Validation of a Lamb Wave-Based Structural Health Monitoring System for Aircraft Applications

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ABSTRACT

Structural Health Monitoring technologies have the potential to reduce life-cycle costs and improve reliability for aircraft. Previous research conducted by the Metis Design Corporation has demonstrated the ability of Lamb wave methods to provide reliable information regarding the presence, location and type of damage in coupon-level specimens. Several critical system components have been developed during the course of this research, including circuitry and packaging, and integrated into the Monitoring & Evaluation Technology Integration (M.E.T.I.) Disk. In order to demonstrate the validity of M.E.T.I.-Disks for aircraft applications, a testbed has been fabricated by dividing a 1/8" plate of aircraft-grade aluminum into four equal quadrants with several c-channels. M.E.T.I.-Disk nodes were then placed in the center of each quadrant, and data was collected and interpreted by the METISv2.10 software package. The results produced by this software validated the M.E.T.I.-Disk by using a single undamaged cell to calibrate the system, and then correctly identify that there was no damage present in the remaining quadrants. Next, representative damage was introduced into several combinations of the quadrants, and the software was executed again to query the structure. The resulting data revealed the presence and location of damage, while still identifying the two undamaged regions.

Keywords: Structural Health Monitoring, Lamb waves, ultrasonic sensors, piezoelectric, NDE, NDT, algorithms

1. INTRODUCTION

Currently successful laboratory non-destructive testing methods, such as X-radiographic detection and C-scans, are impractical for service inspection of large integrated aircraft subsystems. Heritage techniques such as the "tap-test" are extremely technician-sensitive and statistically unreliable. More recent techniques, such as acoustic emission testing, modal surveys, thermographs, and X-rays are not easy to employ due to the size and complexity of the support equipment required [1]. Worse yet, these techniques are difficult to employ once the component item in question has been integrated into an assembly and access to the item in question has become limited. The principal problem is determining the presence and extent of suspected structural anomalies in a structure when visual inspections may not suffice, and more perceptive NDE techniques are not practical. It is clear that new approaches for aircraft inspection need to be developed [2-5]. To address this necessity, the Metis Design Corporation (MDC) has been working to develop a structural health monitoring (SHM) system to facilitate damage detection using Lamb waves driven and received by piezoelectric wafers. This method has successfully demonstrated the ability to provide reliable information about the presence, severity and type of damage in simple coupon specimens. Therefore the focus of the present research is to validate the utility of this SHM method when applied to a representative built-up aircraft structure.

The basis for much of the work reported in this paper is a continuation of the authors' previous Lamb wave research, investigating piezoelectric-based methods for in-situ damage detection of composite materials [6]. During this investigation several potential NDE methods and SHM components were investigated for detecting damage in composite materials. Other publications by the authors on this same subject can be found in several journals and conference proceedings, focusing on the different detection methods and system architectures [7-17]. The conclusion of this research was that Lamb waves offered the best resolution and power to range ratios for the detection of damage in large structures. Lamb waves are a form of elastic perturbation that can propagate in a solid plate with free boundaries [18-20]. The present work utilizes piezoelectric patches to excite the first anti-symmetric Lamb wave (A_0 mode) in composite specimens. Lamb wave techniques have proven to provide more reliable information about the presence and

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type of damage in a complex specimen than other methods. They have also demonstrated suitability for health monitoring applications since they have a large coverage area, can be applied with low power and conformable actuators and sensors, and they can provide useful information about the state of a structure during operation. Over the past several years, MDC has developed several infrastructure components to facilitate Lamb wave testing, collectively called the Monitoring & Evaluation Technology Integration System, or M.E.T.I.-System. The main product in this line of SHM devices is the M.E.T.I.-Disk, which contains an actuator, sensor, integrated circuit, connectors and a protective case, which will be further described in the following section. The research presented in this paper is an important step in demonstrating the viability of Lamb waves for aircraft in-situ damage detection. Eventually SHM technology will enable the elimination of scheduled inspections, and will allow condition-based maintenance for efficient structural design, increased reliability and reduced overall life-cycle costs [21].

