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WIRELESS SENSOR NETWORKS FOR ONLINE MONITORING OF HEAVY-DUTY VEHICLE SYSTEMS

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ABSTRACT

Materials and parts in complex systems, such as ground vehicles, can suffer from fatigue due to use, age and other stresses experienced during service. It is therefore essential to evaluate damage and predict the remaining life, reliability and safety of the vehicle. This paper describes the design of a wireless system for real-time monitoring of ground vehicles using Lamb waves. The proposed approach integrates sensor technology, signal processing and wireless networking into a single solution for online structural health monitoring (SHM). Lamb wave inspection is accomplished by inexpensive piezoelectric transducer patches (PZT), which are surface-mounted on the critical components of the vehicle without interrupting its operation. Lamb wave scattering from damage is obtained by comparing the recorded signal with the healthy sample and then damage-related features are identified using Probability Diagnostic Imaging (PDI). The problem of multiple Lamb wave modes is addressed by new Mode Decomposition (MD) algorithm based on Time-Frequency Representation (TFR) of the differenced signal. Hardware components of the proposed system include Sensor Nodes (SN) designed for Lamb wave actuation and data acquisition; and a basestation, where signal processing is implemented. The schematic of wireless sensor network (WSN) is presented and finally, communication protocol for wireless data transmission between SN's and a basestation is described.

1. INTRODUCTION

Motivation

Real-time structural health monitoring is an emerging concept that provides an efficient solution to minimizing catastrophic failures of safety-critical structures. A typical SHM system consists of a sensor network, hardware components and a processing algorithm in an integrated framework that utilizes acquired data to evaluate the structure's condition. SHM technology has a great potential to overcome the shortcomings of conventional NDE methods; current industrial practice involves well-established NDE techniques such as eddy current, ultrasonic and magnetic particle testing, because of their capability to furnish precise information about the damage, its location and severity. However, these NDE inspections are required at scheduled intervals to assess the structural integrity of the component during its downtime. Since damage can occur in service, maintenance schedules may not be adequate to detect an impending hazard. In contrast, modern SHM systems can achieve near real-time monitoring when anomalous event occur, thus offering enormous potential for cutting cost and time as inspection practices move from schedule-based to condition-based procedures [1]. Another significant advantage of online monitoring systems is that the inference about the presence of damage is done automatically by a signal processing software, specifically designed and tested on a particular vehicle. Therefore, SHM does not rely on a technician's judgment and does not require additional expenses to train personnel for conducting the inspection with hand-held devices.

State of the art – online wireless SHM

The major obstacle preventing the widespread use of SHM systems is that in-situ wired sensors require a large amount of cabling for power and data transfer, which can drive up costs of installation and maintenance. Wireless sensors enable the integration sensor data and automated data processing into online monitoring systems that have several industrial applications. From this perspective, wireless sensor networks (WSN) offer a promising solution for continuous SHM of complex systems. WSNs are inherently scalable and configurable and do not require high installation and maintenance cost. A review of wireless sensor networks and their applications can be found in [2].

Guided waves – active sensing modality

Current technologies, showing most amount of promise for online monitoring applications, belong to the field of ultrasonics. Ultrasonic testing can further be broken down into passive (Acoustic emission) and active (Guided waves) modalities. Passive sensing is useful for detection of anomalous events that indicate the possibility of damage occurrence, while active sensing provides the methods necessary for damage detection and localization.

Guided waves (GW), also called Lamb waves, have proven to be one of the most effective modalities for active sensing in SHM. Lamb waves are elastic waves that follow the boundaries of the media in which they propagate. GW can travel long distances without high attenuation, which provides large area coverage of the components to be monitored. The capability of Lamb wave to penetrate through the thickness of the structure makes them sensitive to different imperfections such as cracks, impact damage and delaminations, essential in real-time SHM of ground vehicles. Finally, Lamb waves can be actuated and sensed by inexpensive piezoelectric wafer transducers (PZT) [3]. A PZT vibrates when an electric field is applied to it or vice versa, which allows it to be used as a transmitter or receiver. PZTs have been largely used for guided waves inspection of thin plate structures and tubes [4]. A detailed description of guided waves can be found in [5].

