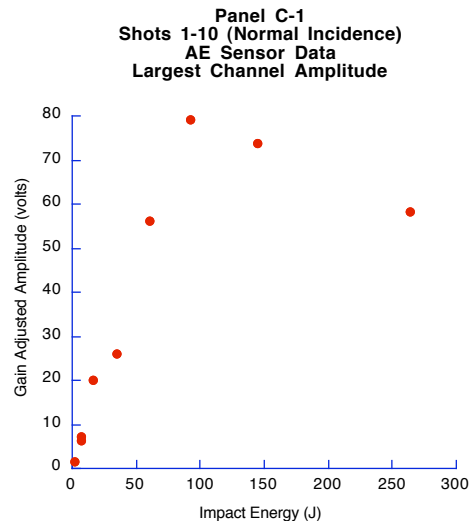


Figure 7. AE signal amplitude versus impact energy

Propagation effects on AE signals from the impacted material through attachment mechanisms to likely sensor locations on the spar are also being investigated. Initial testing for this consisted of multiple plates connected by threaded rods. More recently, a realistic Shuttle wing spar test article has been fabricated and is being tested. Again, because of the expense of RCC panels, initial testing is using a fiberglass replica of a leading edge panel. These tests have shown that the much higher frequency hypervelocity impact signals are much more heavily attenuated than was observed for the lower frequency foam impact signals. Further analysis is necessary to determine the transfer function. In addition, hypervelocity impact testing of an actual RCC panel is planned.

### Impact Hammer Testing

Impact hammer and pulse-receive ultrasonic measurements were made on the wing spar of the Shuttle Endeavor to investigate the effects on wave propagation due to differences in wing spar construction. As noted previously, the LESS and T-35 test articles represented the Columbia wing spar construction which is different from the remainder of the fleet. Transducers were attached to the leading edge of the Shuttle's wing, as indicated in Figure 8. At various locations, ultrasonic signals between 10 to 150 KHz were introduced and recorded on the fixed transducers. In addition, a series of low energy, instrumented hammer impacts (20, 60, 150 and 250 lbs) were performed on the wing's leading edge. Similar experiments were performed on the LESS and T-35 test articles to develop a correlation between the different structures. Figure 9 shows the frequency response of AE sensors to a hammer impact on the Shuttle Endeavor wing spar as well as on the LESS test article. Although the overall peak amplitudes of the time domain signal are similar, the frequency response shows that the peak amplitude is at a much lower frequency with much higher frequency attenuation for the LESS as compared to the Shuttle. These differences are significant in that they indicate that higher frequency signal components may propagate from impacts on the Shuttle to and along the spar. Such higher frequencies may enable improved signal to noise for detection as the background noise is expected to decrease with increasing frequencies. However, no database exists for measurements of the background noise for ultrasonic frequencies on the Shuttle. A flight experiment to obtain this information is being planned to enable optimized sensor frequency selection for a planned upgrade to the Shuttle impact sensing system.

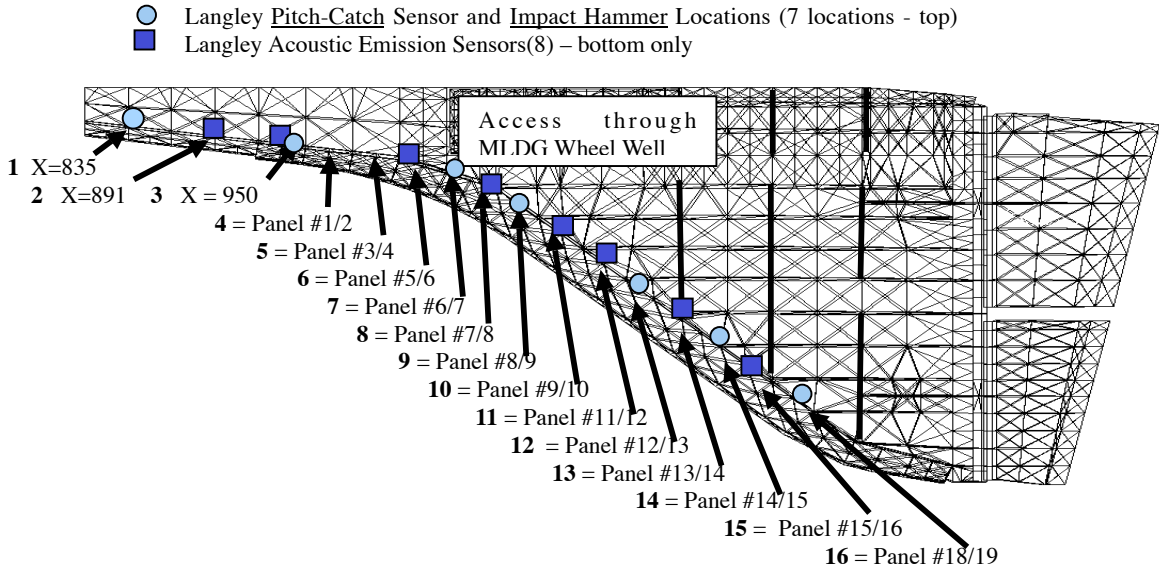


Figure 8. Layout of transducer locations inside the Shuttle Endeavor's wing.

