Selection of Materials and Sensors for Health Monitoring of Composite Structures

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ABSTRACT

Embedded structural health monitoring systems are envisioned to be an important component of future transportation systems. One of the key challenges in designing an SHM system is the choice of sensors, and a sensor layout, which can detect unambiguously relevant structural damage. This paper focuses on the relationship between sensors, the materials of which they are made, and their ability to detect structural damage. Sensor selection maps have been produced which plot the capabilities of the full range of available sensor types vs. the key performance metrics (power consumption, resolution, range, sensor size, coverage). This exercise resulted in the identification of piezoceramic Lamb wave transducers as the sensor of choice. Experimental results are presented for the detailed selection of piezoceramic materials to be used as Lamb wave transducers.

INTRODUCTION

Structural health monitoring is the term used to encompass a variety of approaches utilizing permanently mounted sensors to monitor the integrity of structures. Health monitoring methodologies are envisioned as replacements or supplements to existing inspection and maintenance schedules. Amongst the attractions of *in situ* health monitoring are that it has the potential to be less intrusive than many visual inspections, which require disassembly of built up structure, and that it has the potential to only require disassembly of the structure when there is some indication that damage has occurred. These potential benefits are particularly pronounced for the case of structures made from fiber-reinforced composite materials. In these cases, damage can often not be detected by visual means, and also the fabrication processes for composites are most economic if they avoid use of mechanical fasteners, which limits the ability to disassemble the structure. There is thus considerable interest in developing structural health monitoring systems for composite structures [1,2]. However, as yet, despite considerable progress, no systems have been accepted into service. One of the key issues in defining a structural health monitoring system is to determine the first level system architecture, comprising the sensor type and sensor density (or sensor spacing). This decision must account for the nature of the damage that is expected, and the size of damage that must be detected for the system to fulfill its purpose. Decisions at this level will have a flow-down effect on the higher-level system decisions.

This paper documents an effort to select the operating principles and materials for a structural health monitoring system, beginning with overall systems considerations and then focusing on the detailed selection transducer materials via experimentation.

SELECTION OF OPERATING PRINCIPLE

There are a variety of transducers or physical principles available for use in SHM systems. These include discrete sensors such as embedded optical fibers, acoustic emission sensors, strain gauges, eddy current devices or the use of multiple sensors in concert to extract information on changes in the overall frequency response of the structure via modal analysis. The key question is how to choose between these different sensor types in constructing an SHM system? Three of the most important issues are the size of the damage that can be resolved with a particular sensor or system, the size of the sensor itself and the power consumption associated with the particular approach. This latter provides differentiation between active systems, in which a signal has to be generated by an actuator (as in the case of an eddy current approach) or more passive systems such as strain gauges or acoustic emission detectors, in which there is a very low power draw. These metrics can be cross-plotted and the performance of the different candidate sensors can be assessed, based on literature data. Data for these performance metrics are available, and have been collected and published elsewhere [3]. In passing, it is worth noting, that at this preliminary selection phase, the fact that data may only available in the form of order of magnitude estimates, it is still possible to quantitatively distinguish between the capabilities of various sensor approaches. Figure 1 shows the size of damage plotted against sensor size. Figure 2 provides the power requirement for detecting damage of a particular size. This information can be applied to the case of choosing sensors for a structural health monitoring system.

