Development, Validation and Application of a Structural Health Diagnosis Technique Using An Active Sensing Network

Q. WANG, Z. SU and L. CHENG

ABSTRACT

An online health diagnosis technique was established for in-service engineering structures. Locally canvassing the modulation on acoustic-ultrasonic (AU) waves by structural damage (*e.g.*, wave scattering, mode conversion and energy dissipation), this technique enables real-time quantitative evaluation of structural damage or multi-damage. It comprehensively integrates AU wave generation, signal acquisition, central controlling, signal processing, data fusion and results presentation. Identification results are presented in pixelated images with the assistance of an imaging algorithm, facilitating visualization of damage and depiction of overall structural health status in a quantitative, rapid and automatic manner. An active sensor network, comprising a number of standardized piezoelectric sensing units, was developed to supplement this technique, offering improved flexibility to accommodate structures of different geometries, desirable redundancy and enhanced reliability when operated in noisy environment. The effectiveness of the technique was validated experimentally using different damage scenarios.

Keywords: structural health monitoring, active sensor network, engineering structures

INTRODUCTION

Intensive research on structural health monitoring (SHM) has been conducted for more than two decades since its inaugural, leading to a variety of SHM techniques and methodologies readily available for different engineering structures [1], such as aircraft,

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high-speed trains and civil infrastructure. Among different SHM techniques, those replying on acoustic-ultrasonic (AU) wave propagation have shown great potential in achieving a reasonable compromise among resolution, practicality and detectability. AU waves offer a number of merits including the ability to interrogate a large area using a few transducers, the capacity to access hidden components, the high sensitivity to different types of damage and the potential to be used for online health monitoring.

Hitherto, the major research efforts in this field are focused on the development of various methodologies and principles, signal processing and interpretation approaches, signal feature extraction and detection algorithms, with natures of theoretical derivation, numerical simulation or simple testing under the laboratorial environment. Driven by the recent advances in active sensor network, multi-channel data acquisition, real-time signal processing and data fusion, there is an obvious increase in the interest in developing cost-effective SHM techniques and systems towards real-world engineering applications [2-6].

Residing on the endeavors of the authors in the past decade, an online diagnosis technique based on AU wave propagation was developed, and realized through a self-developed system. The system comprehensively integrates AU wave generation modulus, signal acquisition modulus, central controlling and past-processing modulus (including signal processing, data fusion and results presentation). In-house software was coded to fulfill all the functions for real-time diagnosis. An active de-centralized sensor network was developed, comprising a number of miniaturized and standardized piezoelectric sensing units. In conjunction with use of the active sensor network, the system claims improved flexibility to accommodate structures of different geometric features, desirable redundancy and enhanced reliability when manipulated in noisy measurement environment. Diagnostic results can be presented in pixelated images, enabling visualization of damage and depiction of overall structural health status in a quantitative, rapid and automatic manner. Validation of the online diagnosis system was conducted using different damage scenarios.

SYSTEM DESIGN

A virtual instrument technique based on PXI (PCI extension for instrument) platform was adopted for the system design and development. The hardware of the system consists of three basic components: arbitrary waveform generation with high-power amplifier, high-performance multi-channel data acquisition and active sensor network. Three parts were integrated through the PXI bus, and controlled by in-house software which was developed using NI LabVIEW®. The software fulfills all the major functions for real-time diagnosis, including management of hardware, man-machine interface (MMI), signal processing, damage detection, and presentation of diagnostic results. The basic frames of the hardware and software development are shown in Figs. 1(a) and (b), respectively.

