Packaging of Structural Health Monitoring Components

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ABSTRACT

Structural Health Monitoring (SHM) technologies have the potential to realize economic benefits in a broad range of commercial and defense markets. Previous research conducted by Metis Design and MIT has demonstrated the ability of Lamb waves methods to provide reliable information regarding the presence, location and type of damage in composite specimens. The present NSF funded program was aimed to study manufacturing, packaging and interface concepts for critical SHM components. The intention is to be able to cheaply manufacture robust actuating/sensing devices, and isolate them from harsh operating environments including natural, mechanical, or electrical extremes. Currently the issues related to SHM system durability have remained undressed. During the course of this research several sets of test devices were fabricated and packaged to protect the piezoelectric component assemblies for robust operation. These assemblies were then tested in hot and wet conditions, as well as in electrically noisy environments. Future work will aim to package the other supporting components such as the battery and wireless chip, as well as integrating all of these components together for operation. SHM technology will enable the reduction or complete elimination of scheduled inspections, and will allow condition-based maintenance for increased reliability and reduced overall life-cycle costs.

Keywords: Structural Health Monitoring, packaging, Lamb waves, Polymer-matrix composites, piezoelectric, NDE

1. INTRODUCTION

The benefits of composite materials in modern air and spacecraft are well known: compared to metals, composites can have lighter weight, superior structural properties, and the capability to be readily formed into custom shapes to meet unique requirements. Currently successful laboratory non-destructive testing methods, such as X-radiographic detection and C-scans, are impractical for service inspection of large integrated air and spacecraft subsystems. Heritage techniques such as the "tap-test", commonly used to check fiberglass payload fairings, were extremely technician-sensitive and statistically unreliable. More recent techniques, such as acoustic emission testing, modal wave 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 composite 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 extent and nature of suspected structural anomalies in composite structure when visual inspections may not suffice, and more perceptive NDE techniques are not practical. It is clear that new approaches for inspection of composites need to be developed [2-5]. To resolve this issue, the Metis Design Corporation (MDC) has been working with MIT to develop a structural health monitoring (SHM) system for damage detection in composite materials using Lamb waves driven and received by piezoelectric wafers. This method has proven to provide reliable information about the presence, severity and type of damage in complex specimens. Now that this system has been successfully demonstrated in laboratory conditions, during the course of the present research, MDC has teamed with MIT to study manufacturing, packaging and interface concepts for critical SHM components. The intention was to be able to cheaply manufacture robust actuating/sensing devices, and isolate them from harsh operating environments including natural, mechanical, or electrical extremes. These system durability issues had been largely unaddressed.

SHM is predicated on the ability to integrate sensors within a structure in such a way that the overall system reliability is increased. This requires that not only are the sensors able to detect the damage and algorithms are in place

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to recommend appropriate intervention, but that the sensors themselves are sufficiently reliable so that they do not require replacement at intervals less than the economic lifetime of the part they are monitoring. This requirement is a major consideration in the integration and packaging of the SHM sensors into the overall structure. The packaging has to perform multiple functions. First it must provide an interface between the SHM sensors and the structure they are integrated with. This requires that there is a direct connection suitable for ensuring that Lamb waves generated by the sensors can be transmitted into the structure. Second, the electrical connections to and from the sensor for signal and power must be guaranteed and thirdly, the sensors must be protected from the environment so that temperature, moisture and local damage events (such as impact) do not compromise the ability of the sensors to fulfill their function. Finally, these connections must be achieved in a way that they are not subject to durability issues (fatigue, creep, moisture etc.)

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 [7]. 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 [7-15]. The conclusion of this research was that Lamb waves offered the best resolution to range ratios for the detection of damage in large composite structures. Lamb waves are a form of elastic perturbation that can propagate in a solid plate with free boundaries [16-18]. 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, severity and 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. The research presented in this paper is a critical component of work necessary to increase precision, accuracy and robustness of these Lamb wave devices so that they can be successfully integrated into a structure as a commercial product to provide SHM capabilities. 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 [19].

2. DESIGN REQUIREMENTS

The first goal of this project was to determine functional interfacing requirements for each projected SHM component. This included the actuators and sensors, communication devices, power supplies and computation devices. Key issues to be addressed in this activity were the required sensor sizes and the desired operating lifetime. The operational environments of interest also needed to be determined for protective packaging, including considerations for temperature extremes, moisture, incidental contact, mechanical vibration and inertial shock. To complete this task a questionnaire was distributed to several contacts within the aerospace community. There were three sections of the questionnaire addressing general, technical and environmental concerns for SHM. Responses to these surveys were received from multiple sources, both from the engineering and maintenance perspectives of aerospace corporations and relevant government agencies. By comparing the answers, initial requirements were compiled for the system:

- Maximum diameter: ~1.6" (total volume not to exceed 1in^3)
- Maximum height: ~0.5" (greater tolerance inside, less on aerosurface)
- Moisture: assume always in hot/wet/salty environment
- Temperature: -20°F to 180°F
- Strain: 2000 microstrain
- Vibration: resonance must be above 66 Hz
- Chemical: resistant to fuel, oil, paint, acetone, etc.
- Other: resistant to incidental impact, constant EMI exposure

These requirements were then used to define the desired packaging envelopes to meet both the environmental and geometric tolerances, and to devise an appropriate architecture for laying out each of the SHM system components. The specifications of the components fabricated, along with their interconnections, will be described in the design section. Key issues to be addressed included whether the device was to be surface mounted or embedded, whether the power and data communication would be transferred with wires or wirelessly, and the integration of the packaged components with the structure to be monitored.

