A Wireless Piezoelectric Sensor Network for Distributed Structural Health Monitoring

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***Abstract*—This paper presents the development of a newly designed wireless piezoelectric (PZT) sensor platform for distributed active structure health monitoring (such as aircraft wings and bridges). The developed wireless PZT-sensor network features real-time data acquisition with high sampling rate up to 12.5MSPS (sample per second), distributed lamb-wave data processing and energy saving by reducing the amount of data in wireless transmission. In the proposed wireless PZT network, a set of PZT transducers deployed at the surface of the structure, and a lamb wave is excited and its propagation characteristics within the structure are inspected to identify possible damages. The developed wireless node platform benefits from a digital signal processor (DSP) of TMS320F28335 and an improved IEEE 802.15.4 wireless data transducer RF233 with up to 2Mbps data rate. Each node supports up to 8 PZT transducers, one of which may work as the actuator generating the Lamb wave at an arbitrary frequency, while the responding vibrations at other PZT sensors are sensed simultaneously. In addition to hardware, embedded signal processing and distributed data processing algorithm are designed as the intelligent 'brain' of the proposed wireless monitoring network to extract features of the PZT signals, so that the data transmitted over the wireless link can be reduced significantly.**

Keywords—wireless sensor network; piezoelectric sensor; structural health monitoring; distributed lamb wave processing

I. INTRODUCTION

Structural Health Monitoring (SHM) is a system to monitor the integrity of civil structures (e.g. bridges, aircraft wings, etc.) and ensure their performance and safety. It has become an attractive research topic in the cross-disciplinary field of mechanical, civil and electronic engineering. One of the main targets of SHM is on-line damage detection, which not only reduce costs by minimizing maintenance and inspection cycles, but also prevents catastrophic failures at an earlier stage. This is particularly useful for developing self-monitoring structures, into which 'smart' materials are integrated.

As a nondestructive evaluation (NDE) method, the well-known Lamb wave-based damage detection has been widely used in SHM [1], which utilizes the features of piezoelectric (PZT) materials and shows great promises for online SHM. There have been recent interests in the use of PZT transducers, due to their simplicity, robustness and low cost. In such a PZT-based SHM system, a set of PZT transducers are deployed at the surface of the structure, and one or more PZT transducers work as exciters to induce lamb waves into the structure. Since the propagation of lamb waves are affected by the structure's degradation, defects and damages (e.g. cracks), the characteristics of the lamb waves propagating from the exciter to these receiving PZT sensors are closely monitored and carefully inspected so that the occurrence of defects and damages within the structure can be identified.

There have been a lot of researches in literature [1-3] on using lamb-wave for damage localization. However, majority of them are wired systems requiring intensive cabling work with high deployment and maintenance costs, which make the wired system unsuitable for distributed sensing in large structural health monitoring. Martens et al. in [4] investigated a platform for piezoelectric sensor based on TMS320F28335 chip with high-resolution PWM and multi-channel ADC with 4MHZ sampling rate. This platform is a wired system and, without wireless module, is not suitable to forming a large PZT network for wide area monitoring.

With the mature of wireless communication techniques, one of the recent challenges in the structural engineering community is the emerging wireless SHM system, which provides a promising solution for rapid, accurate and low-cost structural monitoring [5]. On the other hand, conventional design of wireless sensor node is not suitable for active sensing in SHM, where the lamb waves to be sensed are high frequency ultrasonic signals and contain frequency components up to a few hundred Hz. As a result, high sampling rate is required and a huge amount of data will be collected during the procedure of lamb-wave interrogation. In addition, due to the complexity of lamb-wave propagation, the damage detection algorithms in SHM usually are computation intensive and require considerable data processing capabilities. However, the existing wireless communication protocol (i.e. IEEE 802.15.4) and wireless hardware motes (e.g. Mica2, MicaZ and TelosB) in wireless sensor networks are designed for low data rate and low computation applications, which make it is impossible to transmit all the lamb-wave data to a central server that carries out centralized data processing and structure damage identification.

