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An *in-situ* Structural Health Diagnosis Technique and Its Realization via A Modularized System

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***Abstract*—**By scrutinizing local propagation characteristics of damage-modulated guided waves (GWs), an *in-situ* health diagnosis technique, targeting in-service engineering structures, is developed. This technique characterizes structural damage quantitatively, regardless of its quantity, and consequently evaluates structural integrity in a real-time manner. A self-contained system is accordingly configured to materialize this technique, which integrates modularized components through a PXI bus, for active GW generation, multi-channel data acquisition, central control, signal post-processing, and results presentation. Monitoring results are presented in pixelated images by virtue of a diagnostic imaging algorithm, facilitating comprehension of the overall structural health status intuitively, promptly, and automatically. In conjunction with the system, a sensing technique, based on a concept of "decentralized standard sensing", is demonstrated, which has a capacity of constructing a sensor network with convenience and flexibility. An optimal benchmarking strategy in accordance with signal correlation is formulated to compensate for the adverse ambient influence (*e.g.*, temperature fluctuation) in rugged measurement conditions. Experimental validation is carried out to verify the technique and the system by evaluating mock-up damage in planar and tubular structures quantitatively, showing superior detectability, sensitivity, and accuracy. Notably, its expandable nature allows the system to be tailor-made towards diverse real-world applications, and enhances the universality, flexibility and compatibility of the developed diagnosis technique.

***Index Terms*—measurement units, waveguide theory, monitoring, nondestructive testing, signal processing**

I. INTRODUCTION

Structural health monitoring (SHM) has been a subject of intensive scrutiny over the years, and continued endeavors in this connection have led to a diversity of technique deployments which are based on different principles and mechanisms. Of various SHM strategies, those exploiting guided waves (GWs) have exhibited prominent competency in striking a commendable compromise among resolution, practicality and detectability [1]–[7], by taking advantage of the merits of GWs such as the ability to quickly and three-dimensionally interrogate a relatively large area with only a few transducers, the capacity to access hidden components, and the high sensitivity to different types of damage, as well as the excellent excitability and receivability. GW-based SHM has now been on the verge of maturity for real-world applications [8], [9], with superior potential to provide continuous, automated online integrity evaluation for engineering assets and structures in a cost-effective manner.

Even so, it is envisaged that the majority of the past and existing efforts towards development and implementation of GW-based SHM have cast particular focuses on mechanism study, methodology establishment, damage modeling, algorithm development, and periphery issues such as signal processing and sensor network optimization, with a nature of theoretical derivation, numerical simulation or experimental validation. For validation of a developed approach, isolated and incoherent measurement devices, such as function generator and oscilloscope, are usually employed for GW generation and acquisition. The demonstrated effectiveness is, in many cases, limited to simple cases in well-controlled laboratorial environment, in which the scales of specimens and the numbers of sensors are far fewer than those in reality. In the contrary, real-world engineering assets and structures to be monitored are often large in dimension, entailing a great number of sensors to cover an extended inspection region; measurement noise and uncertainties may corrupt captured GW signals considerably, mask damage-associated signal features, and impose intricacy in signal interpretation; stringent constraints on the weight and volume penalties from instrumentation may be applied, especially under the circumstances in which aircraft or spacecraft structures are concerned. All of these have posed great challenges on development and deployment of application-oriented SHM methodologies.

With recent technical advances and breakthroughs in sensor technology, instrumentation and measurement, manufacturing, electronic packaging and material sciences, the practicability of GW-based SHM has been consolidated substantially, reflected by the emergence of several well-packaged techniques and systems. As a pioneer dedicated to prompting GW-based SHM applications, Acellent Technologies Inc., in partnership with Stanford University, has patented a sensing technique called SMART Layer® (initials of *Stanford Multi-Actuator-Receiver Transduction Layer*) and an electronic diagnostic unit named SMART Suitcase™ [10], [11]. This unit is capable of interacting with up to 64 networked piezoelectric elements allocated in SMART Layer® to generate and capture GW signals. Moreover, fiber-optic sensors can be integrated into SMART Layer® to receive GW signals generated by piezoelectric elements, thus forming a hybrid sensor network [12]. As a commercial product, the SMART Suitcase™, however, is not expandable by users. In contrast to this, an open data bus-driven SHM scanning platform has recently been developed [13]. As a key feature of the technique, the system can be customized with various modules based on needs. Making use of a tomography-based detection algorithm, Wavemaker™ Pipe Screening System (Guided Ultrasonics Ltd.) and Teletest® (Plant Integrity Ltd.) are two fully commercialized SHM systems for detecting damage in pipelines [14], [15]. These two systems are used with a circumferential transducer belt comprising a certain number of piezoelectric elements, to be clamped onto the pipe at one end of a section, for activating cylindrical GWs and subsequently collecting the echoed signals, whereby damage along the pipeline can be located by calibrating the reflection coefficient of damage-scattered GWs. Both systems are able to quickly pinpoint external or internal corrosion, as well as axial and circumferential cracking, in a section of a pipeline with a length up to 25 m in both directions, regardless of the service conditions of the pipeline—buried, insulated, or filled with fluid [16]–[18].