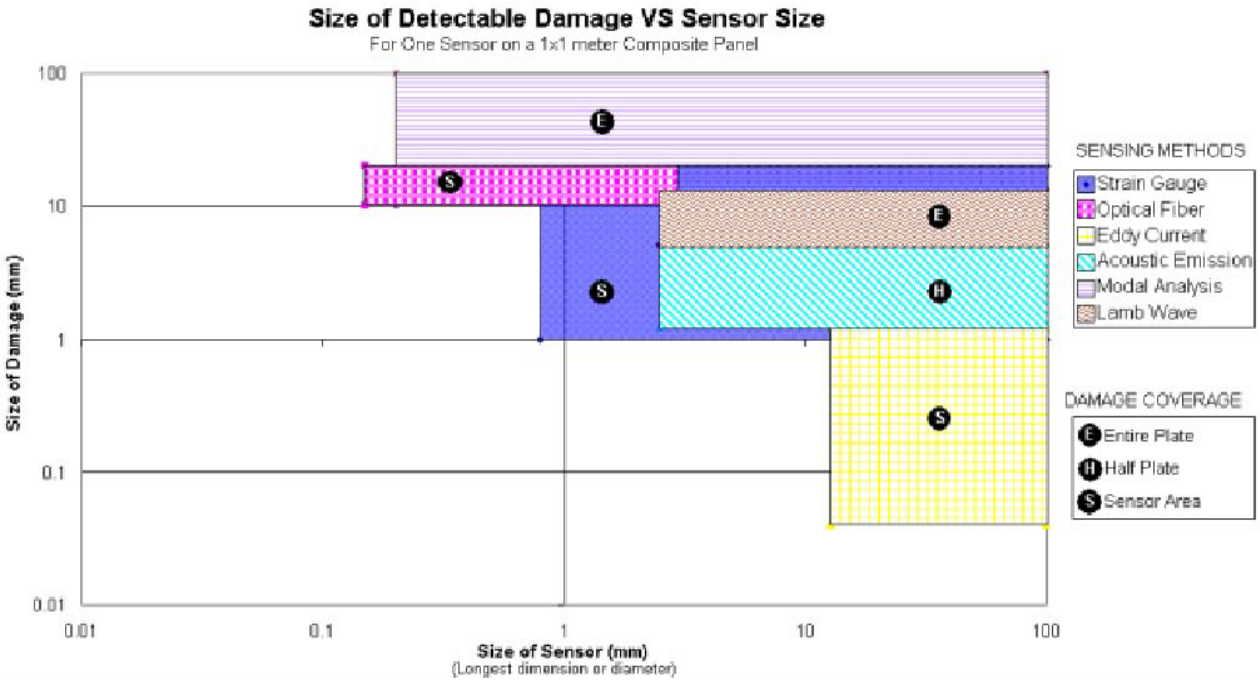

Figure 1. Size of damage vs. size of sensor. In addition the range of detection of the sensors is crudely indicated by the symbols indicating whether damage can only be detected in the sensor area, over approximately half of a 1 m^2 plate, or over the entire 1m^2 plate.

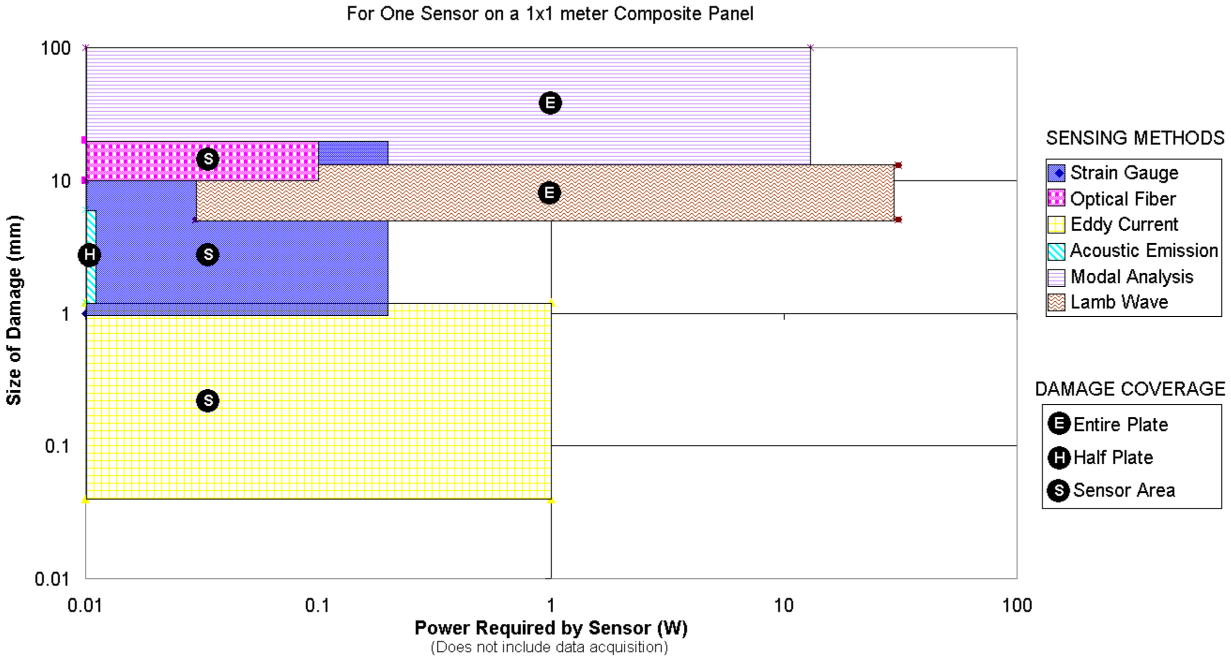

Figure 2. Size of damage vs. power required for several sensor types.

A typical damage size that might be thought of as the minimum critical size in a composite structure is of the order of 10 mm in diameter. The most common concern for the health monitoring of composite structures is damage of this size, or greater, due to impact events, resulting in delamination, fiber fracture and intralaminar cracking. Based on this information, and the desire to minimize the areal density of sensors and the power requirement, it is apparent that a system utilizing Lamb waves for damage detection is a very strong candidate. Frequency response methods also have some advantages, particular if a low power draw can be guaranteed, but the ability to detect damage at the requisite size is marginal. The other sensors are less attractive, due to their poorer range/coverage.

