Instantaneous Baseline Damage Detection using a Low Power Guided Waves System

S. PARK, S. R. ANTON, D. J. INMAN, J.-K. KIM and D. S. HA

ABSTRACT

In recent years, new structural health monitoring (SHM) methodologies with a concept of "instantaneous baseline damage detection" are being developed by many researchers, since it has been found that the most of SHM technologies are too vulnerable to environmental and/or operational variations. In this context, this paper presents online instantaneous baseline structural damage detection using a low cost and low power, in-situ guided waves-SHM system. Firstly, four small, low cost and light weight smart piezoelectric ceramic (PZT) patches are surface-mounted and assumed to have the same bonding conditions to detect structural defects on an aluminum plate. Then, a miniaturized low power guided waves-SHM system with a digital signal processing (DSP) module is employed for signal generation/excitation, signal sensing, and data processing. The instantaneous baseline damage detection based on discrete wavelet transform (DWT) analysis is carried out on the DSP module. Finally, effects of Lamb waves due to artificial 'cut-damage' with different locations are investigated using both "pitch-catch" and "pulse-echo" wave propagation schemes. Conclusively, this study shows a good potential for online and in-situ crack monitoring on panel structures such as an aircraft wing.

INTRODUCTION

To detect or locate incipient cracks, the guided wave propagation method launches an elastic wave through the structure [1]. The changes in wave attenuation, time-delay, and/or reflection are sensed to detect and locate damages on surfaces. However, there are significant technical challenges to realizing this pattern comparison. For instance, structural defects typically take place long after the initial baseline collected, and other operational and environmental variations of the system

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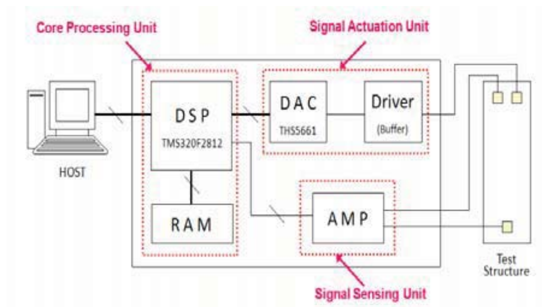
can produce significant changes in the measured responses, masking potential signal changes due to structure defects [2]. To solve the drawbacks of the conventional SHM techniques, some reference-free schemes that do not rely on the previously obtained baseline data have been developed for damage detection in a structure [3-4]. Particularly, Kim and Sohn (2007) [3] proposed a reference-free scheme based on the fact of that mode conversion due to crack formation can be instantly detected by examining measured Lamb wave signals for crack detection in a plate-like structure with a uniform thickness. However, since the mode conversion effects are caused by non-symmetric damages such as a notch in the plane structure, this approach could not be applied for symmetric damages such as a 'through-thickness' hole or crack. To overcome this limitation, this study utilizes the instantaneous baseline SHM method proposed by Anton (2008) [4]. Anton's approach enables to detect the symmetric damages including a 'through-thickness' cut without using any prior baseline information. On the use of the instantaneous baseline SHM method, a low-power guided waves system developed by Kim *et al.* (2009) [5] is employed for this study. The miniaturized guided waves-SHM system with a digital signal processing (DSP) module executes signal generation/excitation, signal sensing, and data processing. A Hanning windowed sinusoidal signal is applied to one PZT patch to generate Lamb waves that travel through the host structure, and then the propagating Lamb wave signals are captured at the other PZT patches. The instantaneous baseline damage detection based on discrete wavelet transform (DWT) analysis is carried out on the DSP module of the low power guided waves system. Finally, effects of Lamb waves due to artificial 'cut-damage' with different locations are investigated using both "pitch-catch" and "pulse-echo" wave propagation schemes.