2. EXPERIMENTAL SETUP

2.1. Device design

In order to implement Lamb wave methods on a representative structure, MDC has developed a device named the M.E.T.I.-Disk 2. As seen in **Figure 1**, the overall package footprint of the device covers an area of less than 5cm^2, and the device stands 8mm high. The main elements of this device are concentric piezoceramic actuator and sensor wafers machined from PZT-5A. Bonded to the top and bottom of these elements are thin-film flexible circuits that extend patterned electrodes to the wafers and provide a Faraday's Cage for electrical shielding. The flexible circuits terminate in micro-connectors to allow simple electrical connections with a strain relief. Finally, all of these components are contained within an injection molded Delrin casing to provide protection against incidental impact and moisture absorption. In the near future, similar tests to the ones described in this paper will be conducted using a slightly larger diameter device called the M.E.T.I.-Disk 3, which incorporates datalogging and function generating capabilities within the device package as well. Also in development is the M.E.T.I.-Disk 4, which further adds wireless capabilities to this SHM device.

2.2. Hardware

While using the M.E.T.I.-Disk 2, there are three hardware components necessary to evaluate the state of damage in a structure. First an arbitrary function generator (AFG) is necessary to produce a 20Vpp signal between 10 and 100kHz in order to excite the actuator and stimulate Lamb waves. In this case, MDC used the Agilent 33220A AFG, which easily meets these requirements. Next, an oscilloscope is needed to collect the resulting ~20mVpp signal from the sensors at 1MHz on two channels, one for the sensor to measure damage and one for the actuator to measure the device's health. In this case the Tektronix TDS3014 digital oscilloscope was used, selected because of its Ethernet connectivity. The final piece of necessary hardware is a computer to run the applicable software to conduct the SHM testing. In this case a Dell workstation was used, however there are no particular requirements for the PC other than Ethernet connectivity. Each of the three pieces of hardware were connected to the same LAN workgroup, so that all the testing could be performed remotely via a LabVIEW executable program, which is further described in the following section. Finally, the M.E.T.I.-Disk 2 devices were connected to the necessary hardware using modified coaxial cables with micro-connectors on one end and traditional BNC connectors on the opposite end.

2.3. Testbed

The representative aircraft structure chosen for the present research was a 3mm thick sheet of 6061 aluminum, divided into four equal quadrants with several bonded c-channel ribs to simulate a skin and stringer fuselage configuration. As seen in **Figure 2**, each quadrant was roughly 45cm square, and the overall testbed was roughly 1m square. One M.E.T.I.-Disk 2 node was bonded into the center of each quadrant using a thin-film room-temperature adhesive, cured under a 1.5kg weight for 24 hours. Representative damage was introduced by placing a 4x6cm rectangular 1.5kg weight on predetermined locations in each quadrant using an ultrasonic shear couplant. Damage is normally detected by Lamb wave methods due to the local change in the stiffness/density ratio of the structure causing a wave reflection. By adding the mass and thickness of the weight to the structure, an effectively inverse-damaged region is created, thereby simulating the same effect that damage would have on the propagating Lamb waves. This representation has been found in the literature as an acceptable way to simulate damage non-permanently in specimens.

3. ALGORITHMS

3.1. Theory

Damage detection using Lamb waves is accomplished through a relative comparison of test measurements with baseline measurements obtained from an undamaged structure. The MDC algorithm seeks to classify whether the test measurement belongs to the undamaged set through three separate analysis phases, each of which contributes in varying degrees to determine the presence and location of damage. If the test measurement does not belong to the undamaged set, it is considered to be damaged and the damage location is extracted. This multi-phase approach is extremely effective because each analysis focuses on decomposing different, but not mutually exclusive, aspects of the signal using different methods. Therefore, the approach yields a composite view of the test measurements relative to the baseline measurements. The first phase utilizes an energy packet analysis where the energy level of identified wave packet at distinct time periods between the baseline and test signals is compared. A second phase employs a normalized difference method where the difference between the baseline and test voltages is used to detect changes. The third phase exploits the continuous wavelet transformation of the weighted difference between the baseline and test signals. This analysis phase allows the test measurements to be analyzed both in the time and frequency domains. The results from each individual analysis are weighted according to their relative accuracy and sensitivity in identifying the presence and location of damage. The weighting scheme is calibrated using statistics from the original baseline set of data, and subsequently used for any damage test analysis conducted in conjunction with that baseline measurement.

