EMBEDDED ULTRASONIC TRANSDUCER DESIGN AND WIRELESS COMMUNICATIONS FOR INTELLIGENT MONITORING OF STRUCTURES

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ABSTRACT. This paper describes a wireless demonstrator system designed for generation and detection of fundamental symmetrical Lamb waves (S₀) characterized by high velocity and low attenuation. The demonstrator comprises two piezoceramic transducers embedded within an epoxy plate, drive and pre-amplification electronics, a microcontroller and a communications interface. This arrangement can be configured to operate in an active pitch-catch or pulse-echo interrogation mode or as a passive acoustic emission (AE) sensor. The history of AE incidents, for example, may then be transmitted by wireless link.

INTRODUCTION

In-service monitoring of structures is exciting a high level of current interest, particularly in the aerospace, automobile, process and power generation industries. Early detection of defects such as impact damage, fatigue cracks, corrosion or erosion can avert catastrophic failure or at least permit planned intervention to minimize plant or equipment down-time. Conventional systems employing many sensors distributed throughout the structure depend on electrical or fiber-optic cabling for data collection. Cabling complexity and protection from damage result in high installation and maintenance costs. Current systems also suffer from limited interrogation range, in turn leading to greater numbers of sensor required and hence further increase in cabling costs.

Ultrasonic techniques employing Lamb waves have been proposed as a solution to extending the scope of individual sensors mounted on, or embedded into, plate-like structures [1,2,3,4]. In conjunction with investigation of ultrasonic transducer technologies suitable for these applications, considerable research has been undertaken to provide improved data collection by means of appropriate electronic systems designs coupled with wireless transmission to obviate the severe cabling constraints.

Work in progress to the ultimate aim of constructing a demonstration system, which would allow assessment of power requirements, antenna design, communication protocols and hardware design for ultrasonic sensors, was reported at Review of Progress in QNDE 2001 [2]. This paper describes the demonstrator system achieved with emphasis on transducer design, electronics design and system performance leading to an assessment of envisaged future system enhancements.
MONITORING SYSTEM

System Overview

Two of the paper's authors have previously reported an ultrasonic inspection system incorporating wireless communication [5] of data obtained from through-air scanning equipment and transmitted to a remote receiver. The demonstration system described here was envisaged to provide duplex control and data gathering by wireless link from a central processing unit to a remote sensor station. The basic concept is depicted in Figure 1. In the configuration shown separate interrogation and reception transducers are implemented as active sensors.

In general practice the wireless transceiver would be a single device capable of both receiving commands from the central control unit and transmitting data for further processing in the central processing unit. Similarly, the microcontroller would be a single device handling all the local control functions for both the ultrasonic transmitter and receiver and the wireless transceiver, in addition to providing some low-level signal processing prior to data transmission. Such a configuration would be applicable to pulse-echo operations in which the transducers would also be a single entity capable of being switched between transmission and reception.

In applications requiring pitch-catch operation the transmitting and receiving devices would be situated on either side of a suspected defect or a vulnerable section of the structure, so in this case the full configuration shown would be implemented.

For a passive, 'listening-mode' application only the receiving sensor sub-system would be required.

FIGURE 1. Block diagram of structural monitoring system with a single active sensor in wireless communication with a central control and processing station.
A practical monitoring system would be expected to comprise several sensor stations distributed over the structure to be monitored, all in wireless communication with a single central control and processing station. For very large structures a hierarchical approach may be adopted which would allow an intermediate level of control and processing stations each handling the sensors in a designated area and each communicating with a central control and data gathering station.

**Transducer Design**

To demonstrate the application of embedded ultrasonic sensors as described above a monitoring system capable of detecting and reporting acoustic emission (AE) events was designed and constructed.

AE events occurring in plate-like structures are known to produce ultrasonic Lamb waves [6,7] which can propagate over long distances. Several Lamb wave modes are generated of which the symmetric S₀ mode is almost non-dispersive at low frequencies and suffers less attenuation than the corresponding anti-symmetric mode. Detection of this S₀ mode allows time-of-flight information to be extracted and hence, by triangulation using several sensors, the defect position may be computed.