Aimed at generating and acquiring GWs efficiently, microcontroller-based electronic devices have been developed. As a recent development trend, wireless-based data transmission is being increasingly introduced [19]. Representatively, PAMELA SHM$^{\mathrm{TM}}$ [20] is a light and compact phased array transducer unit with twelve piezoelectric wafers. Notably, the acquired GW signals can be transmitted through an Ethernet or a wireless network embedded. A piezoelectric transducer has been integrated with a commercial transceiver module from ZMDI (Dresden Germany), to configure a sensor node [21]. This module features a microcontroller to handle arbitrary GW generation, analog-to-digital conversion, data acquisition, synchronization and filtering, with a wireless data transmission capacity. In another instance, transducers encompassing optical fibers have been invented for data transmission, as well as power supply, to monitor wind turbine blades, using either GWs or acoustic emission [22]. All of these systems and devices have provided significant advances for deploying desired yet practical GW-based SHM techniques, to accommodate diverse engineering applications.

Oriented to real-world applications, an *in-situ* structural health diagnosis technique, targeting in-service engineering assets and structures, is established in this study, and deployed via a self-contained modularized system. The technique scrutinizes local propagation characteristics of damage-modulated GWs (*e.g.*, wave scattering, mode conversion and energy dissipation), on which based the damage can be characterized quantitatively, and consequently the structural integrity can be evaluated in a real-time manner. In conjunction with the use of an active sensor network based on a concept of “decentralized standard sensing”, the system integrates modularized units of active GW generation, multi-channel data acquisition, switch control, central control, post-processing and results presentation, through a PXI bus. As illustrated in [13] and [23], a PXI system exhibits demonstrated universality, flexibility and compatibility, making use of its expandable nature. Supplemented with a diagnostic imaging algorithm, the system presents monitoring results in pixelated images, facilitating intuitive, rapid, and automatic online SHM. Experimental validation is conducted to validate the technique and the system through identifying mock-up damage in typical engineering structures.

This paper is organized as follows: Section 2 discusses the theory and principle of the proposed *in-situ* structural health diagnosis approach, as well as an optimal benchmarking strategy to compensate for ambient influence. Section 3 recapitulates the infrastructure of the configured system and its key modules; the concept of “decentralized standard sensing” is also recounted. Section 4 embraces a series of experimental validation.

II. THEORY AND PRINCIPLE

A. SHM Strategy based on Active GWs

Distinct from bulky waves, GWs are of a highly dispersive and multimodal nature. Without loss of generality, consider a thin planar structure with a thickness of $2h$ (“thin” herein refers to the premise that the planar dimensions of the structure is far greater than that of its thickness; and in the meantime the wavelengths of the propagating GWs are of the same order of h), where GWs in the structure take the modality of *Lamb waves*. Theoretically, the dispersive and multimodal nature of Lamb waves can be ascertained by solving the Rayleigh–Lamb equations, which read, for symmetric and anti-symmetric modes, respectively [3], as

$$\left(k^2-q^2\right)^2\cosh(ph)\sinh(qh)-4k^2pq\sinh(ph)\cosh(qh)=0\text{ , (\textit{for symmetric modes})}\quad(1a)$$

$$\left(k^2-q^2\right)^2\sinh(ph)\cosh(qh)-4k^2pq\cosh(ph)\sinh(qh)=0\text{ , (\textit{for anti-symmetric modes})}\quad(1b)$$

where $p^2=k^2-k_l^2$ and $q^2=k^2-k_t^2$, where k signifies wavenumber, with k_l and k_t being the wavenumbers of the longitudinal and shear wave modes, respectively. Solutions to (1) depict a series of dispersion curves, manifested as different propagation velocities for different modes, subjected to the algebraic product of both the excitation frequency and h. As a consequence of wave dispersion and co-existence of multi-mode, the wave packet spreads out temporally and spatially, making the extraction and interpretation of GW signal features a highly challenging task.

Targeting an *in-situ* health diagnosis approach for in-service engineering structures, an active GW-based SHM strategy is developed. The essence of the strategy embraces five cardinal steps in a hierarchical sequence, as illustrated schematically in Fig. 1:

1) a certain number of GW transceivers (*e.g.,* piezoelectric patches) are surface-mounted on or internally embedded in the structure to be monitored, configuring a distributed sensor network, with each of them generating GWs (probing GW signals) in turn while the rest acquiring GWs in the meantime. Signals with narrowband waveforms are usually excited at prudentially selected frequencies, so as to minimize the effect of wave dispersion. Mode selection techniques (*e.g.,* mode tuning [24]) can further be employed to strengthen a desired wave mode dominant over the others, achieving optimized recognizability of the characteristic wave packet;
2) the probing GW signals propagate omni-directionally in the structure. Interaction between the probing GW signals and structural damage, if any, leads to wave scattering and mode conversion;

3) appropriate signal processing treatments are applied to screen measurement noise, uncertainties and other interferences, and subsequently to extract GW features which are associated with damage and structural health status (*e.g.*, time-of-flight (ToF) [25]–[27], wave reflection/transmission coefficients [28]–[30], energy dissipation [31], [32], mode conversion [33], [34], time reversibility [35], [36], signal correlation [37], and wave nonlinearities (*e.g.*, high-order harmonic generation) [38]–[43]);
4) extracted GW signal features via different sensing paths in the sensor network are fused for qualitative or quantitative damage assessment using pre-developed models and detection algorithms (*i.e.*, the correlations between GW features and damage parameters); and
5) based on Step (iv), the overall structural integrity is further evaluated.