The next sections of the paper are organized as follows: the overall approach of a wireless sensor system proposed for SHM of ground vehicles is described in Section 2. Section 3 presents the main properties of the sensor nodes used for Lamb wave actuation and data acquisition along with the schematic of wireless communication protocol. Signal processing algorithms for damage detection are presented in Section 4, highlighting the basic performance requirements needed in hardware design. Finally, an experimental set-up for validation of DSP algorithms is shown, followed by Section 5, which gives the concluding remarks.

2. SCHEMATIC OF A SYSTEM FOR ONLINE MONITORING OF GROUND VEHICLES

In a proposed WSN system, sensors are fixed in predetermined locations on critical components of the vehicle and each group of neighboring sensors is interfaced to a sensor node (SN) – a compact board, which has computation, storage, and communication capabilities using a limited energy source (battery). During the inspection, a SN actuates one PZT at a time while all others are capturing the response of the structure. Apart from actuation of Lamb waves and data acquisition, functionality of SN includes data transmission to the basestation (BS); a basestation consists of a personal computer (PC) that controls and configures all the nodes. The BS is connected to a mote through the serial port using a gateway board.

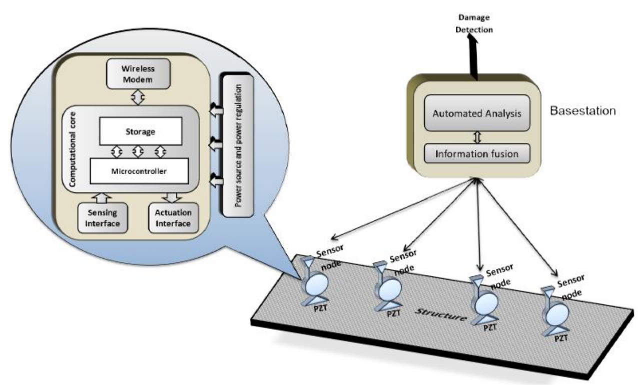

FIGURE 1. The architecture of a wireless sensor network implemented with a star network topology. All the sensor nodes are interfaced with a PZT transducer and have a two way wireless communication with the base station.

All the SNs will communicate with the base station wirelessly, thus forming a wireless sensor network. A schematic of the overall system is shown in Fig. 1. Once the data from all the nodes has been received by a base station, damage-related features are extracted with the help of DSP algorithms. It should be mentioned that signal processing stage is implemented in the BS in order to simplify the design of sensor nodes and make them power efficient. The base station can initiate an appropriate warning message to the operator after the automated analysis of signals is completed.

3. HARDWARE DESIGN OF SENSOR NODES AND PROTOCOL FOR WIRELESS COMMUNICATION

The sensor nodes

To keep the cost of the system as low as possible, as well as maintain a compact design, an off-the-shelf sensor node, the PSoC wireless module, sold by Cypress Semiconductor [6], was chosen. The PSoC kit and the properties of its different components are shown in Fig. 2. At the wireless interface, PSoC uses the Arduino adaptor which is IEEE 802.15.4 (Zigbee) compatible. The measured communication ranges were up to 50 m in indoor environment and 300 m in an outdoor environment according to the datasheet [7]. PSoC board provides a sampling rate of nearly 750 KHz through the Delta-Sigma Analog-to-Digital convertor (ADC), as well as having a wireless interface that allows for transmission of data from a remote location to a base-station. In achieving a sampling rate this high, the full waveform can be recovered after the ADC which makes possible to apply DSP algorithms for damage detection and locating. The board also provides the ability to sample up to eight signals from PZT's simultaneously, which allows for continuous monitoring using multiple sensors.