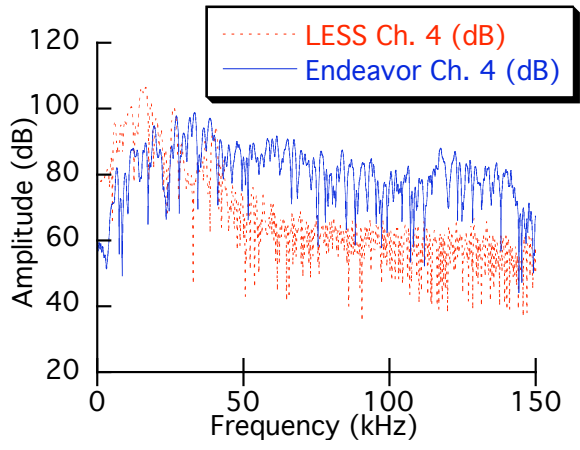


Figure 9. Frequency response for 150 lb hammer impact on Shuttle Endeavor wing spar and Leading Edge Structural System (LESS) test article.

SHUTTLE IMPACT DETECTION IMPLEMENTATION

Although AE sensors have been successfully demonstrated for the detection of impacts on Shuttle wing structures, no AE sensor systems are currently flight qualified for Shuttle application. Thus, the initial implementation of an impact sensing system on board the Shuttle for the return to flight mission will consist of wireless accelerometer sensors. These sensors were previously flight qualified for the Shuttle for other applications. Additionally, they have been successfully tested alongside the AE sensors for the purpose of impact detection. Sixty-six accelerometers will be mounted onto the both the left and right wing leading edge spars. Data from all will be recorded at 20 kHz during the launch and ascent. Because of battery life constraints, once the Shuttle is in orbit, selected sensor data acquisition units will be powered down, and then rotated into powered status to provide continuous coverage during the mission. Data from the sensors will be periodically transmitted to a laptop computer onboard the Shuttle for preliminary analysis. Peak sensor readings will then be telemetered to Mission Control for further analysis to determine if an impact has occurred, and if so, what corrective actions need to be taken. This initial implementation will only address impact detection on the wing leading edge, which is where the

Columbia was impacted. Pending successful deployment of this system, along with further analysis of impact test results on wing tile areas, NASA will investigate deployment of additional sensors to monitor the lower wing surface.

As discussed previously, one concern for this sensing system is how background noise will affect the detection of impacts. Previous accelerometer data from the wing spar location on early Shuttle flights suggests that the noise will be below the signal level for most impact conditions. A significant advantage that might be gained from ultrasonic AE sensors might be in reduced background noise. However, no flight data of ultrasonic background noise exists. Thus, in addition to flying accelerometers, there are plans to flight qualify ultrasonic AE sensors to collect background noise data for the Shuttle wing leading edge. These would be monitored by a similar wireless data acquisition system, but acquiring data at 500 kHz. These measurements will provide a database on which to determine the optimum frequency range for impact detection on the Shuttle leading edge. Development, flight qualification, and deployment of an upgraded impact system is then planned.

### CONCLUSIONS

AE sensors and accelerometers were used to monitor foam impact tests on Shuttle test articles as part of the Columbia accident investigation. These tests demonstrated that acoustic sensing could be used to detect and locate catastrophic impact events on the Shuttle wing leading edge. Follow-on testing has demonstrated this capability for a wide range of impact conditions on both the leading edge as well as the lower wing surface. These tests have included much smaller impact energies at and below the threshold of damage, different impact materials, and hypervelocity impact conditions designed to simulate micrometeoroid and orbital debris damage. Additional testing has analyzed the effects of different wing spar constructions on the propagation of impact generated acoustic waves along the spar.

As a result of this testing, an initial impact sensing system has been developed for the Shuttle return to flight. A major driver in the choice of accelerometers for this initial system was the availability of previously flight qualified wireless sensors that could be easily integrated into the Shuttle wing spar. However, because of the potential for lower background noise at higher frequencies, acoustic emission sensors are being used to monitor all of the impact tests and are planned for flight on the Shuttle to measure the background noise level. Results from the ultrasonic background noise flight measurements, along with the impact experimental database and model calculations will be analyzed to determine the optimum frequency range for a future upgrade to the Shuttle impact detection system.

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