In the proposed SHM strategy, the detection algorithm addressed in Step (iv) lies on such a premise—a GW signal captured via a sensing path (called "*current signal*" hereinafter) on a damaged structure may deviate from an earlier signal collected via the same path when the structure is deemed "healthy" or pristine (comparatively named "*baseline signal*"). Notably, such a deviation is associated with the distance between the damage and the sensing path, and there are multiple ways to interpret this deviation and relate it to damage location. For example, in a sparse transducer network as illustrated in Fig. 2, deviations may appear in the form of damage-scattered wave packets in the current signal, because the damage may scatter incident waves from the actuator, which takes more time to arrive at the sensor than the direct arrival from the actuator to the sensor. By comparing the current signal with regard to its baseline and finding the ToF of this damage-scattered wave packet, and knowing the velocity of the probing waves, it is possible to locate the damage by plotting an elliptical or an ellipse-like locus with the two transceivers forming the sensing path being the foci. If more sensing paths are available, the location of the damage can be more accurately determined. In another method using signal correlation, if the damage locates right on or close to a particular sensing path, the deviation can be significant, leading to a relatively weak correlation between the current and baseline signals; in contrast, the deviation would be trivial if the damage is far away from that sensing path, presenting a relatively strong correlation between two signals. Thus, both the ToF of damage-scattered waves and the correlation between current and baseline signals can serve as a quantitative indicator to damage location, with regard to a sensing path via which the signals are acquired. As demonstrated [3], these algorithms, along with several others listed in Step (iii), have their own advantages with respect to particular damage parameters, and can be independently or jointly employed for damage characterization, which are all considered in the development of a robust yet flexible SHM strategy in this study.

B. Compensation for Ambient Effects

It is however envisaged that the accuracy and precision of the above proposed damage characterization algorithms may be confined during practical implementation. That is because the baseline signals are pre-acquired under specific conditions, which, owing to adverse ambient effects (*e.g.*, temperature fluctuation), may vary in continuous measurement, therefore presenting discrepancies, more or less, in the signals captured via the same sensing path at different moments even in the absence of damage (*i.e.*, *outdated benchmarking*). The discrepancy due to adverse ambient effects is different from damage-induced deviations in signals.

To circumvent outdated benchmarking, the proposed SHM strategy is revamped compensating for possible ambient effects. After update, the compensated baseline signal b_C is calculated as

$$b_C = m b_\tau \tag{2a}$$

where

$$\begin{cases} \tau = \tau \Big|_{\max\left|\langle a, b_\tau \rangle\right|} \\ m = \left|\langle a, b_\tau \rangle\right| \Big/ \left|\langle b_\tau, b_\tau \rangle\right|. \end{cases} \tag{2b}$$

In the above, b_τ is a lagged version of the original baseline signal with respect to a which has counteracted the possible time shift due to ambient effects, with τ being the time lag at which the cross correlation of a and b_τ reaches its maximum. Operation $\left|\langle , \rangle\right|$ denotes the correlation between two signals. m is a scaling factor, namely the ratio of $\left|\langle a, b_\tau \rangle\right|$ to $\left|\langle b_\tau, b_\tau \rangle\right|$, which is solely attributed to ambient effects, so that the scaled, time-shifted baseline signal b_C completely eliminates possible discrepancies due to ambient effects. Upon compensation, the baseline signal is paired to its corresponding current signal as if it were measured under a consistent condition. In this sense, any phase shift or amplitude change due to ambient effects, rather than damage, is eliminated in the benchmark.

C. Diagnostic Imaging

In applications, it is always desirable to visualize structural damage in images such that comprehension of the overall structural integrity can be reached in a quick and, most importantly, intuitive manner. Methodologies leading to presentation of damage detection results in images are collectively called *diagnostic imaging* [32], [44]–[47], exemplified by tomography, thermography, and shearography. In these well-defined imaging techniques and tomography in particular, image construction is often at the expense of using a large number of distributed transceivers (or a few but manipulated at numerous spatial positions for acquisition of a large quantity of GW signals), and this might incur intensive labor and monetary cost. Dissimilar to these traditional approaches, a probability-based diagnostic imaging (PDI) is developed in this study, in conjunction with the use of a sparse active sensor network comprised of only a few spatially distributed sensors. The PDI attempts to describe a damage event in a two-dimensional binary color-scale image (each pixel corresponding exclusively to a spatial point in the inspected area of the structure), and the value borne by a pixel (called *field value*) is linked to the probability of damage occurrence at the spatial point corresponding to that pixel. Rather than using deterministic parameters to define a damage event (*e.g.*, coordinates of damage location, or size of damage), PDI presents diagnostic results in terms of probability of damage presence, appropriately addressing the underlying substance of "*damage prediction*" – an exercise of "*predicting*" an event with uncertainties and therefore the results should ideally be delivered in accordance with "*probability*".

In PDI, depending on the algorithms used for signal feature extraction and damage localization, the field value at each pixel is defined differently. By way of illustration, consider a sensor network with n sensing paths operated in pulse-echo mode. The ToF-based algorithm is applied with the field value S at pixel (i, j) defined as

$$S\left(i, j\right) = \sum_{r=1}^{n} A_r D_r \left(\frac{\sqrt{\left(i \cdot f - x_r^a\right)^2 + \left(j \cdot f - y_r^a\right)^2} + \sqrt{\left(i \cdot f - x_r^s\right)^2 + \left(j \cdot f - y_r^s\right)^2}}{v} \right), \qquad (3)$$

where, for the r^{th} sensing path as illustrated in Fig. 2, A_r is a weight coefficient assigned to the path for imaging, $D_r(t)$ is the damage-scattered signal as a function of time, obtained by taking the energy/amplitude profile of the difference between the current and compensated baseline signals (using a time-frequency analysis such as wavelet transform). (x_r^a, y_r^a) and (x_r^s, y_r^s) are the coordinates of the actuator and sensor forming the r^{th} path respectively. The term inside the parentheses calculates the time it takes for probing waves to travel from the actuator to the pixel (i, j), and then to the sensor (assuming the wave is always scattered by possible damage there). f is the resolution of the constructed diagnostic image such that $(i \cdot f, j \cdot f)$ specifies the location of the pixel with units. In order to convert $S\ (i, j)$ into a meaningful probability value, the field values can then be normalized by their global maximum. If multiple damage-scattered wave packets are identifiable in the current signal, it is possible to locate multiple defects using this algorithm with reasonably high accuracy (assuming each defect contributes one unique scattered wave packet). This capability is explicitly illustrated by the developed technique and system in the experiment later (detailed in Section IV.A and Fig. 12(b)), where two defects are delineated simultaneously in the diagnostic image using Eq. (3), including their respective locations, shapes and sizes.

