Detection of Impact Damage in Composites Under Complex Environment Using Guided Waves

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ABSTRACT

This paper presents an experimental study on detection of impact damage in composites under complex environment using guided waves. An experimental set-up consisting of an electrical oven, a MTS testing machine and a monitoring system is established to perform the study. First, the combined effects of temperature, load and vibration on the propagation of guided waves in a composite coupon is studied. Then, a statistical approach is proposed to detect impact damage under these combined effects. Damage feature is extracted after the guided wave signals are processed by wavelet transform. A Monte Carlo procedure is employed to estimate the probability density functions (PDFs) of the feature before and after damage, respectively. By comparing the PDFs, the probability of existence of impact damage is determined. Experimental study on a composite coupon under combined effects of temperature, load and vibration is conducted to demonstrate the effectiveness of the proposed method.

INTRODUCTION

In aerospace engineering, one of the critical problems threatening the structural integrity especially for composite structure is impact damage. With the development of advanced structural health monitoring technology, methods have been proposed to detect and identify impact damage [1-2]. Among these methods, the guided wave-based approach is considered as one of the most promising techniques. Using advanced signal processing techniques, the damage could be detected and identified by extracting characteristic information contained in transient guided waves transmitting in the structure. A wide range of theoretical and experimental studies have been

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performed to demonstrate the effectiveness and efficacy of detection and identification of damage in composite structure using guided waves [3-7].

Many of the guided wave-based methods use the time of flights (TOFs) of the scattered waves to identify the damage. By extracting the time arrivals of the guided waves scattered by damage, the damage location can be identified using the relationship among distances, wave velocities and TOFs of the scattered waves [8,9]. This kind of methods needs to subtract the guided waves before damage (baseline) from those after damage to obtain the damage-scattered waves. However, in real application, the complex environment, such as changes of temperature, load, vibration and noise, can greatly influence the guided wave propagation in the structure. Under such a circumstance, even in the pristine state, the guided waves could be significantly different from the baseline waves acquired at a specific time and environmental condition, leading to incorrect judgment and suspicious identification if use the subtracted signals as the scattered waves to identify the damage under environmental effects.

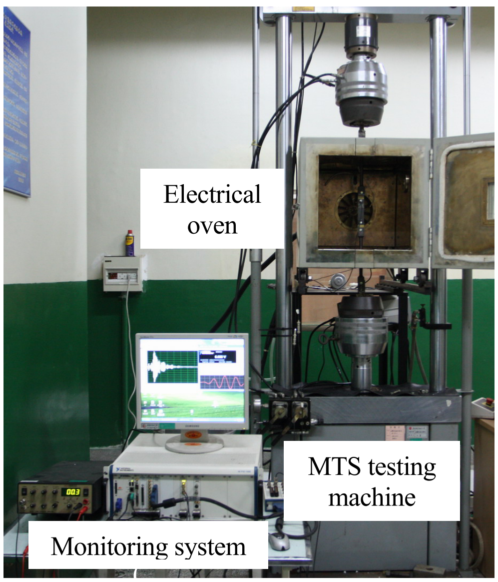
Another kind of guided wave-based methods can be categorized as pattern recognition-based methods [10,11]. By extracting the damage-sensitive feature from the received guided waves in time, frequency and time-frequency domains through signal and information processing techniques, the damage can be classified and identified by pattern recognition. According to the training samples and learning algorithms, the pattern recognition-based methods can be further classified as unsupervised and supervised methods. In unsupervised methods, the training samples are only from the structure under pristine state, while in the supervised methods, the training samples are from both the pristine and damaged states. Generally, it is difficult to obtain training samples from different damage scenarios beforehand, thus unsupervised methods are more advantageous for low level damage detection in structural health monitoring. However, only a little investigation has considered the effects of real operational environment on impact damage detection which are very important for practical applications of composite structure.

