Design of a piezoelectric-based structural health monitoring system for damage detection in composite materials

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ABSTRACT

Cost-effective and reliable damage detection is critical for the utilization of composite materials. This paper presents the conclusions of an experimental and analytical survey of candidate methods for in-situ damage detection in composite structures. Experimental results are presented for the application of modal analysis and Lamb wave techniques to quasi-isotropic graphite/epoxy test specimens containing representative damage. Piezoelectric patches were used as actuators and sensors for both sets of experiments. Modal analysis methods were reliable for detecting small amounts of global damage in a simple composite structure. By comparison, Lamb wave methods were sensitive to all types of local damage present between the sensor and actuator, provided useful information about damage presence and severity, and present the possibility of estimating damage type and location. Analogous experiments were also performed for more complex built-up structures. These techniques are suitable for structural health monitoring applications since they can be applied with low power conformable sensors and can provide useful information about the state of a structure during operation. Piezoelectric patches could also be used as multipurpose sensors to detect damage by a variety of methods such as modal analysis, Lamb wave, acoustic emission and strain based methods simultaneously, by altering driving frequencies and sampling rates. This paper presents guidelines and recommendations drawn from this research to assist in the design of a structural health monitoring system for a vehicle. These systems will be an important component in future designs of air and spacecraft to increase the feasibility of their missions.

Keywords: Composites, Modal Analysis, Lamb Waves, Structural Health Monitoring, Non-Destructive Testing

1. INTRODUCTION

Structural Health Monitoring (SHM) denotes a system with the ability to detect and interpret adverse "changes" in a structure in order to improve reliability and reduce life-cycle costs. The greatest challenge in designing a SHM system is knowing what "changes" to look for and how to identify them. The characteristics of damage in a particular structure plays a key role in defining the architecture of the SHM system. The resulting "changes," or damage signature, will dictate the type of sensors that are required, which in-turn determines the requirements for the rest of the components in the system. The present research project focuses on the relationship between various sensors and their ability to detect "changes" in a structure's behavior.

There are several advantages to using a SHM system over traditional inspection cycles, such as reduced down-time, elimination of component tear-down and the potential prevention of failure during operation. While some effort has been placed towards infrastructure and civil engineering applications such as bridges and highways, aerospace structures have one of the highest payoffs for SHM applications since damage can lead to catastrophic and expensive failures, and the vehicles involved undergo regular costly inspections. Currently 27% of an average aircraft's life cycle cost, both for commercial and military vehicles, is spent on inspection and repair; a figure that excludes the opportunity cost associated with the time the aircraft is grounded for scheduled maintenance [1]. New military fighter-craft such as the Eurofighter, the Joint Strike Fighter and the F-22 all incorporate Health Usage Monitoring Systems (HUMS), which record peak stress, strain and acceleration experienced in key components of the vehicle [2]. While these measurements provide useful information about the state of the vehicle between flights, the value of such a system could be greatly increased if continuous data could be accessed instantaneously.

As companies strive to lower their operational costs, many SHM schemes have been developed by industry, universities and research institutes. In a collection of papers written by Zimmerman, he suggests that an algorithmic approach could be used to enhance the model correlation and health monitoring capabilities using frequency response methods [3]. Minimum rank perturbation theory is used to address the problem of incomplete measurements, since a true structure does not conform to ideal conditions. Other researchers have developed algorithms to attempt to correlate modal response under arbitrary excitation to models using a probabilistic sub-space based approach [4]. Recently, Boeing has been exploring the use of frequency response methods in SHM systems for composite helicopter blades [5]. Their system, which is called Active Damage Interrogation (ADI), uses piezoelectric actuators and sensors in various patterns to produce transfer functions in components that are compared to baseline "healthy" transfer functions to detect damage. Giurgiutiu used Lamb wave techniques to compare changes in thin aluminum aircraft skins after various levels of usage to detect changes, and used finite element techniques to attempt to predict the level of damage with some success [6]. More detailed work was performed by Cawley's group at Imperial College, who used Lamb waves to experimentally examine representative metallic aircraft components such as lap joints, painted sections and tapered thickness [7]. This paper concludes that these methods present good sensitivity to localized damage sites, however the responses are often complicated to interpret, and many limitations exist for the implementation of these methods over large areas. Honeywell and NASA have been working on a collaborative project since the mid-1990's to introduce an acoustic emission-based SHM system into critical military aircraft components [8, 9]. This program, which involved the monitoring of T-38 and F/A-18 bulkheads, is one of the most thorough examples of a SHM system to date. These experiments were able to demonstrate successfully the collection of fatigue data and triangulation of some cracks from metallic components while in flight, which could then be analyzed post-flight to make decisions about flight-readiness. In another program Northrop had similar success using AE to monitor small aircraft [10]. They suggested using between 100 and 1000 sensors to implement this system in a larger aircraft depending on whether the entire structure is being monitored or just critical components.