3.2. Software implementation

The theories described above were then translated by MDC engineers into algorithms to be implemented using LabVIEW software. LabVIEW is a unique platform that allowed the integration of hardware control, data collection fusion and analysis and result reporting all within a singe executable file. The release of software that was used for the present research was METIS v2.10, which includes the latest proprietary MDC algorithms, a simplified graphical user interface (GUI) and quick-report feature for plotting. Using the GUI, seen in **Figure 3**, the user enters in the geometric dimensions of the quadrant and the Cartesian coordinates of the sensor nodes. Next the operating frequency is selected, and the test button is selected to initiate baseline testing. Once a baseline measurement has been saved, this file is then used to be compared with future tests of similar configuration to determine if the state of the structure has changed. When a baseline and a test file are selected for comparison, the analysis algorithms are performed, and a graphical display indicates the presence and predicted location of damage, seen in **Figure 4**. For the purposes of the present research, this software was executed several times while changing the excitation frequency and location of the weight simulated damage. The results from each of these tests were then recorded in Microsoft Excel to be plotted, which are discussed in further detail in the following section.

4. RESULTS

4.1. Baseline testing

Before damage can be detected while using a Lamb wave-based system, baseline measurements are necessary. Using the software previously described, the MDC investigators collected data from each of the four quadrants in an undamaged or pristine state. The purpose of these baseline measurements is to identify the location of reflections due to boundary conditions, to measure the undamaged magnitude of reflections, and to observe the frequency spectrum expected. This information can then be used to test for "changes" to a structure. Each baseline measurement is actually comprised of a dozen independent measurements taken a few millisecond apart in order to not only define baseline values, but standard deviations to be used in the analysis. In a practical commercial application, these baseline measurements would be taken in the same location on a few different separate aircraft in order to calibrate standard deviations that would compensate for differences deriving from vehicle manufacturing tolerances.

4.2. Undamaged specimens

Once the baseline measurements were collected, testing was conducted on the undamaged quadrants to investigate the accuracy of these parameters. First, using a baseline measurement collected for a singe quadrant, 1000 tests were conducted to test for damage in that same region for excitation frequencies ranging between 60 and 100 kHz.

From this series of tests, not a single false positive was recorded indicating there was damage. Next, 50 undamage tests were conducted in each of the other three quadrants using the baseline for the initial quadrant. Again, no false positives were recorded. These results prove the robustness of the MDC algorithms to accurately identify an undamaged structure without generating false positives, which would offset the economics gains attributed to implementing an SHM system.

4.3. Damaged specimens

Of course a "zero" false positive rate is only useful if a system can also correctly identify the presence of damage reliably. Using the previous baseline measurements, 2500 tests were conducted at various frequencies between 60 and 100 kHz with a weight located between 13mm and 165mm from the sensor, each one correctly indicating the presence of damage. Using the MDC algorithms to decompose the reflected wave response, wavespeed and weight location prediction were also recorded for each test and subsequently plotted versus excitation frequency, seen in **Figure 5**. The accuracy of these predictions will be discussed further in the following subsection.

4.4. Discussion

Overall, the test results from the current MDC algorithms greatly exceeded expectation. Out of a total of 3500 tests conducted during the course of this research, no false positives were indicated and the presence of damage was correctly identified in each appropriate case. The only variability for these tests was in the damage location results, which for damage between 50mm and 165mm was accurate to about ±10%, as seen represented by the error bars in **Figure 5**. There were generally two sources of error contributing to the differences in damage location. First, as seen in **Figure 6**, there was some variation between the calculations of wavespeed used to convert time-of-flight to a distance and the theoretical wavespeed value, which was due to the center-finding portion of the MDC algorithm. Second, error would arise due to the difficultly in decomposing reflections substantially overlapping other waveform features, which becomes more prevalent as the damage location moves closer to the sensor node. This is why the error is higher for damage between 13mm and 50mm even though damage presence is correctly determined. Work continues at MDC to further refine these areas of the algorithm in order to circumvent these outlier cases to minimize the error in damage location calculation. Despite these small sources of error, overall these results demonstrate the viability of using the M.E.T.I.-Disk 2 along with the METIS v2.10 software to detect damage in commercial applications.