Some researches [6-7] develop some compressive sensing method on lamb wave. They verified lamb wave can be reconstructed well by compressive sensing method. However, the compressive sensing method have not easily embedded into wireless node so that distributed processing for PZT network is not able to be achieved. In literatures, some PZT sensor and actuator nodes have been proposed for structural health monitoring. A wireless sensor node is proposed in [8], where field programmable Gate array (FPGA) was used for piezoelectric active diagnosis. However, these wireless sensor nodes have very limited on-board data processing capability for acquired signal. Furthermore, authors in [9-10] design the wireless PZT sensor and actuator node based on TMS320C2811 and TMS320F2812, respectively. Dong X et al. [11] discussed a Martlet node with TMS320F28069 chip which can support 3MHZ sampling rate for MEMS accelerometer. However, there are lack of compressive sensing and distributed data processing on these platforms.

To address the challenges of high-sampling rate, big data, compressive sensing, distributed data processing and the bottleneck of limited wireless communication bandwidth in wireless lamb-wave interrogation, we propose and develop a wireless piezoelectric (PZT) sensor platform. The newly designed wireless node features with a TMS320F28335 digital signal processor (DSP) and an improved IEEE 802.15.4 wireless data transducer with up to 2Mbps data rate. Each node supports up to 8 PZT transducers and sampling rate up to 12.5MHz, one of which works as the actuator generating drive the external piezoelectric sensor the Lamb wave at an arbitrary frequency, while the responding vibrations at other PZT sensors are sensed simultaneously. In addition to hardware, embedded signal processing and distributed data processing algorithm are also designed as the intelligent 'brain' of the proposed wireless monitoring. As a result, the amount of data to be transmitted over the wireless link is reduced significantly. These features enable the developed PZT sensor-actuator node being deployed easily and suitable for wide area SHM.

The rest of this paper is organized as follows: Section 2 presents the network architecture of the proposed wireless piezoelectric sensor and actuator network in SHM, followed by the sensor and actuator hardware development in section 3. The software development is presented in Section 4. Some preliminary results are discussed in Section 5 for the purpose of demonstration. And Section 6 is the summary of conclusions and future work.

II. NETWORK ARCHITECTURE

The proposed wireless piezoelectric sensor network consists of several groups of PZT transducers that are deployed at different regions of the structure to be monitored, as illustrated in Fig 1. Although these PZT transducers are connected to the nearby wireless PZT nodes in their regions via a set of short wires, the featured difference of the proposed system is that the longer distance lamb-wave analogue signal cables in wired SHM are replaced by the digital wireless data links between PZT nodes and the remote monitoring system. Therefore, the massive signal cables and costly cable installation are avoided, which is the key benefit of the proposed wireless PZT sensor network. As illustrated in Fig. 1, the proposed WSN consists of the following components:

(1) PZT transducer: The piezoelectric transducer either converts mechanical to electric signals, or vice versa. The PZT transducers have two work modes: it can work as either a PZT actuator to excite an elastic Lamb-wave according to the electrical signal applied on the piezoelectric crystal, or a PZT sensor to transform the responding elastic Lamb-waves into an electrical signal.

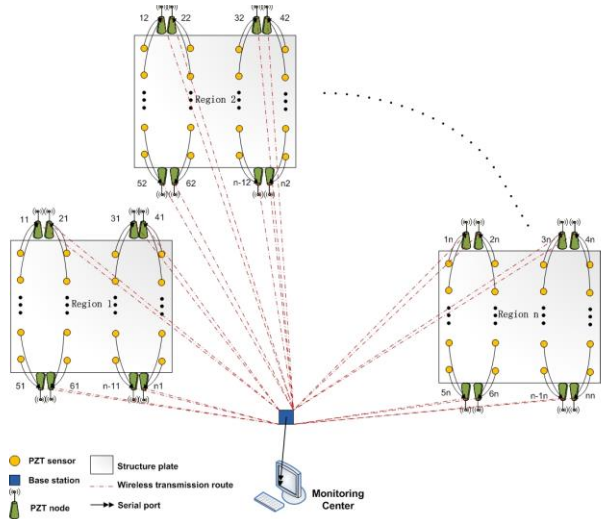

Fig. 1. Topology of the wireless PZT sensor and monitoring network

(2) Wireless PZT node: PZT sensor and actuator nodes are in charge of PZT transducer parameter monitoring. Each node connects to two PZT transducers. The node can generate excitation signal for driving PZT transducer and then acquires data from PZT transducer s. PZT sensor and actuator node has embedded compressive sensing method or other methods for lamb wave processing. All wireless PZT nodes form a network and send the damage results or original lamb wave signal to the Base station according to TDMA or CSMA protocol. And wireless PZT nodes in one structure plate should comply with data sampling synchronization to ensuring the damage localization curacy.

