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 led NASA to develop and implement on-board impact detection technologies. AE sensing, both with accelerometers and ultrasonic sensors, was 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 was performed on both reinforced carbon composite wing leading edge materials as well as Shuttle tile materials on representative aluminum wing structures. Results of these impact tests are presented with a focus on the acoustic emission sensor responses to these impact conditions. These tests demonstrated the potential for on-board Shuttle impact detection and provided a data base on which to analyze signals from sensors onboard the Shuttle Discovery during the STS-114 Mission. On this flight, arrays of accelerometers mounted on the wing leading edge spar were monitored for potential impact damage. Preliminary results from this Shuttle Wing Leading Edge Impact Detection System (WLEIDS) are discussed.

Keywords: Impact detection, Space Shuttle, Thermal protection system, Reinforced carbon-carbon

1. 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 had 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 impact damage. However, additional testing was necessary to develop this sensing approach for application to the remaining Shuttle fleet. 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 test articles and the remaining Shuttle fleet. An overview of these test results is presented, along with preliminary results from sensors deployed on the Shuttle Discovery during the STS-114 Mission.

2. 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 Fig. 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 Corp. 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 Fig. 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 K-points acquired for each sensor.

For the defining test of the investigation, a foam block weighing 758 g (1.67 lbs) was launched at a velocity of 237 m/sec, striking panel 8 as indicated in Fig. 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 Fig. 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. Quantitatively 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.

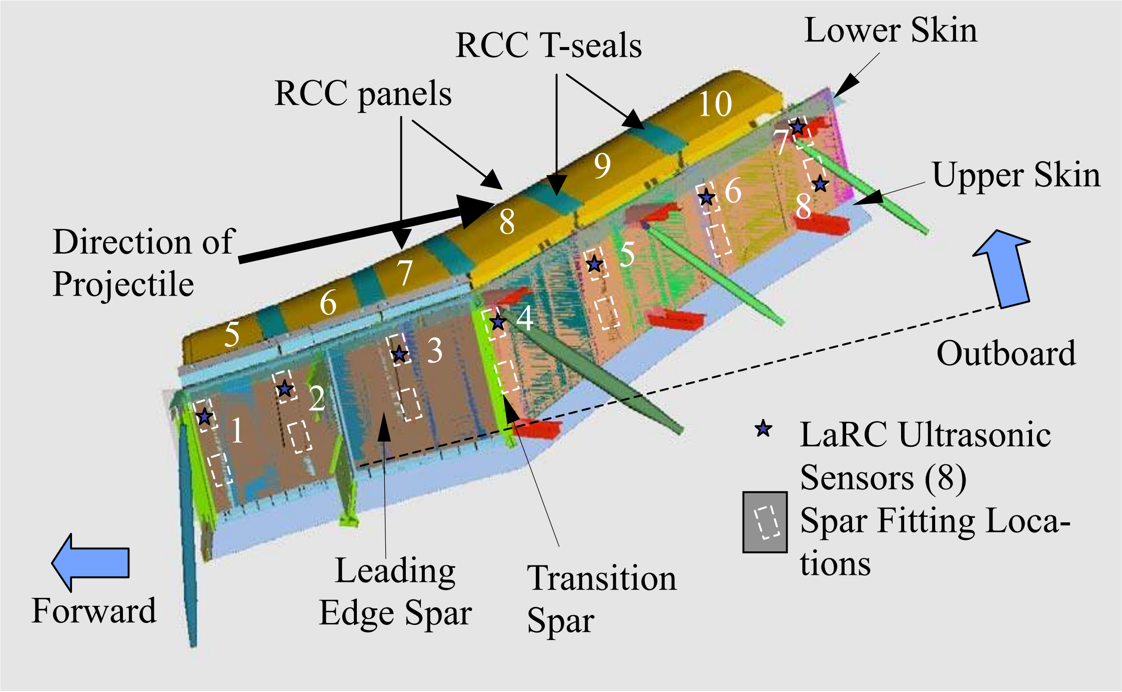


Fig. 1 Leading Edge Support Structure with RCC panels 5-10 and T-seals shown. The locations of the AE sensors 1 through 8 are indicated with black stars.