This paper aims to study the combined effects of temperature, load and vibration on the propagation of guided waves in composite structure and to propose a statistical approach to detect impact damage under these combined effects using guided waves. Damage feature is extracted after the guided wave signals are processed by wavelet transform. A Monte Carlo procedure is employed to estimate the probability density functions (PDFs) of the feature before and after damage, respectively. By comparing the PDFs, the probability of existence of damage is determined. Experimental study is conducted to demonstrate the effectiveness of the proposed method.

ENVIRONMENTAL EFFECTS

Experimental set-up

To study the combined effects of temperature, load and vibration on the propagation of guided waves, an experimental set-up consisting of an electrical oven, a MTS test system and a monitoring system is established to perform the study. The electrical oven is used to simulate temperature changes, and the MTS testing machine is employed to apply different loads to the coupon. Vibration is also generated when the fan inside the electrical oven and the hydraulic actuator of MTS testing machine are working. The monitoring system consists of a PXI-5442 arbitrary function generator, a PXI-6115 data acquisition (DAQ) board, a KH-7600 wideband amplifier and an embedded controller produced by National Instrument Corporation. The overall experimental set-up is shown in figure 1. Figure 1 also shows the carbon fiber composite coupon. The thickness of the coupon is 3 mm. On the surface of the coupon, two PZT transducers are mounted with distance of 100 mm. The diameter and thickness of the PZT transducers are 10 mm and 1 mm, respectively. In the following experiments, one PZT transducer is acted as actuator and the other as receiver, respectively. The PXI-5442 arbitrary function generator sends signal which is amplified by KH-7600 amplifier and drives the actuator to generate transient guided waves into the coupon, the response wave signals are then sensed by the receiver and acquired by the PXI-6115 DAQ board, whose sampling rate is set at 10 MHz.



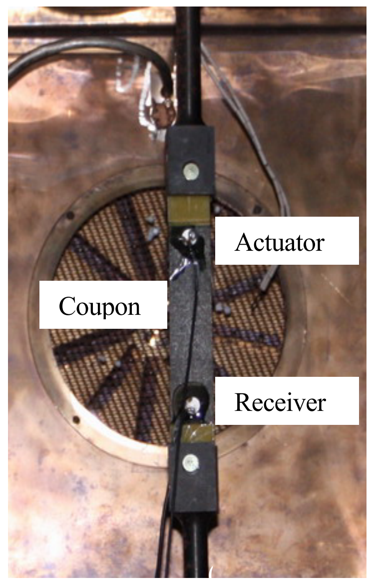


Figure 1. Experimental test-up (left) and composite coupon (right).

Environmental effects on guided waves

During the experimental study, the electrical oven and the MTS testing machine are used to simulate different temperatures and loads to study the combined effects of temperature change and loads on the propagation of guided waves. Though there is no specific equipment employed to excite vibration to the coupon, the effect of vibration is also included since vibration is introduced by the fan of the electrical oven and the hydraulic actuator of MTS testing machine as aforementioned. During the experimental study, the range of temperature applied by the electrical oven is about 20-60 °C and the range of loads applied by the MTS testing machine is 1-10 kN. Narrow-band modulated five-peak sinusoid signals with center frequencies of 200 kHz and 300 kHz are employed as diagnostic waves to be excited into the composite coupon.