(3) Base station: This is the sink node which has wireless link to the all PZT sensor and actuator nodes. Base station can support big data transmission access, multi-point operations and time synchronization mechanism for all PZT sensor and actuator nodes. The synchronization manage module in base station is in charge of starting the operation of the whole network by sending initial command. The module provides global timestamps periodically for synchronizing the data acquired from all PZT sensor and actuator nodes deployed in different structures.

(4) Remote monitoring and HCI center: The center is charged of responding the users and starting the operation of network. Moreover, the center gets data from base station and analysis data.

III. WIRELESS PZT SENSOR NODE ARCHITECTURE

The architecture of the proposed wireless PZT node is shown in Fig. 2. The wireless PZT node consists of three components, namely, conditioning board, DSP base board and radio board.

A. Conditioning board

The conditioning board is an analogue signal processing board that has two tasks: (1) to amplify the 3.3V lamb waveforms generated by the DSP based board to an appropriate level so that a required lamb wave can be induced at the PZT transducer (actuator mode). (2) to filter and amplify the weak and noisy lamb-wave signal detected by the PZT transducer (sensor mode) to 3.3V level so that the ADC's performance are optimized (such as the aliasing and quantification noises).

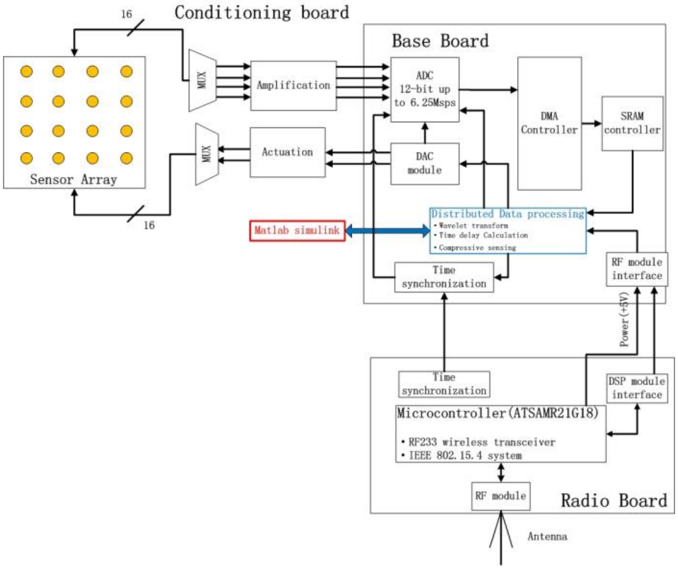

Fig. 2. Hardware architecture of the wireless PZT node

B. DSP board for sensing and distributed data processing

A common wireless sensor node usually has limited memory, limited computational ability and battery power. These conditions should be taken into account when the compressive sensing algorithm is embedded into wireless sensor board. The base board is chosen according to following aspects: (1) It should have SPI or I2C interface for communicate with RF board; (2) It should support high data transmission rate for large amount of lamb wave or other complex signals; (3) It should support high enough crystal frequency for working; (4) It should support certain memory storage for data cache. For low-cost low-power measurement devices, the programmable DSP could be an efficient digital, programmable and real-time platform.

