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Development of embedded piezoelectric acoustic sensor array architecture ☆

Anindya Ghoshal [a,*,1], William H. Prosser [b], Heung Soo Kim [c], Aditi Chattopadhyay [d], Ben Copeland [e]

[a] United Technologies Research Center, 411 Silver Lane, MS 129-73, East Hartford, CT 06108, USA
[b] Nondestructive Evaluation Sciences Branch, NASA Langley Research Center, Hampton 23681, USA
[c] Department of Mechanical, Robotics and Energy Engineering, Dongguk University-Seoul, 26 Pil-dong 3-Ga Jung-Gu, Seoul 100715, South Korea
[d] Department of Mechanical and Aerospace Engineering, Arizona State University, Tempe, AZ 85287, USA
[e] Materials Branch, NASA Langley Research Center, Hampton 23681, USA

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ABSTRACT

This paper examines development of novel piezoelectric acoustic sensors, which are capable of sensing high frequency acoustic emissions in a composite/metallic plate. The fabrication of the piezoelectric acoustic sensors, made from piezoceramic ribbons, is described in the paper. An attempt was made to build directionality into the sensing system itself. Continuous sensors placed at right angles on a plate are discussed as a new approach to measure and locate the source of the acoustic waves. Novel signal processing algorithms based on bio-inspired neural systems for spatial filtering of large numbers of embedded sensor arrays in laminated composite media are presented. It is expected that the present work would help in the development of microelectronic sensing aiding diagnostics and prognostics techniques for highly efficient health monitoring of integrated aerospace vehicles and structures.

1. Introduction

The initiation and propagation of damage in metallic and composite aerospace structures can produce acoustic emissions (AE) during loading. The acoustic emissions are high frequency waves caused by the initiation and propagation of cracks and delaminations, and by fretting or looseness in joints [1–16]. In plate structures, these AE signals propagate as Lamb waves.

It is envisioned that future aerospace vehicles will contain distributed embedded sensor arrays mimicking our own human neural system. At NASA Langley Research Center, and at the University of Cincinnati, efforts are currently underway to work with different conceptual types of distributed embedded sensor architectures to develop a biologically inspired sensory system for aerospace vehicles [17–23]. An active fiber continuous sensor (AFCS) was recently developed and is comprised of piezoceramic ribbons made by CeraNova Corporation, that are cast in epoxy with electrode imprinted Kapton films on either side. The advantages of the ribbons are that they are easy to handle and more flexible than piezoceramic cylindrical fibers.

In this paper, the fabrication of perpendicular piezoelectric acoustic sensor module is discussed followed by the discussion of the biologically inspired distributed sensor architectures for intelligent aerospace skin structures and smart signal processing techniques. The piezoelectric sensors in this paper are tuned to detect Lamb wave propagation in the plates. The AE waves generate structural plate modes; however, the present effort does not discriminate between the two different modes. Normally the far-field plate modes are considered part of the AE waves.

2. Fabrication of the perpendicular piezoelectric acoustic sensor

Fig. 1 shows the sequence of the construction of the directional piezoelectric acoustic sensor module. Initially the PZT ribbons were cut to small pieces (according to the length of the required length of the sensor) and then immersed in epoxy and laid onto one of the electrode imprinted Kapton film. This was done manually with tweezers. However an aluminum mold can be used to fabricate large numbers of sensors. Also CeraNova now produces the ribbons in a jacket, which would facilitate the easier fabrication and ensures that the finger spacing remains constant after curing. Once the ribbons were arranged with specified finger spacing and placed perpendicularly across the imprinted electrodes, then the sensor was cured for about half an hour at about 120 F. After cooling, the face of Kapton film with the attached ribbons is again immersed in epoxy and the other Kapton film is then attached to make the whole sensor. Once the prepreg of the sensor is done, it is again heated for about 70–90 min to complete the curing cycle in an autoclave.

Next, the PZT sensor is placed in a thermal chamber, heated for about 10–15 min at 175 F (79.4 °C) and with 3000–4000 V applied across it. The NASA LaRC Thunder Poling program was used in the

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* Corresponding author.
E-mail address: anindo_ghoshal@yahoo.com (A. Ghoshal).