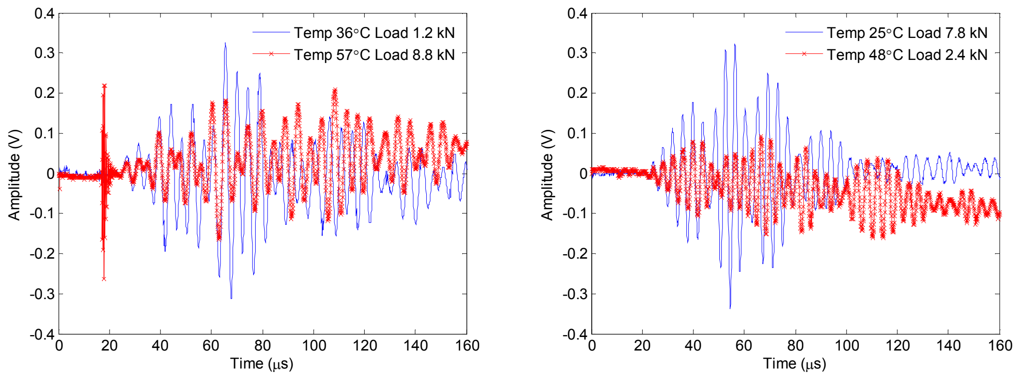


Figure 2. Raw wave signals of 200 kHz (left) and 300 kHz (right) under two environmental conditions before damage.

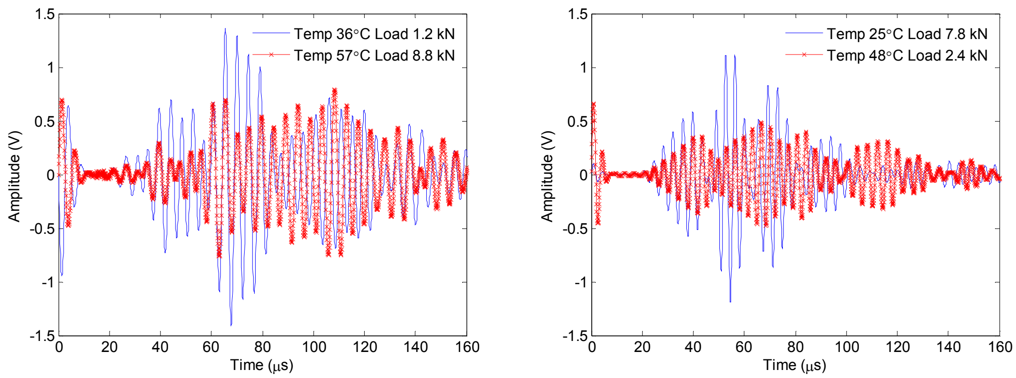


Figure 3. Wavelet filtered signals of 200 kHz (left) and 300 kHz (right) under two environmental conditions before damage.

Figure 2 shows two sets of typical guided wave signals with center frequencies of 200 kHz and 300 kHz under environmental conditions with different temperature and loads. It is observed that the raw signals contain noises and drift, thus wavelet transform is employed to preprocess the wave signals. In this study, the Gabor wavelet is adopted as the mother wavelet [12]. Figure 3 shows the wavelet filtered signals represented by the wavelet coefficients corresponding to those raw signals in figure 2 at 200 kHz and 300 kHz, respectively. It can be seen that the noises and drift are successfully removed by wavelet analysis. From figure 2 and 3, it is clear that temperature and loads (vibration is also included) have a significant effect on the guided wave propagation in composites, leading to changes, especially amplitude changes, of the received signals. It will inevitably lead to false judgment and suspicious identification if these environmental effects are not considered in the damage detection procedures.

STATISTICAL DAMAGE DETECTION APPROACH

Damage feature

The environmental effects on the propagation of guided waves are stochastic, statistical approach is favorable for such a kind of problem. A statistical diagnostic method is proposed to detect the impact damage under the combined effects of temperature, load and vibration in this study.

For damage detection, the first step is to extracted damage feature from the sensed guided wave signals to indicate the presence and progress of damage. The damage feature is a characteristic parameter or a set of parameters that could be obtained by signal and information processing techniques in time, frequency and time-frequency domains. As a preliminary study, a simple damage feature is defined for damage detection here. This damage feature stands for the energy received by the sensor from a specific diagnostic excitation. It is defined in the time-frequency domain as

$$WE = \int_{t_s}^{t_e} \left|WT(V_s, f_c)\right|^2 dt \tag{1}$$

in which WE is short for "wavelet energy", WT stands for wavelet transform, V_s is the wave signal, f_c represents the frequency at which the wavelet energy is calculated, [t_s, t_e] defines the lower and upper bounds of the time range for calculating the wavelet energy. By carefully choosing t_s and t_e, the component introduced by environmental effects can be removed in some extent.