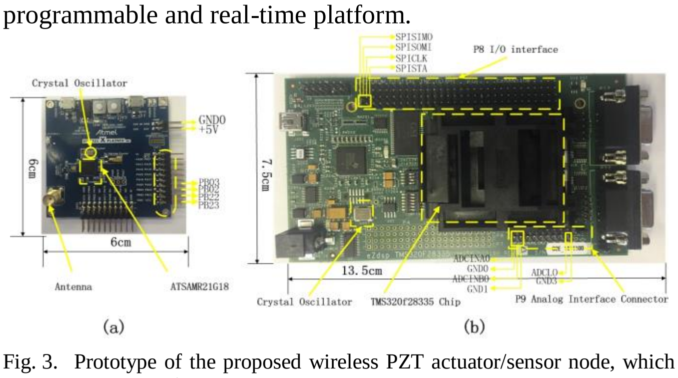

Fig. 3. Prototype of the proposed wireless PZT actuator/sensor node, which is consisted of two parts: (a) an IEEE 802.15.4 radio board; and (b) a DSP base board

In order to implement high-sampling data acquisition, onboard data processing, the proposed wireless PZT sensor node adopts a prototype eZdsp F28335 by Spectrum Digital Inc with a Texas Instrument microcontroller TMS320F28335 running up to 150MHZ clock frequency. Additional important features of this DSP are built-in DMA-controller, multichannel 12-bit analogue to digital converter (ADC) with two independent sample-and-hold (S/H) circuits, enough internal flash memory and floating point hardware arithmetic. With the built-in DMA controller, the sampling rate can achieve up to 12.5M sample per second (SPS). The two independent simultaneous S/H circuits enable simultaneous sampling two ADC channels and makes it possible to calculate the lamb-wave's time of flight at much higher accuracy.

C. Enhanced IEEE 802.15.4 radio board

The radio board, as detailed in Fig. 3(a), is equipped with an Atmel SMART SAM R21 chip integrating both an ultralow-power 32-bit ARM Cortex-M0+ microcontroller and an enhanced IEEE 802.15.4 radio chip RF233. This wireless transceiver can achieve a maximum data rate of 2Mbps at 2.4GHz ISM band. The radio board is connected to the DSP base board through the SPI bus (using pin PB03, PB22, PB02 and PB23 of the radio board and the SPICLK, SPISIMO, SPISOMI and SPISTA pins of the DSP board. In transmitting state, the radio board consumes 35.5 mW of power (or 26 mA of power at 1.8V) but less than 2 μW of power (or only 1.1 μW of power at 1.8V) in power down mode. The wireless data packet is compatible with the standard IEEE 802.15.4 data frame format and the maximum payload is 112 Bytes.

IV. SOFTWARE ARCHITECTURE

Fig. 4 illustrates a procedure within a three-stage wireless sensor network for autonomous damage or defect detection. The entire wireless sensor network may consist of PZT node, base station connected to PC. Several PZT nodes and a base station form a group to cover a geometrical area. The diagnosis command is initiated from the PC through base station. After informing all wireless PZT nodes, the base station broadcasts a initial command to wireless PZT node and triggers the signal excitation of sensor nodes. Each wireless PZT nodes immediately start data acquisition after receiving the initial command and record the measurements. The measurements are subtracted from the pre-stored sensor data for healthy structure to obtain the scattered wave signal form the damage.

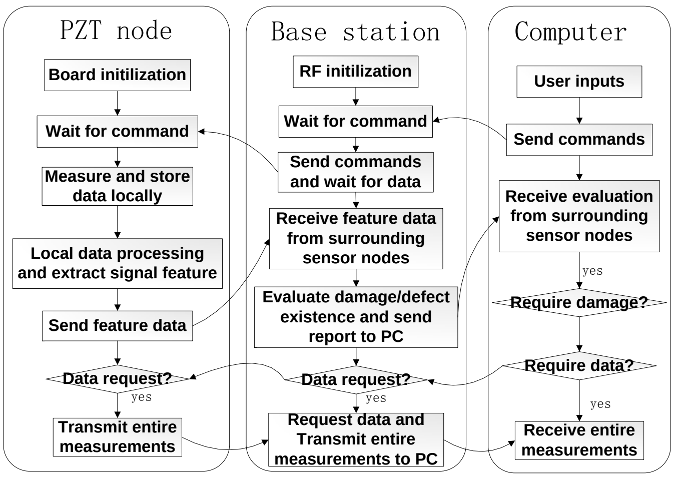

Fig. 4. Function blocks of the proposed wireless PZT network.