5. FUTURE RECOMMENDATIONS

This paper discusses the experimental validation of using M.E.T.I.-Disk 2 sensor nodes along with the METIS v2.10 software to detect damage on a built-up representative aircraft structure. While this research covered key topics for the commercial viability of these products, several other components must be researched further to produce a fully functional SHM system. These components include the sensor networking, batteries and wireless communication. Metis Design is currently working with partner organizations and universities in an effort to address each of these issues over the course of the next couple years. Other important areas of research include the microfabrication of each of the components described in this paper, to increase reproducibility and further improve reliability. Second, the economical assembly and packaging of both the analog (M.E.T.I.-Disk 2) and digital (M.E.T.I.-Disk 3) wired and wireless (M.E.T.I.-Disk 4) SHM sensor nodes must be addressed. Third, an installation tool to apply pressure to the piezoelectric wafers and align the devices with the structure to be monitored needs to be designed. Finally, each of these device designs must be further tested on true aerospace structures, seen in **Figure 7**, for accuracy, durability and longevity.

6. CONCLUSIONS

Overall, this research was very successful in the validation of the MDC sensor nodes and algorithms an analog "wired" SHM system. First a representative testbed was fabricated out of aircraft-grade aluminum and divided into quadrants with c-channel ribs. Next, M.E.T.I.-Disk 2 nodes were bonded in the center of each quadrant prior to testing. Simulated damage was introduced to the structure by placing small weights on the plate with shear couplant. Damage evaluation testing was then conducted using the METIS v2.10 software. This software was comprised of several new MDC algorithms which derived average baseline signatures along with standard deviations, and further utilized cross-correlated wavelet decompositions to determine the location of damage. Of 1000 tests conducted on undamaged specimen, no false positives were indicated during testing. This was followed by 2500 further tests which all properly indicated the presence of damage, along with the location of damage to within 10% of the actual value. The sources of error for these algorithms were identified within the peakfinder logic, and continued research aims at minimizing this error further. These tests were very successful, and MDC now plans to conduct similar tests varying the material thickness and curvature, using composite materials, and exploring durability (hygro-thermal) effects. In addition, an identical test matrix will be carried out for the other digital and wireless versions of the M.E.T.I.-Disk to assess their reliability. Robust integrated SHM systems will be an important component in future air and spacecraft designs to increase safety and reduce life-cycle costs, and Lamb wave methods will likely play an important role in their success.

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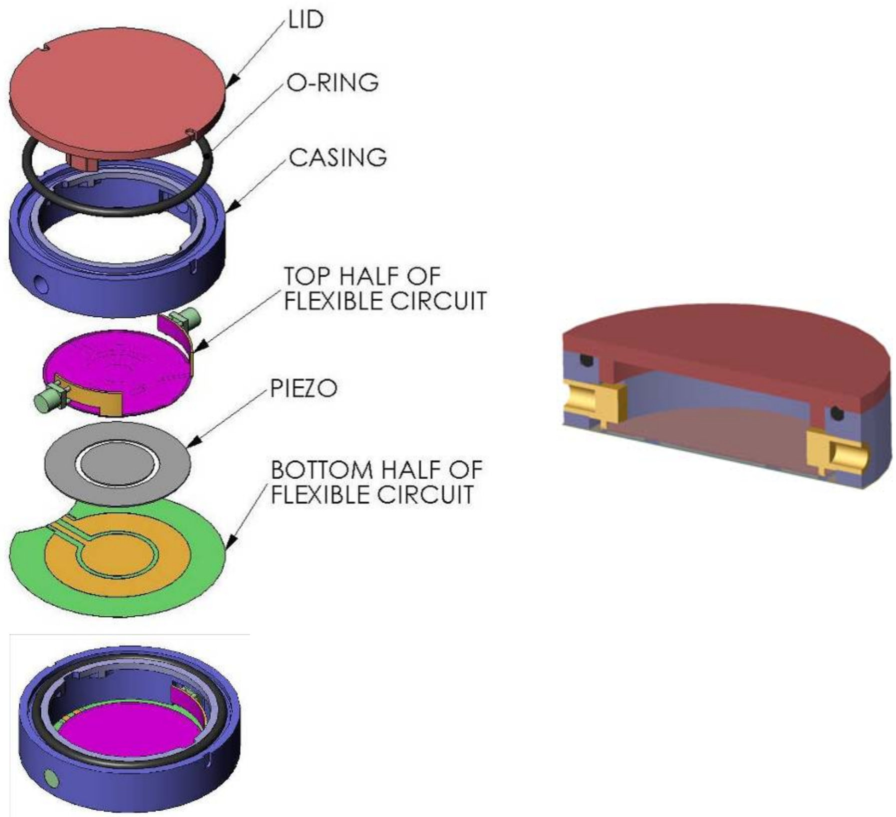