In the meantime, if pitch-catch mode is used instead, the field value at each pixel is defined by mapping the level of difference between the current and baseline signals from each sensing path to that pixel, as

$$S(i,j)=\sum_{r=1}^{n} B_r \cdot \max|d_r| \cdot \left(\frac{\sqrt{\left(x_r^s - x_r^a\right)^2 + \left(y_r^s - y_r^a\right)^2}}{\left(\sqrt{\left(i \cdot f - x_r^a\right)^2 + \left(j \cdot f - y_r^a\right)^2} + \sqrt{\left(i \cdot f - x_r^s\right)^2 + \left(j \cdot f - y_r^s\right)^2} \right)} \right), \quad (4)$$

where B_r is a weight coefficient for recuperating a GW signal by offsetting its attenuation in magnitude over propagation distance of the r^{th} path, and d_r is the difference between the current signal and the compensated baseline signal, or alternatively, one minus the correlation coefficient between the two signals, either of which can reflect the correlation between the current and the compensated baseline signals, upon eliminating all adverse ambient effects.

It is noteworthy that a typical image constructed using (4) often shows a narrow band of elevated field values (high probability of damage presence) along a sensing path, if part of the damage is on the path or very close to it, whereas pixels in other regions of the image have very low field values. This means the field value defined by (4) is highly inert to distant damage. Such a trait creates the possibility of detecting multi-damage within the inspection region using different paths in pitch-catch mode as well, because a particular sensing path can only sense damage in its vicinity. However, the resolution of detecting multiple defects using (4) might not be as good as that of the ToF algorithm, given the sparse sensor layout, thus requiring larger separation between two damage spots.

III. MODULARIZED SYSTEM FOR IMPLEMENTATION

A. Key Modules and Communication Interfaces

In prevailing studies with experimental nature, isolated and incoherent measurement devices such as ultrasonic probes, arbitrary function generators and oscilloscopes, are usually employed for GW generation and acquisition, and signal features are identified by the individuals—a procedure involving subjective discretion. Applicability of developed approaches is often limited to simple structures in well-controlled laboratorial environment. To implement the proposed SHM strategy towards engineering assets and structures with substantive dimensions, a modularized system is configured by virtue of a virtual instrument technique. As illuminated in Fig. 3, the core framework of the self-contained system consists of five pivotal modules: (i) active sensor network, (ii) GW generation (with power amplifier), (iii) multi-channel data acquisition (with signal conditioner), (iv) switch control, and (v) central control and post-processing. Five modules are integrated through a PXI (PCI extension for instrument) bus, for mutual communication and data synchronism via their respective interfaces:

1) *Active Sensor Network based on "Decentralized Standard Sensing"*: a single sensor, regardless of its type, acquires signals fairly locally and likely provides inadequate information to depict the overall structural integrity. A number of spatially distributed sensors are networked to configure a sensor network. By "communicating" with each other cooperatively, all networked sensors holistically and collectively perceive changes in the structure, meanwhile rendering redundancy of data acquisition. In this study, an active sensor network technique is

developed in accordance with a concept of “decentralized standard sensing” (DSS). DSS addresses a twofold feature: mutual independence of individual sensors in perceiving GW signals including subsequent signal processing; and a standardized sensor formality for cost-effective, yet flexible deployment of sensor networks, especially for large-scale structures, so that deliberate positioning of each sensor can be avoided to save time and efforts. Inspired by DSS, a standardized sensing element (SSE) is developed and fabricated by immobilizing a circular miniaturized piezoelectric lead zirconate titanate (PZT) wafer (with a customizable radius between 3 and 15 mm) onto a polyimide film via a printed circuit, as seen in Fig. 4. Diverse sensor networks can be constructed conveniently and quickly, by flexibly allocating a certain number of SSEs at strategic locations. Either surface-mounted onto or embedded into a structure, a SSE is managed to have a thickness of only 0.2 mm, contributing little weight and volume penalty and therefore minimizing the impact of sensor integration on the integrity of the host structure. Being a standalone functional unit, a SSE can be independently prefabricated, stored, and integrated into a sensor network. During signal processing, a SSE is independent of the rest in the network at-a-time, opposing against traditional network processing algorithms involving batch processing of measurements collected from multiple sensors (a process otherwise known as “centralized sensing and processing”), emphasizing a decentralized signal processing architecture. The decentralized sensing and processing present remarkable advantages compared with a centralized one, particularly given partial of the sensor network becomes mal-functional. This endows the developed diagnosis method with enhanced robustness when manipulated in rugged measurement conditions.