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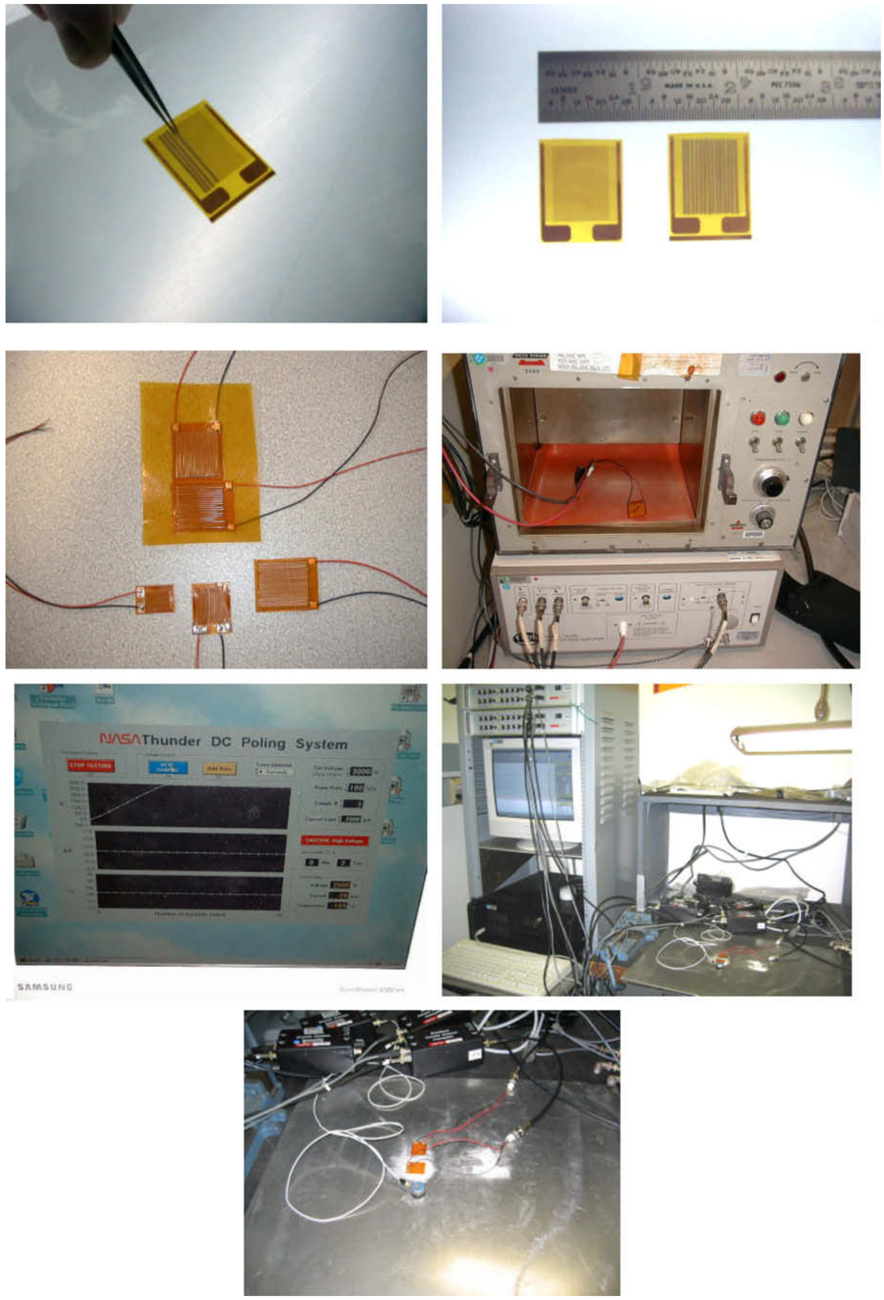

Fig. 1. Sequences for fabrication and testing of perpendicular acoustic AFC sensor module.

fabrication process. This allows the PZT crystals to align themselves during the poling process. Once, two such sensors are placed perpendicular to each other, as shown in Fig. 1, the fabrication of the perpendicular/directional acoustic piezoelectric sensor module is complete. The sensors have been tested on aluminum plates and the initial results regarding directionality sensitivity are encouraging.

3. Bio-inspired embedded sensor array architecture

3.1. Continuous array system

A continuous sensor array is defined as multiple piezoelectric sensory nodes attached in series or in parallel [17–23]. The continuous sensor array system is used for structural health monitoring in which the sensors are arranged in a continuous series or in parallel connection for increasing the likelihood of detecting a critical event. In the preferred embodiment, the discrete sensor nodes in one or more subgroups are electrically connected in series, thereby forming a continuous series connection between each of the discrete sensor nodes to improve the likelihood that a critical structural event will be detected [21,22]. These sensors can be embedded in coupons of laminated composite plate structures forming a 'smart skin'.