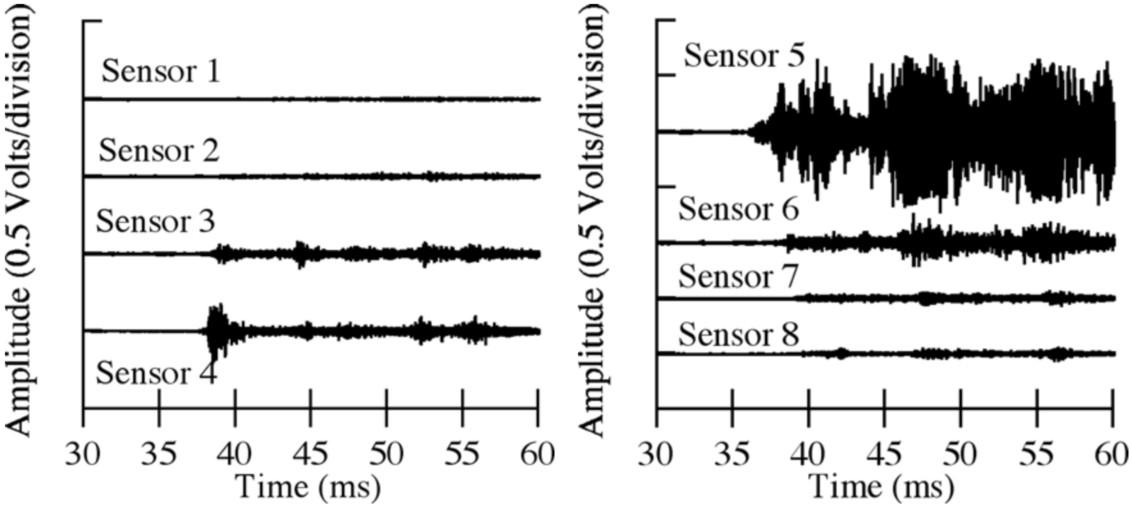


Fig. 2 AE signals from foam impact on Shuttle RCC wing leading edge.

3. 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 preformed to acquire this critical data.

3.1 Launch Debris Impact Testing

Additional foam impact tests were preformed 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 allowed 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 for a given type of impact material. However, different impact materials such as foam and ice exhibited different amplitude- impact energy relationships. 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 Fig. 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.

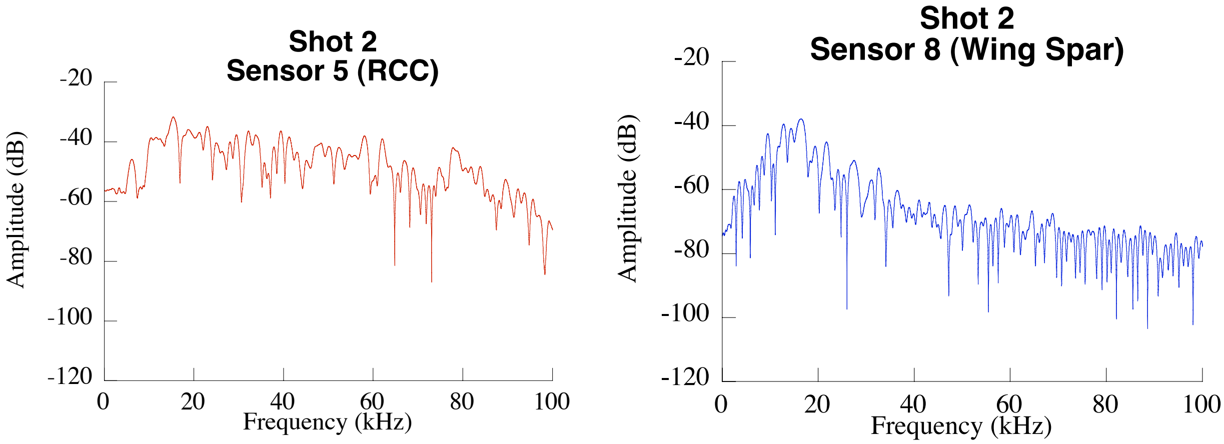


Fig. 3 Frequency content of foam impact signals for sensors on RCC panel and wing spar.