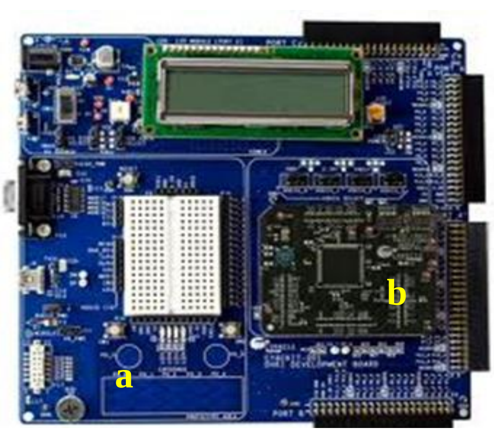

FIGURE 2. a) PSoC development kit; b) PSoC board

Base Station/Sensor Nodes Communication Protocol

An application on the PC utilizes Matlab to control, configure, and read data from nodes available in the wireless sensor network. The application communicates through the serial port with a mote connected to the PC. This mote forwards data received from the sensor nodes through the wireless radio to the serial port, and vice versa. An administrator can use the base station application to discover the available nodes in the network, and configure each one of those nodes by changing their state as described below.

Each sensor node in the network has a state machine which is controlled remotely by the base station. Fig.3 shows the state machine of the sensor nodes on the left, and the right side shows the steps that an administrator using the basestation application can go through to change the state of the sensor nodes. A sensor node would usually start in Idle mode, where it is just listening to the wireless interface and ready to receive commands from the basestation. When the basestation application is started up, the administrator should broadcast a network request to find the current active nodes. All active nodes will reply back with their information (location, channel, and ID). Then the administrator can set the mode of each discovered node to be either idle, actuator, or sensor. When the administrator broadcasts the start command to the network, each sensor node will behave according to its current state. The idle nodes will just discard the command and stay in the idle mode. The actuator nodes will send an excitation voltage to a chosen PZT sensor via its digital to analog convertor.

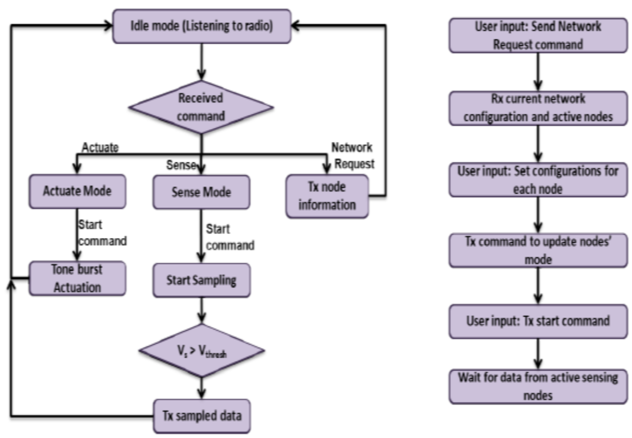

FIGURE 3. The sensor node state machine is shown on the left, and the possible commands and actions that could be taken at the base station are shown in the right part.

The sensor nodes will enable the ADC and start sampling. In order to ensure that the sensor nodes will not just sample noise, they compare each obtained sample to a threshold, and when this threshold is exceeded, the succeeding sample points in a window of 1.5 ms are wirelessly transmitted to the basestation. The basestation application can display and analyze data received from all the sensor nodes.

4. SIGNAL PROCESSING ALGORITHMS FOR DAMAGE DETECTION

Objectives and overall approach

A schematic of the approach for processing of Lamb wave signals is shown in Fig. 4. The first objective of the processing algorithm is to identify Lamb wave scattering from anomalies in contrast to reflections from various boundaries in the complex structure. This can be accomplished by subtracting the sensor response recorded on the healthy sample from the corresponding set of signals acquired by sensor nodes during the inspection.

Once the measurement from damage is isolated, the analysis algorithm should be capable of extracting damage-related features, such as the size, depth and location of the defect. For this purpose, Probability Diagnostic Imaging (PDI) method is used, which essentially estimates the most probable location of the defect from the TOF of individual reflection [8]. Usually PDI relies on the assumption that the group velocity (Lamb wave mode) of each wavepacket is known a priori. However, Lamb wave signals are typically composed of wave packets, which belong to different modes [9].

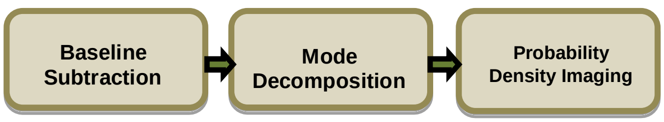

FIGURE 4. Signal processing approach for online monitoring system.