A new conceptual Perpendicular Unidirectional Active Fiber Composite Sensor Module (PAFCSM) developed at Langley Research Center is shown in Fig. 2a. While this particular directional sensor uses the interdigitated approach, the one developed at University of Cincinnati uses a parallel plate capacitance with a dielectric in between the plates. Continuous sensors placed at right angles on a plate are being developed as a new approach to measure and locate the source of acoustic waves. Fig. 2b represents conceptual hierarchical sensor array system concept comprising a 3×3 continuous sensor array on the top level with 4×4 cross ar-

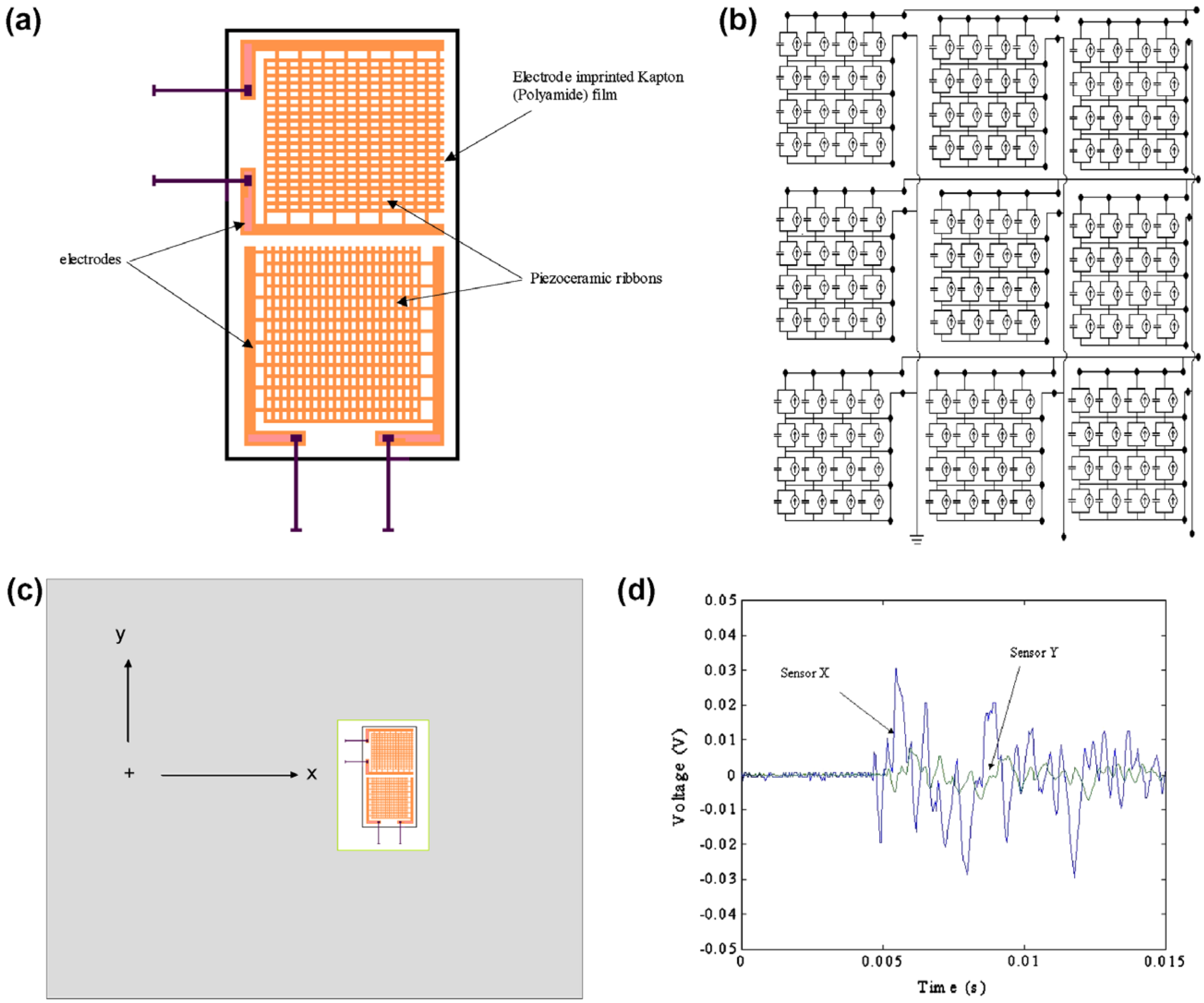

Fig. 2. (a) Perpendicular active fiber composite sensor module, (b) a hierarchical sensor array with a combination of cross array, (c) schematic of the Al-plate with the PAFCS module and impact location with *x* and *y* co-ordinates shown and (d) the sensor outputs from a perpendicular acoustic sensor module mounted on an aluminum plate and tapped with an uncalibrated impact hammer.

ray sensors located at each unit level. It is expected that most of the signal information would be locally processed at the unit level to generate a distributed sensor architecture that is integrated by the flight computer at a higher level. Fig. 2c illustrates a schematic view of the Al plate with the impact location with respect to the sensor nodes indicated with *x* and *y* co-ordinates. The impact location is defined to be parallel to the *x*-direction and perpendicular to the *y*-direction. Fig. 2d shows the sensor output from a perpendicular acoustic sensor (perpendicular acoustic active fiber composite sensor module) mounted on an aluminum plate and tapped with an uncalibrated impact hammer. The directional sensor outputs clearly show that in this case, the amplitude in the sensor node in the *x*-direction is about five times higher than the sensor node in the *y*-direction. This clearly shows the built-in directionality capability of such sensors with regards to the localization of the source of the impact.

3.2. Bio-inspired distributed neural sensor array system and advanced signal processing

Modeling and testing need to be conducted to develop a bio-inspired distributed neural sensor array architecture. Distributed sensors built from a combination of piezoelectric sensor arrays and FBG sensor arrays, could tremendously reduce the complexity of a structural health monitoring (SHM) system. For distributed sensors, the number of channels, as well as the associated electronics is greatly reduced, while the sensitivity is improved by having closer more numerous sensors closer to the damage sites. Conventional sensors such as point AE or ultrasonic sensors and accelerometers are accurate sensors, but many channels of data acquisition will be needed to monitor even moderate size structures. The cost and weight of such systems is often impractical. In the distributed neural sensor concept being developed, sensors are distributed