Figure 1: M.E.T.I.-Disk 2 assembly diagram and cross-section view of assembled product

Figure 2: Photograph of representative aircraft testbed with M.E.T.I.-Disk 2 sensors attached.

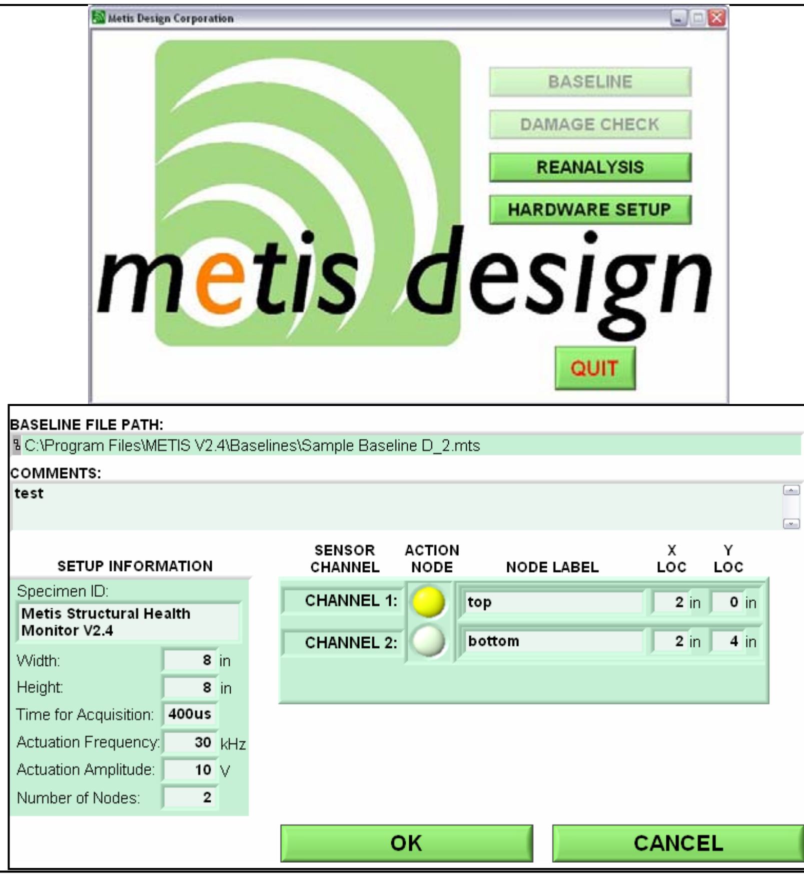

Figure 3: Opening screen and baseline data entry fields for METIS damage detection software