Mode Decomposition (MD) stage is introduced to address this issue. In general, MD algorithm should be able to accurately estimate the time–frequency centers, the modes and individual energies of the reflections in order to guarantee the correct performance of PDI [10]. In addition, it should be computationally efficient and amenable to automated processing in order to be implemented in an online monitoring system.

Issues in signal processing of Lamb waves

Current SHM practice involves excitation of Lamb waves with surface-bonded piezoelectric transducers. Interaction of permanently mounted PZT with the structure was first described by Giurgiutiu [9]. Such configuration results in actuation of at least two Lamb wave modes at a single frequency. The multimodal nature of Lamb waves is caused due to dispersion – each mode has a unique non-linear relation between phase velocity c_p and actuation frequency, which is called a dispersion curve [6]. Furthermore, different modes propagate in isotropic medium with their own group velocity c_g (Fig. 3), where c_g is defined as the derivative of

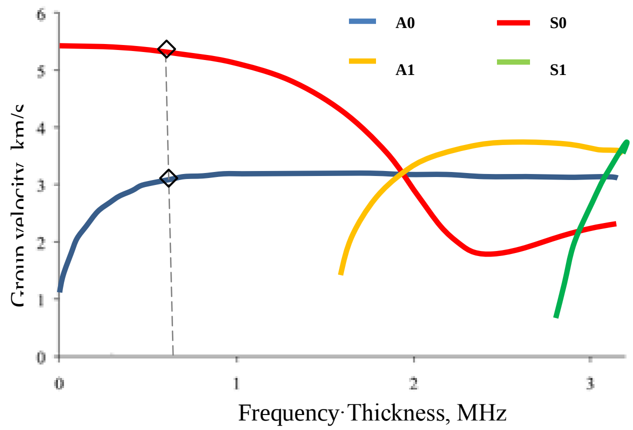

FIGURE 5. Group velocity dispersion curves computed for 2mm thick aluminum plate

the angular frequency with respect to the wavenumber. Similar to c_p, group velocity depends on the frequency of actuation, which causes different frequency components of a single-mode wave packet to propagate in the structure with different speeds. This feature results in stretching of wave packets in time domain as they propagate away from the actuator. Therefore, the analysis of Lamb wave signals simplifies when the actuation is narrowband, as in the case of Morlet wavelet (Fig. 9a) applied to the electrodes of the PZT. In this case, the group velocity gives a good approximation to the speed of the peak of the wavepacket's envelope.

Typically, algorithms for damage detection in SHM systems utilize Time of Flight (TOF) information in order to compute the distance *d*, travelled by individual wave packets of the signal after actuation [11]. Therefore, knowledge of mode and the region of group velocity dispersion curve of a particular wave packet is essential for accurate estimation of *d*. This objective is accomplished by Mode Decomposition (MD).

Mode decomposition

The schematic of MD algorithm is described in Fig. 6. In the case of narrowband excitation, Lamb wave signals can be approximated by line segments in frequency domain [12]. If the excitation frequency is less than 1 MHz for 2 mm thick aluminum plates, only two Lamb wave modes are actuated: S0 and A0. Their group delay versus frequency is plotted in Fig. 7. It follows that in the frequency range up to 1 MHz this parameter is always positive for S0 and negative for A0. Hence, it is possible to use the slope *c* of linear segments in the frequency domain as a characteristic feature for mode identification and decomposition.