Damage detection procedure

The idea by using the damage feature defined in equation (1) to indicate the existence of damage is that the damage will alter the transmission of guided waves in the actuator-receiver path, reducing or increasing the energy transmitted to the receiver from the actuator. By comparing the damage feature before and after damage, the existence of damage can be determined. However, as aforementioned, the temperature, load and vibration stochastically effect the propagation of guided waves, such a comparison should be performed in a statistical way. In this study, a Monte Carlo procedure is employed to estimate the PDFs of the damage feature both in the pristine state and the unknown state (there may be damage or not), respectively. Comparing these PDFs, the probability of existence of damage can be determined.

The Monte Carlo procedure for damage detection contains following steps:

Step 1: In the pristine state, randomly sample M sets of combination of temperature and load from the temperature range and load range, apply these combinations of temperature and load to the coupon using electrical oven and MTS testing machine one by one, and obtain M sets of guided wave signals under these environmental conditions. Compute the damage features of these M sets of guided wave signals according to equation (1) to form the baseline dataset WE^B, and estimate the PDF of WE^B, denoted as $g(WE^B)$.

Step 2: In an unknown state, perform the similar procedure as presented in Step 1 to obtain N sets of guided wave signals under different environmental conditions. Compute the damage features to form a unknown state dataset WE^U, and estimate the PDF of WE^U, denoted as $h(WE^U)$.

Step 3: If the damage reduces the energy transmitted to the receiver from the actuator, compute the probability of WE^U smaller than WE^B which is expressed as

$$P_D = P(WE^U < WE^B) = \int_{-\infty}^{+\infty} g(WE^B) \cdot \int_{-\infty}^{WE^B} h(WE^U) dWE^U dWE^B \tag{2}$$

Otherwise, compute the probability of WE^U greater than WE^B which is expressed as

$$P_D = P(WE^U > WE^B) = \int_{-\infty}^{+\infty} h(WE^u) \cdot \int_{-\infty}^{WE^u} g(WE^B) dWE^B dWE^U \tag{3}$$

The larger the value of P_D is, the greater the possibility that damage has emerged on the actuator-receiver path. Thus, P_D is employed as a statistical measure for damage detection.

EXPERIMENTAL RESULTS

To demonstrate the effectiveness of the proposed method, experimental study is performed. First, for collecting the baseline dataset WE^B, 90 sets of environmental conditions with randomly sampled temperature and load from a predefined range of 20-60 °C and 1-10 kN are applied to the composite coupon. Diagnostic waves with center frequencies of 200 kHz and 300 kHz are excited into the coupon under the sampled environmental conditions. Two 90 sets of response wave signals are recorded and their energies in time-frequency domain are calculated. Next, an quasi-static compression test is performed to introduce damage in the coupon due to lack of impact device. Figure 4 illustrates the ultrasonic C-scan result of internal damage. After the damage occur, the same as the test procedure under baseline state, two 90 sets of response wave signals under excitation of 200 kHz and 300 kHz are recorded. Figure 5 shows two sets of typical guided wave signals with center frequencies of 200 kHz and 300 kHz under environmental conditions with different temperature and loads before and after damage. Figure 6 and figure 7 show the wavelet preprocessed signals and wavelet energy distribution at 200 kHz and 300 kHz corresponding to those raw signals in figure 5. Also, the noises and drift are successfully removed by wavelet analysis. The corresponding wavelet energies are calculated to form the unknown state dataset WE^U.

