Title: *Concepts and Development of Bio-Inspired Distributed Embedded Wired/Wireless Sensor Array Architectures for Acoustic Wave Sensing in Integrated Aerospace Vehicles*

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Abstract

This paper discusses the modeling of acoustic emissions in plate structures and their sensing by embedded or surface bonded piezoelectric sensor arrays. Three different modeling efforts for acoustic emission (AE) wave generation and propagation are discussed briefly along with their advantages and disadvantages. Continuous sensors placed at right angles on a plate are being discussed as a new approach to measure and locate the source of acoustic waves. Evolutionary novel signal processing algorithms and bio-inspired distributed sensor array systems are used on large structures and integrated aerospace vehicles for AE source localization and preliminary results are presented. These systems allow for a great reduction in the amount of data that needs to be processed and also reduce the chances of false alarms from ambient noises. It is envisioned that these biomimetic sensor arrays and signal processing techniques will be useful for both wireless and wired sensor arrays for real time health monitoring of large integrated aerospace vehicles and earth fixed civil structures. The sensor array architectures can also be used with other types of sensors and for other applications.

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. In plate structures, these AE signals propagate as Lamb waves. For some damage mechanisms in thin plates, the largest amplitude signals are produced by the lowest order asymmetric Lamb mode, also referred to as the flexural plate mode. In this paper, acoustic wave models, biologically inspired distributed sensor architectures for intelligent aerospace skin structures and smart signal processing techniques are discussed.

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Acoustic Wave Propagation Models

The present section discusses three main models that have been developed for acoustic wave generation and propagation in plates using AE sources. A closed-form model of flexural plate wave propagation in quasi-isotropic and orthotropic composite plates is presented in refs [1-3]. A 3-D Finite Element model for pencil lead breaks (Hsu-Nielsen AE source) as dipoles and monopoles derived from the elastic stress wave equations for anisotropic materials is shown in [4,5]. A FE model using an improved zigzag layerwise theory for delaminated composite laminated plates with embedded continuous and discrete sensors with a Hsu-Nielsen AE source and a surface bonded actuator is shown in ref [6]. Modeled AE signals have been compared with experimentally simulated AE signals generated from lead breaks and an impact hammer. A Hsu-Nielsen source (a lead break of a 0.3 mm mechanical pencil at a pre-calibrated angle) is modeled as a step input with a magnitude of 1 N. The Hsu-Nielsen source mimics the acoustic energy released by a propagating crack or delamination in the structure, thus generating similar acoustic waves containing similar frequencies and wave speeds. A surface lead break would induce both flexural and extensional waves whereas an edge break closer to the mid-plane would only generate extensional waves, similar to what a propagating crack would generate. The comparison of the simulated (both closed form and FE models) and experimental acoustic wave signals indicates that, as expected, the closed form model is a far-field solution, thus predicting accurate signal outputs only when the sensors are located away from the wave source. In the near field, closed form model results were not in good agreement due to the presence and overlap of extensional mode waves. In contrast the FE models does simulate both extensional and flexural wave modes. The lower frequency flexural mode plate waves were found useful to indicate the time of arrival of the waves at the continuous sensors, and to locate the wave source. Experimental and simulated results of scattering of AE waves from lead breaks due to the presence of voids shows similar outputs. The voltage outputs of both surface bonded sensors and embedded sensors due to acoustic waves generation and propagation in plates had been modeled and compared. While the FE models are very accurate in predicting the displacement and sensor outputs, the main disadvantage of both the FE models are that they are time consuming and highly computationally intensive to solve with respect to the normal mode closed form solution. It is expected that the AE models will be helpful in optimizing the design of continuous sensors, and for applying flexural wave propagation for locating the source of AE signals.