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 290 m/sec is shown in Fig. 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.

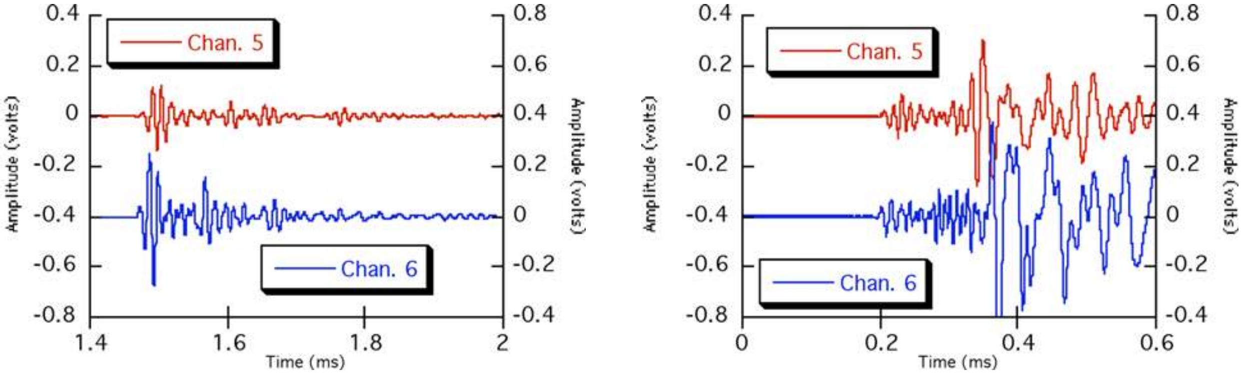
Fig. 4 A wing acreage tile test article showing the resulting tile loss due to a foam impact.

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 for a given impact material.

3.2 Hypervelocity Impact Testing

Hypervelocity impact tests were 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 2-mm diameter aluminum projectile while the larger was created by a 6-mm aluminum projectile, which fully penetrated the plate. Figure 6a shows the signals from a hypervelocity impact, while for comparison, a lead break simulated AE signal near the impact site is shown in Fig. 6b. Curiously, the flexural mode amplitude was generally smaller than the extensional mode, especially at the higher energy shots. This is interesting since low velocity impact usually produces a large amplitude flexural mode due to the source motion perpendicular to the plate target. In the present case the attenuators played a role in filtering the low frequencies that generally confirm the presence of a flexural wave. However, the source function for hypervelocity impact is quite a bit different than ball drop at low velocity or a lead break. It is also 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. In the fiberglass plates, for impacts exceeding 100 J, the projectile penetrates the plate and a decrease in AE signal amplitude was observed. However, for actual RCC leading edge specimens, a decrease in AE was not observed after impact penetration.

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



a) hypervelocity impact

b) pencil-lead break

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

Propagation effects on AE signals from the impacted material through attachment mechanisms to likely sensor locations on the spar were also investigated. Initial testing for this consisted of multiple plates connected by threaded rods, followed by testing on a realistic Shuttle wing spar test article. Again, because of the expense of RCC panels, testing included hypervelocity impacts on a number of fiberglass replicas of a leading edge panel, followed by shots on an actual RCC panel. These tests demonstrated 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 was performed to determine the transfer function from the RCC to the spar where the sensors are located on the flight vehicle.