spatially over the whole structure. It has an inherent higher probability that one of the sensor array nodes will be closer to the damage than the discrete sensors. Being close to the damage site is probably the most important factor in detecting damage due to corrosion and other forms of damage. The inherent advantage of this type of sensor array architecture is that they are multifunctional as they can diagnose the damages caused by different sources. Thus, the distributed sensor can use a small number of channels to detect damage on a large structure, which makes it practical for SHM, whereas current techniques using conventional sensors and data acquisition are not practical for many SHM applications.

Using the nature of the distributed neural sensing concept, several different novel signal processing algorithms would be developed. Use of continuous sensor arrays allows large spatial coverage using a small number of output channels for data acquisition. However, certain localization information may be lost in the process requiring the need for novel signal processing especially for the localization, diagnosis, and prognostics of the damage in the aerospace structure. Also for continuous real-time monitoring, a different paradigm for signal processing is necessary, otherwise the flight computers could be overloaded with streams of huge volumes of data. The following techniques allow a great reduction in the amount of data that needs to be processed and also reduce the probability of false alarms from ambient noises. The principle behind the following signal processing algorithms is to use selective data acquisition and filtering of signals at the structural level (using the 3-dimensional space of the structure as a spatial filter) and then using classical signal processing techniques like neural network, fuzzy logic, wavelet analysis, time–frequency analysis and wave velocity methods at the backend software level in the onboard flight computer. The hardware, which may include high-speed MEMS switches, can be embedded and the electric circuitry etched onto the smart composite laminate, which would act as a ply of a laminated composite structure. It is expected future sensing technology would be comprised of wired connectivity at the local levels whereas wireless connectivity would be used at the global level. At the local level, the discrete or the continuous sensor components would be wire connected to a local bus with an antenna (receiver and transmitter) device, which would communicate wirelessly to the onboard flight computer (Fig. 3). This would eliminate a significant number of wireless channels which otherwise would be needed to monitor large number of discrete sensors using wireless connectivity. It is envisioned that these techniques would be useful for both wireless and wired sensor arrays. The associated wired and wireless protocols have to be developed such that they do not interfere with the on-flight communications or compromise the stealth of a combat aerospace vehicle.

