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Structural health monitoring using active sensors and wavelet transforms

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ABSTRACT

Health monitoring methods using active sensors (e.g. piezoelectric transducers) and wavelet transforms are being developed in the Department of Mechanical Engineering at the University of South Carolina. In these methods, wave propagation signals are collected using arrays of piezoelectric transducers placed on or embedded in a structure. The collected signals are analyzed using appropriate wavelet transforms. The final interpretation of the sensor signals is based on signal patterns uncovered by the wavelet transforms in correlation with elastic-wave propagation theory. A number of specimens have been instrumented and tested, which include simple steel beams and actual composite aircraft panels. Impact tests simulating low velocity impact by foreign-object have been conducted and will be used to illustrate the wavelet-based methods.

Keywords: Active sensors, damage detection, heath monitoring, piezoelectric transducers, wavelet transform

1. INTRODUCTION

Structural health monitoring and damage detection has been an important concern in the design, operation, maintenance, and repair of many military and civil structures and machinery equipment. Under scheduled maintenance conditions, damage detection has been accomplished with nondestructive inspection and evaluation techniques. Examples of these techniques include magnaflux, radiography, thermal imaging, acoustic microscopy, and various eddy current and ultrasonic methods. Damage detection techniques have also been developed for in-situ and in-service structural health monitoring. In principle, these techniques allow the detection of incipient damage in service environments by monitoring vibration characteristics, strain variations, acoustic emission, dielectric response, or electromechanical impedance of the host structure.

The development of successful in-situ and in-service monitoring methods depends on two key factors: sensing technology and the associated signal analysis and interpretation algorithm. In the area of sensors, piezoelectric transducers have many advantages. They are active sensors in the sense that they can be used both to receive and generate signals, and their signals usually do not require conditioning treatment. A current trend in utilizing active sensors has been to embed or surface-mount them in a structure. For example, Choi and Chang[1] and Tracy and Chang[2] developed a method for identifying foreign-object impact on composite plates using distributed built-in piezoelectric sensors. Similarly, Blanas et al.[3] and Wenger et al.[4] studied the suitability of embedded piezoelectric sensors for in-situ nondestructive monitoring of damage-induced acoustic emissions in fiber-reinforced composites. In principle, these active sensors can perform two functions. (1) In the passive mode, they can monitor dynamic events (e.g. foreign-object impact and damage-induced acoustic emission) by sensing the response of the structure. (2) In the active mode, they can evaluate real-time structural properties and identify existing damage by sending and receiving programmed diagnostic signals.

In the area of algorithms, modal analysis for vibration signals has been the method of choice. Techniques such as neural networks and genetic algorithms are also becoming popular. These techniques usually use sensor signals in the time or frequency domains. More recently, time-scale (or time-frequency) analysis methods based on the wavelet transform have been applied by a number of researchers to vibration signals[5-8] and wave dispersion signals[9-10]. The advantage of algorithms based on the wavelet transform is that they may be able to reveal certain important temporal and spectral patterns in a signal.

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These patterns may constitute the signatures of the dynamic events in question and may be the key to the effective and reliable interpretation of the sensor signals.

In this paper, the authors present the results of impact tests conducted on steel beam and composite panel specimens. Piezoelectric transducers are attached to the surface of the specimens to monitor wave propagation events caused by point impact to the specimens. The sensor signals are then analyzed with the wavelet transform and are interpreted together with elastic wave propagation theories in elastic solids and structures[11-12]. The findings of this study indicates that the combination of distributed sensor networks and wavelet-based analysis and interpretation algorithms can provide an effective and efficient means of monitoring dynamic events in host structures, which we hope will lead to the development of desirable structural health monitoring and damage detection systems.

The paper is divided subsequently into four sections. An outline of the wavelet transform is given in Section 2 for completeness. Test results and analyses for the beam impact tests are presented in Section 3 and those for the composite panel impact tests in Section 4. The paper is closed with a summary and some remarks in Section 5.