LAMB WAVE SENSORS

Lamb waves [4,5] are a form of elastic perturbation, which are manifest in finite thickness plate-like structures. They can be used to detect damage in structures by measuring the attenuation and phase shift of waves transmitted through damaged regions or from the time-of-flight of reflected waves. A Lamb wave transducer, as considered for an SHM system, thus must consist of an actuator, that generates Lamb waves, and a sensor that monitors the impinging waves. Further definition of Lamb wave transducers requires consideration of the selection of the operating principle for the sensor and actuator. Previous work has developed approaches for actuator [6, 7, 8] and sensor [8, 9,10] selection and has accumulated data for sensor and actuator performance. This framework and the existing data was used as the basis for the the present work. The generation of Lamb waves requires the introduction of mechanical strain energy (i.e. the product of actuator force and displacement) at a relatively high frequency (typical actuation frequencies are in the range 10-100 kHz). The precise frequency is determined by the structure to be monitored and the damage modes that are of concern. In addition a compact actuator is preferable. By plotting the performance of various actuation concepts, on a chart of stress-strain product (energy density) vs frequency, as shown in figure 3, it is possible to differentiate between various actuator schemes. Piezoelectric and electrostrictive (ceramic) actuators are apparently the best candidates for actuators operating in the required frequency range. Piezoelectric polymers might also be worth investigating further.

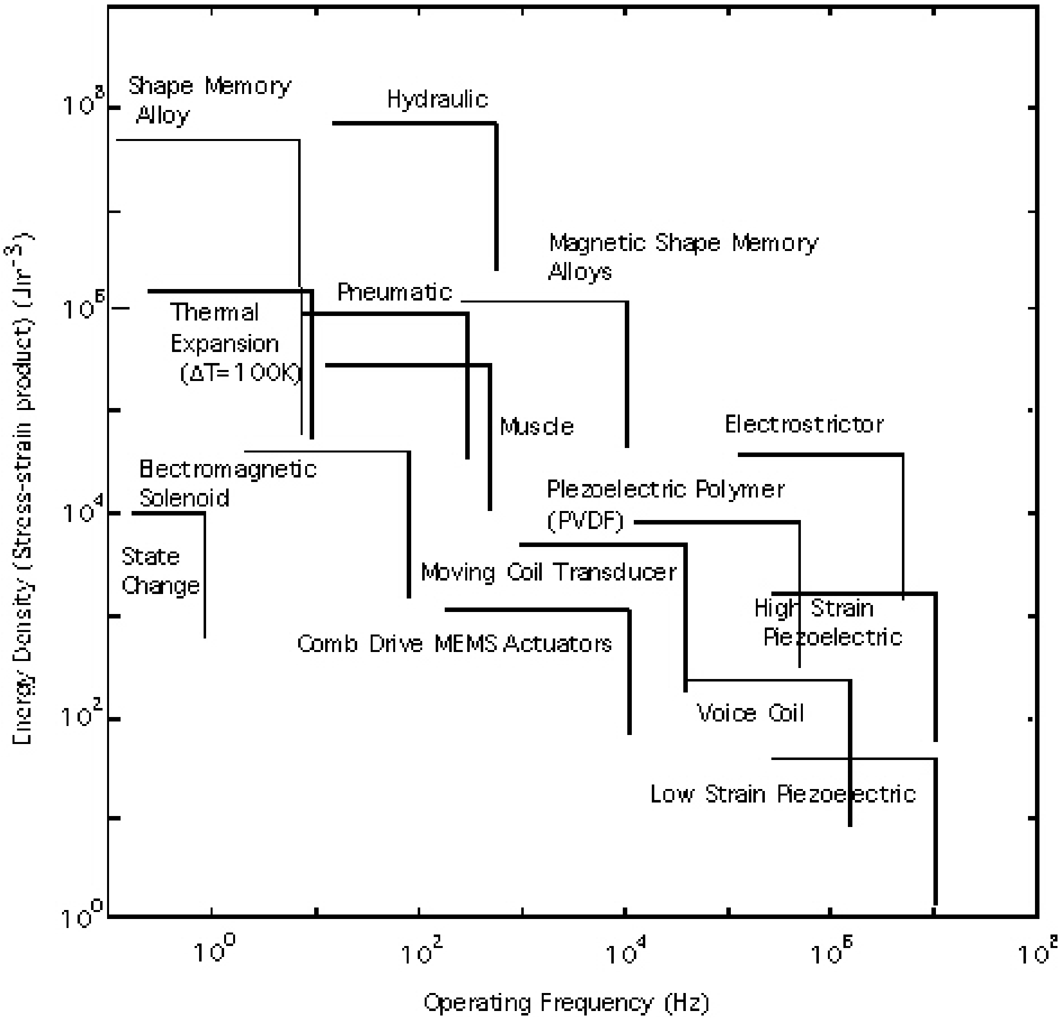

Figure 3. Lamb wave actuator selection chart. Energy density (stress-strain) product vs. frequency. After [6]