The primary goal of SHM is to be able to replace current inspection cycles with a continuously monitoring system. This would reduce the downtime of the vehicle, and increase the probability of damage detection prior to catastrophic failure. Several parts of SHM systems have been developed and tested successfully, however much work remains before these systems can be implemented reliably in an operational vehicle. The present research attempts to fill some of the gaps remaining in SHM technologies. NDE techniques with the highest likelihood of success were thoroughly examined, including frequency response, Lamb wave, acoustic emission and strain monitoring methods. For each of these methods, an analytical and experimental procedure was followed to optimize the testing parameters and data interpretation. Their strength, limitations and SHM implementation potential were evaluated, and suggested roles for each are presented. The requirement of the other components necessary in an SHM system are described, and recommendations are offered for a structural health monitoring system architecture based on the results of this research.

2. COMPONENTS OF AN SHM SYSTEM

2.1 Architecture

The requirements of the end users are incorporated into the architecture in order to define the types of damage to be monitored, the critical flaw size, the weight and power budget for the system, and the level of importance of the various structural members that need to be monitored. It includes the layout of where the physical components of the SHM system lie and how they interact. One decision is the choice between a real-time (continuous) and discontinuous SHM system. A real-time SHM system is one that continually monitors a structure during operation, and produces data that can be directly utilized at any point by either an operator or ground control station. A discontinuous SHM system is one that data can only be accessed post-operation and could contain either a stored record of operational health data or might involve performing an integral inspection upon demand. Additionally the level of redundancy for each component needs to be assigned to achieve a desired level of reliability in catching false-positives as well as true-positives. The designer must also determine the sensor placement density and pattern; the more sensors the better the damage resolution, with increased power and weight as penalties. One architectural concept is that of the SHM patch. This scheme clusters several sensors and other components together to be incorporated on the structure to operate independently of other patches.

2.2 Damage characterization

Damage characterization is probably the most fundamental aspect of detecting damage; the familiarity of what kinds of damage are common in a type of material, and the knowledge of what "changes" correspond to these forms of damage. These damage characteristics dependent on the type of material the structure is manufactured with, as well as the structural configuration. With metallic structures, designers are mostly concerned with fatigue cracks and corrosion, while for composite materials, delamination and impact damage are more of a concern. Structural configuration including ribs or core may introduce new areas for damage to exist, or influence the effect of damage on the primary structure. Once an understanding of the damage signature in the material of concern is reached, then the sensing method and sensors can be selected.

2.3 Sensors

Sensors are used to record variables such as strain, acceleration, sound waves, electrical or magnetic impedance, pressure or temperature. In the literature it has been estimated that a SHM system for an aerospace vehicle would require between 100 and 1000 sensors, depending on its size and desired coverage area [10]. Sensing systems can generally be divided into two classes: passive or active sampling. Passive sampling systems are those that operate by detecting responses due to perturbations of ambient conditions without any artificially introduced energy. The simplest forms of a passive system are witness materials, which use sensors that intrinsically record a single value of maximum or threshold stress, strain or displacement. Examples of this can be phase change alloys that become magnetized beyond a certain stress level, shape memory alloys, pressure sensitive polymers, or extensometers. Another type of passive sensing is strain measurement by piezoelectric wafers. Lastly, several vibrational techniques can be performed passively, such as some accelerometers, ambient frequency response and acoustic emission with piezoelectric wafers. Active sampling systems are those that require externally supplied energy in the form of a stress or electromagnetic wave to properly function. A few strain-based examples of active systems include electrical and magnetic impedance measurements, eddy currents and optical fibers which require a laser light source. Active vibrational techniques include the transfer function modal analysis and Lamb wave propagation. Good references for selection of actuators for various active systems can be found in a review paper in the literature [11]. Passive techniques tend to be simpler to implement and operate within a SHM system and provide useful global damage detection capabilities, however generally active methods are more accurate in providing localized information about a damaged area. A comparison of the sensing methods can be seen in **Table 1**. Sensor selection charts plotting size of detectable damage against sensor size and power requirement for various coverage areas, can be found in **Figure 1** and **Figure 2**. It can be seen that they are all generally capable of detecting the same size of damage and can be implemented with similar size and power sensors, however frequency response and Lamb wave techniques are the only ones that can offer full surface coverage for a 1 x 1 m plate. While other methods, such as eddy currents, can offer better resolution, they are only capable of detecting damage directly below the sensor, which would drive the system to use either very large sensors or a large volume of sensors.