2. THE WAVELET TRANSFORM

In wavelet transforms specialized functions called wavelets are used as kernels in integral transforms. Wavelets have compact support in both the time and frequency domains and can be generated from a function (called the mother wavelet) meeting certain admissibility conditions.

Let $\psi(t)$ be a mother wavelet. Then the following family of wavelets can be generated

$$\psi_{a,b}(t) = |a|^{-p}\,\psi\left(\frac{t-b}{a}\right) \tag{1}$$

where *a* and *b* are real-valued parameters, and *p* is usually taken to be 1/2. The operation in (1) by parameter *a* is a “dilation” operation, and the operation by *b* a “translation” operation. Hence they are often called, respectively, the dilation and translation parameters.

Let *f*(*t*) be a signal in the time domain. Its wavelet transform is defined by (e.g. Daubechies[12])

$$c_{a,b} = \int_{-\infty}^{+\infty} f(t)\overline{\psi}_{a,b}(t)dt \tag{2}$$

where an overbar denotes the complex conjugate of a function. The wavelet transform $c_{a,b}$ is called the wavelet coefficient for the wavelet $\psi_{a,b}$ with dilation *a* and translation *b*. Wavelets with integer parameters are often used in wavelet transforms, and for example, can be generated from the mother wavelet according to

$$\psi_{j,k}(t) = 2^{j/2}\psi(2^j t - k) \tag{3}$$

where integers *j* and *k* are the scale (dilation) and position (translation) indices, respectively. The corresponding wavelet transform from (2) can be denoted by $c_{j,k}$ (at scale *j* and position *k*).

The wavelet transform has a number of salient properties. The most useful ones include (a) conservation of energy property, (b) localization in time and frequency domains, (c) multi-resolution properties, (d) ability to detect abrupt changes in a signal, and (e) relationship between scale and frequency.

Haar wavelets[13] are the simplest ones. Most wavelets, such as the Daubechies wavelets[14] can not be written in terms of closed-form expressions. However, some marginally admissible wavelets do have simple closed-form expressions. Examples of such wavelets include the Morlet and Paul wavelet functions, given below respectively,

$$\psi(t) = \exp\left(-\frac{t^2}{2} + ikt\right) \tag{4}$$

$$\psi(t) = \frac{\Gamma(m+1)i^m}{(1-it)^{m+1}} \quad (5)$$

where $i=\sqrt{(-1)}$ and k and m are real-valued parameters.

Textbooks by Daubechies[14] and Chui[15] contain very detailed mathematical expositions of the wavelet transform.

3. STEEL BEAM IMPACT TESTS

A slender cantilever beam specimen made of steel has been used in the beam impact tests. Figure 1 shows the experimental setup used in the tests.

Fig. 1 Experimental setup for beam impact tests with piezoelectric wafer transducers and wavelet transforms.

The specimen was instrumented with several piezoelectric wafer transducers and the impact on the beam specimen was achieved with a hammer. In each test, two sensor signals were recorded with a two-channel digital oscilloscope. The signals were then fed to a personal computer for wavelet analysis.

Test results from two beam impact tests will be presented here. A schematic of Test #1 is shown in Fig. 2, where the impact location is to the left of two piezoelectric sensors (which is to the left of the free end of the beam).

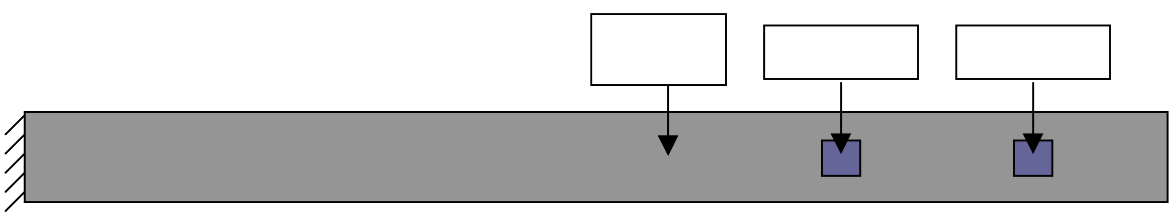

Fig. 2 A schematic of impact and sensor locations on a beam specimen (Test # 1).