First, after discussions with potential customers—Air Force and Boeing—it was decided that surface mounted sensors would offer several advantages over embedded ones. They added much less complexity to the manufacturing/integration process, they could be placed into ageing structures just as easily as new ones, and they would not pose a possible area for an internal flaw in the structure. Next, it was decided that there would be a market for both wired and wireless versions of this damage detection system for various applications, and for the scope of this present research the wired version was pursued (however the wireless components are being developed as part of a parallel research under AFOSR funding). With a wired system, issues such as operational battery life and communication range were temporarily ignored. Last, the issue of interfacing with the structure itself was addressed. A high peel strength film adhesive was selected to couple the packaged sensor to the structure. This film offered the advantage of being able to be applied easily at room temperature with little pressure, but could be removed with a solvent at elevated temperatures.

3. DEVICE DESIGN

During the course of this research, fabrication techniques and packaging strategies were developed for the piezoelectric actuator and sensor components designed during prior research. These activities were aimed to harden the piezoceramic actuators and sensors to be compatible with the constraints generated during the earlier tasks. The design effort can be divided into four separate areas of research: electrodes, encapsulation, mounting and connectors.

3.1. Electrode design

The electrodes were perhaps the most needed improvement over prior designs of this sensing system. Previously, a pair of co-axial cables were used, with one lead soldered onto the actuator, the other to the sensor, and the two ground wires soldered together and to a thin brass shim that was adhered to the bottom of the wafers using electrically conductive tape. There were several problems with this setup; the temperature of the soldering iron could exceed the depoling temperature of the PZT, there was the possibility of a “cold” solder joint creating a bad contact, and the general stability and durability of this setup was weak at best. Additionally the brass layer added unnecessary stiffness that retarded the actuation, even at 0.002”. All together, these issues contributed to the greatest variability between manufactured actuator/sensor sets in previous testing. The structural weakness of the exposed wiring also led to mechanical failure issues when moving the experiments, and the exposed sections of the wires at the solder joints were prime locations for EMI noise. To resolve these issues, a stacking sequence of materials was devised, as seen in **Figure 1**. Working from top to bottom, the initial layer was a ~1” diameter circle of copper coated Kapton. The exposed layer of Kapton provided an insulating surface for mounting of other future electronic components, while the underside of copper would provide an EMI shield. The next layer was a strong insulating adhesive film, capable of bonding to Kapton. The next layer was a mostly circular layer of etched copper coated Kapton, using Ferric Chloride to create the electrode pattern. The copper coated Kapton layer was masked using a laser printer, and this electrode pattern would provide contacts to both the actuator and sensor, as well as providing a shielding ground loop between the two leads to prevent in-plane parasitic noise. Next, a hybrid layer of z-plane electrically conductive adhesive and insulating adhesive was used in order to connect the leads to the appropriate piezoelectric wafers beneath without creating a short circuit. Finally a fully electrically conductive layer of adhesive was placed under the wafers to create a common ground. The remaining layers of a polyester film and insulating adhesive were used to provide a semi-rigid backing for mounting, and will be described in further detail in the mounting section. This newly devised electrode design eliminated the use of solder, a major flaw in the previous design, as well as the need for exposed wires. The actual connections to these copper leads will be discussed further in the connector section.

3.2. Encapsulation

The next area of interest was to encapsulate the electronics to prevent exposure to moisture, temperature extremes, EMI noise and incidental impact. Originally it was thought that the sensors would be encapsulated using a layer of epoxy or a similar polymer, however upon further consideration and some initial testing it was decided that this would not be a practical means of protecting each of the components, especially with regards to impact. The alternative approach that was pursued was to build a hermetically sealed “cap” to surround the entire electrical assembly. After some discussion with the plastic manufacturer Quadrant, it was decided that the acetyl family of plastics was the most appropriate due to its low density, negligible moisture diffusivity, ease of machining and bonding characteristics. For this project specifically Delrin™ was chosen for its availability. The cap was machined into 2 pieces: a cylinder for sidewalls and a top piece. The cylinder section was a nearly straight extrusion with an outside diameter of 1.4” and an inside diameter of nearly 1.2”, leaving a wall thickness of 0.1”. Three features were present in this cylinder. First, two holes were cut into opposite sides of the cylinder for micro-connectors. Next, a groove was machined in the top face of the cylinder to accommodate an #025 size O-ring. Finally, the top half of cylinder above the connector holes was threaded. The top piece was essentially flat at 0.1” with a threaded rim descending twice that thickness to engage with the threads in the cylinder. For the purpose of this research, the prototype caps were machined, however in production these components would likely be injection molded. A cross section view of the cap and lid can be seen in **Figure 2**, with the micro-connectors and O-ring in place. Once fabricated, an extremely thin layer of gold was evaporated onto the inside surfaces of the plastic cap and lid to create a global EMI shield. An electric path to ground was formed for this shield by connecting the gold to the base layer of conductive adhesive. This shield would be very effective against electric fields, but would have to be modified if there was a desire to protect against a magnetic field.