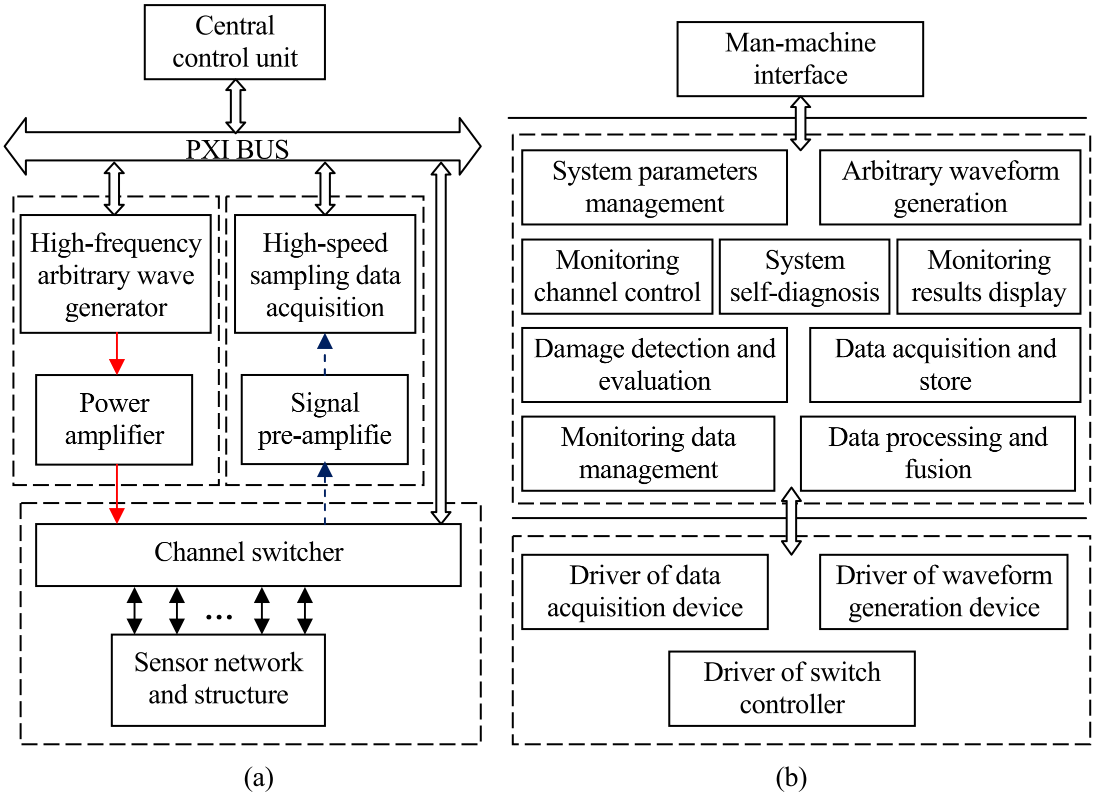


Figure 1. Basic frames for developing (a) hardware and (b) software of the system.

DE-CENTRALIZED SENSING UNIT

A single sensor, whatever the type, performs local acquisition of signals, and it generally tends to provide inadequate information for evaluating the overall structural integrity. A series of spatially distributed sensors is often networked to configure a sensor network. By ‘communicating’ with each other, the sensors in the network certainly provide more information. With sensors acting cooperatively, a sensor network provides desirable redundancy and reliability of signal acquisition. In this system, a sensor network technique, based on a de-centralized sensing philosophy, was developed. A single circular piezoelectric lead zirconate titanate (PZT) element (with different radii ranging from 5 to 10 mm) was mounted a polyimide film through printed circuit, as seen in Fig. 2. To minimise the impact of embedded sensors on the integrity of the inspected structure, each wafer is only 0.2 mm in thickness, contributing little weight and volume penalty.

As an individual functional unit, each sensing unit can be pre-fabricated, stored, transported and finally integrated into a large-scale sensor network. Diverse active sensor networks can thus be configured by flexibly arranging the standardized sensing units of different numbers in strategic locations. The sensor network can be either surface-mounted on or embedded in the structures under monitoring.

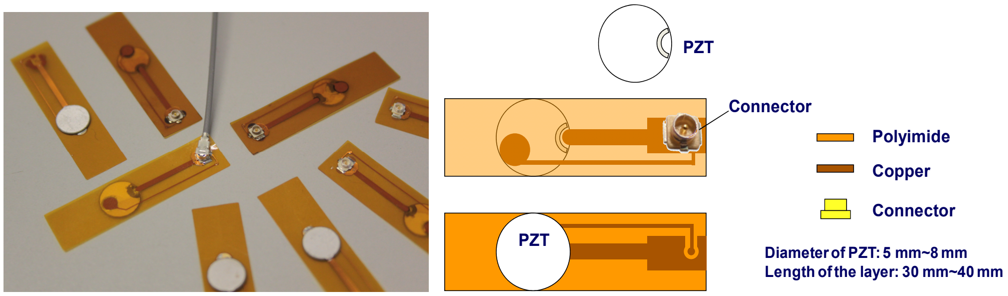


Figure 2. A De-centralized sensing unit.

Allowing for the fact that the number of sensors in a strategically configured sensor network is much greater than that of the signal acquisition channels in a data acquisition system, a time division multiplexing method was introduced. As shown in Fig. 3, all the sensors in the sensor network are connected with a switch array, as a supplementary component to the system, which links the sensor network with the system. Through the switch array, once a particular sensing unit is selected as actuator, the others are acting as the sensors to capture the signals. With such a unit, only two acquisition channels are of necessity in the system.