3.3. The neuron firing and inhibition technique

The continuous sensor array format (PAFCSM), as shown in Figs. 2 and 3 can be easily extended to $n \times n$ size continuous sensor array systems. Experimental investigations are conducted using plate specimens as shown in Fig. 4 where the plates are excited using a Hsu–Nielsen source, by an impact hammer, or a surface bounded actuator. When a propagating crack releases acoustic energy, it is envisioned that it will trigger a preset flag in the processor of the continuous sensors. Exceeding this preset threshold limit is known as 'firing' of the neuron. The threshold limit is predetermined by the attenuating nature of the material of the structure and the sensor sizes. Using the 'inhibition' analogy as in the human neural system, this acoustic event is noted by the signal conditioning equipment, and electronic switches, to allow streams of data to be downloaded onto the flight computer from the row and the column continuous sensors, which had been activated first. The other channels can be 'inhibited', which is to reduce their tendency to 'fire'. This particular technique has been developed at University of Cincinnati and at NASA LaRC [17,18]. Classical signal processing techniques like wavelet analysis, neural network or time frequency analysis can then be used to process the data for structural health monitoring of the system. Fig. 4a shows a smart laminate with three embedded continuous sensors. Fig. 4b shows the S-Glass $[0, 90]_{4s}$ with embedded continuous sensor laminate while Fig. 4c shows the Digital Wave Corporation AE equipment with the sample.

Fig. 5a shows a $[0, 90]_{4s}$ S-Glass epoxy plate with an embedded smart sensor layer. The sensor layer (made by Acellent Technologies) contains several discrete independent piezoceramic wafer sensor elements. The sensor elements in this layer are connected based upon the neural system architecture to form three parallel continuous sensors, each containing three sensor nodes. The sensory nodes are connected row-wise and then column-wise. These would be part of a laminated composite structure forming the 'smart skin'. An Hsu–Nielsen AE source excitation is applied at the 'x' location as shown in Fig. 5a. Fig. 5b shows the outputs from the row-wise and column-wise parallel sensors compared with the acoustic emission sensor output from a point sensor at the AE source. A Digital Wave Corporation AE system has been used with a gain of 21 dB to acquire the data. The trigger was preset at 0.6 V after amplification. The downloaded neuron data is then analyzed by a computational algorithm, which simulates the firing that would otherwise be done by associated electronics at the sensor level. The neurons that fired are Parallel Row Sensor 2 and Parallel Column Sensor 2, respectively and the other neurons are inhibited or prevented from firing.

In Fig. 5c, sensor ID numbers 1, 2 and 3 are the Parallel Row Sensors and 4, 5, and 6 are the Parallel Column Sensors. The bar chart

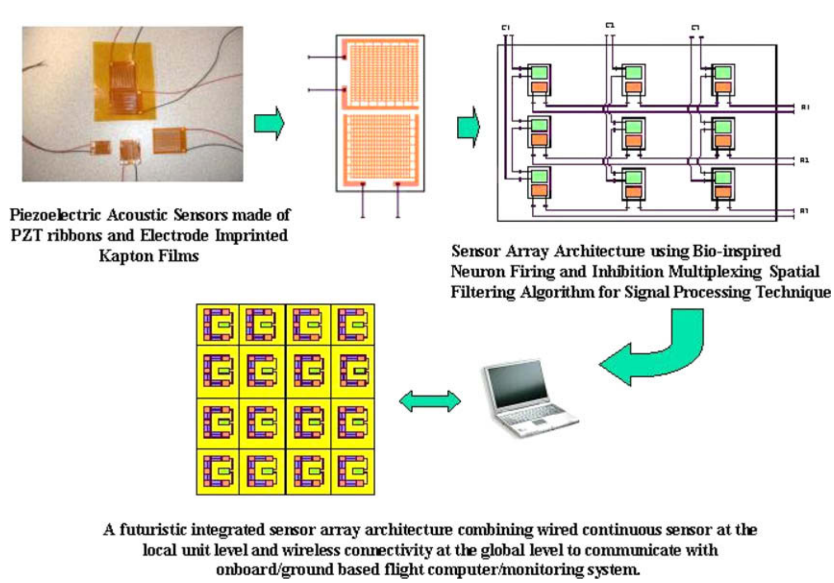

Fig. 3. Conceptual bio-inspired distributed embedded wired/wireless distributed sensor array architecture for acoustic wave generation and propagation.

