Signal Acquisition/Conditioning for Automated Data Collection during Structural Health Monitoring with Piezoelectric Wafer Active Sensors

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ABSTRACT

Damage detection with piezoelectric wafer active sensors (PWAS) is emerging as an effective and powerful technique for structural health monitoring (SHM). PWAS, act as both transmitters and receivers of guided Lamb waves and can be used with the embedded pitch-catch, pulse-echo, phased-array, and electromechanical (E/M) impedance methods. In our research, we have developed automated data acquisition methods and hardware that permits the implementation of all these four methods with the same PWAS installation and a single automated signal collection unit (ASCU) driven by various LabVIEW based programs. With arrays of PWAS attached to the structure, excitation electric signals are sent to one of the PWAS to generate mechanical waves and the propagating wave signals inside the structure are received at all the PWAS. The electrical excitation produced by an arbitrary functional generator is applied to the transmitter PWAS where is converted into Lamb and Rayleigh guided waves that travel into the structure. At the receiver PWAS, the waves are converted back into electric signals and collected by a DAQ device, e.g., a digital oscilloscope. To minimize instrumentation the transmission is done on only one excitation channel, whereas reception can be simultaneously done on several DAQ channels, according to the DAQ device capabilities. For the E/M impedance method, each PWAS is sequentially switched to the impedance analyzer instrument. A round-robin programming graphical user interface is used and an automatic (program controlled) signal switching unit is employed to act as the conduit between the PWAS array and the instrumentation (signal generator, digital oscilloscope, impedance analyzer etc.).

Though such a program-controlled switch can execute the data collection in a way which is more efficient and reliable than the manual switching operations, problems such as speed of signal acquisition, fluctuating of reference voltage and electromagnetic interference noise also arises in practice and need to be resolved. The appropriate design of the signal conditioning is needed in mapping the desired sensor output precisely to the data acquisition input and removing undesired noises to provide precious and efficient data collection. The paper discusses the signal conditioning issue that arises in the automatic data collection and the applicable conditioning methods that can be used. The system layout of the computer program controlled data auto collection is firstly introduced, and then the signal conditioning related problems encountered in practical applications –phase array, pitch-catch, pulse-echo, and E/M impedance are presented. Effective signal conditioning methods such as grounding, isolating and filtering are applied and discussed.

Key words: Structural health monitoring, piezoelectric wafer active sensors, pitch-catch, pulse-echo, phased-arrays, electromechanical impedance, signal switching, signal conditioning, round-robin, SHM, PWAS, ASCU.

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 extend 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.

By using Lamb waves in a thin-wall structure, one can detect the existences and positions of cracks, corrosions, delaminations, and other damage. 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). 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.

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 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.
The standard PC parallel port has eight output digital lines and a number of handshaking lines (Error! Reference source not found.). 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.

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.

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. 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.

3. 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 piezo-electric 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 5](image_url)

Figure 5  Schematic diagram of the equipment set-up in the electro-mechanical impedance technique

![Figure 6](image_url)

Figure 6  Experiment setup for the electromechanical impedance method

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. The impedance signal measured at each PWAS was recorded to “csv” files on the laptop computer by the control LabVIEW program as shown in Figure 7.

![Figure 7](image.png)  
**Figure 7** Screen shot of control program for collecting impedance signals

4. SIGNAL CONDITIONING OF ASCU

Though such a program-controlled switch can execute the data collection in a way which is more efficient and reliable than the manual switching operations, problems such as speed of signal acquisition, fluctuating of reference voltage also arises in practice and need to be resolved. The appropriate signal conditioning design is needed in mapping the desired sensor output precisely to the data acquisition input and removing undesired noises to provide precious and efficient data collection. In a data acquisition system, effective signal conditioning methods such as signal grounding, shielding, isolating and filtering are always applied. Some of these methods are applied in our ASCU and discussed below.

4.1 Switching power supply noise reduction and signal grounding

Switching power supplies have been commonly used in electronics applications and systems because of their advantages such as high efficiency, low temperature rise, small size, and lightweight. The ASCU system also employs a DC switching power supply which provides ±15V and +5V DC power. Compared with regulated, low noise linear power supplies, switching power supplies may introduce higher noise output to the electrical systems. This noise generally extends over a broad band of frequencies, and occurs as both conducted and radiated noise, and unwanted electric and magnetic fields. Voltage output noise of switching supplies is short-duration voltage transients, or spikes. To reduce the noise from the switching power supplies, 3-Terminal Voltage Regulators are usually used to provide cost efficient and regulated DC power voltage. Sometimes the input supply line may be noisy. To help smooth out this noise from the power line and get a better 5 volt output, a 220 uF capacitor at the input side and a 0.1 uF capacitor at the output side are added to the circuit as shown in Figure 8.

![Figure 8](image.png)  
**Figure 8** DC voltage regulator (C1=220 uf; C2=1 uf).