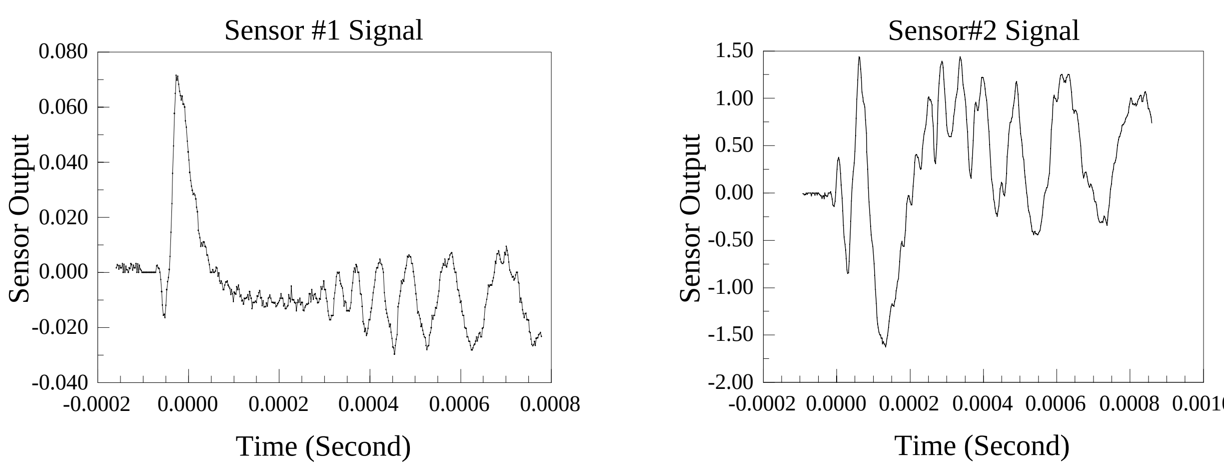

Fig. 3 Recorded signals in Test #1 by sensor #1 and sensor # 2.

The original sensor signals are given in Fig. 3. The signals were triggered when the propagating flexural wave induced by the hammer impact reaches sensor #1. The duration of the signals is long enough to contain both the incident wave from the impact and the reflected wave from the right end of the beam.

Several observations and conclusions can be made from the signals in Fig. 3. First, the waveform of the signals is quite complex and is not preserved from sensor #1 to sensor #2 due to the dispersive nature of the flexural wave phenomenon in beams. Second, it is difficult to identify any simple patterns in the signals that can be used for direct interpretation of the signals based on wave propagation theories. Third, although it appears that the arrival times of the incident wave at the two sensor locations can be estimated from the first few peaks of the signals, it is usually difficult to obtain a consistent value for the wave speed from these estimates. Fourth, the arrival times of the reflected wave at the sensor locations cannot be easily and reliably determined from either of the signals.

In order to gain a clearer understanding of the wave signals, the wavelet transform is now applied to the signals. Figure 4 shows the magnitude of the wavelet transform (wavelet scale = 14) of the wave signals as a function of time. (The wavelet scale is related to the frequency of the wave propagation). Note that the signals have been transformed into simple patterns, which can be considered the signature of the dynamic event. Because of this signature, the transformed signals can be effectively and reliably related to the impact location and time through an elastic wave propagation analysis. For example, we note that the first peak in both of the transformed signals represents the arrival of the incident wave while the second peak represents the arrival of the reflected wave.