Modeling of the Bio-Inspired Distributed Sensory System

It is envisioned that future aerospace vehicles will contain distributed embedded sensor arrays mimicking our own human neural system. At NASA Langley Research Center, at the University of Cincinnati and at North Carolina A&T State University, 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 [7-11]. 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. Figure 1(a) shows a typical neuron of human nervous system and Fig 1(b) shows the equivalent circuit of a dendrite or axon [7]. A new conceptual Perpendicular unidirectional Active Fiber Composite Sensor Module (PAFCSM) developed at Langley Research Center is shown in Figure 1(c). While this particular directional sensor uses the interdigitated approach, the one developed at Cincinnati uses the parallel plate capacitance with a dielectric in between the plates approach. 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. A continuous sensor array is defined as multiple piezoelectric sensory nodes attached in series or in parallel [7-11]. These sensors are embedded in testing coupons of laminated composite plate structures forming the 'smart skin' currently being developed. Figure 2(a) shows the circuit model of n sensor nodes connected in series to form a continuous sensor [7]. Figure 2(b) represents a conceptual hierarchical sensor array system concept comprising a 3x3 continuous sensor array on the top level with 4x4 cross array 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.

Evolutionary Signal Processing Techniques for Neural Systems:

Using the nature of the distributed neural sensing concept, several different novel signal processing algorithms are being developed. Use of continuous sensor arrays allows large spatial coverage using a small number of output channels for data acquisition. However, certain localization information maybe 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 can overload 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 chances 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.

The Neuron Firing and Inhibition Technique

The continuous sensor array format (PAFCSM) as shown in Figures 2 and 3 can be easily extended to n x n size continuous sensor array systems. Experimental investigations are currently underway using plate specimens as shown in Figures 2 and 3 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 is currently under development at University of Cincinnati [7,11] and at NASA LaRC. 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.

Figure 4(a) 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 3 parallel continuous sensors, each containing 3 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 Figure 4(a). Figure 4(b) 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 download 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.

Figure 4(c) shows the $[0,90]_{4s}$ S-Glass epoxy composite laminated plate with embedded sensors. In Figure 4(d), sensor ID #s 1, 2 and 3 are the Parallel Row Sensors and 4, 5, and 6 are the Parallel Column Sensors. The bar chart 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. The associated electronics to implement this processing on the structure are currently under development. 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 the lightweight nanosensors or microsensors would be a logical choice for application.

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 [12] 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. Figure 5(a) shows the acoustic emission output from the 9 embedded sensors due to a Hsu Nielsen Source as indicated by the x in Fig 5(b). Figure 5(b) 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 milliseconds. 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.

“Hands Up/Hello” Algorithm

A novel “hands up” algorithm is being developed to process signals from an n x 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 [13]. 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 then 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. Figure 6(a) shows the “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’. Figure 6(b) 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 21dB) registered by the sensors for an acoustic event lasting 1.6 ms.

Conclusions

In essence, all of the above three novel signal processing algorithms still would depend on the sensitivity of the sensors, the sensor array density, placement of sensor nodes, material properties of the structure and boundary conditions. However they simplify signal processing to a point where structural health monitoring using data from large array of sensors become more practical. For the real-time health management of integrated aerospace vehicles like next generation launch vehicles, large civil and aerospace structures, and ultra-lightweight unmanned aerospace vehicles, these AE models, biologically inspired sensor array architectures, and the fast, and efficient spatial signal processing algorithms presented in this paper can be very useful.