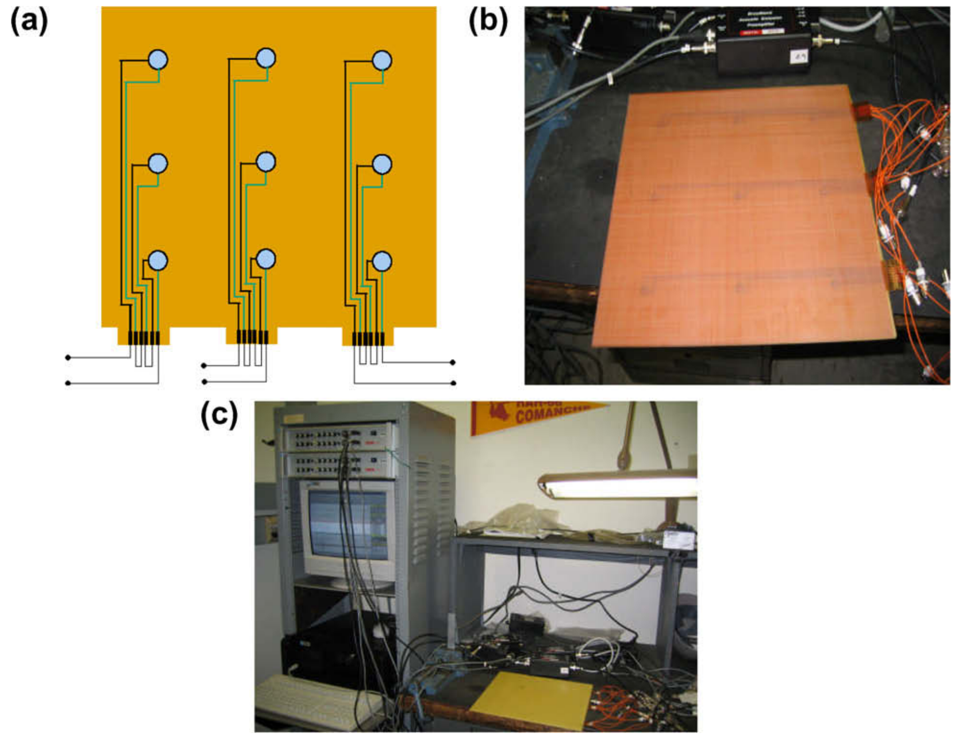

Fig. 4. (a) Smart laminate with three embedded continuous sensors. (b) S-Glass $[0, 90]_{4s}$ with embedded continuous sensor laminate. (c) Digital equipment corporation AE equipment with the sample.