2) *Active GW Generation Module*: with a communication interface shown in Fig. 5(a), this module comprises a NI® PXI-5412 arbitrary waveform generator (AWG) with a sampling rate of up to 100 MS/s, and a linear power amplifier. It generates tailor-made probing GWs in

narrowband waveforms at an arbitrary frequency in a range of 0–2.5 MHz. A narrowband waveform confines the incident wave energy around a particular frequency. The AWG-generated probing GW signals are amplified by the linear power amplifier before applied on each SSE.

3) *Multi-channel Data Acquisition (DAQ) Module***:** with a communication interface displayed in Fig. 5(b), this module consists of a NI® PXI-5105 digitizer and a charge amplifier. It offers eight independent channels with a sampling rate of up to 60 MHz per channel simultaneously. One of the eight channels is pre-set as the default trigger channel with customizable trigger settings, to be used for sampling synchronism. Frequency-domain analysis function and low-pass filters are integrated in this module for preliminary signal analysis.

4) *Switch Control Module*: with a user interface in Fig. 5(c), the core component of this module is a NI® PXI-2529 high-density matrix switch. It selects SSEs in a sensor network, to form desired sensing paths. A relay operating time between 1 and 3.4 ms of this module enables the system to catch instantaneous GW signals. Each switch array in the module provides a capacity of linking up to 32 SSEs to the GW generation module and the DAQ module. On top of that, this module also switches the role of a SSE between active GW actuator and passive GW receiver - once a SSE functions as a GW actuator, the rest SSEs would act as sensors to capture GW signals. Considering that the number of SSE in a practical sensor network can be much greater than that of the signal acquisition channels that the DAQ module can offer, a time division multiplexing method is applied to this switch module, requesting only two acquisition channels at-a-time.

5) *Central Control and Post-processing Module*: all the functional modules briefed in the above are commanded via a central control module, which additionally provides a series of

integrated digital signal processing (DSP) to be applied on captured GW signals including Hilbert transform, correlation calculation, time reversal, and time-frequency analysis (short-time Fourier transform, Wigner-Ville distribution and wavelet transform). These integrated signal processing options can be recalled to minimize the interference from measurement noise and uncertainties, enhance signal-to-noise ratio, extract essential yet concise GW characteristics, and fuse information from the whole sensor network. Consequent to signal processing, this module further constructs diagnostic images using the algorithm defined by (3). By way of illustration, displayed in Fig. 5(d) is a typical diagnostic image in which the diagnostic results are displayed three-dimensionally, with the color scale calibrating the possibility of damage presence at each pixel. The central control and post-processing is supported by an in-house software package programmed on NI® LabVIEW® platform. The software package is managed in a three-layer architecture, as illuminated in Fig. 6: the man-machine interface (MMI) to deal with all system inputs and deliver diagnostic results (alarming if damage detected), the physical layer to drive all involved hardware in the system, and the application layer to support all module interfaces. Via this package, the five cardinal steps enumerated in Section 2.1 are fulfilled for real-time health diagnosis and monitoring.

B. System Integration

All modules are integrated on a PXI bus platform (NI® PXIe-1071) to configure a compact diagnosis system, and encapsulated by a specifically designed aluminum alloy framework, as seen in Fig. 7. In contrast to traditional, separated lab devices used for similar purposes, the integration of multiple functionalities into a single unit enables the system to be deployed in more practical scenarios while achieving high compatibility among individual functional modules. As another key feature of this integrated system, its expandable and open nature, at the same time, allows the system to be tailor-made towards diverse real-world applications, thus enhancing the universality and flexibility of the approach in engineering practices. More modules can be integrated into the system for further development and expansion, depending on the monitoring tasks and the scales of the structures to be monitored. Benefiting from the standard data bus and compatible communication interfaces, the system can also be conveniently integrated with other commercially available measurement systems.

Following an initial self-diagnosis for each module, the system identifies the coordinates of every SSE in the sensor network, creates sensing paths using switch control module, and carries out GW generation and acquisition automatically, and finally delivers diagnostic results. Such a diagnosis exercise is performed repeatedly for a continuous health monitoring, with an adjustable interval between two repeats (default value: 20 seconds). A schematic flowchart illuminating the system operation is shown in Fig. 8.

IV. EXPERIMENTAL VALIDATION

In order to systematically validate the developed diagnosis technique and the configured system, a series of experiments is conducted, by characterizing mono- and multi-mock-up damage in typical engineering structures including planar and tubular structures. The mock-up damage (added mass) was affixed to the structures through a firm adhesive layer, to guarantee phenomenal GW scattering. For the applicability of the developed approach in engineering practices, one can refer to another work of the authors [6], in which this developed system was tailored for health monitoring and damage detection of bogie structures of high-speed trains operated along the Beijing-Shanghai high-speed railway.

A. Planar Structure

An aluminum plate (6061-T6, density: 2711 kg/m^3, and Young’s modulus: 71 GPa), measuring 600 mm × 600 mm × 2 mm, was surface-affixed with an active sensor network comprising eight SSEs as seen in Fig. 9(a) (coordinates of individual SSEs in the network are listed in Table 1(a)), whereby 28 monitoring paths (in the formality of pulse-echo or pitch-catch) were in principle created. The sensor network was then instrumented with the system. *Hanning* window-modulated five-peak sinusoidal tone bursts at a central frequency of 200 kHz were generated by the GW generation module, and applied in turn on each SSE upon amplification to 60 V, to excite the fundamental symmetric Lamb wave mode as the probing GW signal. This particular narrowband excitation form and its frequency were selected after frequency tuning (by consulting wave dispersion curves in the plate), aiming to reduce the dispersion effect and enhance the recognizability of individual wave packets as mentioned earlier. A typical GW signal captured by the DAQ module is shown in Fig. 9(b).