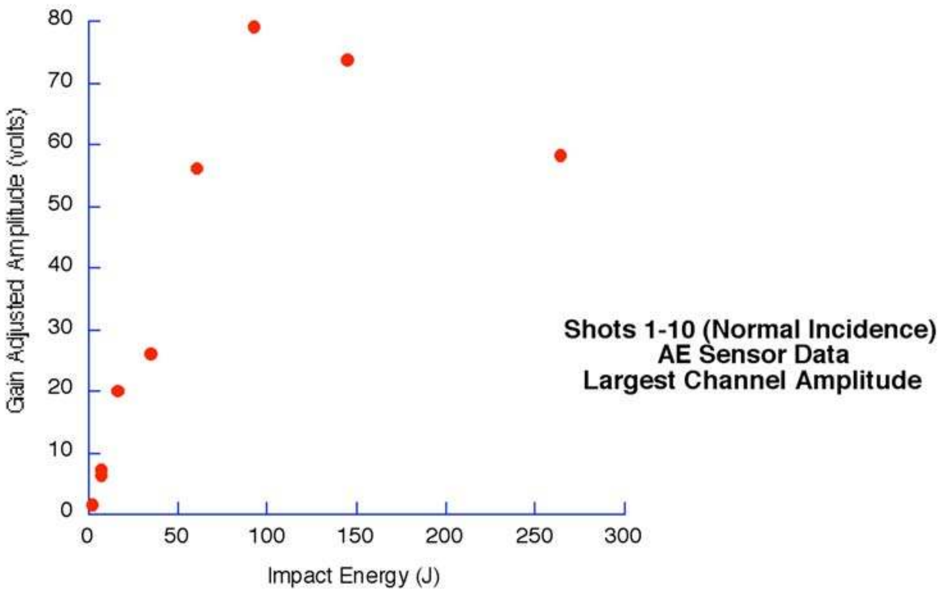


Fig. 7 AE signal amplitude versus impact energy.

3.3 Impact Hammer Testing

Impact hammer and pulsed pitch-catch 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 Fig. 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 (9.1, 27.2, 68.1, 113.5 kg) 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

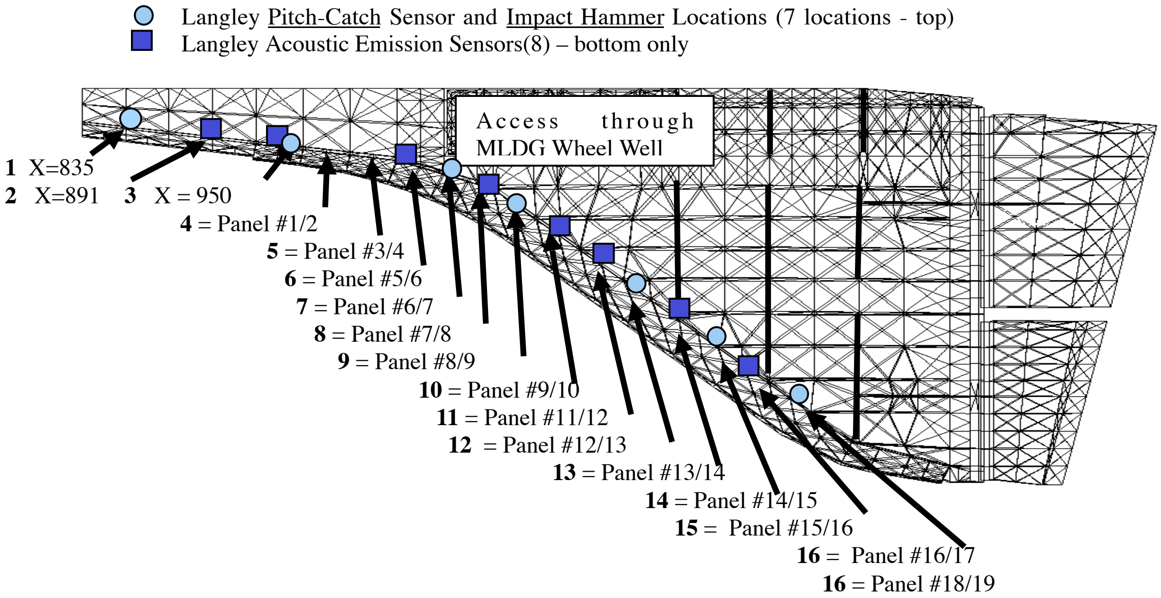


Fig. 8 Layout of transducer locations inside the Shuttle Endeavor's wing.