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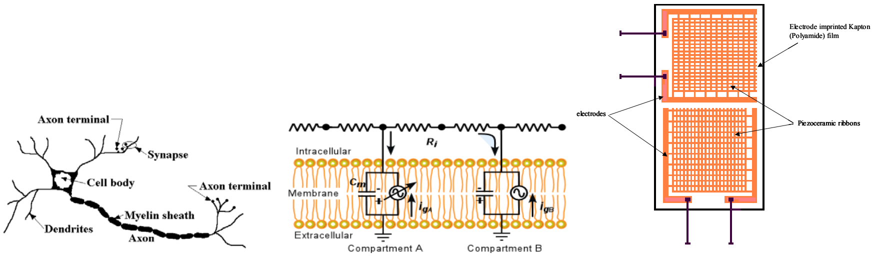
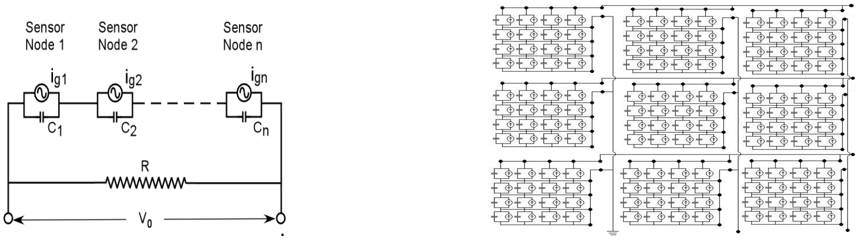
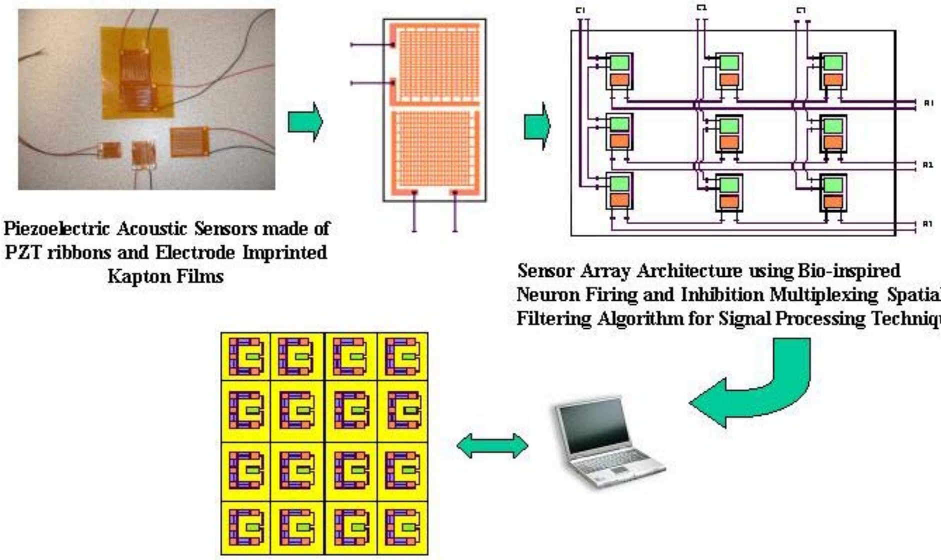


Figure 1(a) A typical neuron [7]. (b). Equivalent circuit of a dendrite or axon [7]. (c): Perpendicular Active Fiber Composite Sensor Module.



(a) (b)

Figure 2(a): The circuit model of n sensor nodes connected in series to form a continuous sensor [7-11].
Figure 2(b): A hierarchical sensor array system

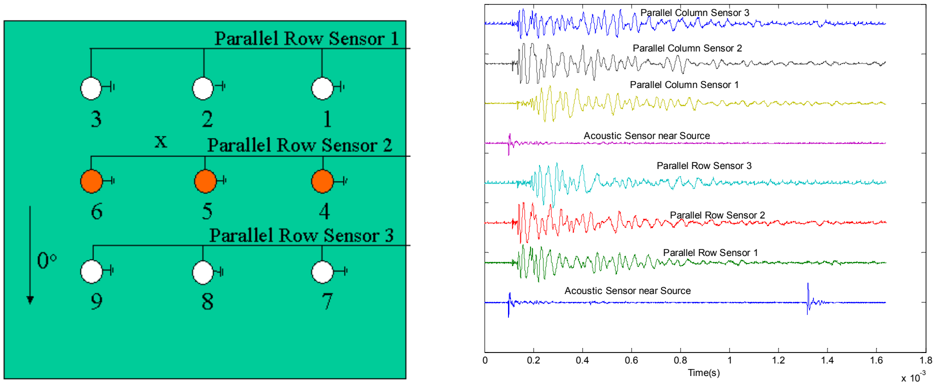


Piezoelectric Acoustic Sensors made of PZT ribbons and Electrode Imprinted Kapton Films

Sensor Array Architecture using Bio-inspired Neuron Firing and Inhibition Multiplexing Spatial Filtering Algorithm for Signal Processing Technique