First, the scenario of mono-damage was examined in which the mock-up damage was located at (-75 mm, 10 mm) (origin of the coordinate system at the center of the plate). Interestingly, as the bonding strength between the mock-up damage and the structure increased with gradual solidification of the adhesive layer over time, the damage-scattered GW waves were observed to be intensified progressively, presenting continuous enhancement in detection accuracy, as seen in Fig. 10(a). An adjustable threshold was further applied on all the field values to strengthen the identification result, which was a preset percentage of the maximum field value of the image, and any field value that was less than the threshold was forced to approach zero. With such a threshold, shown in Figs. 10(b) and 10(c) are the ultimate diagnostic image presented in two and three dimensions, respectively, using all pulse-echo sensing paths rendered by the sensor network. Although these two types of presentation does not differ from each other for plates, the visualization in three dimensions illustrates the system's capability for damage presentation for 3D structures, which is discussed in the next section. As can be seen, the ultimate diagnostic images are capable of characterizing the damage successfully, including its location, size and approximate shape, well matching the reality. Furthermore, as the configured sensor network with eight SSEs provides both pulse-echo and pitch-catch sensing paths, the diagnostic results using all pitch-catch sensing paths in the same sensor network are shown in Fig. 11 for comparison, showing similar detection accuracy comparable with that when pulse-echo sensing was used (Fig. 10).

This validation can be taken a step further by examining multiple mock-up damage spots, which were positioned at (10 mm, 75 mm) and (10 mm, -75 mm) simultaneously. The diagnostic results using pulse-echo measurement are exhibited in Fig. 12(a). Compared with the mono-damage scenario, two damage spots caused more intricate wave scattering, leading to intensified reflections from structural boundaries and creating pseudo-damage nearby. Nevertheless, the system was still able to quickly and accurately characterize the two damage spots with pulse-echo sensing paths, as shown in Fig. 12(b), when the threshold was applied. It is noteworthy that, using the pulse-echo measurement, the minimum separation between two detectable defects, in theory, equals the algebraic product of the wave velocity and the minimum time separation discernible between two identifiable damage-scattered wave packets (where each defect scatters a unique packet). Conservatively, one can take the entire width of the excited tone burses as the minimum time separation (i.e., the two packets are just completely separated in time). In this specific scenario, given a 5-cycle excitation signal at 200 kHz, the minimum separation between two defects is circa 130 mm or even smaller if a pulse-echo measurement used.

For further discussion, diagnostic results using pitch-catch measurement are also shown in Fig. 13. Although changes in the area where the two mock-up defects were adhered can still be observed, the diagnosis is less efficient in delineating exactly the multi-damage with the current number of SSE. Such inefficiency can be attributed to the higher requirement of minimum separation between multiple defects in pitch-catch mode. This has entailed the use of both pulse-echo and pitch-catch sensing paths, to fully reap their respective merits.

B. Tubular Structure

A tubular structure (stainless steel 304, density: 8030 kg/m^3, and Young's modulus: 193 GPa), 1000 mm in length, 108 mm in radius and 4 mm in thickness, was surface-affixed with an active sensor network comprising twelve SSEs, as shown in Fig. 14 (Table I(b) for respective coordinates), which offer 66 monitoring paths in principle. Similar to the previous case, after frequency tuning, *Hanning* window-modulated five-peak sinusoidal tone bursts at a central frequency of 320 kHz were generated to excite the fundamental symmetric Lamb wave mode as the probing signal. A mock-up damage spot was adhered on the outer surface of the tube at (-90 mm, 5 mm) (origin of the coordinate system at the center of the unfolded tube). The diagnostic results are presented two- and three-dimensionally in Fig. 15, using pitch-catch sensing paths. With pitch-catch sensing paths only, the ultimate images clearly and accurately highlight the location, size and approximate shape of the damage (note for convenience of results presentation, the tube is unfolded with regard to its axis for two-dimensional presentation).

V. CONCLUDING REMARKS

An *in-situ* health diagnosis approach is developed for in-service engineering structures by exploring local propagation characteristics of actively generated GWs scattered by damage.

Supported by in-house software and used in conjunction with an active sensor network based on a concept of DSS, this technique is deployed via a self-contained system with integrated modules including active GW generation, multi-channel DAQ, switch control, central control and post-processing (signal processing and interpretation, information fusion, and results presentation). Adverse ambient influence (*e.g.*, temperature fluctuation) during continuous monitoring is compensated by an optimal benchmarking algorithm. The system was then validated experimentally, by characterizing structural damage and evaluating the overall structural health status intuitively, promptly, and automatically. The open platform of the system based on a PXI bus endows the system with enhanced universality, flexibility, and compatibility, allowing users to expand the system to accommodate diverse real-world applications.

REFERENCES

1. S. Legendre, D. Massicotte, J. Goyette, and T. K. Bose, "Wavelet-transform-based method of analysis for Lamb-wave ultrasonic NDE signals," *IEEE Trans. Instrum. Meas.*, vol. 49, pp. 524–530, Jun. 2000.
2. H. Lee, H.-J. Park, H. Sohn, and I.-B. Kwon, "Integrated guided wave generation and sensing using a single laser source and optical fibers," *Meas. Sci. Technol.*, vol. 21, pp. 105207, Oct. 2010.
3. Y. Lu, L. Ye, Z. Su, L.-M. Zhou and L. Cheng, "Artificial neural network (ANN)-based crack identification in aluminum plates with Lamb wave signals," *J. Intell. Mater. Syst. Struct.*, vol. 20, pp:39-49, Jan. 2009.
4. J. L. Rose, "Guided wave nuances for ultrasonic nondestructive evaluation," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control,* vol. 47, pp. 575–583, May 2000.
5. E. Baravelli, M. Senesi, M. Ruzzene, and L. De Marchi, "Fabrication and characaterization of a wavenumber-spiral frequency-steerable acoustic transducer for source localization in palte structures," *IEEE Trans. Instrum. Meas.*, vol. 62, pp. 2197–2204, Aug. 2013.