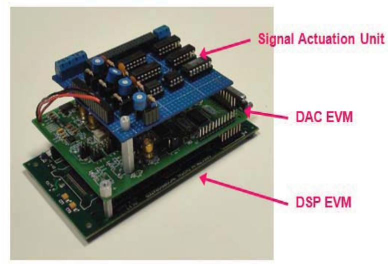
LOW POWER GUIDED WAVES SYSTEMS

Implementation of the Lamb Waves-based SHM

The first step to implement the Lamb wave method is to select an optimal driving frequency and shape of the excitation signal for a structure. The excitation frequency should be as low as possible in order to avoid multiple higher modes in the driving frequency range. At the same time, the excitation frequency should be high enough to make the wavelength of the Lamb wave comparable to the scale of local damage. The shape of the excitation waveform also plays a crucial role. One of the most widely used excitation waveforms is a tone burst of sine wave with Hanning (equivalently raised-cosine with roll-off factor = 1) window. Our system comprises three functional blocks: a processing unit, a signal actuation unit, and a signal sensing unit as shown in Figure 1 [5]. The processing unit is a DSP EVM (TMS320F2812 from Texas Instruments). It controls the overall test procedure and performs excitation signal generation and damage assessment. The signal sensing unit consists of a DAC and op-amps. The DAC module (THS5661 EVM from Texas Instruments) has 12-bit resolution and maximum conversion rate of 100 MSPS. The DAC module generates analog excitation signals, whose signal strength is boosted with op-amps to increase the signal to noise ratio. The propagated Lamb waves sensed at a PZT patch are amplified by op-amps at the sensing unit. The sensing unit also adjusts the signal level to fit the input range of the ADC residing in the DSP core chip. The ADC has a 12-bit resolution with a built-in sample-and-hold circuit. The ADC is configured to operate at 8.3 MSPS for our system. The sensed digital data is stored in the memory on the DSP DVM for further processing.



(a) System architecture



(b) Prototype

Figure 1. A Low-Power Guided Waves System [5]

Wavelet-based Signal Processing

The key to reliable and high-resolution damage detection is good signal interpretation, and wavelet transform technique has been widely used [6]. We used discrete wavelet transform (DWT) to eliminate the undesirable features of Lamb wave signals in a noisy environment. DWT is a special case of the wavelet transform that provides a compact representation of a signal in time and frequency, and it can be computed efficiently. DWT is defined in the following expression:

$$W_{\Psi}(j,k) = \sum_{j}\sum_{k} s(n) 2^{-j/2} \Psi_{j,k}(2^{-j} n - k) \tag{1}$$

where $\Psi_{j,k}$ is called as mother wavelet with finite energy. The flexibility of choosing a proper mother wavelet is one of the strongest advantages of using DWT. If we choose the mother wavelet as the excitation signal itself and the dilation coefficient j = 0, the DWT results in the correlation between the excitation signal and the sensed signal.

INSTANTANEOUS BASELINE SHM TECHNIQUES

Instantaneous Baseline SHM using Lamb Waves

The SHM technique employed in this study involves detecting damage without the use of prerecorded baseline data by acquiring an ‘instantaneous baseline’ measurement each time a structure is interrogated (Anton, 2008) [4]. The transducers must be placed such that the sensor-actuator paths are of equal length and that structural features are spatially uniform between transducers. In an isotropic structure, the Lamb wave signals recorded for different paths will be identical if the structure is undamaged. If damage is present along one of the paths, the Lamb wave signal recorded along that path will differ from the remaining signals. Features from the undamaged paths are used to create a statistical baseline allowing the separation of damaged paths without prior knowledge of the structure by monitoring changes in the Lamb wave shape, magnitude, and frequency. In an anisotropic material, transducers must be placed such that the material properties of equal length paths are identical. If two sets of equal length paths do not have the same material properties, a separate analysis must be carried out for set. Figure 2 illustrates the concept of instantaneous baseline SHM where signals from undamaged paths are used to create an instantaneous baseline from which signals from damaged paths can be compared and signal differences are used to indicate damage. Finally, the differences are compared to threshold values that do not need to be calculated using baseline data.