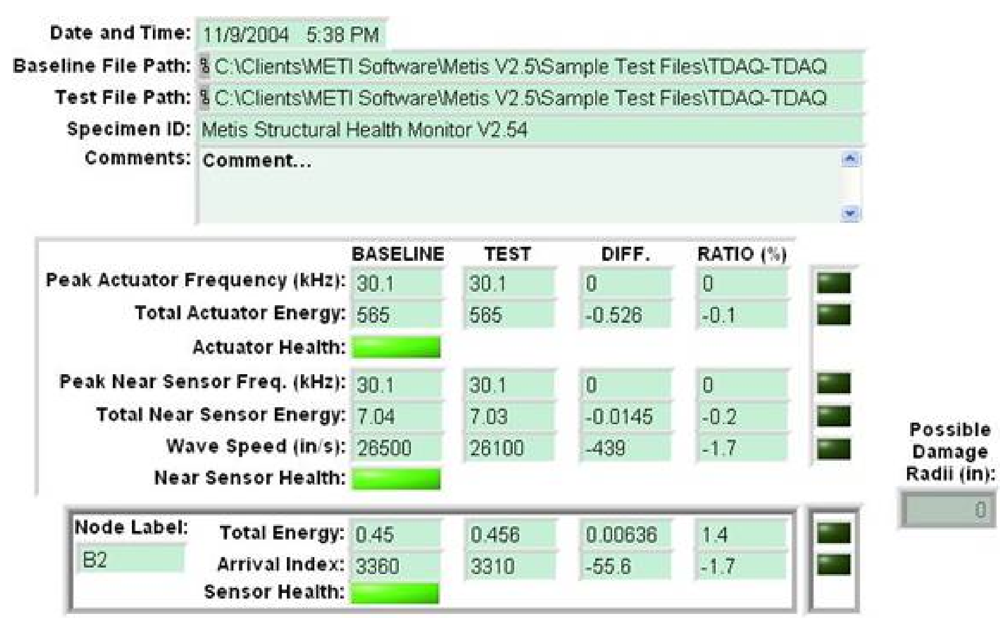

Figure 4: Results display for METIS damage detection software.