6. M. Hong, Q. Wang, Z. Su, and L. Cheng, "*In situ* health monitoring for bogie systems of CRH380 train on Beijing–Shanghai high-speed railway," *Mech. Syst. Signal Process.*, vol. 45, pp. 378–395, Apr. 2014.
7. L. Qiu, S. Yuan, X. Zhang, and Y. Wang, "A time reversal focusing based impact imaging method and its evaluation on complex composite structures," *Smart Mater. Struct.*, vol. 20, pp. 105014, Oct. 2011.
8. S. Coccia, I. Bartoli, S. Salamone, R. Phillips, F. Lanza di Scalea, M. Fateh, and G. Carr, "Non-contact ultrasonic guided wave detection of rail defects," *Transport. Res. Rec.*, no. 2117, pp. 77–84, Jan. 2009.
9. V. Giurgiutiu, B. Lin, G. Santoni-Bottai, and A. Cuc, "Space application of piezoelectric wafer active sensors for structural health monitoring," *J. Intell. Mater. Syst. Struct.*, vol. 22, pp. 1359–1370, Aug. 2011.
10. M. Lin and F.-K. Chang, "The manufacture of composite structures with a built-in network of piezoceramics," *Compos. Sci. Technol.*, vol. 62, pp. 919–939, Jun. 2002.
11. J.-B. Ihn and F.-K. Chang, "Detection and monitoring of hidden fatigue crack growth using a built-in piezoelectric sensor/actuator network: II. validation using riveted joints and repair patches," *Smart Mater. Struct.*, vol. 13, pp. 621–630, Jun. 2004.
12. X. Qing, A. Kumar, C. Zhang, I. F. Gonzalez, G. Guo, and F.-K. Chang, "A hybrid piezoelectric/fiber optic diagnostic system for structural health monitoring," *Smart Mater. Struct.*, vol. 14, pp. 98–103, Jun. 2005
13. L. Qiu and S. Yuan, "On development of a multi-channel PZT array scanning system and its evaluating application on UAV wing box," *Sens. Actuators, A*, vol. 151, pp. 220–230, Apr. 2009.
14. M. Siqueira, C. Gatts, R. da Silva, and J. Rebello, "The use of ultrasonic guided waves and wavelets analysis in pipe inspection," *Ultrasonics*, vol. 41, pp. 785–797, May 2004.
15. Z. Sun, L. Zhang, and J. L. Rose, "Flexural torsional guided wave mechanics and focusing in pipe," *J. Pressure Vessel Technol.*, vol. 127, pp. 471–478, Nov. 2005.
16. R. Long, M. Lowe, and P. Cawley, "Attenuation characteristics of the fundamental modes that propagate in buried iron water pipes," *Ultrasonics*, vol. 41, pp. 509–519, Sept. 2003.
17. W.-B. Na and T. Kundu, "Underwater pipeline inspection using guided waves," *J. Pressure Vessel Technol.*, vol. 124, pp. 196–200, May 2002.

18. D. N. Alleyne, B. Pavlakovic, M. J. S. Lowe, and P. Cawley, “Rapid long-range inspection of chemical plant pipework using guided waves,” *Insight*, vol. 43, pp. 93–96, 2001.

19. J. P. Lynch and K. J. Loh. “A summary review of wireless sensors and sensor networks for structural health monitoring,” *Shock Vib.*, vol. 38, pp. 91–130, Mar. 2006.

20. P. M. Monje, L. Casado, G. Aranguren, V. Cokonaj, E. Barrera, and M. Ruiz, “Integrated electronic system for ultrasonic structural health monitoring,” in *Proc. 6th EWSHM*, Dresden, Germany, 2012, pp. 465–472.

21. U. Lieske, A. Dietrich, L. Schubert, and B. Frankenstein, “Wireless system for structural health monitoring based on Lamb waves,” in *Proc. 6th EWSHM*, Dresden, Germany, 2012, pp. 573–579.

22. B. Frankenstein, D. Fischer, B. Weihnacht, and R. Rieske, “Lightning safe rotor blade monitoring using an optical power supply for ultrasonic techniques,” in *Proc. 6th EWSHM*, Dresden, Germany, 2012, pp. 552–560.

23. I. Bua-Nunez, J. E. Posada-Roman, J. Rubio-Serrano, and J. A. Garcia-Souto, “Instrumentation system for location of partial discharges using acoustic detection with piezoelectric transducers and optical fiber sensors,” *IEEE Trans. Instrum. Meas.*, vol. 63, pp 1002–1013, May 2014.

24. B. Xu and V. Giurgiutiu, “Single mode tuning effects on Lamb wave time reversal with piezoelectric wafer active sensors for structural health monitoring,” *J. Nondestruct. Eval.*, vol. 26, pp. 123–134, Oct. 2007.

25. W. Ostachowicz, P. Kudela, P. Malinowski, and T. Wandowski. “Damage localisation in plate-like structures based on PZT sensors,” *Mech. Syst. Signal Process.*, vol. 23, pp. 1805–1829, Aug. 2009.