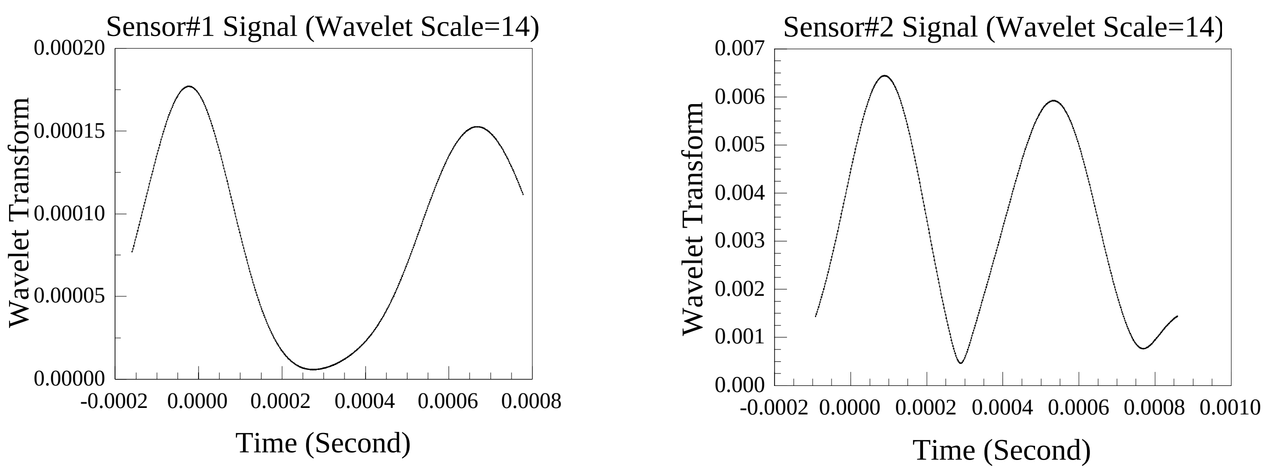

Fig. 4 Magnitude of wavelet transforms (scale=14) of the sensor signals in Fig. 3.

In Test #2, the beam impact location is between the two sensors, as shown in Fig. 5. Again, the original sensor signals (see Fig. 6) are very messy—typical of the kind of signals one would expect from real-life situations—and are not conducive to effective and reliable interpretation. We then analyze these signals with the wavelet transform. Shown in Fig. 7 is the magnitude of the wavelet transform of the two sensor signals at scale 14. Again the first peak in each of the signal represents the incident wave from the impact while the second peak represents the reflected wave from the right end of the beam. Since sensor #1 is further away from the right end of the beam, the second peak in sensor #1’s signal arrives later than that of sensor #2.

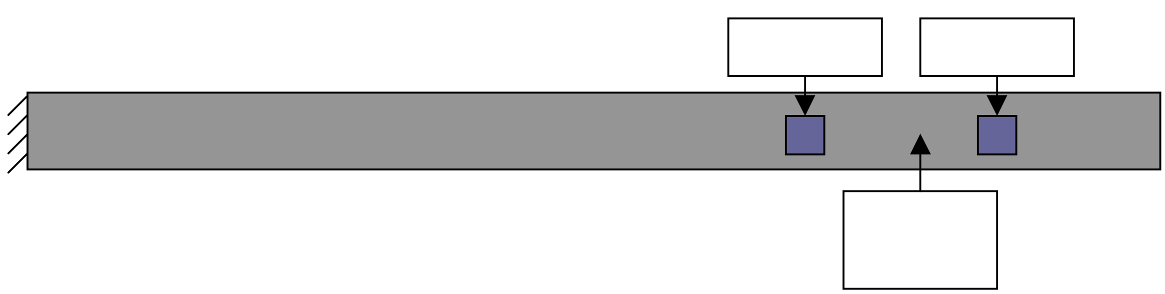

Fig. 5 A schematic of impact and sensor locations on a beam specimen (Test #2).