Experimental measurements of Lamb wave activity generated by AE events were encouraging but the standard pencil lead breaking test method for simulation of AE events was found to be unreliable and difficult to repeat. In order to generate consistent signals to the electronic data gathering system a pair of 20 mm diameter PZT5H disc transducers were embedded in a 3.4 mm thick hard-set epoxy plate as depicted in Figure 2. Previous research [2] showed that the predominant Lamb wave mode generated by a transducer embedded centrally in a host plate, when excited at its fundamental width mode frequency, would be the S₀ mode. One transducer was excited by a Hanning-windowed tone burst at the frequency calculated to generate S₀ Lamb waves (104 kHz). The second, at approximately 250 mm distance between centers, was configured as an ultrasonic receiver. Consistent input signals to the electronic system were obtained as shown in Figure 3.

![Figure 2](image_url)

**FIGURE 2.** Epoxy test plate used to generate simulated AE event S₀ Lamb waves.
The representative signals shown in Figure 3 were obtained for an input excitation amplitude which induced an event trigger in the electronic system signifying the detection of a simulated AE occurrence. The 110 volt peak-to-peak amplitude, 104 kHz drive signal to the transmitting transducer generated Lamb waves which were received by the ‘listening’ transducer and after +50 dB amplification presented a 7.26 volt peak-to-peak input signal to the electronic data gathering circuitry. The received signal shows firstly a small representation of the transmitter drive signal coupled by electro-magnetic radiation. The main signal of interest arrives approximately 120 μs after the initiation of the excitation signal. This time-of-flight measurement is consistent with the transducer edge separation distance of 230 mm and the $S_0$ Lamb wave velocity in the 3.4 mm thick epoxy plate of 1.946 Km/s, as derived from the DISPERSE program [8].

The direct path signal is followed in time by indirect path signals traveling further via reflections from the plate boundaries.

Also of interest is the absence of other discernable Lamb wave modes in the received signal.

**Electronics Design**

An electronic data gathering system was designed to extract time-of-flight data from the received signals. The circuitry is shown in block diagram form in Figure 4.

**FIGURE 3.** Representative $S_0$ Lamb wave signals obtained from epoxy test plate embedded transducer pair.

**FIGURE 4.** Block diagram of AE sensor and electronic data extraction system.
The amplified received signals, as shown in Figure 3, were applied to an envelope detection circuit to allow sampling by an analogue to digital converter (ADC). The sampled digital signals were stored in sequential positions in memory configured as a first-in-first-out (FIFO) shift register. The signal amplitudes were simultaneously examined by the microprocessor used to control all the electronic system functions. If a software-preset amplitude threshold was exceeded sampling was continued for sufficient time to allow the complete event signal to be recorded. The microprocessor then extracted the values stored in memory corresponding to the time period of interest from before the event threshold occurrence.

Using this approach a threshold value high enough to exclude noise could be set and by extracting data from samples before the event threshold trigger a complete time history of the event could be examined and accurate time-of-flight information could be extracted. The concept is similar to an oscilloscope ‘pre-trigger’ function and is schematically illustrated in Figure 5.

The data of interest was then transferred serially to a radio transceiver operating in the license-free 418 MHz band and transmitted to a similar transceiver incorporated in a remote receiver system. The transmitted signals were reconstructed via a digital to analogue converter (DAC) and displayed on an oscilloscope.

Figures 6 and 7 depict captured oscilloscope displays of representative signals from the sensor electronics with an input signal amplitude greater than the preset threshold, and the reconstructed data at the remote receiver.

FIGURE 5. Schematic of ‘pre-trigger’ concept used to extract accurate time-of-flight information.

FIGURE 6. Representative electronic system signals. From top to bottom: Envelope detector output (TX_IN), remote receiver output (RX_OUT), receiver DAC clock (DAC_CK), receiver serial data stream (RXD), transmitter serial data stream (TXD), sensor ADC clock (AD_CS).
With reference to Figure 7 the envelope detector output can be seen to emulate the positive peak amplitudes of the received signal in Figure 3. The ADC clock continues to capture a further 4 samples after threshold detection, then the microprocessor extracts these 4 sample and the 16 samples prior to the threshold event for transmission as serial data to the wireless transceiver. The first serial data byte (0 value) transmitted is shown by trace TXD and detected by the receiver as trace RXD. Data to the receiver DAC is loaded serially, preceded by a control byte, via the serial port and so is superimposed on trace RXD at the DAC clock times.