26. T. Clarke, P. Cawley, P. D. Wilcox, and A. J. Croxford, “Evaluation of the damage detection capability of a sparse-array guided-wave SHM system applied to a complex structure under varying thermal conditions,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 56, pp. 2666–2678, Dec. 2009.

27. J. Moll, R. Schulte, B. Hartmann, C. Fritzen, and O. Nelles, “Multi-site damage localization in anisotropic plate-like structures using an active guided wave structural health monitoring system,” *Smart Mater. Struct.*, vol. 19, pp. 045022, Apr. 2010.

28. J. E. Michaels, A. J. Croxford, and P. D. Wilcox, “Imaging algorithms for locating damage via in situ ultrasonic sensors,” in *Proc. SAS 2008*, Atlanta, GA, 2008, pp. 63–67.

29. Y. Koh, W. K. Chiu, and N. Rajic, “Effects of local stiffness changes and delamination on Lamb wave transmission using surface-mounted piezoelectric transducers,” *Compos. Struct.*, vol. 57, pp. 437–443, Jul. 2002.

30. D. C. Betz, G. Thursby, B. Culshaw, and W. J. Staszewski, “Identification of structural damage using multifunctional Bragg grating sensors: I. Theory and implementation,” *Smart Mater. Struct.*, vol. 15, pp. 1305–1312, Oct. 2006.

31. Z. Wu, X. P. Qing, and F.-K. Chang, “Damage detection for composite laminate plates with a distributed hybrid PZT/FBG sensor network,” *J. Intell. Mater. Syst. Struct.*, vol. 20, pp. 1069–1077, Mar. 2009.

32. X. Zhao, H. Gao, G. Zhang, B. Ayhan, F. Yan, C. Kwan, and J. L. Rose, “Active health monitoring of an aircraft wing with embedded piezoelectric sensor/actuator network: I. defect detection, localization and growth monitoring,” *Smart Mater. Struct.*, vol. 16, pp. 1208–1217, Aug. 2007.

33. J. Zhang, B. W. Drinkwater, P. D. Wilcox, and A. J. Hunter, “Defect detection using ultrasonic arrays: The multi-mode total focusing method,” *NDT&E. Int.*, vol. 43, pp. 123–133, Mar. 2010.

34. C. Ramadas, K. Balasubramaniam, M. Joshi, and C. Krishnamurthy, “Interaction of guided Lamb waves with an asymmetrically located delamination in a laminated composite plate,” *Smart Mater. Struct.*, vol. 19, pp. 065009, Jun. 2010.

35. Q. Wang and S. Yuan, “Baseline-free imaging method based on new PZT sensor arrangements,” *J. Intell. Mater. Syst. Struct.*, vol. 20, pp. 1663–1673, Sept. 2009.

36. H. Sohn, H. W. Park, K. H. Law, and C. R. Farrar, “Combination of a time reversal process and a consecutive outlier analysis for baseline-free damage diagnosis,” *J. Intell. Mater. Syst. Struct.*, vol. 18, pp. 335–346, Apr. 2007.

37. C.-T. Ng and M. Veidt, “A Lamb-wave-based technique for damage detection in composite laminates,” *Smart Mater. Struct.*, vol. 18, pp. 074006, Jul. 2009.

38. K.-Y. Jhang, “Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: A review,” *Int. J. Precis. Eng. Man.*, vol. 10, pp. 123–135, Jan. 2009.

39. C. Pruell, J.-Y. Kim, J. Qu, and L. J. Jacobs, “Evaluation of fatigue damage using nonlinear guided waves,” *Smart Mater. Struct.*, vol. 18, pp. 035003, Mar. 2009.

40. M. Deng and J. Pei, “Assessment of accumulated fatigue damage in solid plates using nonlinear Lamb wave approach,” *Appl. Phys. Lett.*, vol. 90, pp. 121902, Mar. 2007.

41. F. Aymerich and W. Staszewski, “Experimental study of impact-damage detection in composite laminates using a cross-modulation vibro-acoustic technique,” *Struct. Health Monit.*, vol. 9, pp. 541–553, Nov. 2010.

42. M. Meo, U. Polimeno, and G. Zumpano, “Detecting damage in composite material using nonlinear elastic wave spectroscopy methods,” *Appl. Compos. Mater.*, vol. 15, pp. 115–126, May 2008.

43. H. Sohn, H. J. Lim, M. P. DeSimio, K. Brown, and M. Derriso, “Nonlinear ultrasonic wave modulation for online fatigue crack detection,” *J. Sound Vib.*, vol. 333, pp. 1473–1484, Feb. 2014.

44. J. E. Michaels and T. E. Michaels, “Detection of structural damage from the local temporal coherence of diffuse ultrasonic signals,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 52, pp. 1769–1782, Oct. 2005.

45. X. Chen, X. Li, S. Wang, Z. Yang, B. Chen, and Z. He, “Composite damage detection based on redundant second-generation wavelet transform and fractal dimension tomography algorithm of Lamb wave,” *IEEE Trans. Instrum. Meas.*, vol. 62, pp. 1354–1363, May 2013.

46. C. Zhou, Z. Su, and L. Cheng, “Probability-based diagnostic imaging using hybrid features extracted from ultrasonic Lamb wave signals,” *Smart Mater. Struct.*, vol. 20, pp. 125005, Dec. 2011.

47. G. Konstantinidis, B. Drinkwater, and P. Wilcox, “The temperature stability of guided wave structural health monitoring systems,” Smart Mater. Struct., vol. 15, pp. 967–976, Aug. 2006.