Grounding strategy also plays one important role in electrical systems. Grounding provides safety and signal reference. The general principle is to minimize the voltage differential between the electrical system and a reference point. There are several reference points in the ASCU. The power ground, the signal ground of the oscilloscope and the functional generator, the ground reference of the PC parallel port. Single-point grounding was employed to
isolate the noise within the ASCU since it is most appropriate for low-current, low frequency (<1Mhz) applications. All the reference points were connected at one point on the circuit board and the reference point was connected to the ground of specimen structure to provide a single reference point. Without the single grounding, the signals were greatly distorted and the reference voltage was always fluctuating which make it impossible to obtain applicable signals.

4.2 Signal filtering

Filtering in data acquisition systems not only prevents aliasing of unwanted signals but also reduces noise by limiting bandwidth. Filtering was not added to the ASCU at the beginning, since it is not necessary when ASCU was operated at ideal laboratory conditions. The signals are clean enough to be processed for damage identification, but new problems arose when the ASCU was used in a fatigue test experiment where the specimen were holed on a materials fatigue testing machine shown in Figure 9.

![Figure 9 Specimen hold on fatigue testing machine](image)

The purpose of the fatigue test is to monitor the propagation rate of crack under cycling load. The specimen was scanned at a frequency of 372 kHz during 110,000 cycles with a cyclic load of 400 lbf to 4000 lbf at a frequency of 5Hz. The operation of the fatigue machine certainly introduces low frequency frequencies to the data collection system. The tiny response signals from the sensors were submerged in the noise, only meaningless jumping noise signals were collected as shown in Figure 10. To solve this issue, filtering is needed to clean the desired signal.

![Figure 10 Signal recorded without filter under cyclic load](image)

In a multiplexed system, there are basically two places to put filters: in each channel, and at the multiplexer output. The filter at the input of each channel is used to prevent aliasing of signals which fall outside the Nyquist bandwidth. Since the input signal is generated by the digital function generator, it is not necessary to put a filter in input channel, only a high-pass filter is needed in the output channel. RC filter is the simplest filter in electrical systems. It is easy to construct and requires no additional power supply. This resistor and capacitor combination as shown in Figure 11 yields a turn over frequency at 1063 Hz.
When the filter was added to the ASCU, the low frequency noises are greatly reduced and a cleaner and more stable signal is obtained as shown in Figure 12.

4.3 Instrument control in the data acquisition process

As described before, the data collection (digital to analog conversion and data storage) is performed by the digital oscilloscope under the control of the LabVIEW program. Thus, the efficiency of signal acquisition was closely related to the execution of the program. Faster data collection speed and better signal quality can be achieved by operating the oscilloscope appropriately in the control software.

First let’s examine the data collection process. When one PWAS sensors gets excited, the electrical response of other sensors is was converted to digital signal and recorded by the oscilloscope. Since there is only one oscilloscope in use, the data acquisition will be repeated on every single sensor channel and the time taken on each channel to collect data then becomes a very important factor. This time directly affect the total time of data collection. If it can be reduced, the total time will be dramatically reduced. So the goal here is to minimize the dwelling time on each single channel. While the digital oscilloscope is serving as the DAQ device, averaging of sampled signals is employed to reduce the random noise. The digital oscilloscope in use can perform averaging with different numbers of cycles, from 4 up to 128. The more cycles the averaging takes, the better signal can be obtained, but more averaging cycles also means more data collection time. So, the averaging numbers is provided by the software and user can specify what numbers of averaging to use. The number of averaging cycles depends on the level of 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.

While the numbers of averaging can be modified under different environment, the averaging process must also be executed efficiently. The program must be able to stop sampling the signal waveforms and save the signals right after certain numbers of waveform acquisition are finished. So, the operation status of the oscilloscope must be accessed to decide when to stop the waveform sampling. The oscilloscope can be controlled through the GPIB or RS-232 interface using a large group of commands and queries. So, sub VIs of WRITE TO INSTRUMENT and READ INSTRUMENT DATA are used to transfer the inquiry and access the operation status of the oscilloscope, i.e, the number of acquisitions that have taken place. After the oscilloscope has acquired enough waveforms, the program will start the acquisition on the next channel.
4. CONCLUSION

This paper presents the automation of data collection for PWAS based structural healthy monitoring. A prototype of the system was also constructed and tested. The advantages of ASCU are listed 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.

As an important issue in sensor signal acquisition systems, signal conditioning methods used in practice are presented in this paper after the system introduction. Switching power supply noise reduction, signal grounding, signal filtering and instrument control are discussed.

ACKNOWLEDGMENTS

The financial support of National Science Foundation award # CMS 0408578, Dr. Shih Chi Liu, program director, and Air Force Office of Scientific Research grant # FA9550-04-0085, Capt. Clark Allred, PhD, program manager are gratefully acknowledged.

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