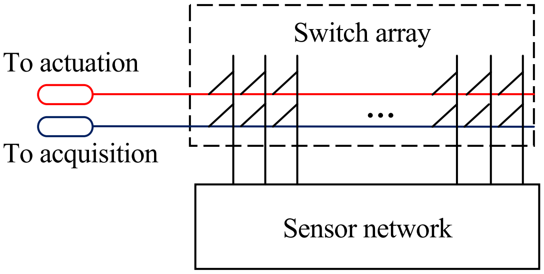


Figure 3. Switch array linking the sensor network to system.

SUBSYSTEM DESIGN AND INTEGRATION

As shown in Fig. 1, the system involves a number of subsystems through the man-machine interface, mainly including arbitrary waveform generation, data acquisition, channel control, damage detection and imaging.

Arbitrary Waveform Generation Subsystem

In a working frequency range of 1~2.5 MHz, the diagnostic waves of different waveforms and frequencies can be customized via the arbitrary waveform generation subsystem to entertain different applications. A narrow band waveform can be helpful to excite a single wave mode in a thin plate structure, while a pulse waveform is suitable for a bulky structure. For the convenience, a number of frequently used waveforms have been pre-stored in the subsystem. The interface of the waveform generation subsystem is shown in Fig. 4 (a).

Multi-channel Data Acquisition (DAQ) Subsystem

Via the interface shown in Fig. 4 (b), the multi-channel DAQ subsystem offers eight independent channels at a sampling rate of 1~60 MHz for each. Frequency analysis functions and low pass filters were integrated in the DAQ.

Switch Controller Subsystem

This subsystem was designed to select the sensors in a sensor network to flexibly configure a desired monitoring path, with the interface shown in Fig. 4 (c). It provides a maximum capacity of connecting 32 sensing units in a sensor network with the signal generation and DAQ subsystems.

Damage Detection and Imaging Subsystem

Based on the captured and subsequently processed signals, damage in the structures under inspection can be characterized quantitatively (including number, individual location, shape and size). Different detection algorithms were developed for different sensing paths rendered by the active sensor network [7-10]. In particular, for a pulse-echo sensing path, the field value at pixel $S(i,j)$ of the image is defined as

$$S(i,j)=\sum_n A_n f_n\left(\frac{R^a_{ijn}+R^s_{ijn}}{v}\right),\quad n=1,2,\cdots \tag{1}$$

$$R^a_{ijn}=\sqrt{\left(i\cdot f_v-x^a_n\right)^2+\left(j\cdot f_v-y^a_n\right)^2},\quad R^s_{ijn}=\sqrt{\left(i\cdot f_v-x^s_n\right)^2+\left(j\cdot f_v-y^s_n\right)^2},$$

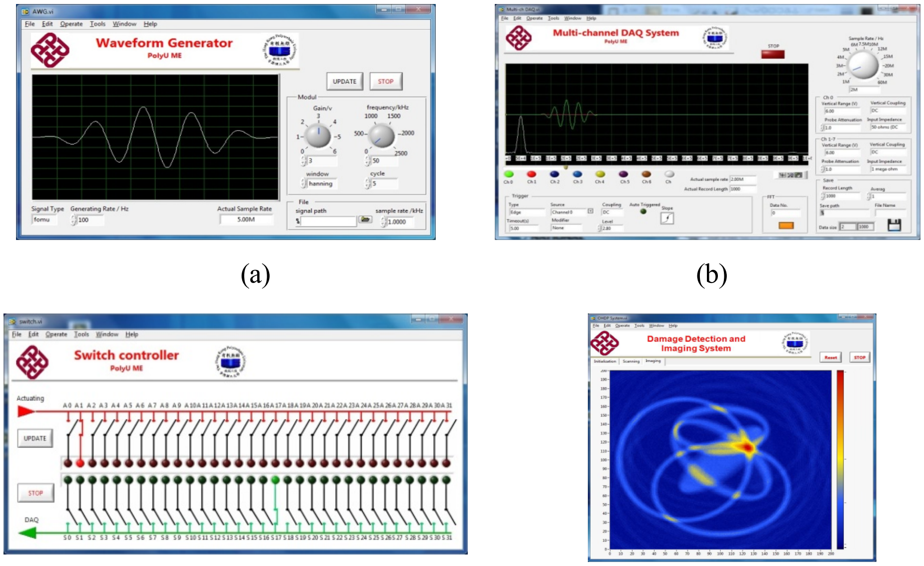
where A_n is a weight coefficient to balance different signals; f_n the damage-scattered signals; v the group velocity of the concerned wave mode; R^a_{ijn} and R^s_{ijn} the distances from $S(i,j)$ to the actuator and sensor, respectively; x^a_n, y^a_n, x^s_n and y^s_n the coordinates of actuator and sensor forming the n^{th} path; f_v the resolution of the image. On the other hand, for a pith-catch sensing path, the field value at pixel $S(i,j)$ is defined as