3.3. Mounting scheme

The third design area considered was the mounting scheme. As described previously, there were three layers assembled below the actuator/sensors: a layer of conductive adhesive, a layer of polyester film and a layer of insulating adhesive. This stack replaces the previous group of two layers of the conductive adhesive surrounding a thin brass shim. There were two basic reasons for this modification of the original design. The first was to eliminate the conductive path between the piezoceramic wafers and the structure being monitored, which was accomplished by replacing the brass layer with the polyester. The brass layer also provided a surface for soldering of the ground lead, which was no longer necessary with the current connection scheme described in the next section. The second reason a modification was made was to optimize the force imparted onto the specimen by the actuator by selecting a particular combination of material stiffness and layer thickness. To accomplish this goal, a finite element model was created with parametric values for the polyester thickness. It was found that much more strain was induced in a stiff specimen if a thin polyester layer was used in the stack than the original brass shim, which also had an order of magnitude higher stiffness. Thus using this new stack of materials, a layer of conductive adhesive was affixed to the bottom of the actuator/sensors, which was surrounded by an ellipse of insulating adhesive that was attached to the underside of the encapsulating cap. Next the 1.4” diameter polyester film was affixed beneath both of these adhesives, with an additional layer of insulating film adhesive beneath it, which was used to mount the entire assembly to the structure to be monitored

3.4. Connectors

The final major area researched was the connection scheme. In previous research, standard coaxial cable was soldered directly to the actuator/sensors, which had a BNC termination at the opposite end. This method made it easy to test the system since the standard BNC connectors mated directly into the function generating and data acquisition equipment. The problem, however, is that these solder joints were not reliable, and would pull off relatively easily. To resolve this issue, a two-piece connection system was devised. For the first section a co-axial 90° pin micro-connector was used. The jack portion of the connector was pushed through the press-fit machined hole in the sides of the cap, and potted with epoxy to prevent moisture ingress. Then, the central pin of each of these connectors was pushed through the copper leads of the actuator and sensor on the opposite side of the electrode layer. The remaining ground pins were pushed through the bottom conductive adhesive layer of the device. The second piece contained co-axial braided wire with a plug-style micro-connector crimped on one end and a BNC adapter on the other. The particular wire was selected because of its thin 0.1” diameter and high temperature survivability, and the BNC adapter allowed the same flexibility for testing previously described. By using this two-piece connection system, the testing remained simple, while removing the unreliable and difficult to reproduce solder joints and adding a simple strain relief to prevent damaging the piezoceramic wafers. A schematic of the final device along with a picture of a real device can be seen in **Figure 3**

4. TESTING & EXPERIMENTAL RESULTS

Once assembled, the devices were subjected to a series of functionality and durability tests to ascertain their ability to meet the design requirements when applied to composite structures. Prior work using piezoceramic wafers for structural health monitoring has established the required performance levels in order for the Lamb wave based sensing to be viable. Tests were conducted on a 10x10” quasi-isotropic CFRP laminate specimen with a 1” center delamination, which was previously used during prior SHM research so that baseline results existed [14, 15]. Four sets of sensor pairs were bonded to the plate, as shown in **Figure 4**: the first pair was the original actuator/sensor setup from prior research; the second pair employed the new top electrode, using the brass shim on the bottom; the third pair replaced the brass shim with the polyester film and new adhesive, still soldering directly to the piezoceramic wafers; the final pair was the entirely packaged sensor using the polyester, the new electrode and the Delrin cap. The standard MDC Lamb wave signal was sent from the Agilent 33220A function generator to excite each of the piezoelectric actuators one at a time, while data was collected from the near and far sensor using a Tektronix TDS2014 digital oscilloscope. This voltage data was then compared to measure the difference in signal strength due to each change of configuration. Three sets of data were taken for each sensors pair, and the results were averaged and compared, as can be seen in the following section.

4.1. Baseline testing

Following the procedure described above, an initial set of baseline test results was collected in order to assess the impact each of the design changes imposed on the sensing system performance. The main criteria for comparison were the signal amplitude measured at the near and far sensor locations. Results from the control set of tests can be seen in **Figure 5**. Voltages taken at the near sensor show little difference between the first three configurations, however the signal is more than doubled by the final cap configuration, likely due to the better conduction path offered by the micro-connectors. For the far sensor the last two configurations that employed the new attachment mechanism had voltages that were damped by nearly 50%, likely due to the additional adhesive present in front of the sensor attenuating the signal. These results were not discouraging, however, as far sensor voltages are not as useful as near sensor ones.

4.2. Elevated temperature environment testing

Following the control set of tests, a series of environment tests were performed on the same plate. First, the plate was placed in a post-cure oven and the air temperature was brought up to 180°F for a period of 24 hours. Three readings were taken immediately following the exposure before the plate was allowed to return to room temperature. Results from the elevated temperature exposure series of tests can be seen in **Figure 6**. Again, the voltage levels for the cap configuration were superior at the near sensor. While little change was observed in the voltage levels for the first three configurations, the cap signal actually increased even further, likely due to reduced resistance in the connectors at the elevated temperatures. At the far sensor, the results resembled those of the baseline results, however each signal strength slightly increased, likely due to better adhesion, thus coupling with the specimen better at elevated temperatures. The cap results were increased slightly more than the rest, again likely due to the micro-connectors.