A similar process can be utilized to select the sensor type. In this case the requirement is to detect, with good resolution, the transmitted or reflected Lamb waves. These are inherently stress waves, so a force sensor with high resolution, and the required frequency capability is needed. Plotting the force resolution capabilities of sensor types against their frequency capability provides a means of selection, as shown in figure 4.

In this case piezoelectric and piezo-resistive sensors (e.g. semiconductor strain gauges) have the best combination of frequency and force resolution capabilities. Given the advantages of making the transducers from a single active material, it is apparent that piezoelectric ceramic materials are the best choice for both the sensor and actuator components of a Lamb wave-based SHM system.

It is also worth noting in passing that the requirement for a high operating frequency, and a long term desire to integrate the sensor, actuator, signal processing, power and communications in a single package lends itself to use of microelectromechanical systems (MEMS) technology.

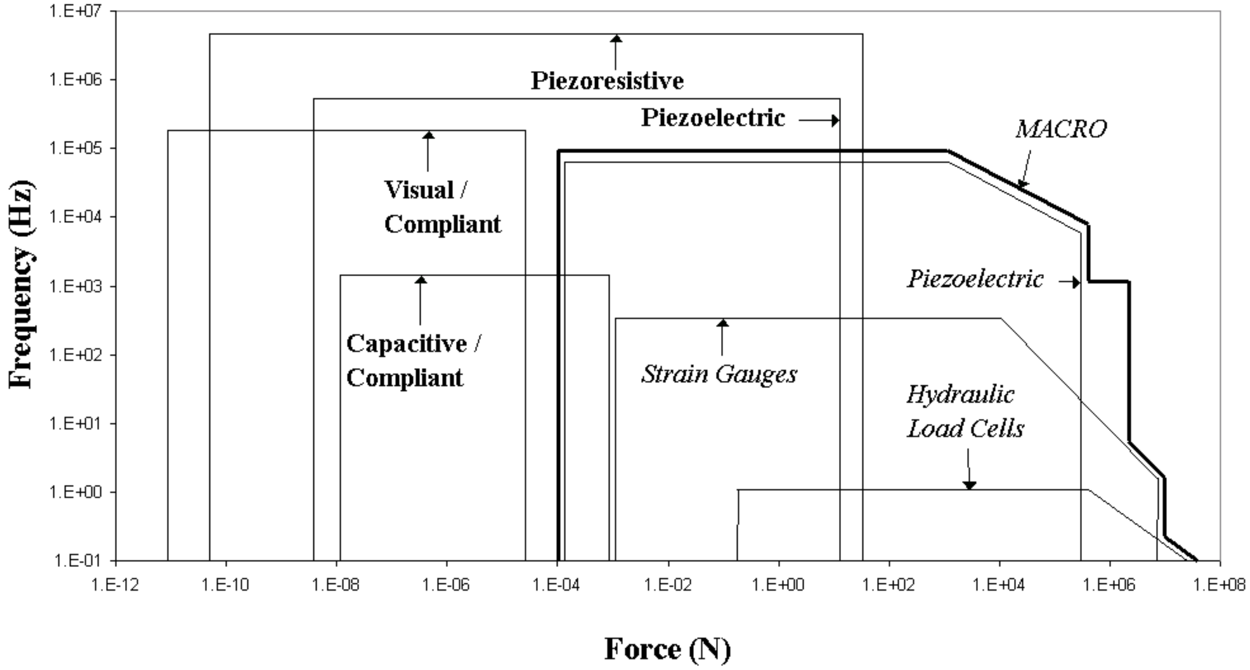

Figure 4. Lamb wave sensor selection chart. Force vs. frequency [8].

PIEZO-MATERIAL SELECTION

Having narrowed the material selection to piezo electric ceramics in general, the next step in defining the transducers for the SHM system is to conduct a detailed selection of the particular material composition and form. In order to perform this task, a wide range of piezoceramic materials was surveyed and the properties tabulated [10]. These are tabulated in table 1 with the relevant performance metrics. The materials are ranked according to the value of the piezo-stress coefficient, e_{31}^{p}, the stress per unit electric field, which is the key performance metric for actuation in the 3-1 mode (a through thickness field causing in plane stress). A high value of e_{31}^{p} implies a high force for a given applied voltage.