$$S(i,j)=\sum_n r_n p\left(\frac{\sqrt{\left(x^s_n-x^a_n\right)^2+\left(y^s_n-y^a_n\right)^2}}{\left(\sqrt{\left(i\cdot fv-x^a_n\right)^2+\left(j\cdot fv-y^a_n\right)^2}+\sqrt{\left(i\cdot fv-x^s_n\right)^2+\left(j\cdot fv-y^s_n\right)^2}\right)}\right), \tag{2}$$

where r_n is the difference between the signals before and after the occurrence of damage; p a weight coefficient to compensate for the propagation attenuation. With the detection and imaging subsystem, the identification results can be presented in pixelated images, enabling visualization of damage and depiction of overall structural health status, as an example shown in Fig. 4(d).

Subsystem Integration

Integrating all the above subsystems and software, an online health diagnosis system was developed. It automatically scans the structures via all available monitoring paths in the sensor network, processes and analyzes captured signals for real-time system health diagnosis. The final diagnostic results are displayed in a user-friendly interface (UFI), either two- or three-dimensionally. The flowchart for operation of the system is show in Fig. 5, and the developed system and UFI in Fig. 6.



(a) (b)

(c) (d)

Figure 4. Interfaces for (a) arbitrary waveform generation; (b) multi-channel DAQ; (c) switch controller; and (d) damage imaging subsystems.

VALIDATION

Two typical engineering structures, an aluminum plate and a steel tube, were used for system validation. The plate (600mm×600mm×2mm) was surface-mounted with an active sensor network comprising eight sensing units, offering 28 monitoring paths. The tube (1000 mm in length, 108 mm in radius and 4 mm in thickness) was surface-attached with a sensor network with twelve sensing units, rendering 66 paths. Figure 7 exhibits these two specimens with attached sensor networks.

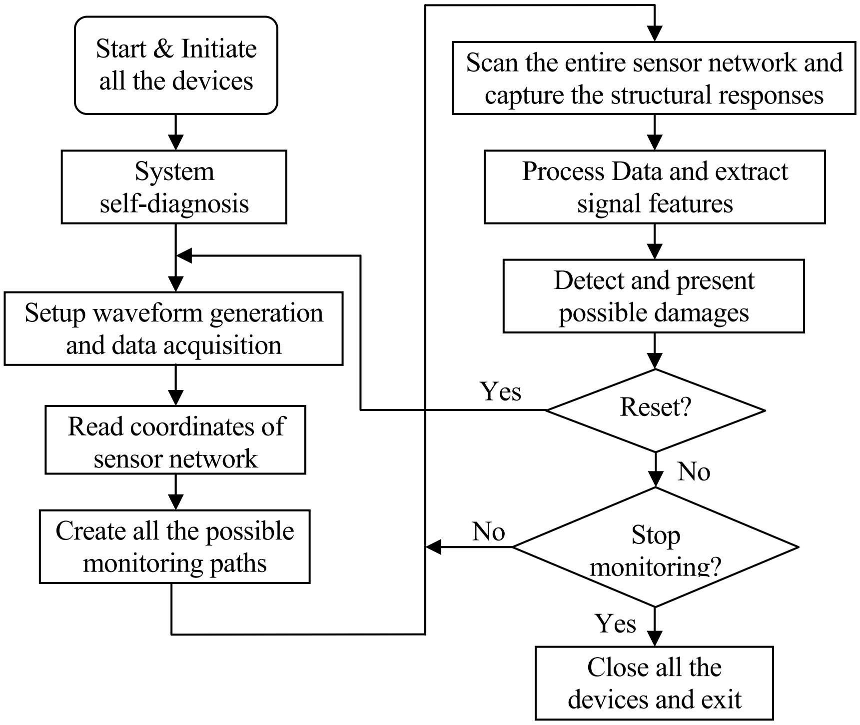


Figure 5. Operation flowchart of the system.