4.3. High humidity environment testing

The third test exposed the configurations susceptibility to moisture. The plate and sensor pairs were placed in a makeshift hygal chamber and held at 100% humidity in room temperature conditions for 24 hours. After the specimen was removed from the chamber, data was collected from each of the sensor pairs in triplicate and then averaged. Results from the moisture exposure set of tests can be seen in **Figure 7**. Little effect from the moisture was observed for any of the configurations. For both the near and far results, each of the first three configurations experienced a slight decay in signal due to an increased resistance caused by the moisture. The cap configurations however experienced a slight increase in signal strength. This result is not simple to explain, although it was consistent across several test trials. Since Delrin has low absorbability, no moisture should have penetrated the cap, so the resistance in the micro-connectors must have somehow been reduced. Future testing is planned to further investigate this effect, and to explore the combined effects of humidity and temperature at much longer durations

4.4. Electrically noisy environment testing

The final test used an old “brush-style” electric hand drill to simulate electrical noise. Preliminary testing to determine an appropriate EMI shielding test showed that this drill method created significant amounts of electrical noise. The composite specimen was placed on a table, and three sets readings were taken from each sensor pair while the drill was being operated directly above the sensor. The final results from the electric noise exposure set of tests can be seen in **Figure 8**. For both the near and far sensors, the voltage levels measured for this experiment remained consistent with the control results. Both of the configurations that used the old soldering method (one and three) experienced high levels of electrical noise, seen as jumps in the signals, while the two that employed the new electrode showed reduced levels of noise. The cap completely eliminated all electrical noise from the sensors that were protected by their encapsulation.

5. FUTURE RECOMMENDATIONS

This paper discusses techniques for fabrication and packaging of piezoceramic actuators and sensors for an SHM device. While this research covers key topics for the viability of these products, several other components must be researched further to produce a fully functional SHM system. These components include the batteries, wireless communication and local storage device as well as system software. 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 assembly and packaging of a wireless SHM sensor assembly identical to the wired one design during the present research must be addressed. Third, the installation tool to apply pressure to the piezoelectric wafers and align the devices with the structure to be monitored needs to be designed. Finally, both the wired and wireless device designs must be tested on true aerospace structures by potential customers.

6. CONCLUSIONS

Overall, this research was very successful in the development of packaging for a “wired” SHM sensor. While many challenges were encountered, each of the technical objectives set forth were met. First, a questionnaire was distributed to several potential SHM customers, and geometric and environmental constraints were determined. Next, based upon these customer discussions, it was decided that two versions of this sensing system should be designed using both wireless and wired technologies. It was decided that the system should not be embedded, and several concepts for installation tools were conceived. The majority of the work performed under this project was aimed at designing the packaging and interfacing for the SHM device. Key areas of research included the development of a new more robust electrode stack, fabricating an encapsulating cap, devising a mounting scheme and specifying appropriate connectors. After each of these elements had been designed, eight complete prototype devices were assembled. A test matrix was constructed to demonstrate that the packaging could protect the components from environmental factors, and that each of the changes made to the system would not affect its functionality. Testing included operation at elevated temperatures, saturated humidity and electrical noise exposure. It was concluded that the newly designed packaging for this SHM device sufficiently protected the components against environmental exposure without inhibiting their functionality. In fact, as seen in the control results for the near sensor, the new developments actually enhanced the signal strength by nearly a factor of two, therefore reducing the system power requirements quite significantly ($P \propto V^2$). The voltage levels measured at the far sensor were slightly reduced due to the attenuation of the adhesive and cap, however they were still adequate, and the near sensor signals are much more crucial to predict damage location. Using the results obtained from this research, two versions of the MDC SHM products, one wired and one wireless, will be fabricated, packaged and ready for commercialization in the near future. Integrated reliable SHM systems in composite structure will be an important component in future designs of air and spacecraft to increase the feasibility of their missions.

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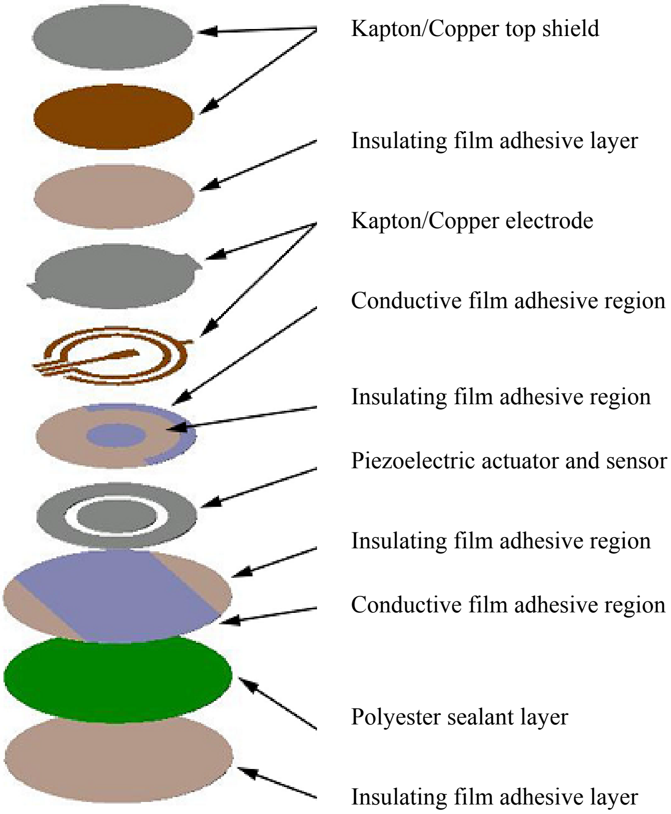