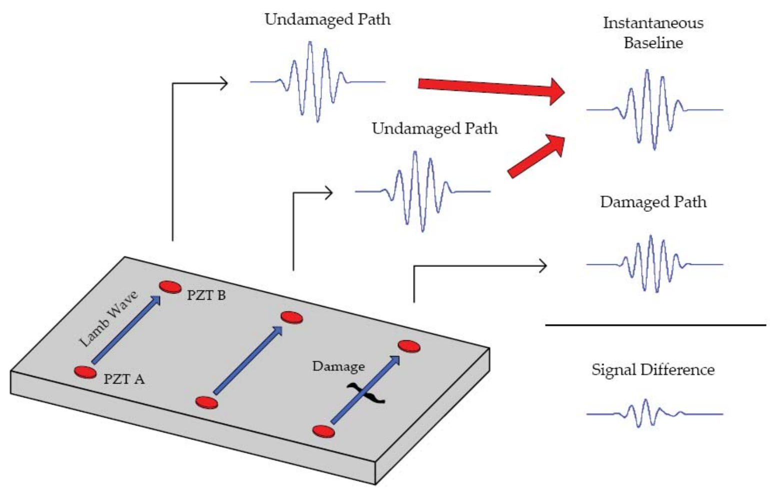


Figure 2. Instantaneous Baseline SHM Method using Lamb Waves [4]

Damage Detection Algorithm

The damage detection algorithm utilized in this study involves the cross correlation analysis of each signal compared to the remaining signals of other equal length paths. Cross correlation analysis determines the degree to which two signals are linearly related. In order to detect damage in the test structures, the cross correlation (CC) value is used as a linear damage index and is defined as

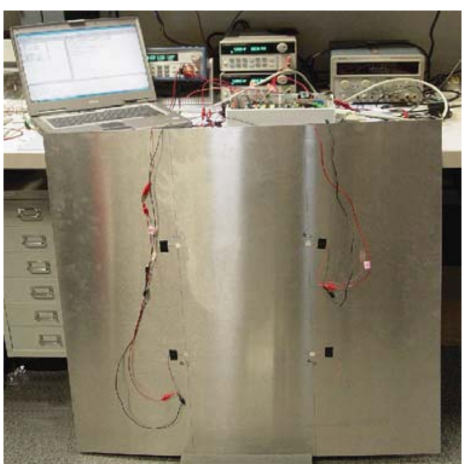
$$CC = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})(y_i-\bar{y})}{\sigma_x\sigma_y} \tag{2}$$

where $\bar{x}$ and $\bar{y}$ are the mean values of the two sets of data and σ_x and σ_y are standard deviations of the signature data sets x and y, respectively. The more closely correlated the two signatures (therefore the healthier the system), the closer the CC is to the value 1. Therefore it is common to use “1-CC” instead of CC in order to have the damage index increase by increasing the severity of damage. The 1-CC describes numerically how well a path correlates to all the other paths, where a path that does not correlate well to any other path will have a high value and a path that correlates well to all others will have a low value. The CC values are calculated for each path and the 1-CC evaluation of the values is used as an instantaneous damage indicator to identify outlying or damaged paths. This algorithm involves calculating the CC values of a single reference path compared to all the other paths. Then, the single reference path is moved to the next path in a sequence. If the four paths (Paths #1, #2, #3, and #4, herein, it is noted that Path #1 is a path between PZTs #1 and #2, Path #2 between PZTs #1 and #3, Path #3 between PZTs #2 and #4, and Path #4 between PZTs #3 and #4.) are considered, six damage indicators can be instantaneously obtained from the path combinations (between Paths #1 and #2, #1 and #3, #1 and #4, #2 and #3, #2 and #4, and #3 and #4). Now, we can predict the crack damage locations by comparing the magnitudes of six instantaneous damage indicators.

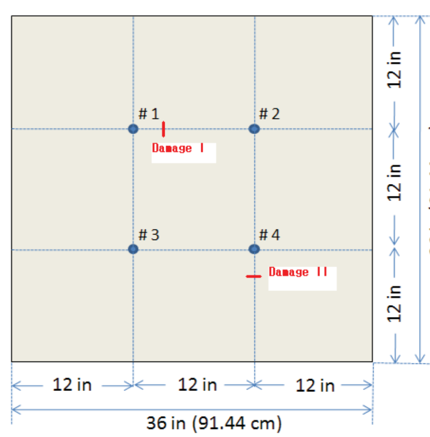
PROOF-OF-CONCEPT APPLICATIONS

Experimental Setup

A 4 ft x 4 ft (1.22 m x 1.22 m) and 0.0625 in (1.5875 mm) thick 6061-T6 aluminum plate was selected as a test specimen. The health of the aluminum plate was monitored using four same PZT patches of 0.5 in (12.7 mm) diameter, 0.01 in (0.254 mm) thick circular PZTs from APC International, Ltd. with an array in a square grid pattern with 12 inch apart with each other as displayed in Figure 3. The PZTs were attached to the plates by applying a single drop of DuroR super glue to the patch. Lamb waves are excited in a round robin fashion such that each PZT acts as both a sensor and an actuator. For example, PZT 1 will act as an actuator and excite a Lamb wave in the plate while the surrounding transducers will act as sensors, recording response data. PZT will then act as an actuator and the surrounding transducers will act as sensors. This process is repeated until Lamb waves traveling along each path are recorded.