Two complete communication cycles are shown in Figure 6. The signals of most interest are the 20 bytes of serial data transmitted and received, and the reconstructed data output from the DAC. It can be seen that the reconstructed output closely resembles the envelope detector output in Figure 7. Knowledge of the ADC sample period and the serial data transmission cycle time allows a complete reconstruction to an accurate time scale.

Absolute time-of-flight data cannot be derived directly from a single AE sensor system. However, employing a minimum of 3 such sensors to detect arrival time of S0 Lamb waves from an AE event would allow the source position to be computed accurately by triangulation methods. Figure 8 illustrates the geometry and timing data required to permit defect location.

**FIGURE 7.** Representative signals as in Figure 6 with expanded time scale to illustrate envelope detector output and threshold detection sequence more clearly.

**FIGURE 8.** Geometrical and timing requirements for defect location by triangulation.
Since the velocity of the $S_0$ Lamb wave at the design frequency for the receiving transducer width mode is almost non-dispersive, the arrival time information from at least 3 sensors in the monitored plate may be used to determine the location of the defect at coordinates $X,Y$ to a high degree of accuracy.

**System Performance**

Laboratory testing to determine the wireless communication range which could be achieved demonstrated that the system could operate over a distance in excess of 15 meters without direct line-of-sight but with an open doorway and a short corridor between two adjacent laboratories. Antennae used for this test were simple rectangular loops with dimensions tuned to provide minimum insertion loss at 418 MHz [1].

The current demonstrator system operates with a sampling period constrained by microprocessor limitations to 2 $\mu$s. In a hard-set epoxy plate with typical $S_0$ Lamb wave velocity of the order of 2 Km/s the maximum spatial resolution for defect location would be approximately 4 mm.

Power requirements for the current system were of the order of 125 mA at 5 volts (625 mW) for the sensor circuitry and 37 mA at 5 volts (85 mW) for the remote receiver.

**Future System Enhancements**

Research is continuing into the feasibility of embedding sensors into carbon-fiber reinforced composite (CFRC) plates which present a new set of challenges in transmission and reception of Lamb waves. The impact on structural integrity of embedding sensors into plate-like structures must also be examined fully.

Investigation are also under way into integrated sensors in which the excitation and data gathering electronics and wireless communications are miniaturized and either embedded with the ultrasonic transducer element(s) or surface-mounted in close proximity.

Although future sensor systems will be designed to make full use of extremely low power electronic devices, incorporating 'sleep' modes where possible, the miniaturization requirements will place severe limitations on available battery capacity. It is envisaged that alternative power sources from the operating environment will be utilized to extend battery capacity and hence time between essential maintenance tasks. These alternative sources could include solar power, thermo-electric power from hot pipework or containment vessel walls and vibrational energy from associated machinery.

There is huge scope for wireless networks of sensors providing complete monitoring solutions for large structures. Passive sensors could be used to ‘listen’ for defect formation or propagation and to provide location data. The same sensors could then be electronically reconfigured as active sensors to monitor the defect situation and feed data to maintenance or intervention planning systems. Alternatively, a mixed network of active thickness measurement sensors and Lamb wave sensors for area mapping coupled in conjunction with passive ‘listening’ sensors could be installed throughout a structure to provide complete monitoring coverage.

Start-of-the-art wireless communication technology such as Bluetooth allows informal networks and hierarchical networks to be installed as depicted in Figure 9. Emerging wireless technologies destined for the mobile equipment market with minimum ranges of tens of meters are power efficient and particularly suited to the applications envisaged. Network protocols and configurations are currently under extensive investigation.
Transducer for thickness measurement

Lamb wave transducers and arrays

Narrowband wireless link between sensors and to intelligent radio-port (IRP)

Wideband wireless link to system controller

FIGURE 9. Possible hierarchical network configuration with informal network elements.

Using currently available technology sample rates of 40 Ms/s at 10 bit ADC resolution and telemetry rates of 723 kBaud are possible, (c.f. 0.5 Ms/s at 8 bit resolution and 19.2 kBaud transmission rate used in the present demonstrator) permitting sub-millimeter spatial resolutions to be achieved in most structural materials.

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REFERENCES