Automation of data collection for PWAS-based structural health monitoring

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ABSTRACT

Crack detection with piezoelectric wafer active sensors (PWAS) is emerging as an effective and powerful technique in structural health monitoring (SHM). Because of the piezoelectric properties of the PWAS, they act as both transmitters and receivers of guided Lamb waves for such applications. With arrays of PWAS attached to the structure, excitation signals are sent to one of the PWAS and wave signals from the structure are received at all the PWAS. The signals are analyzed to detect the position of cracks. One important issue associated with the PWAS-assisted SHM is the connectivity between the PWAS arrays and the measurement instruments. An automatic signal collection unit is necessary to send the excitation signals to PWAS and acquire the response signal from another PWAS. Such a program-controlled switching unit can quickly and precisely execute the data collection in a way which is more efficient and reliable than the manual switching operations. In this paper, we present an innovative design of a LabVIEW controlled automatic signal collection unit (ASCU) for PWAS-assisted SHM. The hardware circuit construction and the control LabVIEW program are discussed. As a conduit between the phase array of PWAS and the signal instruments (signal generators, oscilloscopes etc.), the ASCU provides a convenient way to switch excitation and echo signals automatically to the selected PWAS transducers with the help of GUI in the LabVIEW control program. The control program is easy to implement and can be integrated into an upper level program that executes the whole task of signal acquisition and analysis. Because of the concise design of the hardware, the ASCU concept of the auto signal switch has been extended to other application cases such as the electromechanical (E/M) impedance measurement for SHM.

Key words: Structural Health Monitoring, Signal switch, Lamb wave, Crack detection, E/M impedance, PWAS, ASCU, EUSR

1. INTRODUCTION

1.1 Background

Structural health monitoring (SHM) is a method of determining the health of a structure from the readings of an array of permanently-attached sensors that are embedded into the structure and monitored over time. SHM can be performed in basically two ways, passive and active. Passive SHM consists of monitoring a number of parameters (loading stress, environment action, performance indicators, acoustic emission from cracks, etc.) and inferring the state of structural health from a structural model. In contrast, active SHM performs proactive interrogation of the structure, detects damage, and determines the state of structural health from the evaluation of damage extent and intensity. Both approaches aim at performing a diagnosis of the structural safety and health, to be followed by a prognosis of the remaining life. Passive SHM uses passive sensors which only “listen” but do not interact with the structure. Therefore, they do not provide direct measurement of the damage presence and intensity. Active SHM uses active sensors that interact with the structure and thus determine the presence or absence of damage. The methods used for active SHM resemble those of nondestructive evaluation (NDE), e.g., ultrasonics, eddy currents, etc., only that they are used with embedded sensors. Hence, the active SHM could be seen as a method of embedded NDE. One widely used active SHM method employs piezoelectric wafer active sensors (PWAS), which send and receive Lamb waves and determine the presence of cracks, delaminations, disbonds, and corrosion. Due to its similarities to NDE ultrasonics, this approach is also known as embedded ultrasonics.
1.2 The Concept of the Method

This paper presents an automatic signal collection unit (ASCU) for PWAS-based structural health monitoring (ASCU-PWAS). The complete description of this device made the object of an invention disclosure to the University of South Carolina Intellectual Property Office.2

By using Lamb waves in a thin-wall structure, one can detect the existences and positions of cracks, corrosions, delaminations, and other damage.3 Because of the physical, mechanical, and piezoelectric properties of PWAS transducers, they act as both transmitters and receivers of Lamb waves traveling in the plate. Upon excitation with an electric signal, the PWAS generate Lamb waves into a thin-wall structure. The generated Lamb waves travel into the structure and are reflected or diffracted by the structural boundaries, discontinuities, and damage. The reflected or diffracted waves arrive back at the PWAS array where are transformed into electric signals.

Of particular interest is the phased-array implementation of this concept. This idea is illustrated in Figure 1. An aluminum plate is instrumented with a number \( M \) of PWAS transducers arranged in a linear phased array. The PWAS phased array is used to image the upper half of the plate and to detect structural damage using the concept called embedded ultrasonic structural radar (EUSR)4. In order to implement the phased array principle, an array of \( M^2 \) elemental signals is collected. The elemental signals are obtained by performing excitation of one PWAS and detection on all the PWAS, in a round robin fashion. After the \( M^2 \) elemental signals are collected and stored in the computer memory, the phased array principle is applied in virtual time using the EUSR algorithm and the EUSR LabVIEW program described in ref. 3 and 4. The elemental signals are processed using the phased-array beam forming formulas based on the azimuthal angle \( \theta \). The azimuthal angle \( \theta \) is then allowed to vary in the range \( 0^\circ \) to \( 180^\circ \). Thus, a sweep of the complete half plane is attained. At each azimuthal angle, an A-scan of the Lamb wave beam signal is obtained. If the beam encounters damage, reflection/diffraction from the damage will show as an echo in the A-scan. In Figure 1a, the damage is a 20-mm narrow slit simulating a through-the-thickness crack. The A-scan shown in Figure 1b indicates clearly the crack echo because the scanning beam is oriented at \( 90^\circ \). Azimuthal juxtaposition of all the A-scan signals creates an image of the half plane. The damage is clearly indicated as darker areas. Using the wave speed value, the time domain signals are mapped into the space domain and the geometric position and a measuring grid is superposed on the reconstructed image. Thus, the exact location of the defects can be directly determined.