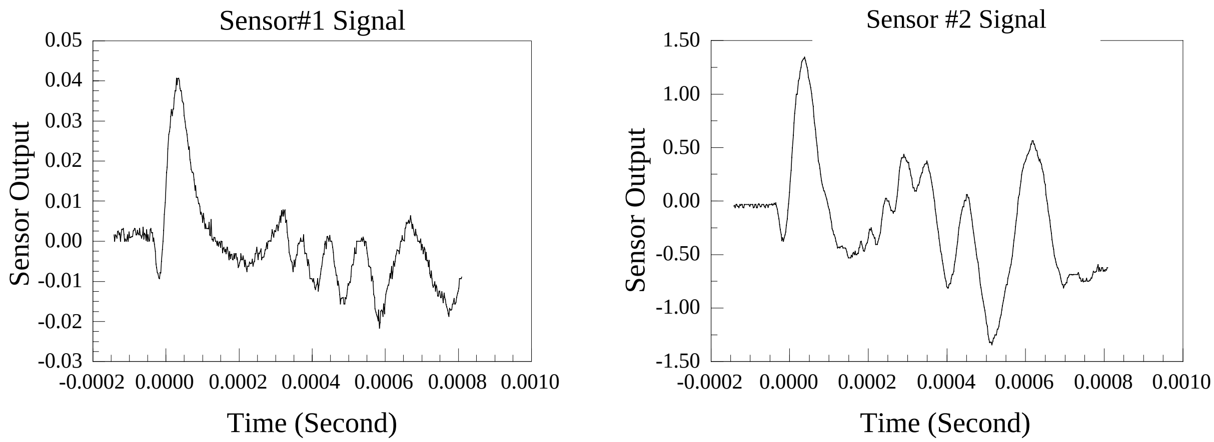

Fig. 6 Recorded signals in Test #2 by sensor #1 and sensor # 2.

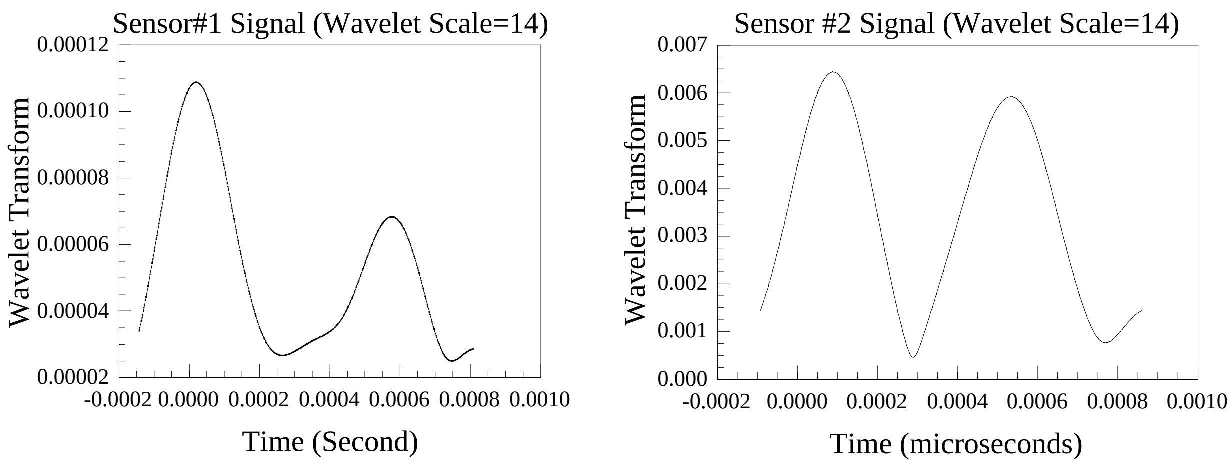

Fig. 7 Magnitude of wavelet transforms (scale=14) of the sensor signals in Fig. 5.

It is noted that, if wave arrival times at sensor locations can be clearly and consistently identified, then it is possible to interpret the wave phenomenon by using wave propagation theories directly. Section 5 will discuss this point further.

4. COMPOSITE PANEL IMPACT TESTS

In order to demonstrate further the applicability of the wavelet transform to the interpretation of wave propagation signals received by sensors used to monitor dynamic events occurring in a host structure, impact tests have been conducted on an actual aircraft composite panel, which is shown in Fig. 8. This is a slightly curved panel and it has three stiffeners. Impact tests were performed on the right portion of the panel only, where the panel was instrumented with seven piezoelectric transducers, as shown by a schematic of the panel in Fig. 9. Note that the long, vertical rectangle on the left stands for the stiffener on the right portion of the panel and the small rectangles represent surface-mounted piezoelectric sensors.