(a) Aluminum plate (4 ft x 4 ft)

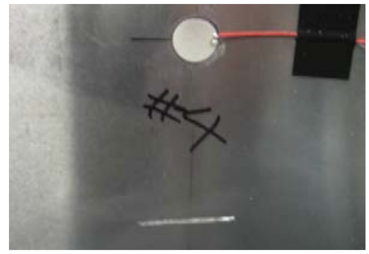


(a) PZT arrangement

Figure 3. Test Set-up

Two artificial different damages shown in Figure 4 are considered to test the instantaneous baseline Lamb waves SHM method. The first cut damage is inflicted between PZT #1 and #2 to investigate the performance of the instantaneous baseline SHM method using “pitch-catch” scheme. (Figure 4(a)). Then, the second damage is inflicted at 2.3 inch below PZT #4 along the extension of the path between PZT #2 and #4, and the damage is intended for testing “pulse –echo” scheme (Figure 4(b)). The cuts in Figures 4(a) and 4(b) are almost identical except their locations.

(a) Cut between PZT #1 and #2

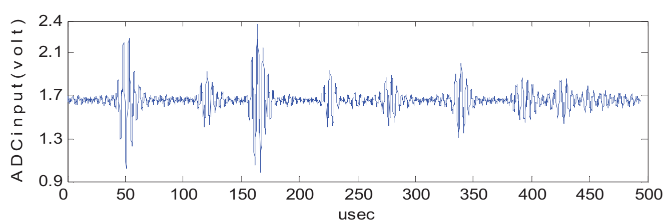


(b) Cut below PZT #4

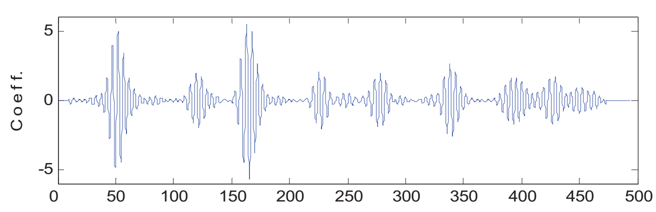
Figure 4. Artificial Cut Damage inflicted on the Plate

Experimental Results

The excitation signal for our experiments is a Hanning-windowed 200 kHz waveform with four cycles of the sinusoidal signal. The excitation frequency of 200 kHz was chosen for a good separation of the fundamental symmetric mode S_0 from the fundamental asymmetric mode A_0. The excitation signal was applied to a PZT patch, and the response was captured at other PZT patches. Specifically, the response was sampled for 0.5 msec by the ADC with the sample rate of 8.3 MSPS and the resolution of 12 bits. Figure 5(a) shows an intact waveform for the PZT #1 as an actuator and PZT #2 as a sensor. Figure 5 (b) is the DWT of the profile, which suppresses noise and the DC offset of the original waveform. The first tone burst in Figure 5 is the fundamental symmetric mode S_0, and the second burst is the fundamental asymmetric mode A_0. All other bursts are reflected modes from boundaries of the plate.