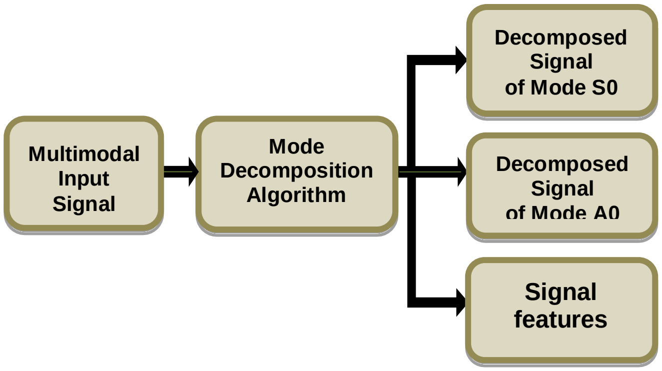

FIGURE 6. Schematic of mode decomposition

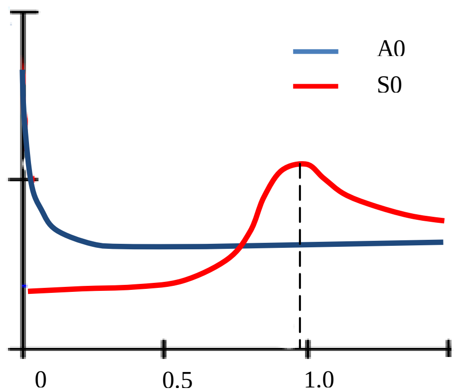

FIGURE 7. Group delay curves

In this paper we propose a new method for mode decomposition based on the time–frequency representation (TFR) of a signal. It utilizes the concept of Reassignment Spectrogram [13] combined with Chirp Transform [14] and post processing steps to identify frequency ridges (line segments and their slope, *c*) of multimodal Lamb wave signal at a low computational cost.

Validation of MD algorithm

The proposed algorithm was tested on a Lamb wave signal (Fig. 8a) obtained on a 4-mm thick 61×61 cm aluminum plate (Fig. 9a). Two 7×8×0.2 mm PZTs were bonded to the surface with epoxy. PZT-1 was used as the actuator of Lamb waves at 255 kHz frequency and PZT-2 was used to sense the response. The received waveform, shown in Fig. 8a, was subjected to mode decomposition using reassigned spectrogram with chirp transform shown in Fig. 8b.

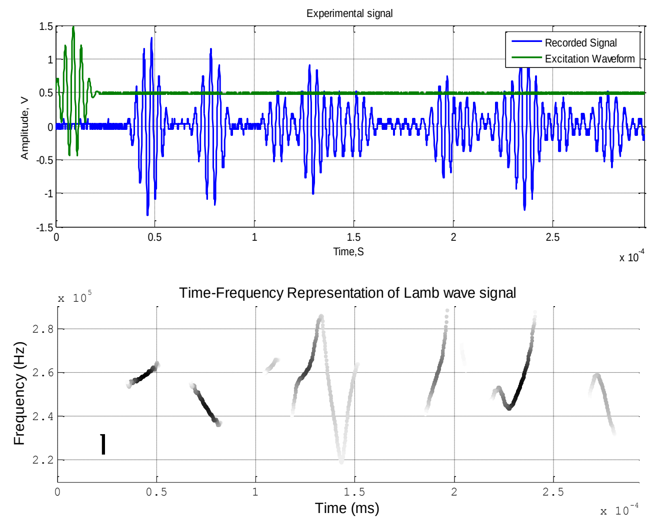

FIGURE 8. a) Lamb wave signal;
b) TFR computed with Reassigned spectrogram and Chirp Transform

Proposed TFR provides high enough resolution to isolate frequency line segments corresponding to individual modes in the received waveform. This data can be used along with the knowledge of the group velocity to give an accurate estimate of TOF used in PDI. Information about the mode is then extracted from Fig. 8b by additional post-processing in order to identify slopes of the segments.

Diagnostic Imaging

Probability Diagnostic Imaging is an algorithm that allows the online monitoring system to visualize structural damage and assess it quantitatively with the help of Lamb wave inspection [8]. The method combines pulse–echo and pitch–catch configurations of sensors in an active network to acquire various signal features associated with damage [11]. Provided that the signal comprises single Lamb wave mode after MD, damage location could be easily identified by measuring the TOF of Lamb waves reflected by anomalies. Here TOF includes the time required for the wave packet to travel to the defect and the time to reach from defect to the receiver. The total distance travelled by the wave packet can be computed using the following equation

$$\frac{L_{Ai-D} + L_{D-Si}}{V} = TOF_i$$

where L_{Ai-D} – distance from ith actuator to defect;

L_{D-Si} – distance from the defect to the ith sensor;

V – velocity of single Lamb wave mode at the actuation frequency.

For a particular sensor pair, equation (1) defines a series of elliptic loci, indicating possible damage locations. Further, a grid of the structure's geometry is constructed whose pixels are illuminated according to the probability of damage presence at the spatial points [15].