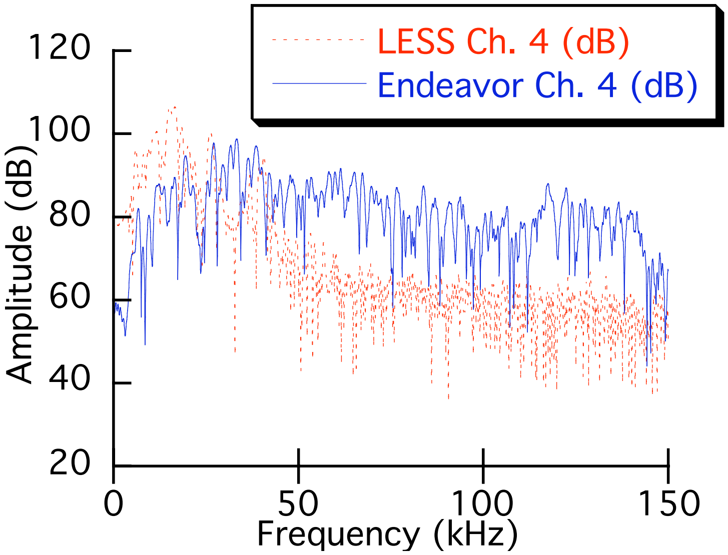


Fig. 9 Frequency response for 68.1-kg hammer impact on Shuttle Endeavor wing spar and Leading Edge Structural System (LESS) test article.

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 the next generation to the Shuttle impact sensing system.

4. Shuttle Impact Detection Implementation

Although both accelerometers and ultrasonic AE sensors were demonstrated to be successful at detecting impacts on Space Shuttle structures, accelerometers were chosen for the initial implementation of the WLEIDS because of the availability of existing flight qualified sensors and instrumentation. Arrays of 66 accelerometers were deployed on each wing leading edge spar of the Shuttle Discovery for the STS-114 Mission. The data from these sensors were recorded by arrays of 22 battery-powered data acquisition/wireless transmission units mounted in each wing cavity. Each data acquisition unit recorded the output from three accelerometers as well as one temperature sensor. The system recorded data from all sensors continuously during launch and ascent to orbit, digitizing the signals at a sampling frequency of 20 kHz. Then, to conserve battery life, the system was switched into on-orbit monitoring mode during which smaller sets of sensors were monitored to record the background noise level and any triggering MMOD impacts. During this time, data was also transmitted wirelessly to a laptop computer in the crew compartment and then downlinked to Mission Control at the Johnson Space Center for analysis. Figure 10 shows the key components of the WLEIDS system.