Essential for the implementation of the EUSR algorithm is the round-robin collection of the \( M^2 \) array of elemental signals. The measurement procedure is performed in the following way (Figure 2): a tone-burst excitation signal from the function generator is sent to one PWAS in the array where is transformed into an S0 Lamb-wave packet. The Lamb-waves packet travels into the plate and is reflected at the plate boundary. The reflected Lamb-waves packet is received back at the PWAS array where is converted back into an electrical signal. The signals received at each PWAS in the array (including the transmitting PWAS) are collected by a DAQ device, e.g., a digital...
oscilloscope. To minimize instrumentation, the collection is done on only one DAQ channel using a round-robin procedure. This generates a column of $M$ elemental signals in the $M^2$ elemental-signals array. After the signal collection for one PWAS acting as exciter is finalized, the cycle is repeated for the other PWAS in a round-robin fashion. For, say, eight PWAS ($M=8$), there will be eight such measurement cycles necessary to complete the whole data collection process.

Figure 2  Experimental setup and system schematics

It is apparent that the round-robin data collection can be tedious if done manually. However, considerable savings can be achieved if the process is automated. The ASCU-PWAS concept described in this paper addresses the automation of the round-robin data collection. A similar concept can be used in conjunction with an impedance analyzer for collection of electromechanical (E/M) impedance data.

2. REALIZATION OF THE METHOD

The realization of the ASCU-PWAS concept is as follows. As shown in Figure 2, the signal generator and the oscilloscope are connected to a PC through a GPIB bus, such that the desired waveform of the excitation signal can be generated, and the collected waveforms can be transferred to the PC for future analysis. The implementation of the data collection automation is done in two parts: (a) the hardware part consisting in a signal switching unit and (b) the software part, i.e., the PC control program. In our implementation, digital control signals are generated by the PC software and sent to the switching unit through the parallel port. According to the control signals received through the parallel port connection, the switching unit will connect the function generator and oscilloscope each to one PWAS of the PWAS array respectively. These two PWAS may also be the same, as in the case of using the pulse-echo method. Thus, one signal measurement route is constructed, the excitation signal is transmitted to the PWAS array and echo signals are received by the oscilloscope. With this method, the measurement loops are performed automatically under the control of the PC software.

2.1 Hardware Description

The measurement equipment setup and the hardware implementation of the ASCU-PWAS concept are shown in Figure 2 and Figure 3. The PWAS array is connected to the switching unit with 8-pin ribbon bus; the function generator and oscilloscope are connected to the switching unit with coaxial cables. The switching unit is connected
to the parallel port of the control PC to receive digital control signals. The hardware construction of the switching unit consists of two main parts:

1. The decoding components of digital control signals
2. The relays matrix

The decoding part will convert the digital control signals from the parallel cable connected to the PC parallel port and give out control voltage to the relays.

Figure 3  Prototype of ASCU unit

Table 1  The 25 pins of PC parallel port

<table>
<thead>
<tr>
<th>25 pins of PC parallel port</th>
<th>Abbreviation</th>
<th>Direction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>STROBE</td>
<td>In</td>
<td>signal to send data to printer buffer</td>
</tr>
<tr>
<td>2-9</td>
<td>DO0-DO7</td>
<td>in/out</td>
<td>data bits, pin 9 most significant</td>
</tr>
<tr>
<td>10</td>
<td>ACKNLG</td>
<td>In</td>
<td>indicates data was received</td>
</tr>
<tr>
<td>11</td>
<td>BUSY</td>
<td>In</td>
<td>device can not receive data</td>
</tr>
<tr>
<td>12</td>
<td>PE</td>
<td>In</td>
<td>out of paper</td>
</tr>
<tr>
<td>13</td>
<td>SLCT</td>
<td>In</td>
<td>Device is in selected state</td>
</tr>
<tr>
<td>14</td>
<td>AUTO FEED XT</td>
<td>Out</td>
<td>Auto line feed</td>
</tr>
<tr>
<td>15</td>
<td>ERROR</td>
<td>In</td>
<td>Device not functioning</td>
</tr>
<tr>
<td>16</td>
<td>INIT</td>
<td>Out</td>
<td>Initialize device</td>
</tr>
<tr>
<td>18-25</td>
<td>GND</td>
<td>Out</td>
<td>Signal ground for pins 1-12</td>
</tr>
</tbody>
</table>
The standard PC parallel port has eight output digital lines and a number of handshaking lines (Table 1). In the design of the switching unit, we only need to send out digital signals; hence, we did not intend to use the handshaking lines. However, if the handshake signals BUSY and PE are left disconnected (i.e., floating), their uncertain state would confuse the control VI in LabVIEW program and an error state would be returned. Hence, these two handshake inputs have to be grounded, which is equivalent to telling the parallel port that the external device is ready to accept data. Thus, the handshake problem was solved. Digital signals generated by the LabVIEW software through the parallel port are sent to latching chips-74LS373, and then the control signals are decoded by the 74HS138 3-8 line decoder to control the relays matrix.