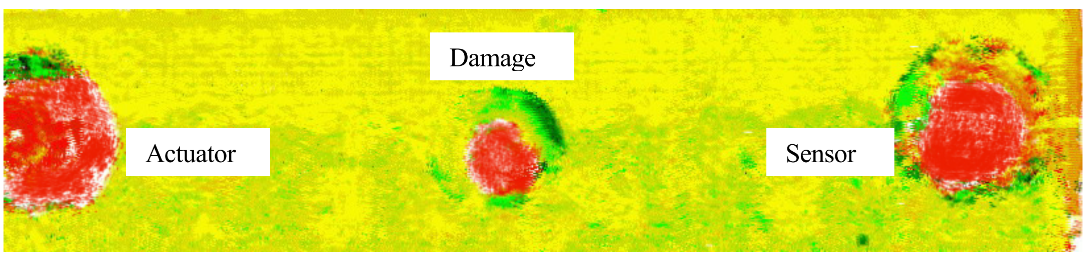


Figure 4. C-scan result of damage inside the composite coupon.

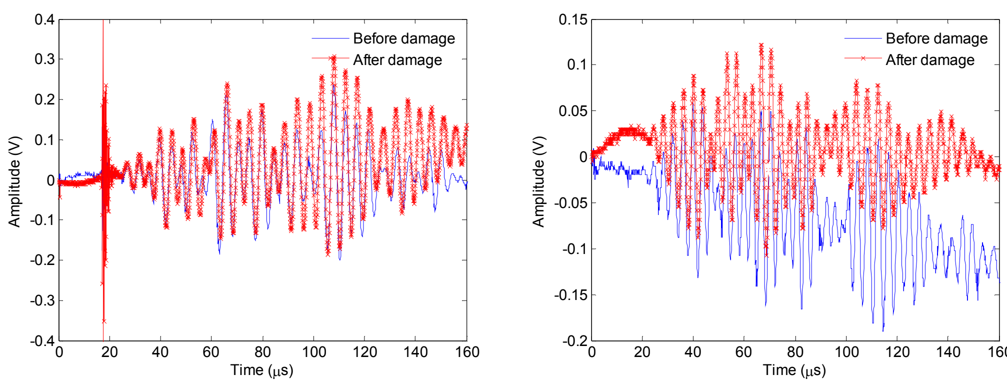


Figure 5. Raw wave signals of 200 kHz (left) and 300 kHz (right) under two environmental conditions before and after damage.

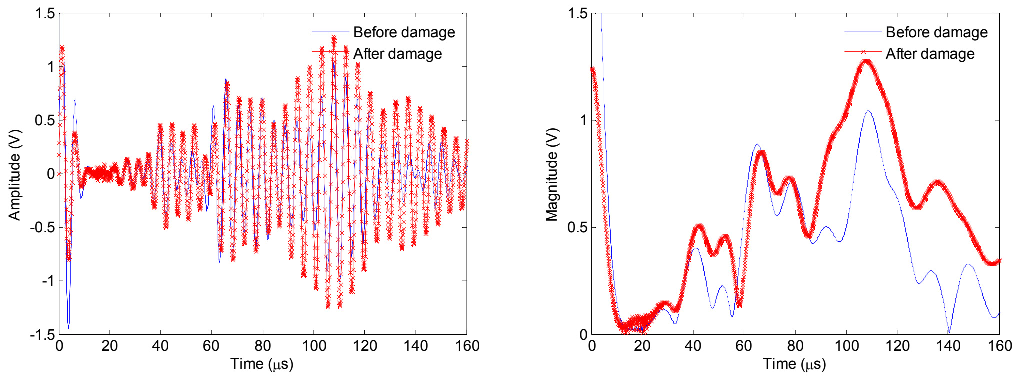


Figure 6. Wavelet filtered signal of 200 kHz (left) and corresponding wavelet energy distribution at 200 kHz (right).