Figure 1: Electrode assembly, fastening assembly and piezoelectric actuator/sensor stack

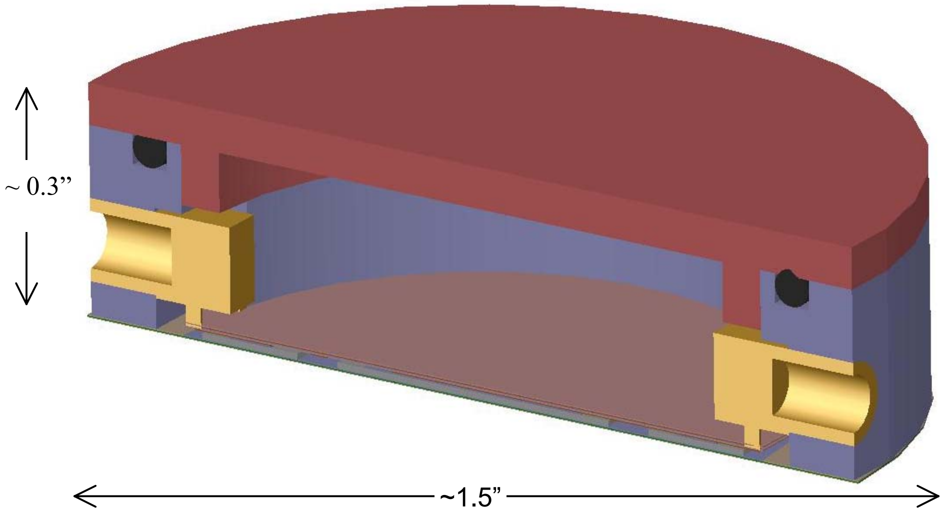

Figure 2: Cross section view of assembled SHM device, roughly 3x scale.

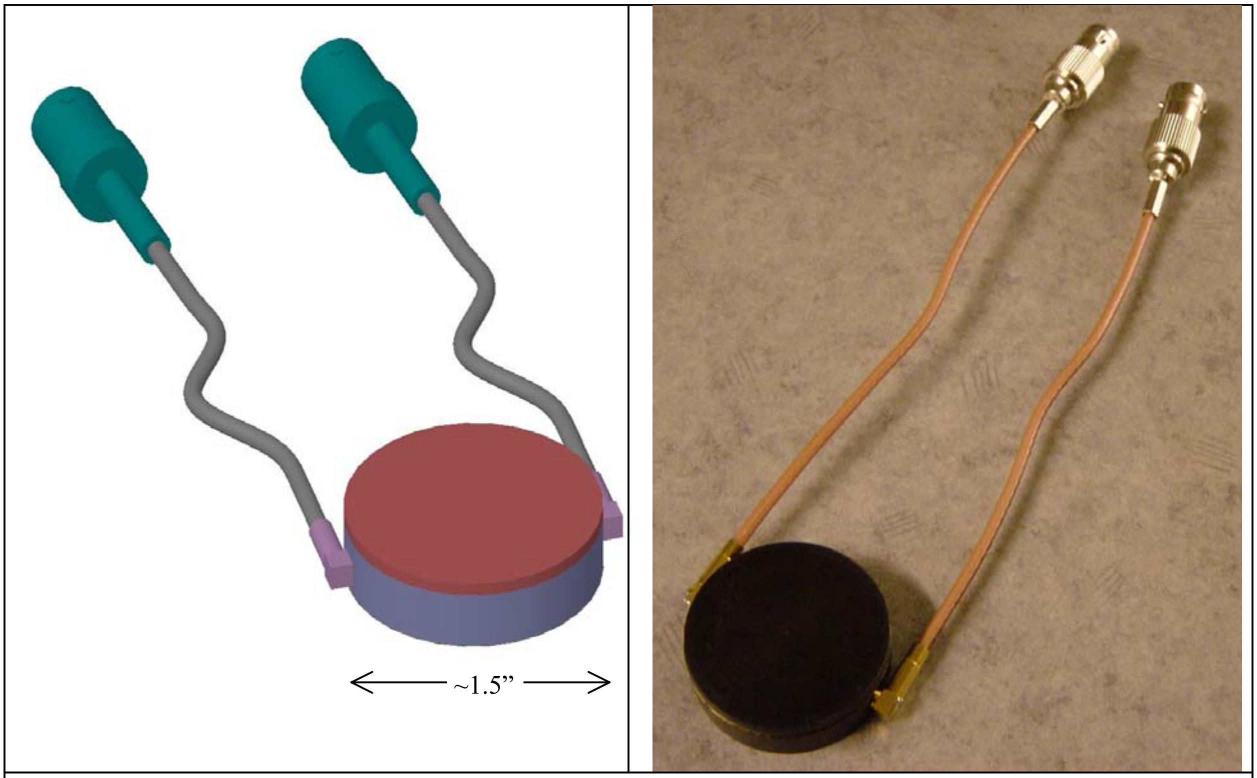

Figure 3: Schematic and real picture of entirely packaged device, roughly to scale.