2.4 Computation

Several processing units are necessary to operate a SHM system. On the local level, a processor must interface with the sensors to acquire the data and convert the raw analog signals to digital ones. If it is an active system, such as with Lamb wave methods, the processor must send instructions or waveforms to the actuator periodically. Data rates between 25 and 50 Megabytes per second would be necessary for each Lamb wave sensor collecting data in the system, or 0.5 to 1 Megabytes per second for acoustic emission sensors [10]. At these rates, it can be seen that a large data storage capacity would become necessary for continuous monitoring, however a single Lamb wave test would only use 50 kilobytes. Local processing may also be necessary to compare data between neighboring sensor patches for damage verification. There are also global computational needs to use algorithms to assess the severity of damage, triangulate damage locations or make failure predictions, and to convey this information to the end-user.

2.5 Communication

Another important component of a SHM system is a communication system. This involves the transfer of data in one form or another between various components of the system. There are essentially four areas where the transfer of data is necessary: intra-patch, inter-patch, patch-processor and processor-operator. Intra-patch communications refers to the transfer of data, either in analog or digital form, between various components within a local sensor patch. This might include the passing of data from the sensor to data acquisition board, an analog-to-digital converter, or possibly a local processor chip for preliminary data analysis. These transfers would most likely be across metallic wires or optical fibers since they would only be traveling a short distance, on the order of a few centimeters to a meter at most, and there could be many sensors involved. The next category is inter-patch communications, which refers to the transfer of information between various patches in different regions. In some SHM schemes, it would be beneficial for local sensor sites to be able to communicate in order to compare or verify data and increase reliability. Most of this category would be performed with low power wireless transfers over a few meters, so that the various patches could be installed and operate independently. Next, patch-processor communication is necessary to transfer the collected sensor data to a central processing unit. Most likely a high-powered wireless method would be necessary to transfer the data to the computer which could be tens of meters away. Lastly, information about the state of the structure must be conveyed between the processor and the end user.

2.6 Power

Most of the components mentioned in the previous sections require power to function. Piezo actuators, for example, operating at 15 kHz with 5 V peak-to-peak would draw 24 mW. A low power micro-computer to process the data would draw about 10 mW, and a short range wireless device would require about 5 mW to function. Distribution becomes difficult when there are many components dispersed throughout the surface of the structure, some of which can even be embedded within the skin. Power could be supplied locally by batteries, or provided from within the vehicle via an electrical bus. Some researchers have proposed systems where energy is transmitted by radio frequencies to inductive loops, or collected passively with harvesting devices to the sensor and processing patches.

2.7 Algorithms

Algorithms are probably the most essential component to a SHM system. They are necessary to decipher and interpret the collected data, and require an understanding of the operational environments and material response. Examples of algorithms that have been used in this research include codes that perform modal analysis and wavelet decomposition. Other algorithms that could be embedded into a SHM system include codes that interpret the sensor data to specify the damage size and location, codes that calculate the residual strength or stiffness of the structure, or codes that predict failure based upon the measured damage.

2.8 Intervention

The last potential component of a SHM system is some form of intervention mechanism. Current intervention usually involves a mechanic performing a prescribed repair. Future advanced intervention systems mechanisms may use the collected damage detection data to mitigate further damage actively, or possibly even temporarily or permanently repair the damage site. Some proposed ways of achieving this intervention include the use of shape memory alloys to stiffen particular areas in the wake of a crack, or inserting epoxy reservoirs or duel phase matrices into a composite to close punctures in the structure.

3. POTENTIAL SHM SENSING METHODS

3.1 Frequency response methods

During the present research, several damage detection methods were tested that showed encouraging implementation potential for an SHM system. A set of narrow rectangular quasi-isotropic $[90/\pm45/0]_s$ laminates were manufactured of the AS4/3501-6 graphite/epoxy system with various forms of damage introduced to them, including matrix-cracks, delaminations and through-holes. These specimens were then reused for each test method by using PZT piezoceramic patches as sensors, which were affixed using 3M ThermoBond™ thermoplastic tape. The first methods surveyed were the frequency response methods. Detailed results for these experiments have been presented in previous papers [12-14]. Experimentally, an impedance meter was used to measure the natural frequencies, and the mode shapes were deduced used a scanning laser vibrometer. A finite element analysis was also performed to predict the frequency response of each specimen up to 20 KHz. From both sets of results it is evident that all the forms of damage investigated in this study caused detectable changes in the natural frequencies of a simple coupon. These changes are present in each of the lower normal frequencies discovered, and become more pronounced at higher frequencies, however coalescing modes made comparison impractical. A representative plot comparing a control and damaged specimen can be seen in **Figure 3**. A strong correlation existed between relative frequency reduction and the area damaged by a particular mechanism, however it is difficult to draw any conclusions about the criticality of the damage since there is no information regarding the form of the damage or its orientation. Based on these results, it is likely that an observer can discern whether a structure has been damaged by observing its frequency response, however it would be difficult to differentiate reliably between damage types, locations and orientations. This method appears to be appropriate for detecting global changes in stiffness for relatively large structures at a low power and weight cost.