A similar process can be performed for the materials to act as the sensor element. In this case the performance metric is:

$$\frac{k_{31}^{2}}{d_{31}\left(1-k_{31}^{2}\right)}$$

Where d_{31} is the piezoelectric strain coefficient and k_{31} is the piezoelectric coupling coefficient. The candidate sensor materials are tabulated according to this performance metric in table 2. In addition to selecting the optimal material, it is necessary to match the actuator size to the structural thickness in order to optimize actuation and minimize power consumption.

Material	k_P (-)	s_{11}^E ($p\ m^2 / N$)	s_{12}^E ($p\ m^2 / N$)	σ^P (-)	ε_{33}^P (nF/m)	e_{31}^P (N / m V)
EBL#23	0.750	15.7	-4.9	0.31	14.7	-29.6
PZT-5K	0.650	16.0	-5.1	0.32	29.6	-29.5
PZT-5M	0.630	15.0	-4.7	0.31	21.5	-26.1
EBL#3	0.640	15.6	-4.6	0.29	18.0	-23.9
PZT-5H	0.635	16.9	-5.1	0.30	17.4	-22.4
PZT-5J	0.630	16.0	-4.7	0.29	14.1	-20.3
PZT-5B	0.640	14.7	-4.3	0.29	12.3	-20.3
EBL#6	0.630	20.3	-6.3	0.31	14.7	-18.6
EBL#25	0.630	22.3	-12.2	0.55	9.6	-17.7
EBL#9	0.600	12.3	-4.4	0.36	8.2	-17.1
PZT-5R	0.630	15.7	-4.0	0.25	10.9	-17.1
EBL#2	0.620	15.1	-4.9	0.33	9.4	-17.0
PZT-5A	0.600	16.1	-5.6	0.35	9.7	-16.8
EBL#1	0.600	10.8	-3.0	0.28	7.4	-16.3
PZT-4	0.580	12.4	-3.9	0.31	7.6	-14.7
EBL#7	0.560	10.8	-3.3	0.31	6.7	-14.3
PZT-7D	0.510	11.8	-3.6	0.31	8.4	-13.7
EBL#4	0.520	10.1	-2.9	0.29	6.8	-13.2
PZT-8	0.520	12.8	-1.2	0.09	6.8	-11.0
EBL#5	0.520	10.6	-3.6	0.33	2.7	-8.5
PZT-7A	0.510	10.6	-3.3	0.31	2.6	-8.2
BT	0.260	7.8	-2.6	0.33	9.1	-8.1

Table 1. Properties and performance metrics of candidate actuator piezo-materials

Based on the data tabulated in table 1, and 2, materials were selected for experimental comparison as sensor and actuator materials. The following materials were used as sensors and actuators EBL#5 (PZT-7A), EBL#23 (PZT-5K), EBL#3 (PZT-5H), EBL#2 (PZT-5A), EBL#1 (PZT-4). In addition two PVDF piezo-polymer materials were investigated as sensors: DT2-052K/L PVDF and SDT1-028K PVDF. The sensors were fabricated as rectangular plates, with dimensions in the range 12.5 x 6.4 x 0.25 mm – 25 x 6.4 x 0.5 mm. The actuators were fabricated as circular disks 12.5 mm in diameter and 0.25 mm thick. The piezo-active materials were metallized on their faces and electrical connections were made using a conductive epoxy.

In order to conduct a side-by side test the sensors were bonded, using double sided tape to the perimeter of a circular quasi-isotropic carbon-fiber composite plate 2mm thick and 400 mm in diameter. One or other of the actuator disks was affixed at the center of the plate. The test set up is shown in figure 5. The signal received by each sensor was monitored as a 20 V peak to peak sinusoidal signal was applied to the actuator through a frequency sweep from 1 to 250 kHz. This process was repeated several times with the sensors and actuators in varying configurations.