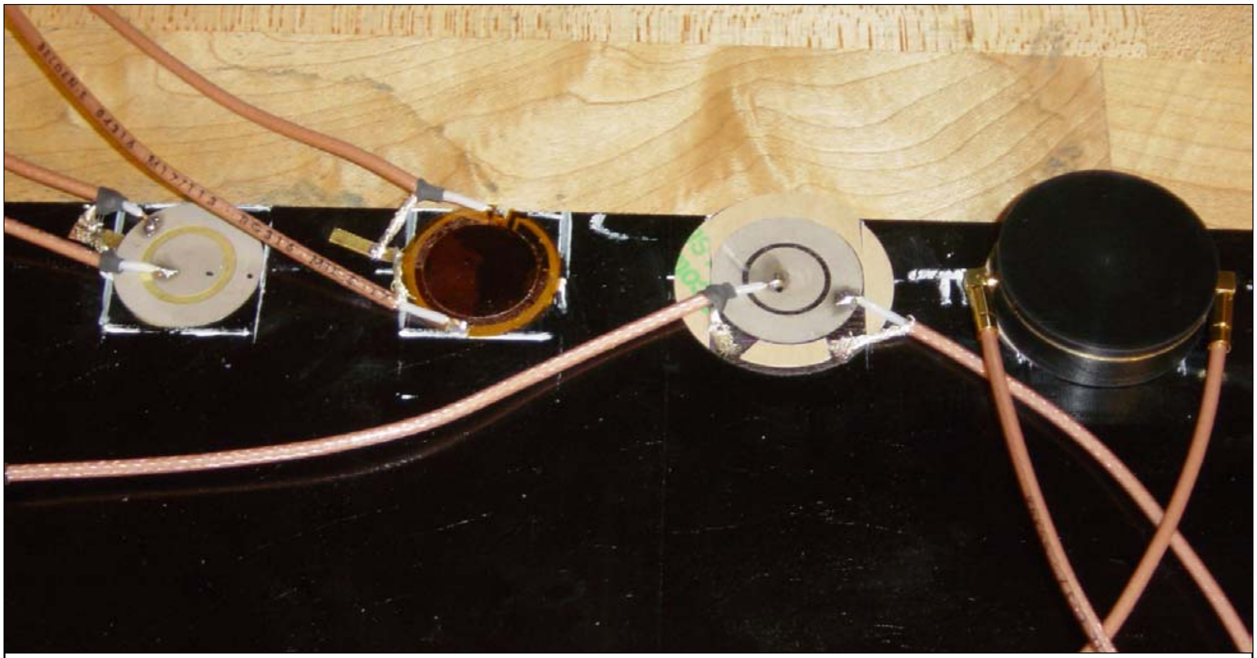

Figure 4: Composite test plate with four pairs of actuator/sensors of various increasing complexity.