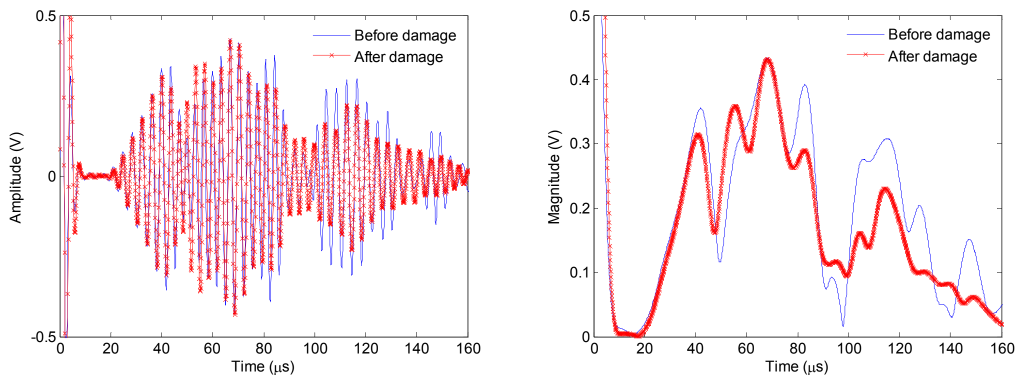


Figure 7. Wavelet filtered signal of 300 kHz (left) and corresponding wavelet energy distribution at 300 kHz (right).

All of the wavelet energy data before and after damage are assumed as normal distributed. The PDFs of the distributions for wavelet energy data of 200 kHz and 300 kHz are then estimated and fitted as shown in figure 8, respectively. Thus using the estimated normal distribution parameters, the probability of existence of impact damage using guided waves centered at 200 kHz is 85.3%, and the probability of existence of impact damage using guided waves centered at 300 kHz is 56.2%. In this case, it has demonstrated that relatively guided waves centered at 200 kHz has a better sensitivity to the same damage scenario than guided waves centered at 300 kHz.

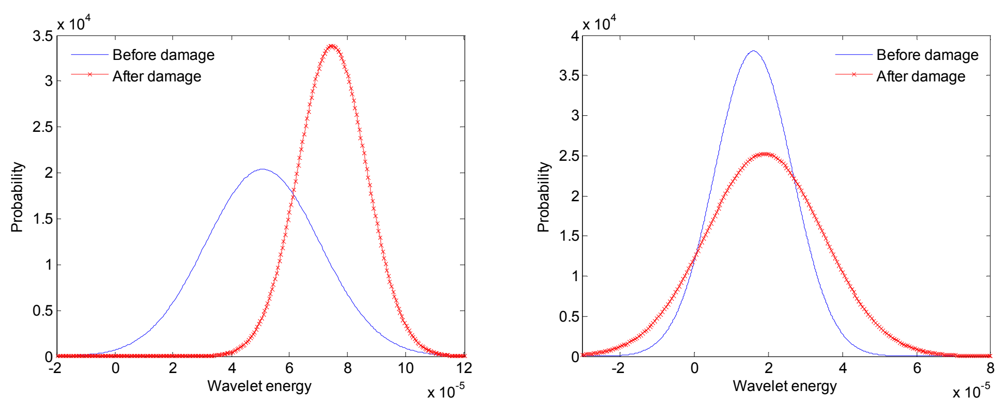


Figure 8. Fitted normal PDFs for wavelet energy data of 200 kHz (left) and 300 kHz (right) before and after damage.

CONCLUSIONS

This paper presents an experimental study on detection of impact damage in composites under complex environment using guided waves. The combined effects of temperature, load and vibration on the propagation of guided waves in composites is studied by using experimental set-up consisted of an electrical oven, a MTS testing machine and a monitoring system. A statistical approach is proposed to detect impact damage under these combined effects. Experimental results have demonstrated that the environment has a significant effect on the guided wave propagation in composites, the proposed statistical damage detection approach successfully detect the existence of damage in the composite coupon under the combined effects of temperature, load and vibration with a probabilistic measure, and diagnostic waves with different center frequencies have different sensitivities to the same damage scenario. Further study would be conducted to study the mechanism of changes of guided waves in composite under complex environment, especially temperature change, and the relationship between the damage size and the probabilistic measure.

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