In one test, the panel was impacted at the location marked "Impact 1," and in the second test it was hit at the location marked "Impact 2." Only the wave signals at sensor #1 and sensor #6 due to Impact 1 are presented here, which are shown in Fig. 10.

The corresponding wavelet transforms (wavelet scale = 14) of the signals are shown in Fig. 11. It can be verified that the first peak in the transformed signals in Fig. 11 represent the arrival of the incident wave caused by the impact and can be used to determine a consistent group wave speed (with dependence on the frequency) and the location of the impact point.
An interesting observation can be made here. On one hand, the sensor signals for the beam impact tests (Figs. 3 and 6) are quite complex but their wavelet transforms are quite simple (Figs. 4 and 7). On the other hand, the sensor signals for the composite panel impact tests (Fig. 10) are not as complex, but their wavelet transforms appear to contain more information.

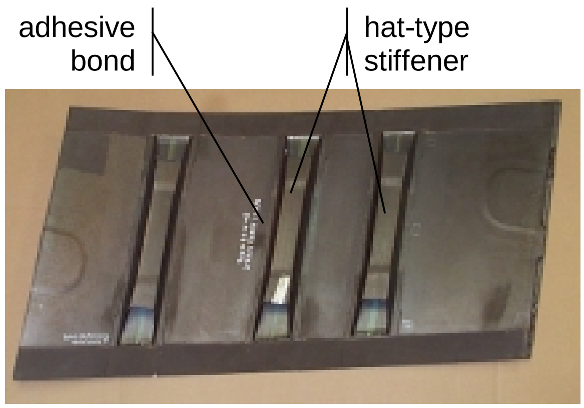

Fig. 8 Top view of the composite panel showing details of the hat-type stiffeners and the location of the damage-critical areas. The placement of piezoelectric wafer transducers will correlate with these damage-critical areas.

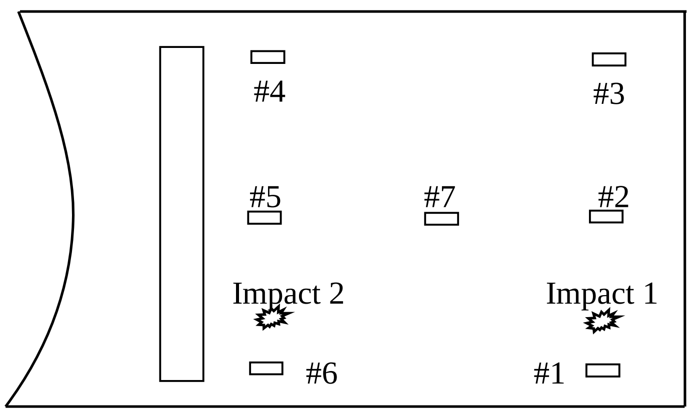

Fig. 9 A schematic of the composite panel specimen and its impact and sensor locations.