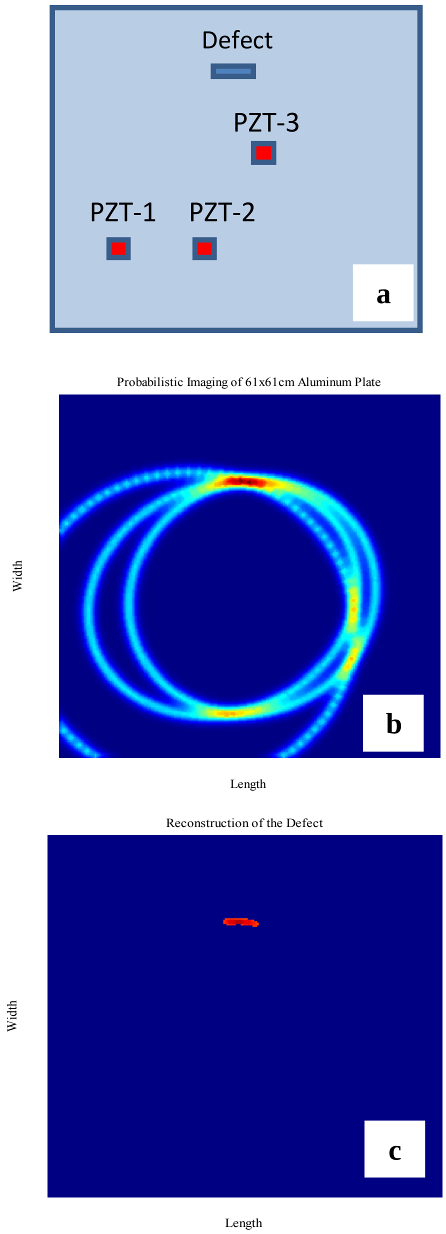

FIGURE 9. Probability Density Imaging: a) experimental set-up; b) computed ellipses of probable damage locations; c) visualization of the defect after post-processing. Pixels on the grid highlighting the highest probability of damage presence on the grid are marked with red.

Finally, a cumulative distribution function F(zi), is introduced to quantify the probabilities of damage presence at all pixels of the grid with regard to all loci

$$I(x_m, y_n) = 1 - [F(z_i) - F(-z_i)] \quad (2)$$

$$zi = \chi i - \mu i \quad (3)$$

where F(zi) – cumulative Gaussian distribution function; Ik(xm, yn) – illumination function; χ – location of pixel (xm,yn) on the grid; μi – location of the closest point on ellipse to the chosen point on the grid.

It follows that damage presence becomes more evident at the pixels at which more ellipses intersect. For other locations, the probability of damage presence decreases with increasing distance from the locus to a particular pixel (Fig. 9b). The results of PDI obtained offline on a 61×61 cm aluminum plate with a notch (Fig. 9a) are shown on the Fig. 9c. Ultrasonic signals were acquired in a pitch-catch configuration of transducers: a particular PZT was activated at a time to actuate Lamb waves at 255 kHz and the remaining PZTs were used to sense the response. Then TOF of S0 mode wave packets was considered after baseline subtraction and mode decomposition. PDI algorithm applied to the set of sensed signals clearly demonstrates the capability to determine the correct location of damage.

5. CONCLUSIONS

This paper presents the design of a wireless system for real-time monitoring of ground vehicles. Integration of sensor technology for Lamb wave inspection and signal processing algorithms for automated data analysis with wireless networking provides high sensitivity to structural damage and at the same time allows the system to circumvent the shortcomings of conventional NDE methods. Active ultrasonic testing was implemented with the help of Sensor Nodes – hardware components for interfacing and clustering the groups of piezoelectric sensors for Lamb wave actuation and sensing. Sensor Nodes were designed on the basis of PSoC development board to meet basic data acquisition requirements such as adequate sampling rate, resolution and dynamic range. Designed SNs are compatible with a protocol for digital communication, which was set up to transfer the inspection data to the base station, where signal processing is implemented. DSP algorithms presented in the paper take full advantage of the sensor network in order to furnish information about the damage and its location. Main processing stages – mode decomposition with reassignment method and Probability Density Imaging were successfully tested on experimentally obtained Lamb wave signals. Validation of the performance of the proposed system along with wireless SHM of composite structures constitute the ongoing efforts of the authors.

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