Conventional wireless sensor nodes normally utilize centralized architecture. In this architecture, analog-to-digital converters (ADC) and memory chips are directly connected to I/O ports of microcontroller. The microcontroller must access the peripheral chips sequentially and clock multiple clock cycles are required to complete an operation which involves several peripheral chips. Most peripheral chips should be active while waiting for signals form microcontroller. For such architecture using conventional design, high speed sampling rate is almost impossible.

A. *Synchronized high sampling-rate sensing*

For comparison, the ADC sampling process in both conventional WSN node and the proposed wireless PZT-sensor network are illustrated in Fig. 5, where the flowchart of typical data sampling cycle in conventional WSN nodes (e.g. Telosb, Imote2 and MICA motes) if shown in Fig. 5(a). These conventional motes have an internal ADC within its microcontroller. The microcontroller sends clock signal and control signals to the ADC to trigger data conversion. After the data has been read out entirely, the microcontroller need write the data into its memory. The flash saving operation involves several instructions and a few clock cycles. Then, the sampling cycle ends and another sampling cycle may start again. This architecture clearly reveals the inefficiency of wireless sensor node designed with an ordinary microcontroller.

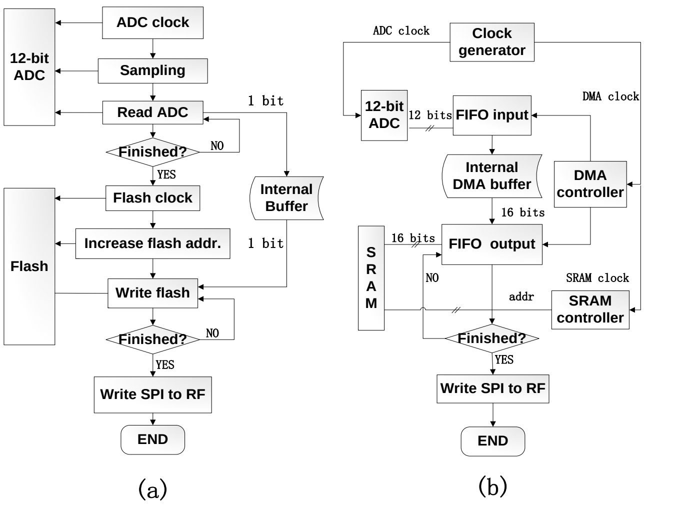

Fig. 5. Data sampling and collection process comparison between (a) the conventional wireless sensor node with low sampling rate (usually up to a few kHz); (b) the proposed wireless PZT sensor/actuator node with burst sampling rate up to 12.5 MHz.

Fig. 5 (b) presents an improved sampling design using TMS320F28335 chip. The chip internally has some controllers, including first-in-first-out (FIFO) DMA controller for sampling data input and output, SRAM controller, a clock generator. The DMA algorithm has been widely used to allow hardware to access memory independently. To enable a wireless sensor node for high speed applications, some algorithms such as semi-DMA approach are applied to extend the traditional architecture of wireless sensor node. In our design, with the DMA controller, the main microcontroller TMS320F28335 chip can be released from the task of data transfer. The sampling data transfer and data acquisition can be more efficient when DMA is adopted. The 12-bit Sampling data is acquired by the ADC and saved into the internal DMA buffer in FIFO input mode by DMA controller. Meantime, the DMA controller and address controller controls the data to access the SRAM in FIFO output mode. The sampling data is moved from the internal DMA buffer to SRAM at 16-bit length which is the I/O width of SRAM. Each clock cycle have 8 continuous sampling operations and one writing operation for writing data for SRAM.

V. Proof-of-Concept Tests and Performance Evaluation

In order to evaluate the performance of the developed wireless PZT sensor nodes, a series of proof-of-concept lab tests have been carried out and the results are presented in this section. Two key performance indices of the proposed wireless piezoelectric sensor and actuator network are (1) distributed signal processing for envelope detection and propagation delay estimation; (2) compressive sensing for reducing the amount of data to match the wireless communication bandwidth, while retaining the structure health information as much as possible.