Material	k_{31} (-)	d_{31} (p m / V)	g_{31} (mV m / N)	Y_{11}^{D} (GPa)	$\| (k_{31})^2/(d_{31} (1 - (k_{31})^2) \|$ V / (mm $\mu\varepsilon$)
PZT-7A	-0.300	-60	-16.2	104	1.65
EBL#5	-0.300	-60	-16	103	1.65
EBL#1	-0.360	-127	-10.7	106	1.17
EBL#7	-0.330	-107	-10.9	104	1.14
EBL#4	-0.310	-95	-10.5	110	1.12
PZT-8	-0.350	-127	-12.2	89	1.10
PZT-4	-0.340	-125	-10.6	91	1.05
EBL#9	-0.340	-135	-10.5	92	0.97
PZT-7D	-0.300	-112	-9.6	94	0.88
PZT-5R	-0.385	-200	-11.5	75	0.87
EBL#2	-0.360	-173	-11.5	76	0.86
PZT-5B	-0.380	-210	-10.1	79	0.80
PZT-5A	-0.343	-177	-11.1	71	0.75
EBL#23	-0.440	-320	-9	79	0.75
PZT-5J	-0.375	-230	-9.8	73	0.71
EBL#3	-0.380	-262	-8.6	75	0.64
PZT-5H	-0.375	-264	-8.9	69	0.62
EBL#6	-0.370	-260	-9.8	57	0.61
PZT-5M	-0.370	-270	-7.6	78	0.59
EBL#25	-0.300	-179	-11	49	0.55
PZT-5K	-0.380	-323	-6.9	73	0.52
PT2/PC6	-0.030	-3	-2.1	135	0.30

Table 2. Properties and performance metrics of candidate sensor piezo-materials

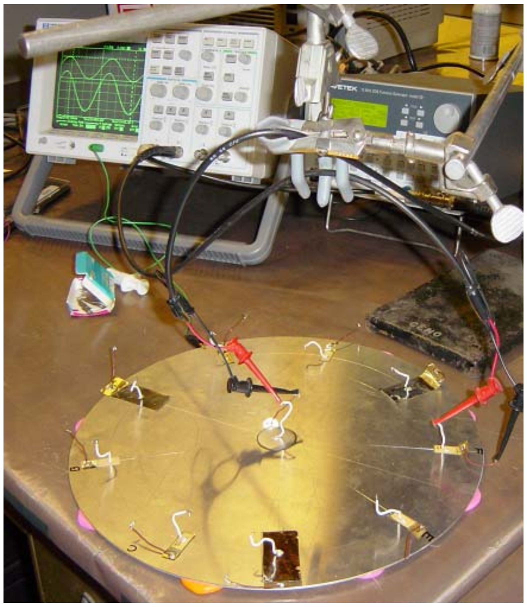

Figure 5. Sensor and actuator test configuration, actuator disk at center of a circular plate

The data for the sensed signals for each sensor material are plotted in figures 6 and those for the actuator materials are shown in figure 7. Three values of sensed signal are presented for each material, the minimum, maximum and average signal received for each sensor or actuator.