3.2 Lamb wave methods

Next the utility of using Lamb waves for damage detection was explored. Again, detailed results for this Lamb wave research has been presented in previous papers [14-18]. The experimental procedures followed a building block approach, and the first set of experiments conducted on narrow composite coupons presented in the previous section [19]. Both the actuation and the data acquisition were performed using a portable NI-Daqpad™ 6070E data acquisition board, and a laptop running Labview™ as a virtual controller, and the results were compared by performing a Morlet wavelet decomposition centered at the driving frequency [20]. This procedure was also carried out for beam specimens, laminated plates with bonded stiffeners, and a sandwich construction cylinder. Finite element models were produced to simulate the small changes in time of flight caused by damage for each of these tests as well. The results from the narrow coupon tests clearly show the presence of damage in all of the specimens; this was made most obvious by comparing the wavelet decomposition plots. The control specimens retained over twice as much energy at the peak frequency as compared to all of the damaged specimens, as demonstrated in **Figure 4**. The loss of energy in the damaged specimens was due to reflection energy and dispersion. Similar effects of damage were observed in each of the built-up composite structure cases. Similar to frequency response methods, their results are limited at higher frequencies, however their low frequency results should provide sufficient data to predict damage. The disadvantage of Lamb wave methods is that they require an active driving mechanism, and the resulting data can be more complicated to interpret. Overall, Lamb wave techniques have the potential to provide more information than other methods since they are sensitive to the local effects of damage in composite materials, and have proven effective for the in-situ determination of the presence and severity of damage.

3.3 Other piezo-based sensing methods

Piezoelectric sensors are light, can be conformable, use little power and are sensitive to small changes, making them ideal for SHM applications. Both of the previous methods presented have demonstrated useful sensitivity to damage, however they are most effectively implemented actively by using powered actuators in a pulse-transmission or pulse-echo mode. Perhaps the greatest advantage of using piezoelectric material for sensors, is that they can be used for a wide variety of detection techniques by simply altering the time scale of analysis or actuating signal. Two further techniques, strain monitoring and acoustic emission, were also implemented via the piezoelectric sensors and system infrastructure used for the previous two methods presented, to detect damage passively without the use of actuators. In the first of these tests, a narrow coupon specimen was tested in tension, to assess the accuracy of the piezoelectric sensors for the measurement of strain. A second test was performed on a laminated plate in order to explore using piezo sensors to monitor damage events using acoustic emission. Piezo patches were affixed in the center of each of the sides along the perimeter of the specimen, and data was collected as a graphite pencil tip was broken in several locations on the laminate. While conclusive results were not obtained from either of the tests performed during this portion of research, along with results that have been presented in the literature these tests have proved the feasibility of implementing other damage detection methods within the infrastructure of sensors that were used for the frequency response and Lamb wave methods. Using strain monitoring methods, measuring the peak strain witnessed at the surface of a laminate could help to make a prediction of failure based upon the strain limitations of the material. Several researchers in the literature have successfully fabricated piezoelectric based strain gauges that are viable for acceptable strain rates and ranges. Similarly, the literature has presented prior successful acoustic emission work that has been performed using sampling rates between 300 kHz and 3 MHz with optimized sensors. To monitor continuously, small-buffered series of data must be collected and purged at high acquisition rates to avoid the accumulation of large a volume of data. Regardless, acoustic emission methods have shown the potential to provide valuable information concerning the occurrence impact events and their proximity to sensors. Coupled with results from the literature, this preliminary data demonstrated that piezoelectric sensors could passively collect useful data with some additional software and data processing capabilities.