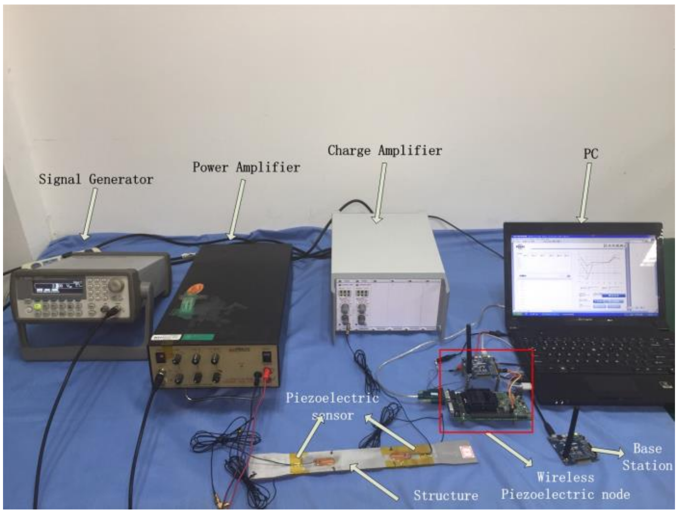

Fig. 6. Lab test platform for the wireless PZT sensor network

The lab test platform is shown in Fig. 6. As a proof-of-concept lab test, the platform consists of a computer working as a graphic user interface to the end-user, a wireless base station that connects to the PC with the wireless network , the designed wireless sensor node (highlighted by a red square). As our focus is to verify the distributed signal processing and wireless transmission, the conditioning board is replaced by a power amplifier and a charge amplifier in this lab test. Two PZTs are attached to the surface of an aluminum plate bar. Left one is the actuator connected to a power amplifier that amplify the five-cycle sinusoidal tone burst signal to generate a lamb wave. The PZT at right end of the aluminum bar is the PZT sensor to receive the propagated lamb waves. The lamb wave signal detected by the PZT sensor is first conditioned by a charge amplifier to the range of 0-3.3 volts. Then the amplified signal goes through the DSP board and RF board for digital-to-analogue conversion, local signal processing and wireless transmission. Once the base station receives the transmitted data, it simply forwards the data to the PC via a USB cable.

In our lab tests, the waveforms generated from a lamb-wave propagation simulator [12] are used for performance evaluation. These waveforms are injected into the signal generator to mimic the PZT transducer. The output signals from the signal generator are connected to the DSP baseboard that processes the signal locally and sends the extracted feature to base station through the wireless link.

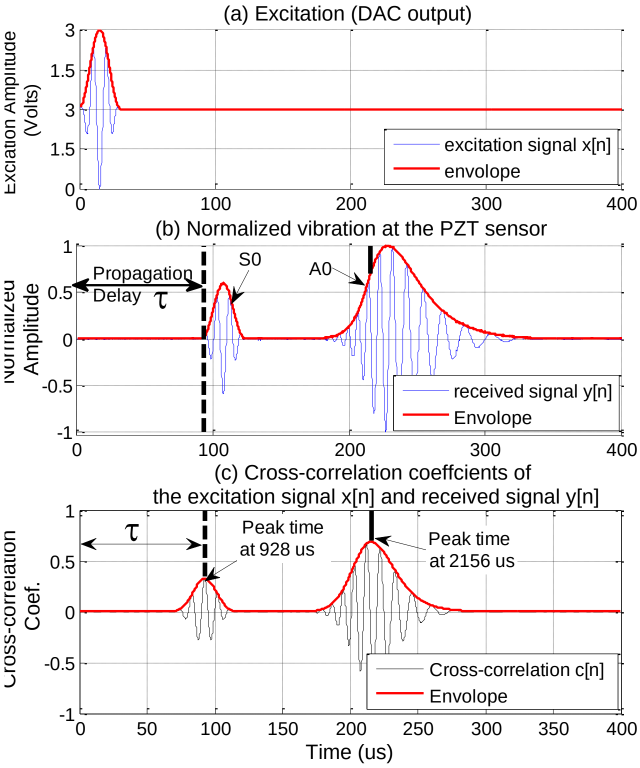

Fig. 7. Lamb-wave detection. (a) excitation signal $\boldsymbol{x}[\boldsymbol{n}]$ at the PZT excitation; (b) received signal $\boldsymbol{y}[\boldsymbol{n}]$ and its envelope at the PZT sensor. (c) the cross correlation function of $(\boldsymbol{x}[\boldsymbol{n}], \boldsymbol{y}[\boldsymbol{n}])$ and its envelope. The envelope is detected by using the Hilbert transform.