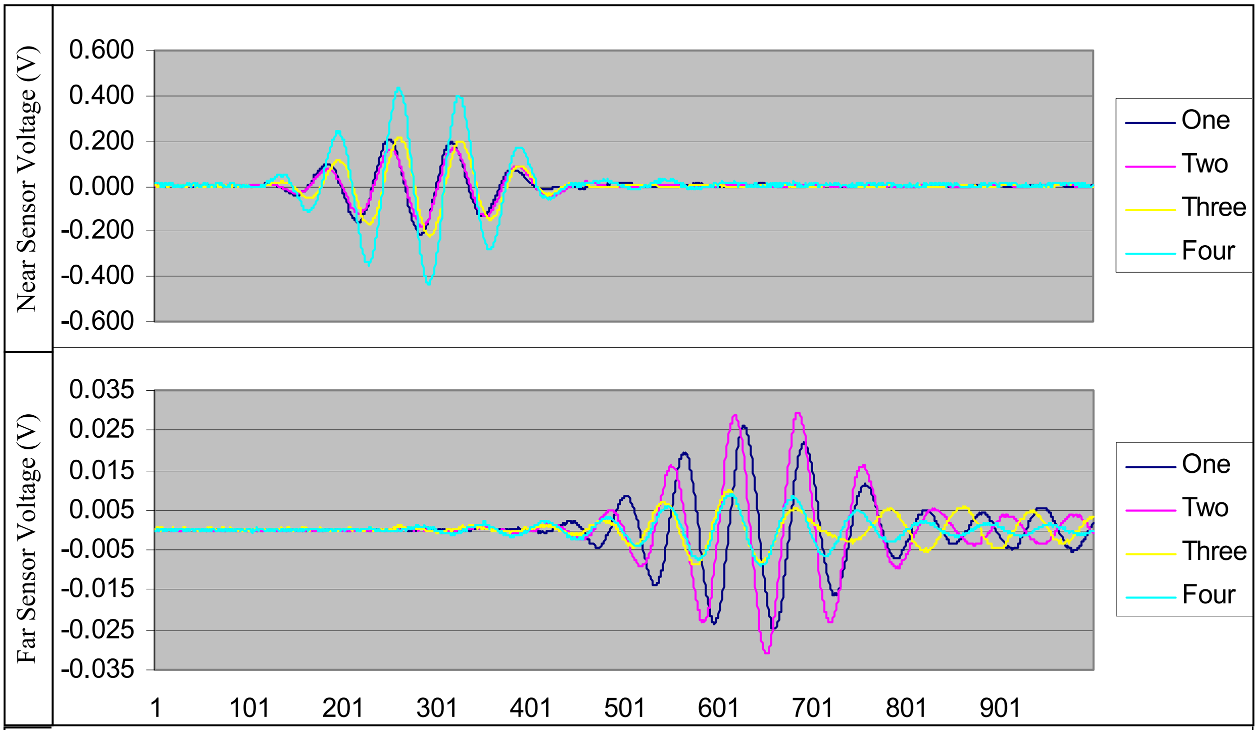

Figure 5: Voltage-time histories for the four sensor pairs, near and far. Baseline results

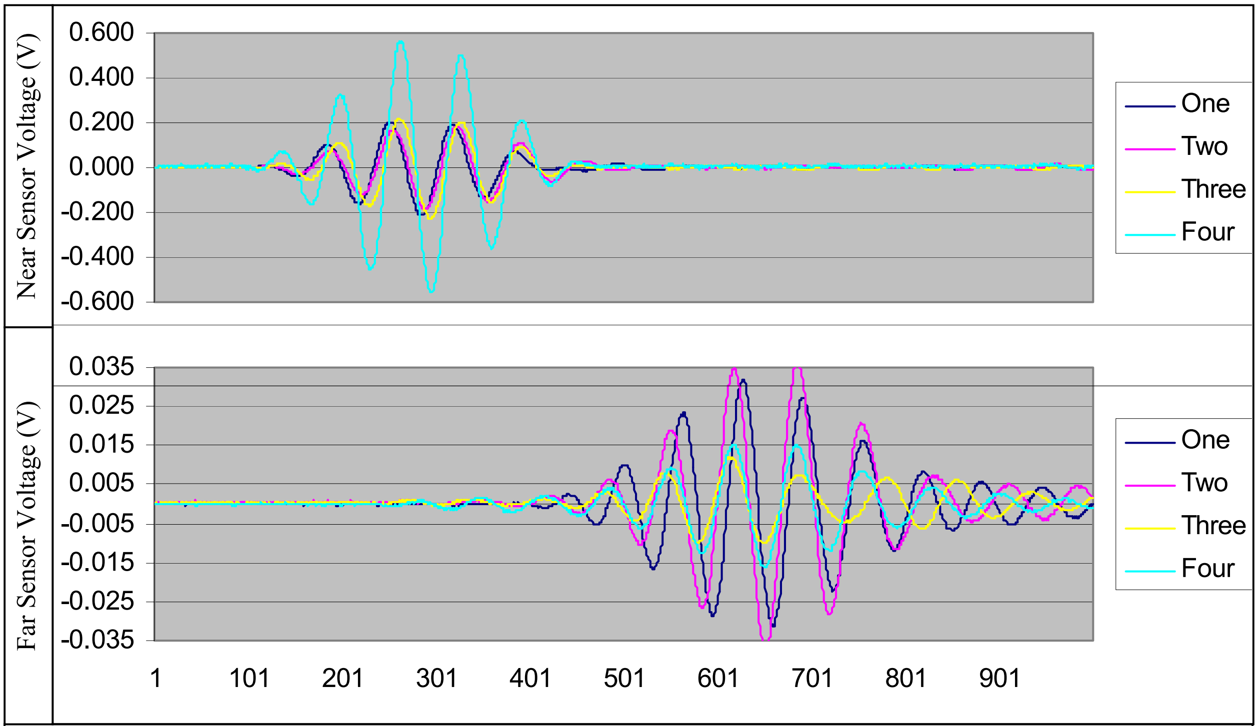

Figure 6: Voltage-time histories for the four sensor pairs, near and far. Elevated temperature results