4. RECOMMENDATIONS FOR SHM SYSTEMS IN COMPOSITE STRUCTURES

The main focus of this research has been to provide design recommendations and guidelines for the implementation of a structural health monitoring system in a composite structure. A successful design will use several different sensing methods, taking advantage of both the strengths and weaknesses of each; for example certain methods work only in conducting materials and others in insulating ones, so potentially, damage to fibers could be differentiated from damaged matrix in a composite by using both concurrently. Using the sensor trade spaces shown in **Figure 1** and **Figure 2** a designer could determine appropriate sensing methods based on the required damage resolution and power budget. An estimate could also be made for sensor density based on desired coverage area using the equations presented in previous papers [14-18]. The trade between redundancy and reliability is essential since missed damage or false-positives could prove detrimental to the utility of the system. Using event-driven processing, such as a passive system triggering a dormant active one could reduce power and complexity, and further gains could be reached by using ambient conditions to provide power or actuation. Lastly, it would be advantageous to design a system that was flexible enough to be retrofitted into existing aging systems.

A design proposed by the authors would use relatively small (0.25 - 1.0 m^2) autonomous sensor patches as its key elements. These patches would include multiple piezoelectric sensors around their perimeter, local wiring between the sensors (longest length of 0.5 m), a data acquisition/processing device (capable of sampling around 1 MHz), a rechargeable polymer battery with an inductive coil for power reception (50 mW required to power all components), and a short range wireless device (10 m transmission range). All of these components would be embedded or deposited onto a conformable insulating polymer sheet with a thermoplastic adhesive backing, so the patch could be removed if it were damaged or if the structure required repair. These patches would be generic so that they could be placed in any region of concern on a vehicle. Other sensor types could possibly be deposited onto the polymer as well as in certain regions, such as meandering wires for eddy current tests or differential parallel metal tracks for thermocouple readings. A neural network algorithm could be used for the sensors to learn the topology of the area of structure they are adhered over, to collect a small database of the undamaged state, and to discern where each patch was in spatial coordinates of the structure. In operation the sensors would passively collect strain and acoustic emission data, passing their data along to their local processing units. When abnormal data is encountered, active transfer function frequency response and Lamb wave methods would be initiated, using the same piezoelectric sensors, to verify the presence of damage. Once damage is located within the patch region, the nearest neighbor patches would be contacted wirelessly to attempt to confirm the damage. This compiled, consolidated and compressed data would then be passed patch to patch to the central processing unit to be interpreted, and the damage type, severity and location would be indicated to the operator and ground crew on a computer terminal along with suggested actions. This system would function continuously during operation, and could also be automatically accessed by the operator or ground crew to perform a mid-air or ground inspection on demand. As a first step towards acceptance of such a system, the operator could rely on it only to speed ground inspections by accessing the in-situ sensor patches via an ethernet connection to replace tear-down inspections.

5. CONCLUSIONS

Structural health monitoring systems will be an important aspect of future aerospace vehicles in order to reduce their life-cycle costs. They will be an essential part of Reusable Launch Vehicle (RLV) technology, which will require constant monitoring to eliminate the need for time-consuming inspections. While RLV projects may presently drive the funding for SHM, commercial and military aircraft have just as much to benefit from SHM systems. To bring SHM systems to fruition, several areas in each of the components described above need to be researched further. A major enabling technology for SHM is Micro-Electro-Mechanical-Systems (MEMS). The miniaturization of each component would greatly reduce their weight and aspect ratio, and would also decrease the manufacturing times and costs. It has also been proven in the literature that for several applications that the sensor gains considerable sensitivity by reducing its scale [21]. To decide between architectural schemes, a SHM system designer will have to compare the cost of development, the cost of implementation, the cost of operation, and the impact to the production of the vehicle with the estimated savings in inspection and maintenance from traditional methods and the reliability and longevity gains. These systems will reduce vehicle life-cycle costs by eliminating routine inspections, averting both underuse and overuse, and predicting failure in time for preventative care. Structural heath monitoring systems will be important components in future designs of composite air and spacecraft, and piezoelectric-based NDE techniques will likely play a vital role.