(a) Raw signal for the path between PZT #1 and PZT #2

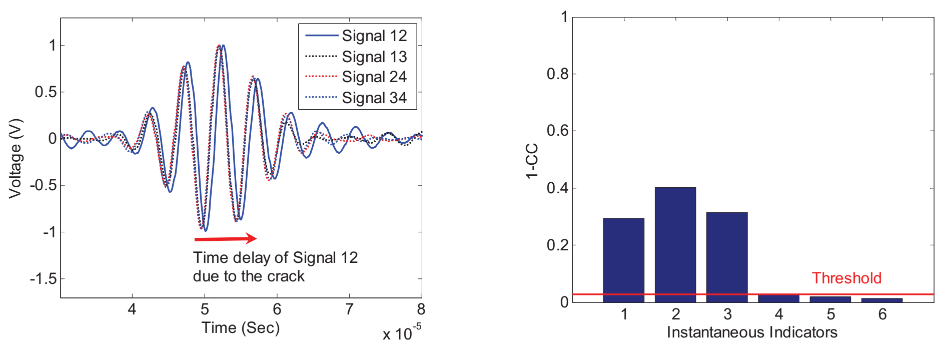


(b) DWT profile for the path between PZT #1 and PZT #2

Figure 5. Waveforms captured at PZT #2 with an actuation at PZT #1

Pitch-Catch Scheme:

Firstly, the pitch-catch experiment was considered to diagnose the existence of the cut damage located between PZTs #1 and #2 shown in Figure 4 (a). Figure 6 shows the successive measurements of all the Lamb wave paths for the fundamental mode S_0 under the cut damage. It is noticeable that the cut damage caused a time delay in the Signal 12 only (Figure 6(a)). All other signals, Signals 13, 24, and 34 could be regarded as instantaneous baselines, and 1-CC values showed the cut damage detection results on the Path #1 (between PZTs #1 and #2) with the threshold set from the maximum of the instantaneous baselines (Figure 6(b)).



(a) Successive captured Lamb wave signals (b) Instantaneous baseline damage detection

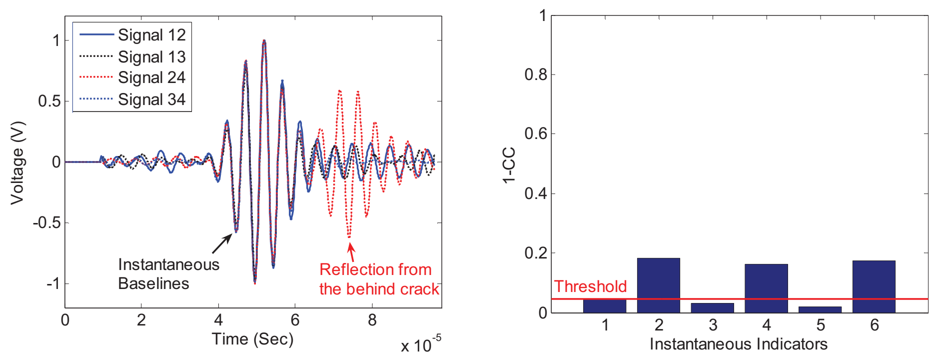
Figure 6. Instantaneous Baseline Cut Detection on Pitch-Catch Scheme

Pulse-Echo Scheme:

Secondly, the pulse-echo experiment was considered to identify a cut damage located below PZT #4 shown in Figure 4 (b) without using any prior baseline information. It is noted that the damage under consideration is not on the path between the two PZT patches, which enables the pulse-echo scheme. Figure 7(a) shows the successive measurements of all the Lamb wave paths for the fundamental mode S_0 under the cut damage. The reflected mode was observed in the Signal 24 only, and other signals, Signals 12, 13, and 34 were regarded as the instantaneous baselines. As shown in Figure 7(b), it has been found that the cut damage below PZT #4 corresponding to Path #3 was successfully detected from the 1-CC value chart with a proper setting of the threshold value obtained from the instantaneous baselines.

CONCLUSIONS

This paper presented online instantaneous baseline structural damage detection method using a low cost and low power, in-situ guided waves-SHM system. A miniaturized low power guided waves-SHM system with a digital signal processing (DSP) module was employed for signal generation/excitation, signal sensing, and data processing, and the instantaneous baseline damage identification algorithm based on discrete wavelet transform (DWT) analysis was applied on the DSP module. Both "pitch-catch" and "pulse-echo" wave propagation schemes were investigated to diagnose two cut damages with different locations, respectively. Conclusively, it has been verified that our integrated SHM method can successfully detect crack damages on aluminum plates without using any prior baseline information.



(a) Successive captured Lamb wave signals (b) Instantaneous baseline damage detection

Figure 7. Instantaneous Baseline Cut Detection on Pulse-Echo Scheme

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