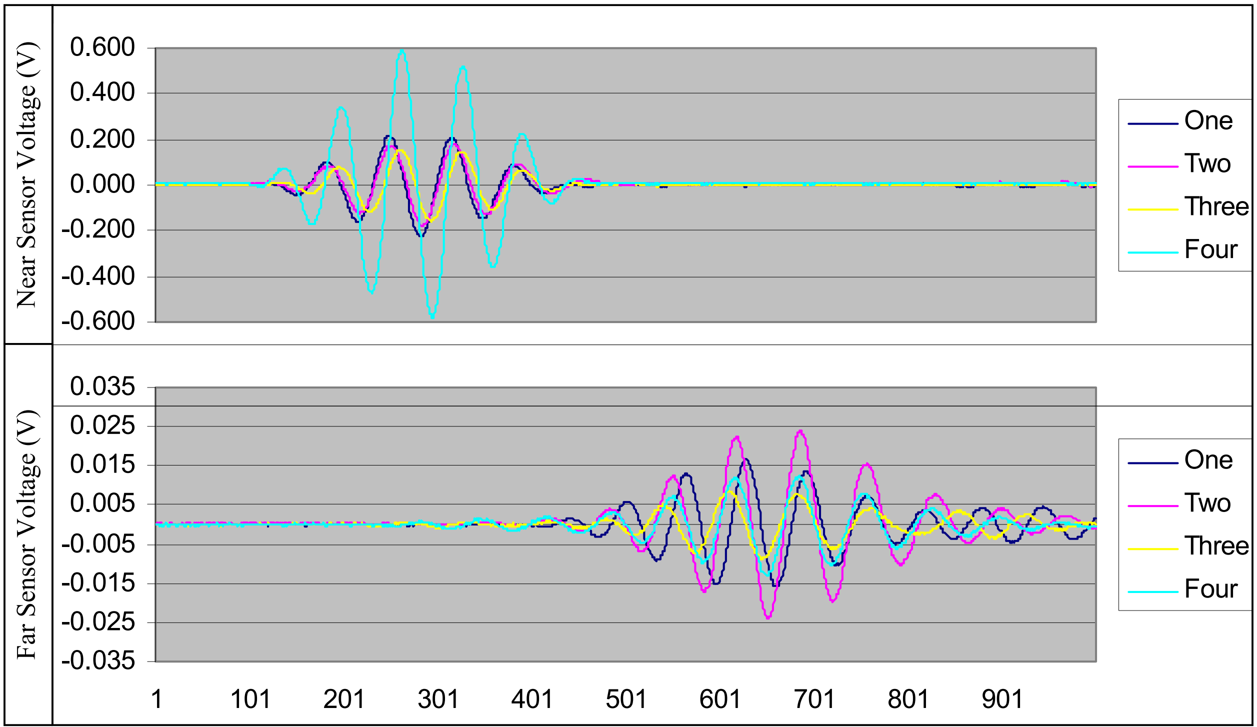

Figure 7: Voltage-time histories for the four sensor pairs, near and far. Moisture exposure results

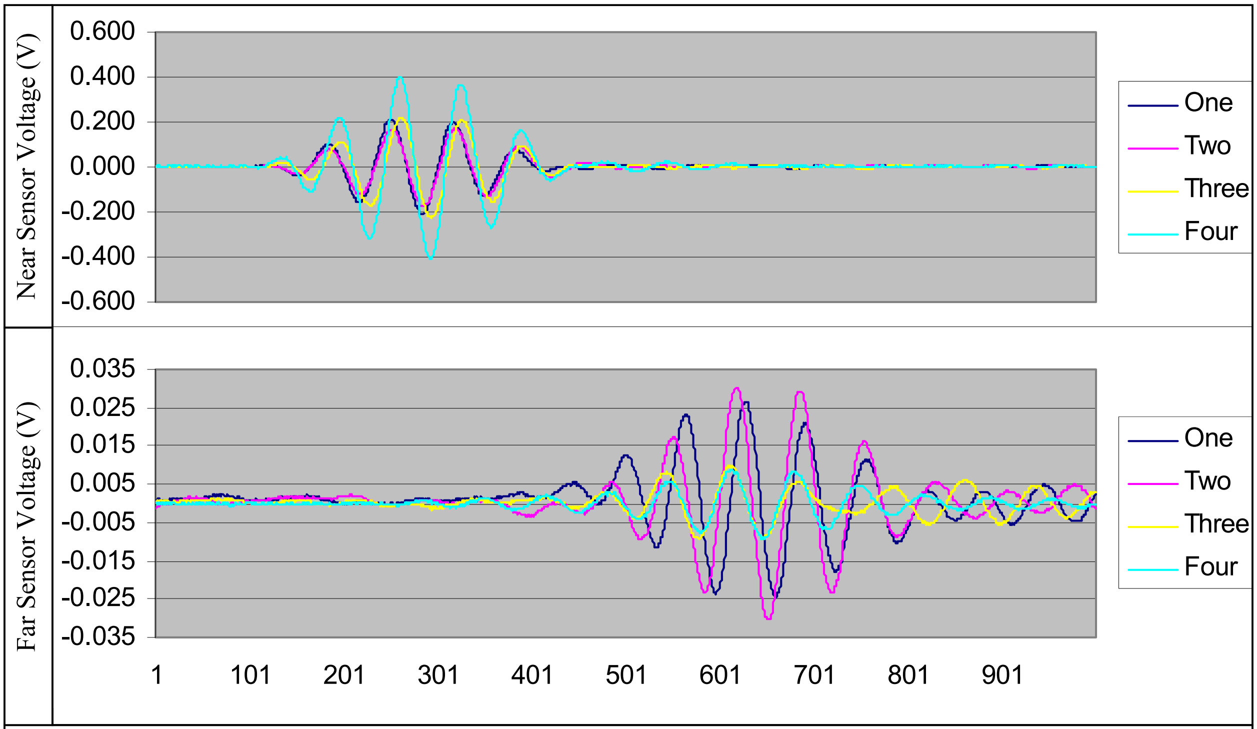

Figure 8: Voltage-time histories for the four sensor pairs, near and far. EMI noise exposure results