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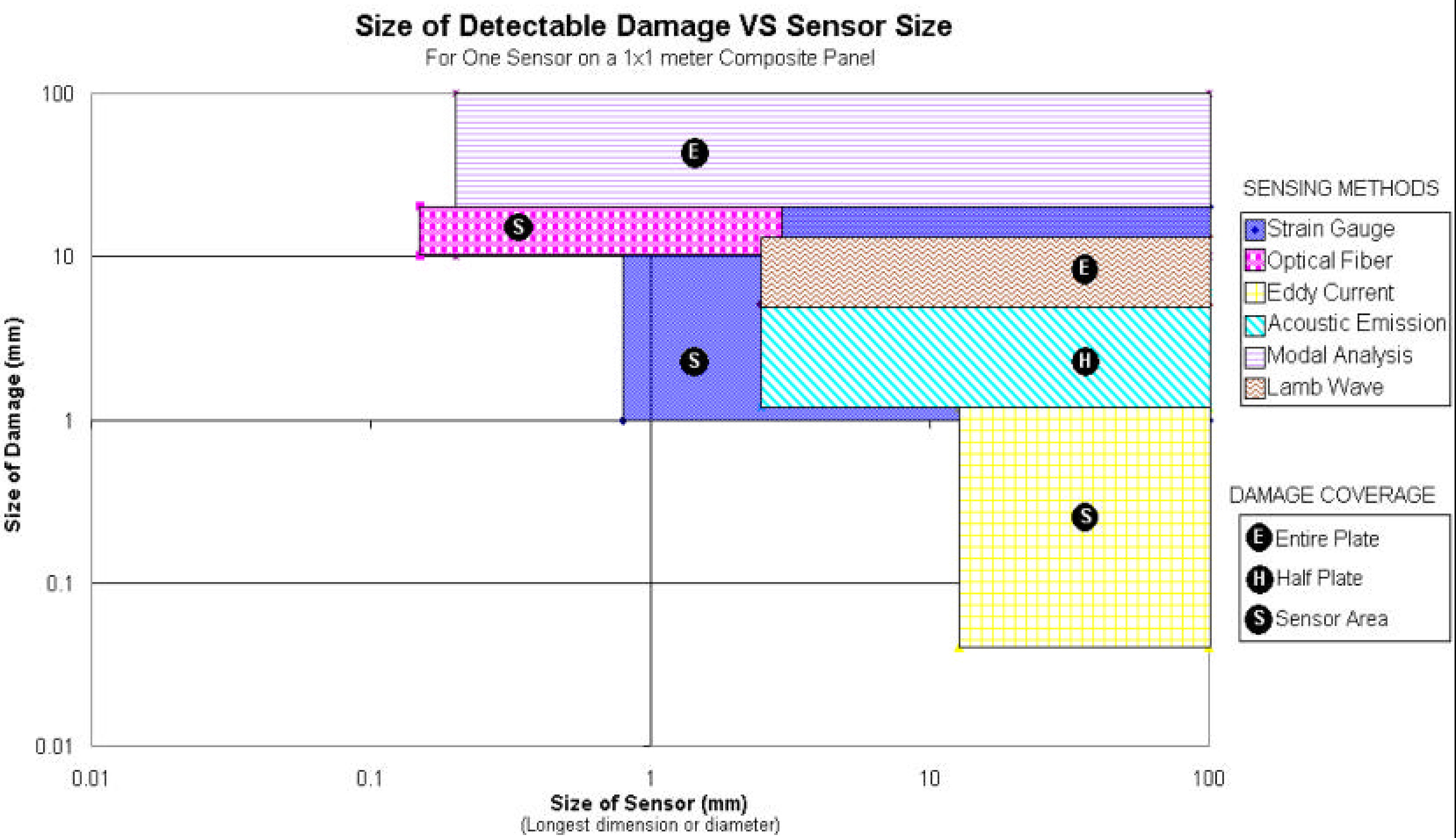

Figure 1: Sensor selection space comparing size of detectable damage with sensor size for various sensing methods