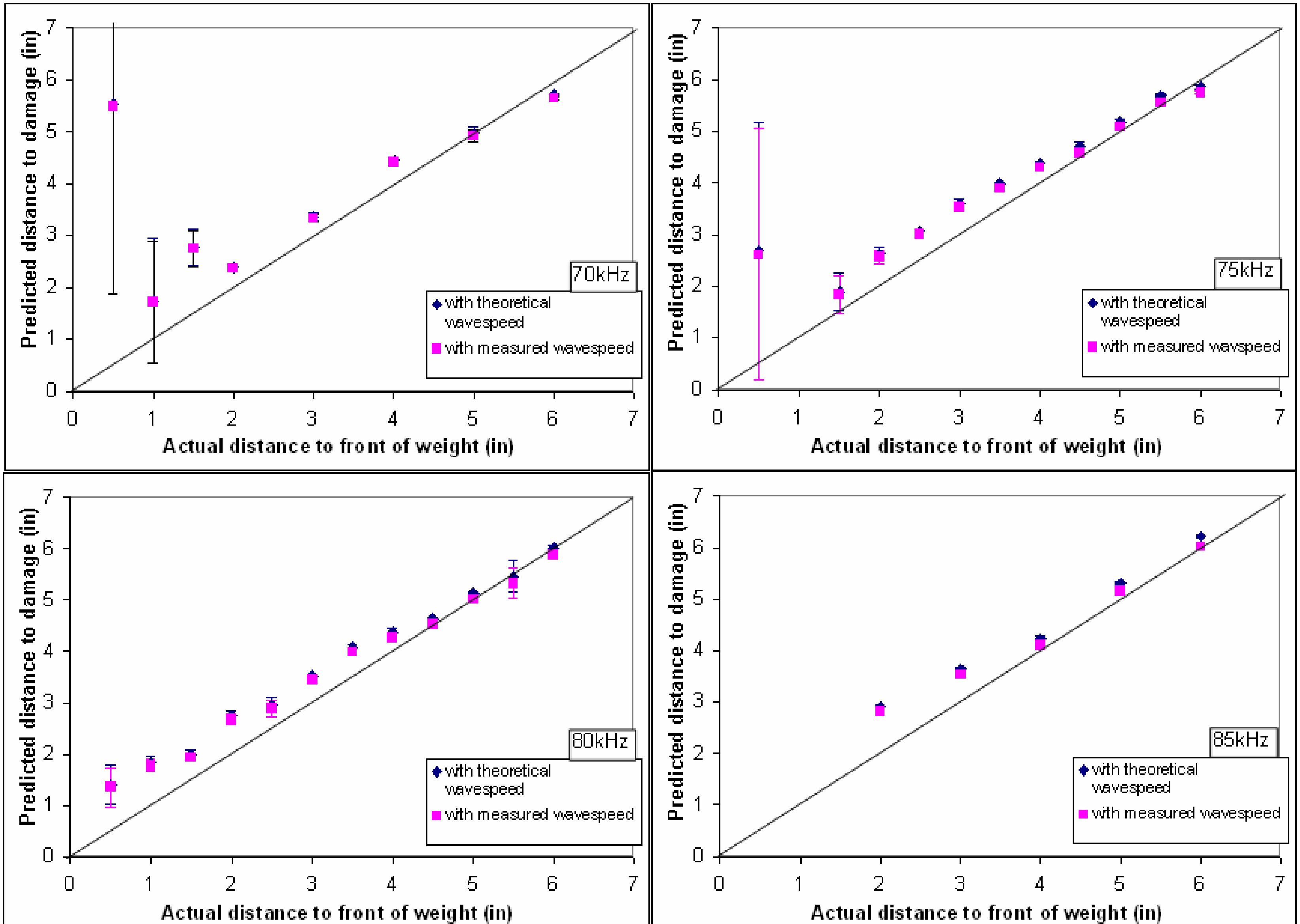

Figure 5: Plots of predicted damage locations at various frequencies versus actual weight location, including standard deviations