The signals used in this proof-of-concept test are for a pair of PZT actuator and sensor on an aluminum plate of 2mm thickness, where the PZT sensor is separated from the PZT actuator at 100mm distance. Fig. 7(a) depicts the hamming-windowed 5-peak tone-burst excitation signal (blue line) of carrier frequency 200 kHz and its hamming window (red line). The excitation signal has 5 cycles of the sinusoidal signal and last for 25us. For the purpose of evaluation, the excitation frequency was tuned to 200 kHz for a good separation of the fundamental symmetric mode S0 wave and the fundamental anti-symmetric mode A0 wave.

At the PZT sensor node, the reception lamb-wave after 100mm propagation was sampled for 400us by the build-in ADC of 28335 DSP at a sampling rate of 12.5MSPS with the resolution of 12 bits. Fig. 7 (b) shows the sampled data (blue line) , which demonstrates the clear separation of the S0 and A0 mode. The dispersion of the A0 mode for such a wave at 200 kHz frequency after 100mm propagation can also be clearly seen.

A. Time-of-flight (TOF) extraction

The fundamental principle of lamb-wave structure health monitoring is the fault localization by time-of-flight of the received waves. With the given wave propagation speed, once TOF τ is found, the location of the reflector damage can be determined according to the equation:

$$d = v_g \times \tau$$

where v_g is the group velocity and d is the distance of the reflector from the sensor. In the TOF estimation, the main concerns are the envelope of the lamb-waves and the envelope of the cross-correlation function, rather than the raw 200kHz waves. The excitation signal $x[n]$ (Fig. 7 (a), blue line) works as the baseline signal to calculate the cross-correlation function with respect to the received signal $y[n]$ (Fi.g 7(b), blue line).

$$c[n] = E\left\{\sum_i x[i]y[i-n]\right\}$$

The cross-correlation coefficients are further processed by the Hilbert transform to derive its envelope for TOF estimation. The calculated cross-correlation function $c[n]$ and its envelope are shown in Fig. 7(c). From the envelope of the cross-correlation function, the first peak of $c[n]$ appears at about 928us, which verifies the observation of the S0 wave propagation delay in Fig. 7(b). The second peak appears at 2156us and it indicates the propagation delay of A0 wave. However, due to the significant dispersion of A0 wave, the calculated propagation delay of A0 is not at the maximum of $y[n]$. Once the propagation delay is calculated, the delay will be sent to the wireless base station and processed further by advanced data fusion and cross-checking algorithms to localize and visualize the faults.

B. Compressive sensing and data recovery

In order to improve the accuracy of the fault location estimation carried out at the base station, single TOF may not informative enough. The envelopes are also needed in most data fusion processes. However, given the sampling rate of 12.5MSPS, 12bit resolution and monitoring duration of 400us, the collected data is about 10k Bytes for just one single PZT sensor channel. If they are not processed by compressive sensing, the sampled data has to be segmented into 92 packets due to the 112 Bytes limits of wireless packet size and it will take about 1 second under ideal conditions (collision-free) to complete the data transmission at 125kbps IEEE 802.15 standard data rate. When the number of wireless nodes increases and the number of PZT sensor channel per node increases, the time for wireless data transmission will increase dramatically. Further concern will be the power consumption demanded for such huge data transmission. Therefore, the amount of data to be transmitted wirelessly has to be reduced to a great extend to enable practical wireless data transmission.

A down sampling algorithm is demonstrated to prove the concept, as shown in Fig. 8. The envelope identified at TOF estimation stage is further processed by a down-sampling process to reduce the amount of data to be transmitted over the wireless link. It can be seen that, the envelope of the lamb-wave is kept after reducing the sampling rate by a factor of 1/20.