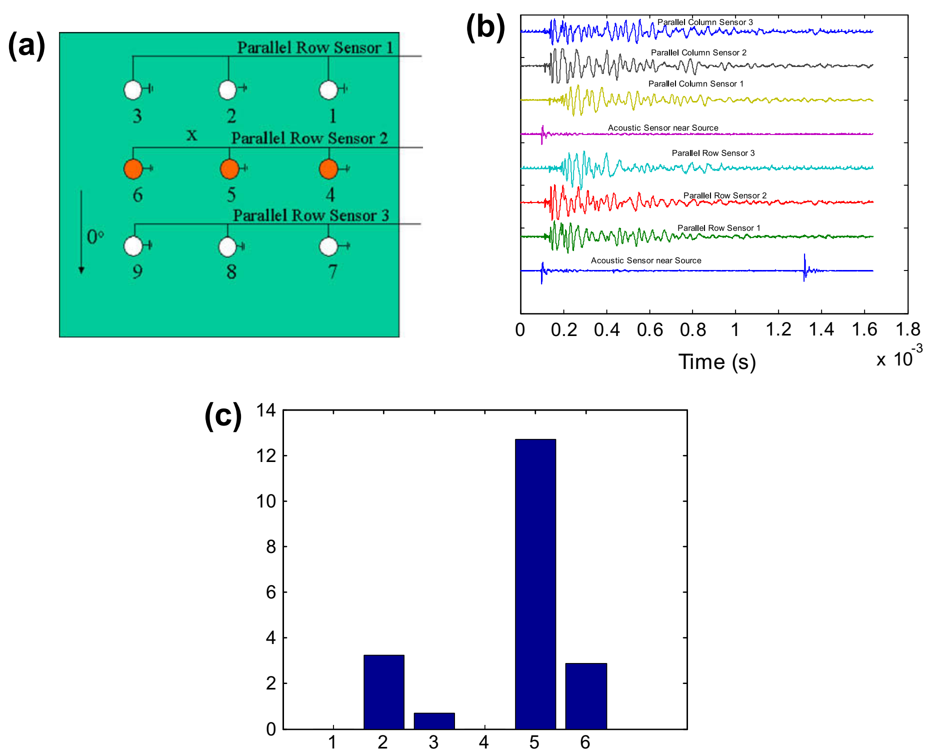

Fig. 5. (a) Smart laminate with three parallel continuous sensors, each containing three sensory nodes made of piezoceramic wafers. (b) The output from the row-wise and column-wise parallel sensors output compared with the acoustic emission sensor output at the source. (c) The bar chart shows the percentage RMS values of the voltage output from the each of the continuous sensors.

shows the percentage RMS values of the voltage output from each of the continuous sensors, and compared with respect to the minimum RMS sensor output value. This clearly shows the AE source is located nearest to the Parallel Row Sensor 2 and the Parallel Column Sensor 2. Future manned and unmanned aerospace vehicles must be ultra lightweight and highly flexible, hence such embedded sensor arrays and associated electronics likewise must be highly flexible and lightweight in nature such that they do not impede the mechanics of the flight structure. Hence lightweight nanosensors or microsensors would be a logical choice for this application.

3.4. The Prosser multiplexing system

When the acoustic event occurs, the row and the column continuous sensors closest to the acoustic source are activated when they reach the preset trigger limit. The Prosser multiplexing system is a technique developed at NASA LaRC [24] that can be used to allow the main computer to accept streams of data from the adjacent continuous sensors and inhibits (turns off) the far away sensors. This helps in looking at the leading edge of the acoustic signal, which would have been otherwise lost, if information is accepted only from the triggered continuous sensors. Fig. 6a shows the acoustic emission output from the nine embedded sensors due to a Hsu–Nielsen source as indicated by the x in Fig. 6b. Fig. 6b shows the first firing neuron as sensor 3. Data from the adjacent sensors 2, 6 and 5 is downloaded using the Prosser multiplexing algorithm. In this case, nine sensor nodes are tracked individually. The acoustic event lasts for about 1.6 ms. In such multiplexing systems, for continuous monitoring, the time preset for following one acoustic event is important. Once the information is downloaded for a particular acoustic event, the system is reset to await detection of the next acoustic event. The associated electronics are currently under development at NASA LaRC.

3.5. "Hands up/hello" algorithm

A novel "Hands up" algorithm [25] is being developed to process signals from an $n \times n$ size wireless/wired discrete and continuous sensor array to extract enough information for locating the source of the AE signal, instead of having to download all the data from each of the sensors. Initially this algorithm was proposed for target tracking systems. When a propagating crack releases acoustic energy it triggers a flag ("Hands up") in the sensors, which reach a certain preset threshold limit. Once the cluster head or the central processing unit is notified of the flags from those particular discrete or continuous sensors, the signal processing is done in two ways. In the first case, the cluster head or the processing unit receives data simultaneously from those sensors, which had the "Hands up" flag triggered. The signal data (voltage–time history in this case) obtained from those sensors can be then processed using conventional signal processing techniques to locate the source of the AE. In the second case, no other data is queried from the sensors; a probabilistic algorithm using the triggered sensing density as a parameter is executed to locate the source of the AE. This allows a great reduction in the amount of data that needs to be processed and also eliminates the chances of false alarms from ambient noises. It is envisioned that this technique would be useful for both wireless and wired sensor arrays. Future biosensors and quantum dot sensors or nanosensors are mostly capable of replicating binary data. This particular technique is highly suitable to process using such binary information very quickly and precisely. Fig. 7a shows the "Hands up" algorithm showing the triggered sensors with "red" flags up due to the Hsu–Nielsen AE source. The