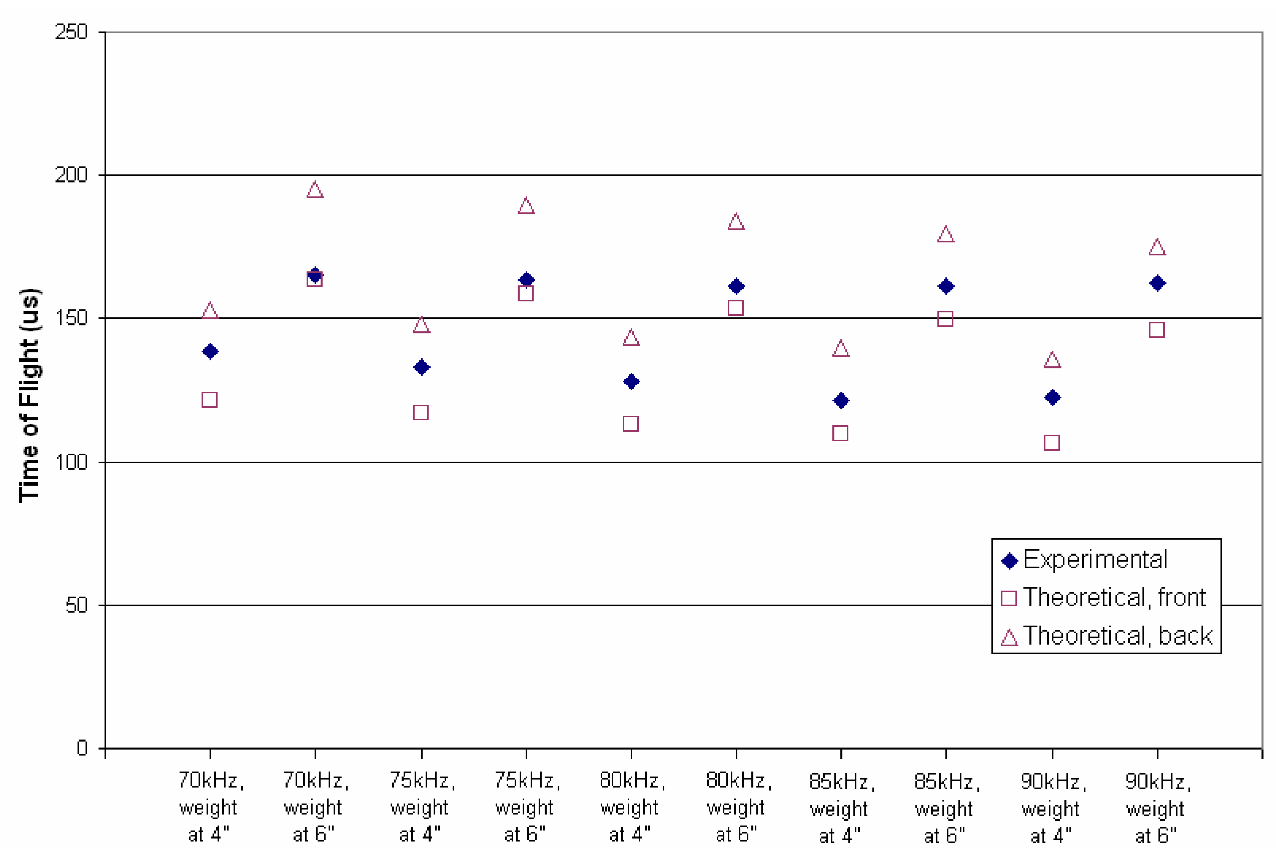

Figure 6: Time of flight data compared to theoretical front and back of weight locations, demonstrates wavespeed error

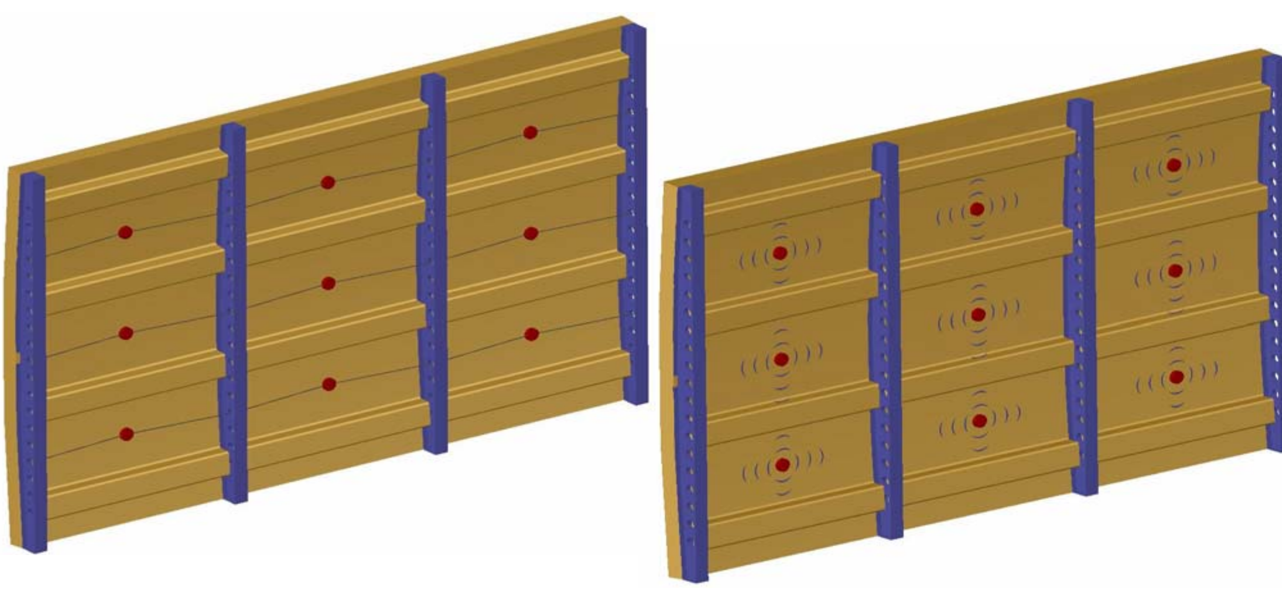

Figure 7: Schematics of “wired” and “wireless” configurations of M.E.T.I.-Disk in aerospace applications