Reed-relays were chosen to construct a low-cost but reliable relays matrix. Similar design can be found in the active healthy monitoring system (ASHMS) proposed by Wang et al. Reed relays were chosen over electronic switches because preliminary tests showed that the latter introduce spurious noise during the tone-burst pulsing process. The reed relays are divided into two groups, one group for signal transmission, and the other group for signal reception. For each of the transmission relays, one pin is connected to the function generator and the other pin is connected to corresponding PWAS transducer. For each of the reception relays, one pin is connected to the oscilloscope and the other pin is connected to the corresponding PWAS transducer. The control voltage from the decoding chips (the 3-8 line decoders) will switch on one transmission relay and one reception relay, thus establishing the measurement route.

2.2 Software Description

The software part is developed in LabVIEW to control the working of the hardware part. The “out port” function in LabVIEW is used to send digital signals through the PC parallel port. We have constructed a graphical user interface (GUI) to facilitate the control of the data collection process in the PWAS array (Figure 4). With the GUI, user can configure the switching unit to work in either a manual or an automatic signal-collecting mode.

In the manual mode, the signal is transmitted to an assigned PWAS and received from another assigned PWAS. The transmission and reception channel numbers are dialed in by the operator through the GUI. The operator also has to input the desired file path name for the data. After these parameters defined, the control software will send out 8-bit digital signals through parallel port and these signals will then be decoded to control the reed-relays.

![Graphical user interface (GUI) of control program circuits](image)
In the automatic mode, the signal is transmitted to the PWAS and received from the PWAS in a round-robin way without any human intervention. When the ASCU is in the automatic mode, the user only has to input into the GUI the start and end numbers of the range of PWAS assigned for measurement, and the file path name for the folder where all the collected signals have to be stored. Based on this inputs, the system will automatically perform the measurement loops. The system will start from the start channel number and will do round-robin collection until it reaches the end channel number. The data from these measurement loops will be saved as separated files in the folder specified in path.

Two rows of indicating LEDs will be lit in green colors to show which sensor is transmitting excitation signals and which one is used to receive echo signals. During the data collection process, the waveform will also be displayed on the GUI. The LabVIEW control program is easy to implement and can be integrated into an upper level program that executes the whole task of signal acquisition and analysis. Because of the concise design of the hardware, the ASCU concept has been extended to other application cases such as the electromechanical (E/M) impedance measurement for SHM.

Table 2  Item list of the ASCU unit

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamlin miniature relay</td>
<td>8*4</td>
</tr>
<tr>
<td>ST sm74hc138 3 to 8 line decoder(inverting)</td>
<td>1*4</td>
</tr>
<tr>
<td>Coaxial BNC connector</td>
<td>1*2</td>
</tr>
<tr>
<td>DB25 parallel port connector</td>
<td>1</td>
</tr>
<tr>
<td>8 pin robin connector</td>
<td>1*2</td>
</tr>
<tr>
<td>74LS373</td>
<td>1*4</td>
</tr>
<tr>
<td>Power supply connector</td>
<td>1</td>
</tr>
</tbody>
</table>

3. REDUCTION TO PRACTICE

Prototype of the automatic signal collection unit for PWAS-based structural health monitoring (ASCU-PWAS) has been constructed to prove the practicality of the method. Reduction to practice was performed in the Laboratory for Adaptive and Smart Structures (LAMSS) at the University of South Carolina. Initially, the circuits of switching unit were constructed on a breadboard with cables connected to the PWAS array, PC parallel port, signal generator, and oscilloscope. The functions of the switching unit were tested with PWAS array attached on a specimen aluminum plate. It was found that the use of the ASCU-PWAS unit could reduce the data acquisition time by at least a factor of ten. In estimating the time saving, it was realized that several factors come into play:

1. The time taken in switching the channels
2. The time dwelled on each channel to collect the data
3. The time taken by the LabVIEW program to effect the signal saving and channel switching

The first factor is addressed by the ASCU-PWAS device. The manual switching method used in previous work required the connectors to be manually switched. The manual switching of the connectors was found to take, on average, about 60 sec., i.e., one minute. For an array of eight PWAS ($M = 8$), 64 signals have to be collected. This corresponds to over 1 hour of time dedicated to channel switching. In contrast, the ASCU-PWAS unit was able to switch each channel in a few ms. In addition, the manual switching was found to introduce unavoidable human errors in channel selection/connection and in channel labeling. With automatic switching, such errors are completely avoided.

The second factor, which is connected to the dwell time on each channel, is not addressed by the ASCU-PWAS device. Since the digital oscilloscope acts as the DAQ device and averaging is employed to reduce the random noise, the dwell time is controlled only by the number of oscilloscope averaging cycles the selected for the process. The number of averaging cycles depends on the level on environmental noise (acoustic and electromagnetic). In our experiment, we found that 16 or 32 averaging cycles are usually sufficient. Under high noise conditions, 64 averaging cycles were used. In extreme noise conditions, 128 averaging cycles were also used. For a 10 Hz
repetition rate of the tone-burst signal, the 64 averaging cycles correspond to approximately 7 seconds, while the other values lead to correspondingly lower or higher times.

The third time to be considered was the time taken by the LabVIEW program for signal saving and channel switching. This time was found to be a system constant with typical value around 2 sec.

When all these times were taken into account, a time saving of approximately one order of magnitude was observed. Table 3 describes the time duration of the data collection per channel with different oscilloscope averaging cycles.

Table 3  Time duration of data collection per channel

<table>
<thead>
<tr>
<th>Averaging cycles</th>
<th>Time of signal collection (s)</th>
<th>Time of saving signal (s)</th>
<th>Total time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>64</td>
<td>7</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>128</td>
<td>14</td>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>

4. APPLICATION IN E/M IMPEDANCE SIGNAL COLLECTION

The damage detection with E/M impedance method has gained increased attention in recent years. The method uses small-size piezoelectric active sensors intimately bonded to an existing structure, or embedded into a new composite construction. Experimental demonstrations have shown that the real part of the high frequency impedance spectrum is directly affected by the presence of damage or defects in the monitored structure. The variation of the electro-mechanical impedance of piezoelectric sensor-actuators (wafer transducers) intimately bonded to the structure is monitored over a large frequency spectrum in the high kHz frequency band. The frequency response reflects the state of structural integrity.

Figure 5 presents the experimental schematic diagram for health monitoring a structure using the electro-mechanical impedance approach. The basic ingredients for the method are: (a) an array of piezo-electric wafer transducers applied to the monitored structure and (b) a high-precision impedance analyzer coupled to a data-acquisition computer.
Figure 6 shows the experiment setup for the electromechanical impedance data collection with the ASCU. Each of the seven PWAS attached on the structure specimen were excited with a frequency sweeping in the 50 – 900 kHz range using a HP Impedance Analyzer. Without hardware modification, The ASCU can be used to control which PWAS was excited. A LabVIEW program is developed and installed on a laptop computer to control the data acquisition process by interacting with the ASCU and the HP Impedance Analyzer. The impedance signal measured at each PWAS was recorded to “csv” files on the laptop computer using the LabVIEW program.

5. CONCLUSION

This paper presents the automation of data collection for PWAS based structural healthy monitoring under the control of PC software using the ASCU-PWAS concept. Both hardware (the switching unit) and software (PC control LabVIEW program and GUI) were developed in this study. A prototype of the system was also constructed and tested. The advantages of this method are as follows:
1. It provides an automatic, efficient, and error-free way to switch different channels of excitation (transmission) and detection (reception) for a PWAS phased array.

2. It is inexpensive and lightweight. The hardware of switching unit can be constructed with low-cost components on a breadboard. (The implementation on a printed circuit board is currently being considered.)

3. It provides a convenient way of connection between the PWAS array and the measurements instruments. In this way, data compatibility in different measurement loops can be achieved.

4. It provides a GUI for easy access by the users. The GUI gives a user-friendly interface to control the switching unit and indicate the running status and result of the collected data.

5. It can be integrated into other upper level signal applications. Both the hardware part and the software part can be easily included in other applications if need. With little change, this switching unit can be applied in the measurements of impedance and admittance of piezoelectric sensor arrays.

The ASCU-PWAS device switch provides a simple solution of sensor array connection and data collection with good prospects for industrial implementation in structural health monitoring.

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