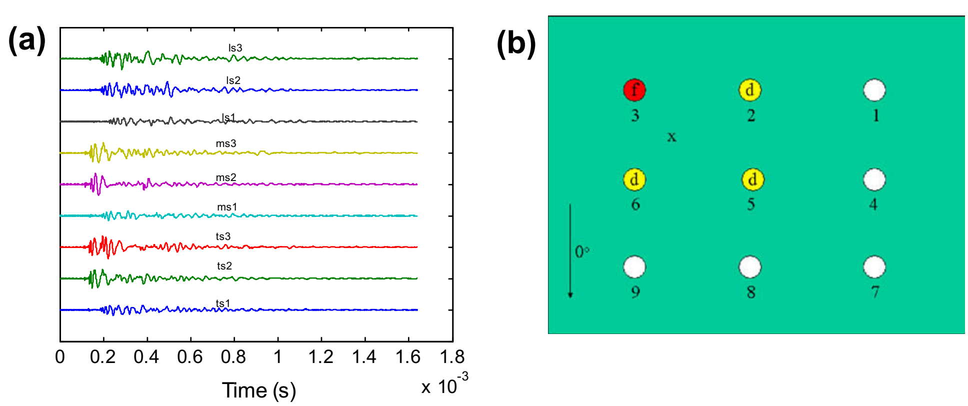

Fig. 6. (a) Acoustic emission output from the nine embedded sensors. (b) This shows the first fired neuron as sensor 3 and the adjacent sensors 2, 6 and 5 are used for downloading the signal data using Prosser multiplexing algorithm.

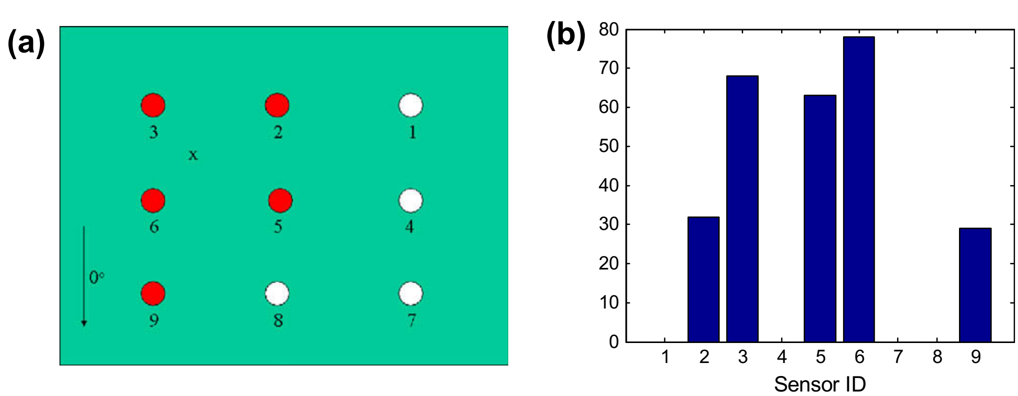

Fig. 7. (a) "Hands up" algorithm showing the triggered sensors with "red" flags up due to the Hsu–Nielsen AE source. The source position is indicated by 'x'. (b) A new damage indicator developed shows that the AE source is closer to the sensors 3, 5 and 6. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

source position is indicated by 'x'. Fig. 7b presents a new damage indicator developed, which shows that the AE source is closer to the sensors 3, 5 and 6. The damage indicator uses the density of peaks beyond the trigger level, (counts the number of times the sensor would fire during one acoustic event) which was preset in this case at 0.5 V (after amplification by 21 dB) registered by the sensors for an acoustic event lasting 1.6 ms. The damage indicator DI is defined as

$$\begin{aligned} \mathrm{DI} &= \sum \mathrm{ncount} : |\mathrm{PV}| > |\mathrm{threshold}\ \forall \mathrm{cycles} : \mathrm{threshold} \\ &= \text{predefined trigger level voltage} \end{aligned} \tag{1}$$

where PV is the peak voltage and ncount is the number of voltage peaks for every troughs and crests in the AE signal greater than the threshold, for that particular AE event. The ratio of the ncounts for each sensor can be used quickly to calibrate the location of the AE source.

The RMS values are indicator of the signal energy detected by the sensors. Due to the effect of structural damping, the closer the sensors are to the impact location, the higher the expected RMS values are and conversely the far-field sensors will have lower RMS values. The Figs. 5c and 7b follow this principle.

4. Conclusion

The fabrication of the directional piezoelectric acoustic sensor module is illustrated. Three bio-inspired sensor architecture and signal processing algorithms have been presented. They simplify signal processing to a point where structural health monitoring using data from large array of sensors becomes more practical. It is expected that these sensors and bio-inspired signal processing systems would be very useful for NDE applications in futuristic integrated autonomous aerospace vehicles.

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