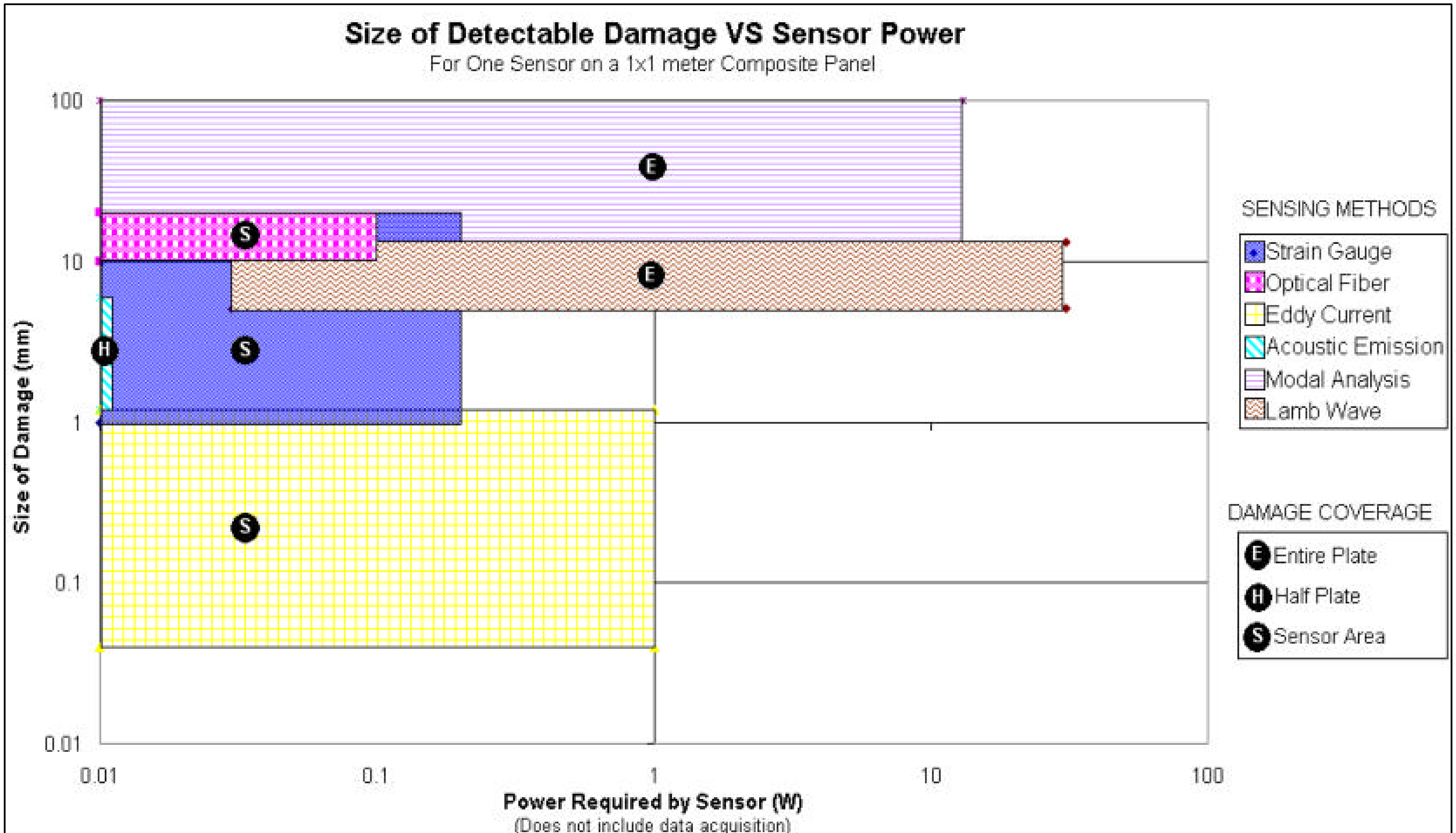

Figure 2: Sensor selection space comparing size of detectable damage with sensor power for various sensing methods

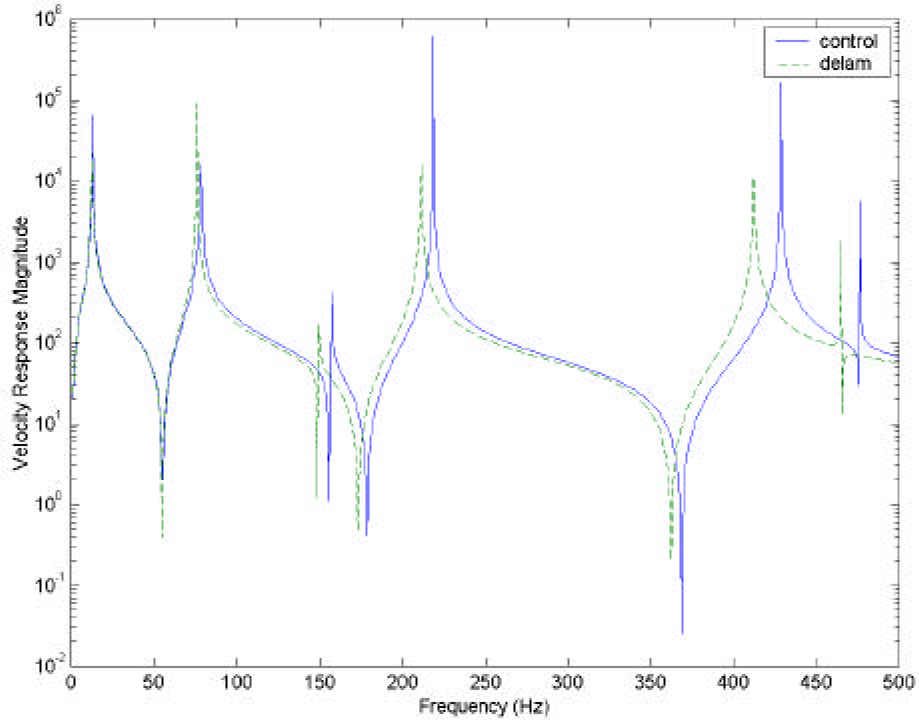

Figure 3: Frequency response transfer function plot from I-DEAS, range of 0-500 Hz