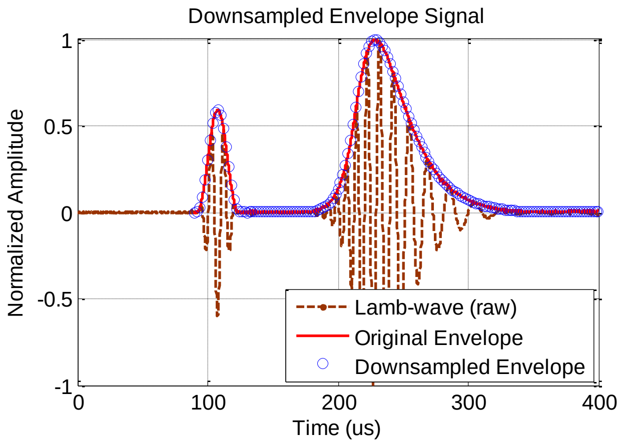

Fig. 8. Downsampled and reconstructed envlope signal. The downsampling ratio is 1:20.

At data sink, the envelope is reconstructed from the down-sampled data. The results of envelope reconstruction are shown in Fig. 9, where the downsampled envelope (blue circle) fits the original envelope (red line) very well. The envelope signal before down-sampling consists of 4000 sample points and is of 8k Bytes. At the downsampling ratio of 20 and by removing the noise data before the arrival of the S0 wave, the number of samples is reduced from 4000 to 156, which make it possible for WSN to collect the data. As a result, sending an envelope signal to the base station is accomplished by transmitting two packets only, which is a significant saving in terms of communication costs and power consumption.

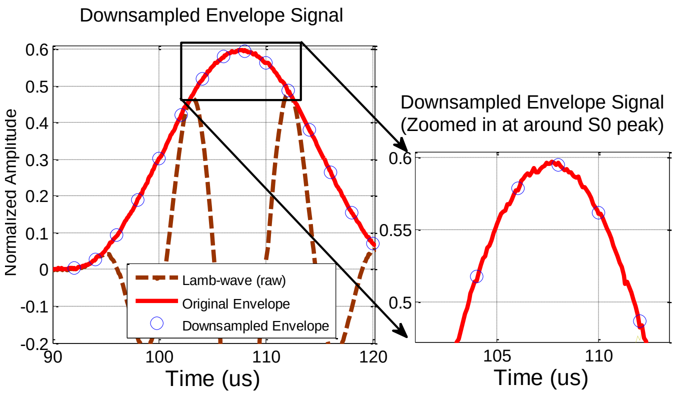

Fig. 9. Downsampled and reconstructed envlope. The downsampling ratio is 1:20.

Another benefit of the proposed down-sampling approach is the noise filtering. Due to the use of FIR filter in the down-sampling algorithm, the reconstructed signal from the down-sampled points is smoother than the original envelope (as shown in the zoomed-in insect in Fig. 9). As a result, it will contribute to the improvement of signal-noise-ration and the accuracy of fault localization.

VI. Conclusions and Future Work

This paper presents a low-cost, wireless PZT sensor network for structural health monitoring. The developed wireless PZT node provides a powerful wireless platform with precise data acquisition at a high-sampling rate up to 12.5MHz and distributed local data processing for feature extraction and data reduction transmitted over wireless link. A series of proof-of–concept tests have been done and the results of both the envelope detection and down-sampling algorithms are presented, from which the performance of the proposed wireless PZT sensor network are verified. In the future, more advanced distributed data processing algorithm (such as wavelet denoising) will be deployed. Another issue to be addressed in such a distributed wireless PZT sensor network for structure health monitoring is the time synchronization among these wireless nodes.

Acknowledgment

This work was partly supported by European Commission project Health Monitoring of Offshore Wind Farms (HEMOW) under grant FP7-PEOPLE-2010-IRSES-GA-269202 and EPSRC project Novel Sensing Network for Intelligent Monitoring (NEWTON) under grant EP/J012343/1.

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