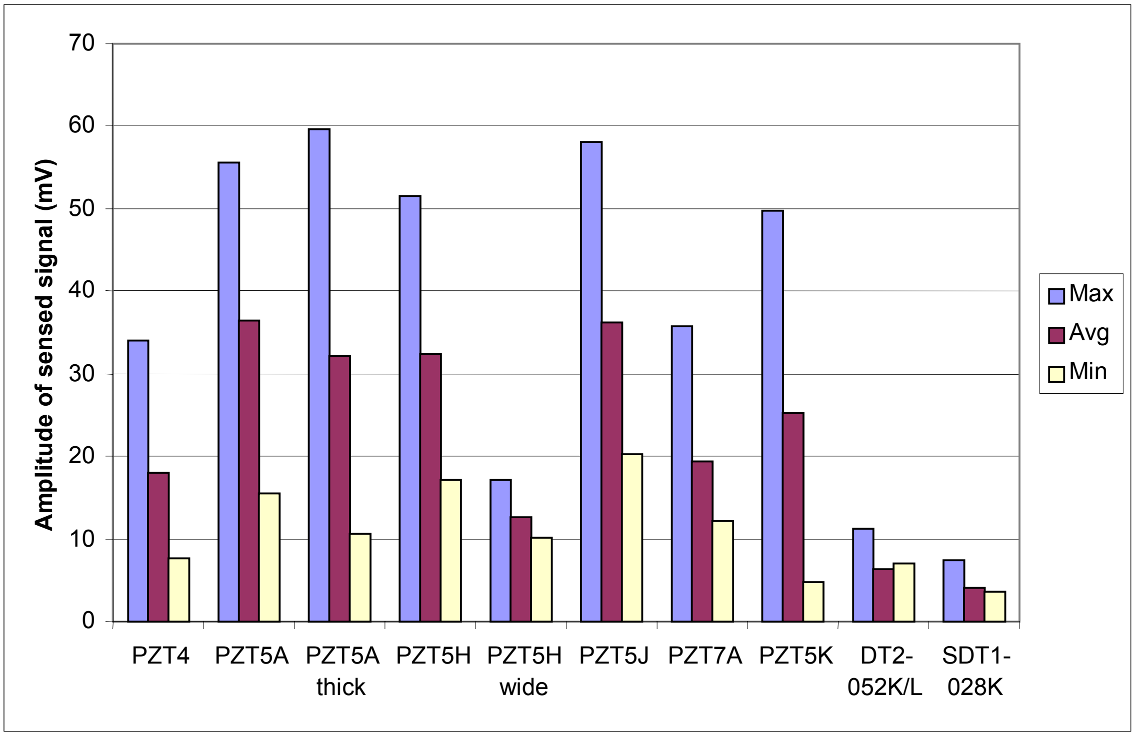

Figure 6. Experimental results for sensor materials

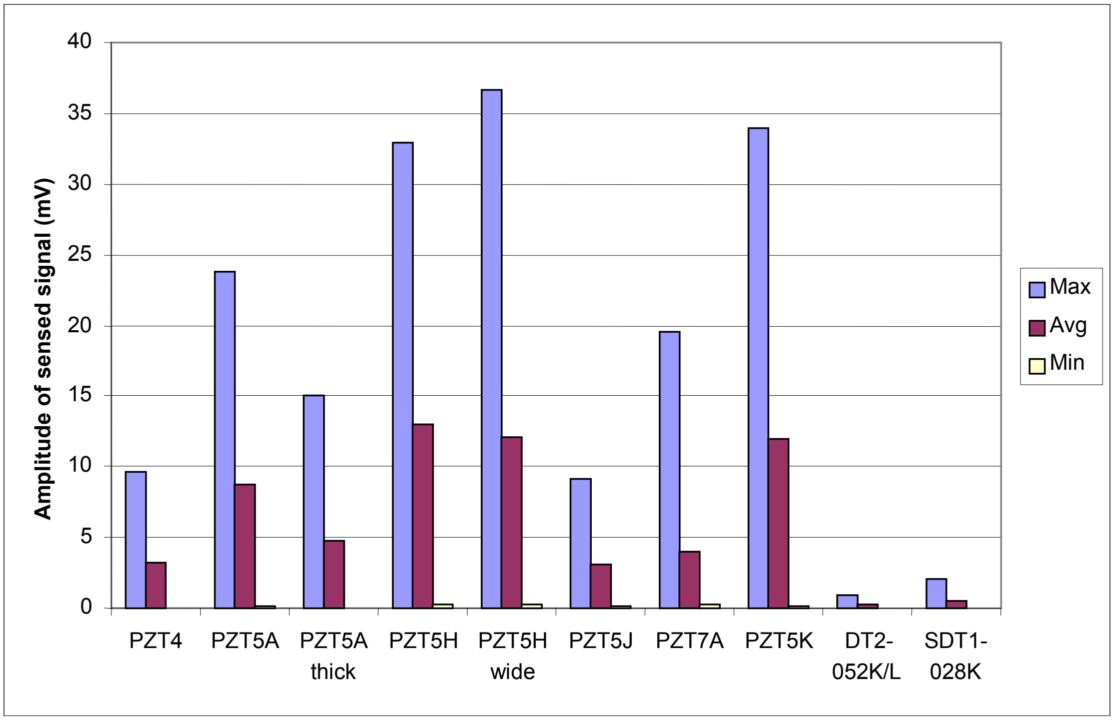

Figure 7. Experimental results for actuator materials

For sensing, several of the materials had very similar performance, PZT-5A and PZT-5J showed the highest means and minimums and PZT-5A showed the best bandwidths of its maximum peaks. For actuating PZT-5H and PZT-5K showed the highest amplitudes, with PZT-5A close behind. Overall, PZT-5A provides the best combination of sensing and actuating properties. In addition, its good thermal stability to above 200°C makes it particularly attractive as this facilitates integration with composite structures that may be exposed to significant temperature cycles during manufacturing and service.

SENSOR DESIGN AND TESTING

Based on the system definition, transducer and material selection stages described above, together with detailed studies, described elsewhere, a compact piezo-ceramic transducer has been developed for health monitoring applications. The interested reader can find more complete descriptions of this work elsewhere [11-13], this section is intended to provide a sense as to the effectiveness of such sensors for structural health monitoring. The device consists of a central circular PZT 5A sensor, surrounded by an annular actuator made of the same material. The sensor and actuator are adhesively bonded and electrical coupled to a metal ground plane. The whole assembly can then be bonded to the structure or component to be monitored. Separate electrical connections are made to the sensor and actuator.