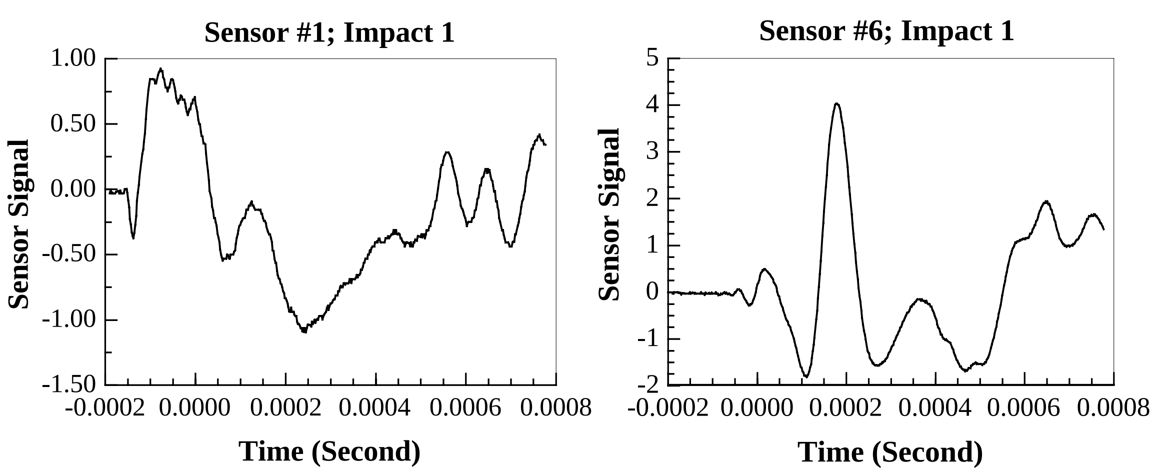

Fig. 10 Recorded signals due to Impact 1 at sensor #1 and sensor # 6.

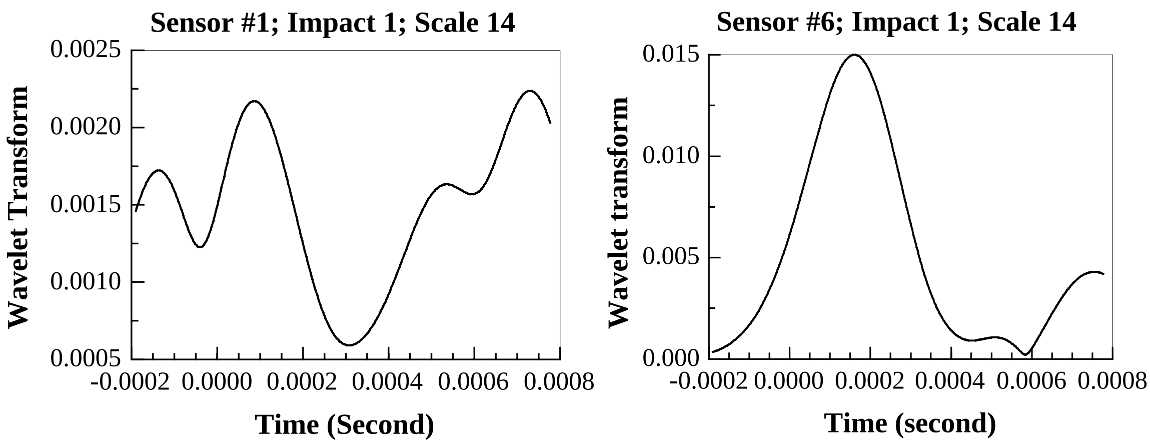

Fig. 11 Magnitude of wavelet transforms (scale=14) of the sensor signals in Fig. 10

5. SUMMARY AND REMARKS

Impact test signals and analysis results have been presented. Wave propagation signals induced by point impact events were obtained with distributed piezoelectric transducers mounted on the surface of steel beam and composite panel specimens. The wave signals were analyzed with the wavelet transform, revealing patterns that can be considered the signature of the underlining dynamic event.

As demonstrated by the impact test results, the combination of piezoelectric transducers and wavelet transforms provides an effective and efficient means of determining the arrival times of wave propagation in beams, plates and other structures. It can be shown that, in an impact event, the time and location of impact and the wave speed at a certain frequency can be completely determined by the wave signals at three sensor locations under one-dimensional conditions, and by the wave signals at four sensor locations under two-dimensional conditions. Thus it appears that dynamic events in a structure may be monitored and identified by using a network of piezoelectric sensors and signal interpretation algorithms based on the wavelet transform and wave propagation theories.

It is noted that the work presented in this paper has so far only used the wave arrival time information. Further details contained in the transformed signals have not been utilized for the purpose of signal interpretation. More sophisticated procedures that make a fuller use of the wave propagation signals and their wavelet transforms are being explored.

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