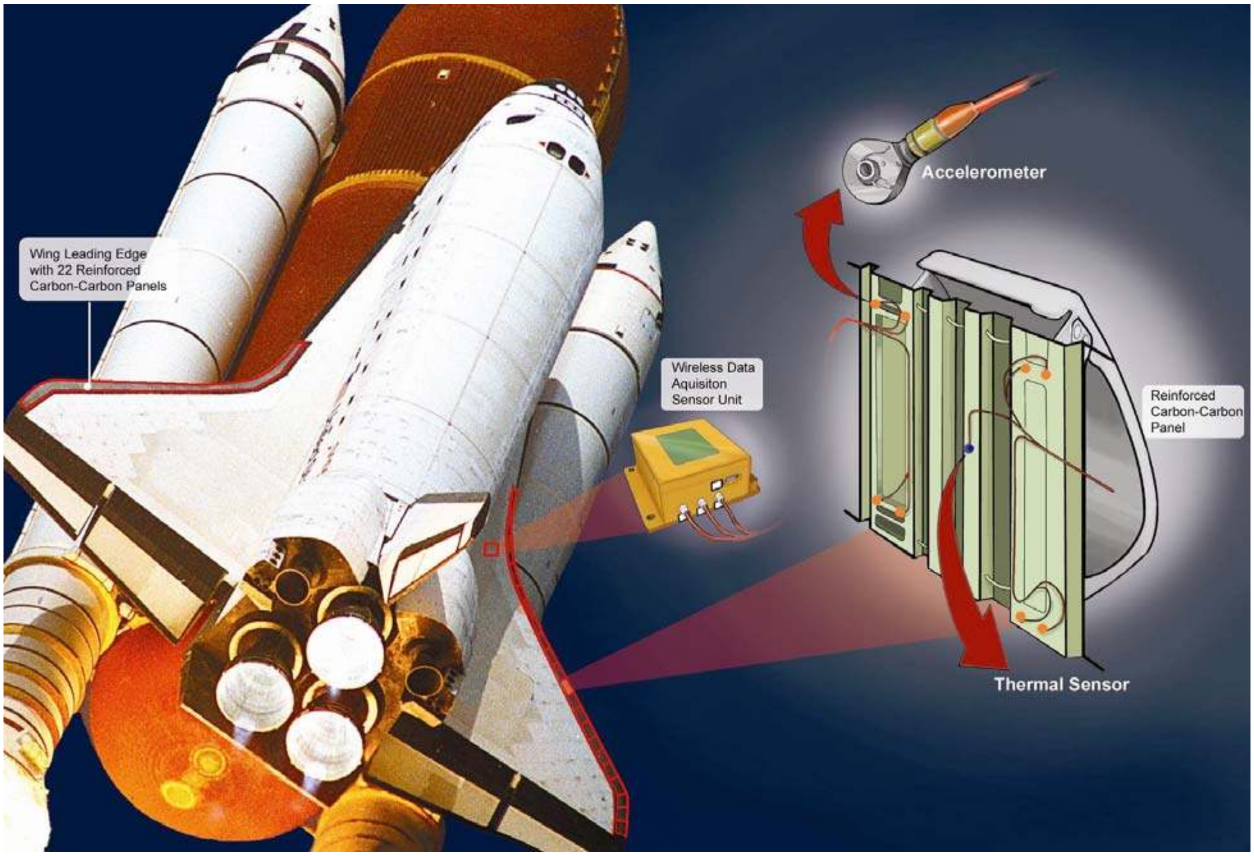


Fig. 10 Key components of the Shuttle Wing Leading Edge Impact Detection System.

Because of limited data acquisition unit battery life and telemetry bandwidth, the complete time history data from all sensors could not be transmitted to Mission Control for analysis during the flight. Preprocessing routines in the data acquisition units calculated Grms (RMS value of the g-forces recorded by the sensors) values for the sensor units and then created summary files of the largest Grms peaks. These summary files were then downlinked for preliminary analysis. Peaks that occurred globally across the wing were discounted as impacts and most often correlated with mission specific events such as main engine ignition, solid rocket booster (SRB) ignition, maximum dynamic pressure, and tank and SRB separation. Local peaks were analyzed as potential impacts by dowlinking and evaluating short intervals of the time history response for multiple sensors near a suspected impact location. Additionally, suspected impact events were correlated with other data sources such as video and radar recordings of the vehicle during launch and ascent.

For the STS-114 Mission, the WLEIDS performed exceptionally well. All sensor data acquisition units successfully triggered at launch and data was recorded from all sensors. The summary files were successfully downlinked and led to the identification of only a small number of probable impact events. None of these probable impact events were of amplitude consistent with critical damage to the RCC leading edge and in-flight inspection at the suspected impact locations using the Orbital Boom Sensing System did not reveal damage. The complete time history data from all sensors was retrieved from the vehicle after the flight and is currently being analyzed. The focus of this post-flight analysis is to determine if any potential impacts were missed during the analysis of the summary files during the Mission, and to develop and evaluate improved algorithms for impact signal identification during future flights.

5. Conclusion

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 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 was developed and successfully deployed on the Shuttle Discovery on the STS-114 Mission. Accelerometers were used in this Wing Leading Edge Impact Detection System due to the availability of previously flight-qualified sensors and wireless data acquisition units that could be easily integrated into the Shuttle wing spar. The system preformed as designed detecting only a small number of probable impact events that were of a magnitude small enough to have not caused damage. Post-flight analysis of the complete data from the Mission is ongoing to develop improved impact detection methodologies for future Shuttle flights.

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