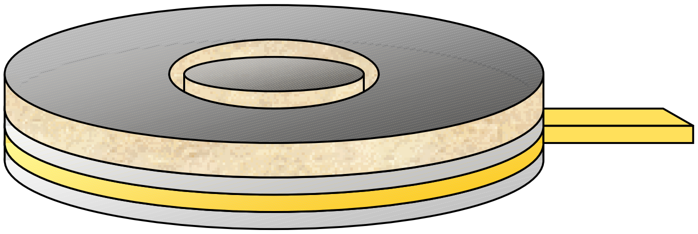

Figure 8. Transducer configuration

Figure 9 shows three transducers attached to a composite coupon. The actuators are excited by a sinusoidal signal gated by a Hanning window. The key to data interpretation is the use of wavelet decomposition [14] to breakdown the signal by frequency content and to differentiate between the various damage modes. The use of Lamb waves in combination with these signal processing techniques has proved highly effective at detecting and interpreting signals due to damage. In addition, the use of multiple sensors allows for the accurate triangulation of damage position. Figure 10 shows a representative signal due to a delamination in a composite coupon.

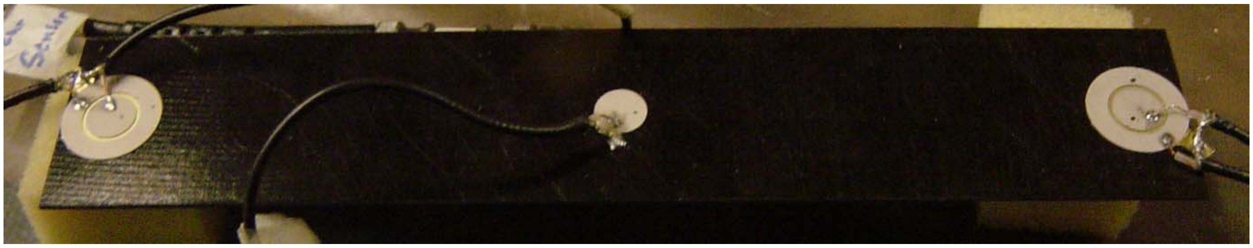

Figure 9. Transducers applied to a composite coupon.

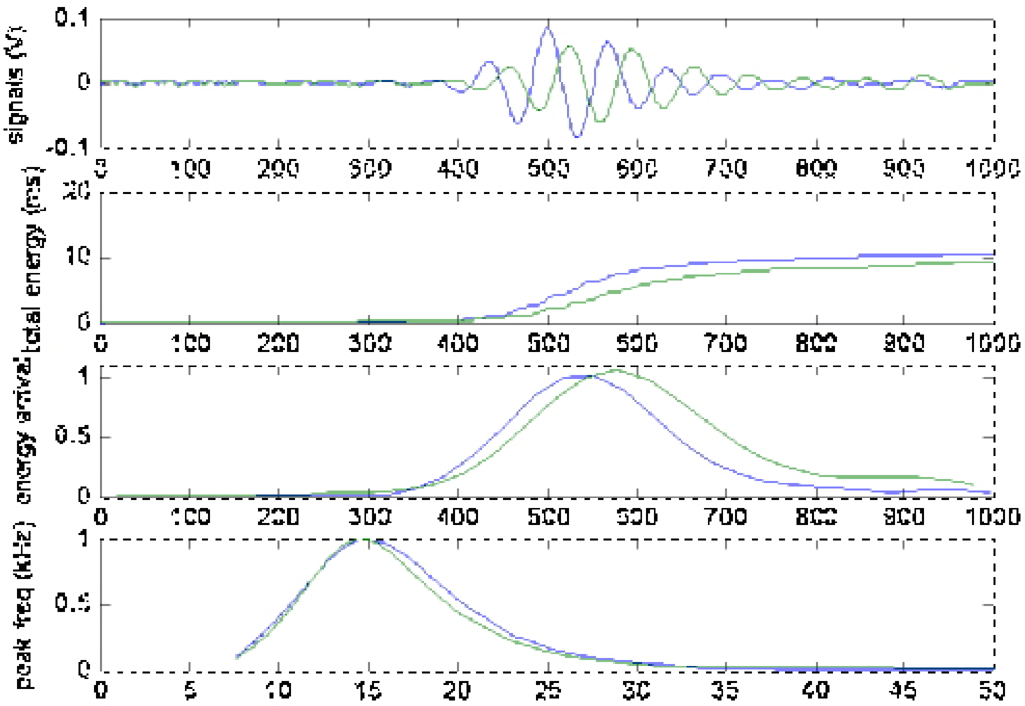

Figure 10. Comparison of signals from an undamaged and a composite specimen containing a representative 25 mm x 25 mm delamination..

CONCLUSIONS

A systematic approach has been presented for the selection of the operating principle for a structural health monitoring system. This has resulted in the selection of a system using Lamb Waves as the primary means of damage detection. Consideration of the requirements for transducer performance has led to the selection of piezo-ceramic materials for the sensor and actuator elements. Detailed experimental results combined with analysis led to the selection of PZT-5A as the material of choice. A brief description of the resulting transducer design and its application to detection of damage in composites illustrated the potential for this approach to structural health monitoring.

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