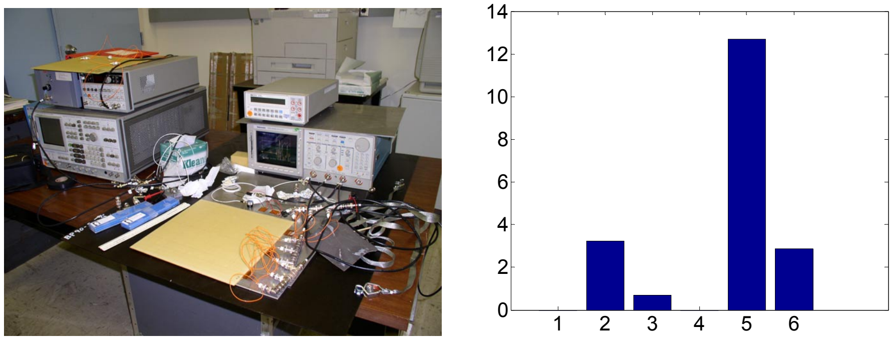
A futuristic integrated sensor array architecture combining wired continuous sensor at the local unit level and wireless connectivity at the global level to communicate with onboard/ground based flight computer/monitoring system.

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



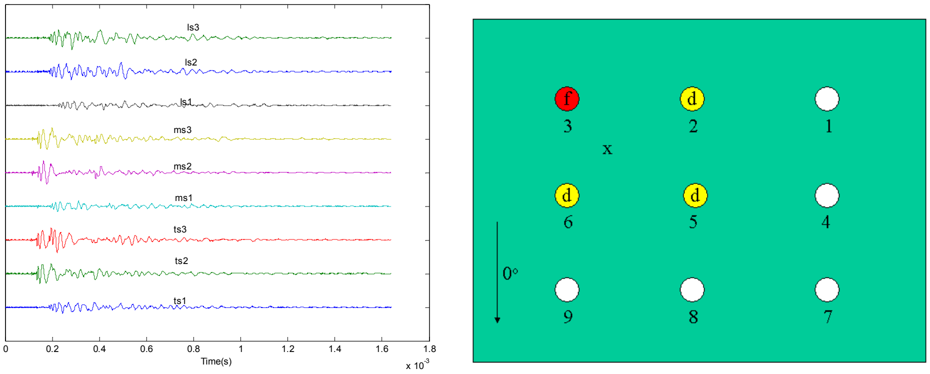
(a) (b)

Figure 4(a): Smart Laminate with 3 parallel continuous sensors, each containing 3 sensory nodes made of piezoceramic wafers. Fig. 4(b): shows the output from the row-wise and column wise parallel sensors output compared with the acoustic emission sensor output at the source.



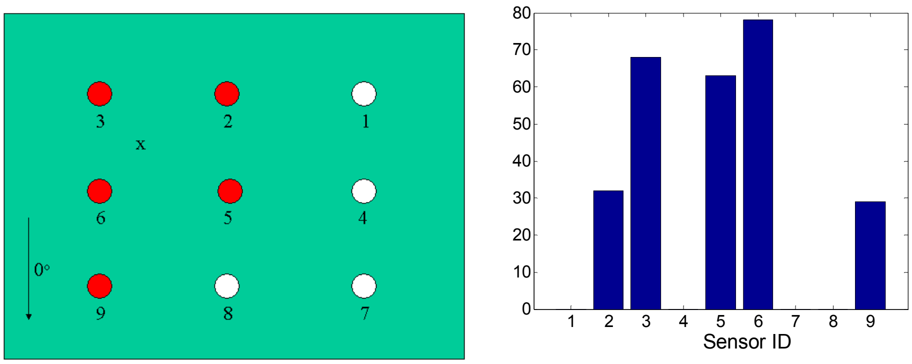
(c) (d)

Figure 4(c) This shows the composite laminated plate with embedded sensors. Fig.4(d): The bar chart shows the % RMS values of the voltage output from the each of the continuous sensors.



(a) (b)

Figure 5(a): Acoustic Emission Output from the 9 embedded sensor. 5(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.



(a) (b)

Figure 6(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'. Figure 6(b): A new Damage Indicator developed shows that the AE source is closer to the Sensors 3, 5 and 6.