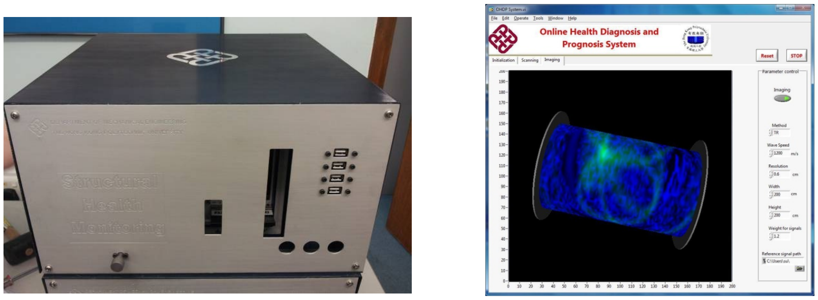


Figure 6. The online diagnosis system (left: integrated system; right: UFI).

Hanning window-modulated five-peak sinusoidal toneburst at 200 kHz and 320 kHz were generated by the generation subsystem to excite S_0 wave mode for two structures, respectively. Added masses were used to simulated damage in two structures, and the diagnostic results are shown in Fig. 8, clearly indicating the location and approximate size of individual damage.

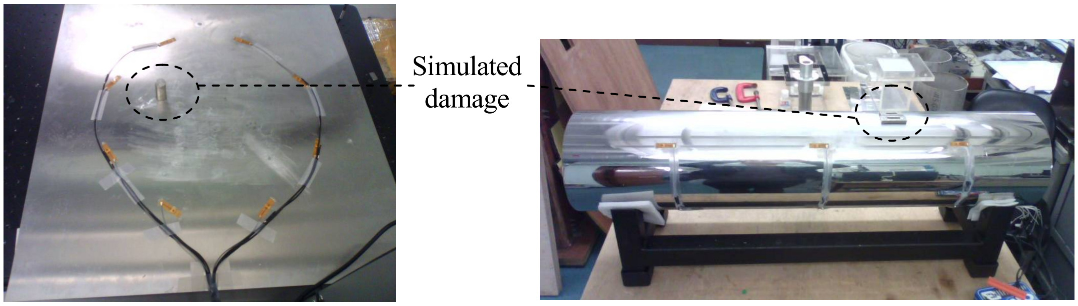
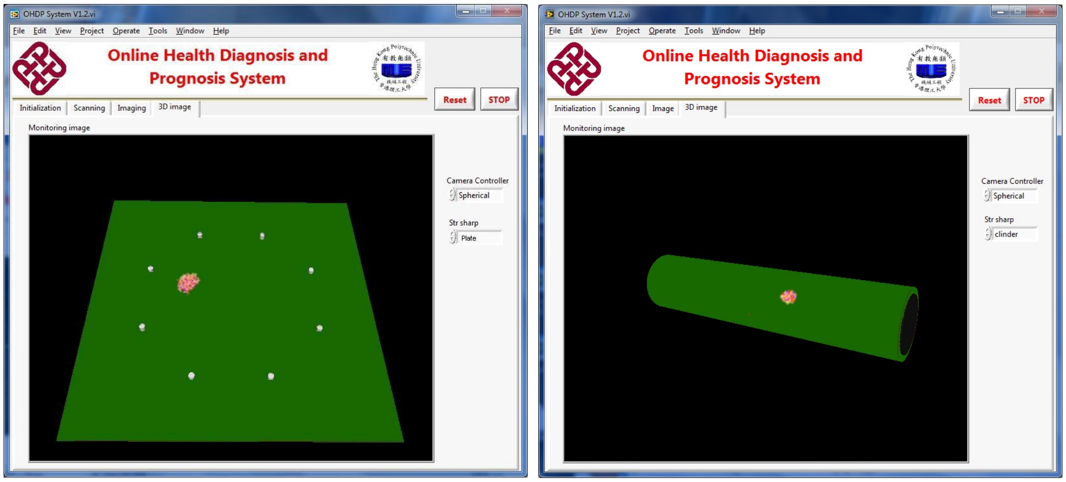


Figure 7. Specimens for system validation.



Camera Controller: Spherical
Str sharp: Plate

Camera Controller: Spherical
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Figure 8. Diagnostic results (left: for plate; right: for tube).

CONCLUSIONS

An online health diagnosis system was developed, taking advantage of propagation of acoustic-ultrasonic (AU) waves. Supported by in-house software and used in conjunction with an active sensor network, the system is able to real-time monitor the health status of a structure under surveillance. Validation of this system on typical plate and tube structures has demonstrated the capacity of the system in providing real-time structural health monitoring.

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