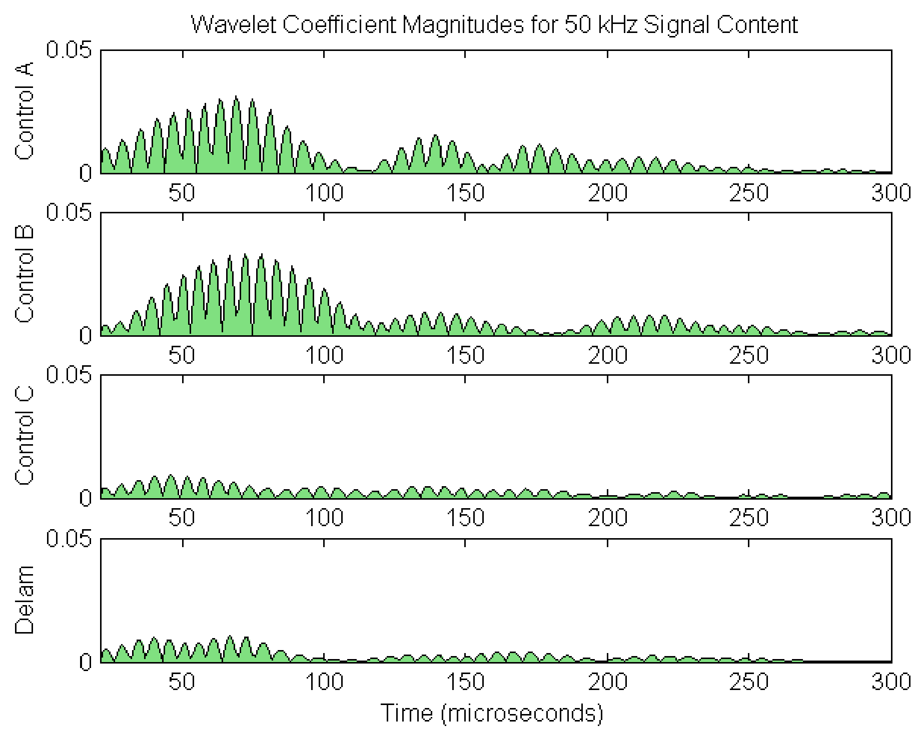

Figure 4: Wavelet coefficients for beam "blind test"; compares 50 kHz energy content for control beam specimen and 2 specimen with delamination

Table 1: Comparison of strengths, limitations and SHM implementation potential for various sensing systems

Method	Strengths	Limitations	SHM Potential
Visual	Inexpensive equipment No data analysis Portable Simple procedure	Only surface damage Only large damage Human interpretation Can be time consuming	Currently none
X-radiography	Penetrates surface Small defects with penetrant No data analysis Permanent record of results Simple procedure	Expensive equipment Expensive to implement Human interpretation Can be time consuming Require access to both sides	Currently none
Strain Gauge	Portable Embeddable Surface mountable Simple procedure Low data rates	Expensive equipment Expensive to implement Data analysis required Localized results	Lightweight Conformable Can be deposited Very low power draw Results for small area
Optical fibers	Inexpensive equipment Embeddable Quick scan of large area	Expensive to implement Data analysis required High data rates Accuracy in question	Lightweight Large area coverage Must be embedded Requires laser
Ultrasonic	Inexpensive to implement Portable Sensitive to small damage Quick scan of large area	Very expensive equipment Complex results Specialized software High data rates Require access to both sides	Currently none
Eddy current	Inexpensive to implement Portable Surface mountable Sensitive to small damage	Expensive equipment Very complex results Specialized software Safety hazard Conductive material only	Lightweight Conformable Can be deposited Very high power draw Results for small area
Acoustic emission	Inexpensive equipment Inexpensive to implement Surface mountable Portable Quick scan of large area Sensitive to small events	Very complex results Very high data rates Specialized software	Lightweight Conformable Can be deposited No power required Results for large area Triangulation capable
Modal analysis	Inexpensive equipment Inexpensive to implement Surface mountable Portable Simple procedure Quick scan of large area	Complex results High data rates Specialized software Results are global	Lightweight Conformable Can be deposited Multi-purpose sensors Low power required Results for small area
Lamb waves	Inexpensive equipment Inexpensive to implement Surface mountable Portable Sensitive to small damage Quick scan of linear space	Very complex results Very high data rates Specialized software	Lightweight Conformable Can be deposited Medium power draw Linear scan results Triangulation possible