

Elevated Temperature Modal Response and Delamination Detection in Carbon-Epoxy Beams

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ABSTRACT

Polymer matrix composites are increasingly adopted in aerospace and automotive industries due to their many attributes, such as their high strength to weight ratio, tailorability, and high fatigue and durability performance. However, these materials also have complex damage and failure mechanisms, such as delaminations, which can severely degrade their strength and fatigue performance. To effectively and safely use composite materials in primary structures, it is essential to assess composite damage response for development of accurate predictive models. Therefore, this study focuses on determining the response of damaged and undamaged carbon epoxy beams subjected to vibration loadings at elevated temperatures. The Hilbert-Huang Transform (HHT) technique is used to analyze the beams' modal response. The HHT shows potential in identifying the nonlinear damaged response of the beams. Using empirical mode decomposition to separate superposed modes of signals, several intrinsic mode functions can be determined which can reveal more information about complex nonlinear signals than traditional data analysis techniques such as the Fourier Transform. The composite beams are fabricated from an out-of-autoclave uniaxial carbon/epoxy prepreg (CYCOM™-5320-1/T650). Delamination damage in the composite layups is introduced by insertion of mold release wax films during fabrication. A shaker-table fixture was used for the vibration testing of all beams in a vertical cantilever configuration. High temperature piezoelectric accelerometers were used to obtain the vibration data for a frequency range of 1-61 Hz. This study investigates the effect of damage on the measured vibration data using intrinsic mode functions and Hilbert Huang spectrums.

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INTRODUCTION

The use of composite materials has many benefits for engineering structures; however, the damage mechanisms of composites are very different from those of metals. Typical damage in composite materials includes matrix cracking, fiber breaks, fiber-matrix de-bonding, and delaminations. These damages are often internal and usually not visible. Because these damages can severely degrade the performance of composites, damage detection is critical for maintenance of structural integrity. Structural health monitoring (SHM) refers to the process of implementing a damage detection and characterization strategy for engineering structures. This involves monitoring a structure using data from an array of sensors and extracting a damage signature from these measurements to determine on-line structural health.

SHM often adopts non-destructive evaluation (NDE) techniques for identification of damage. Commonly available NDE methods are visual inspection, ultrasonic, vibration, strain measurements, thermography, radiography, and eddy-current. Owing to various reasons, not all of these techniques can be adopted in SHM systems which are integrated in nature for online damage detection. However, techniques based on ultrasonic and vibration methods have been studied widely [1, 2]. Ultrasonic methods use the properties of wave propagation in elastic structures for detection damage. Acoustic

emission (AE) is an ultrasonic NDE technique that does not require any external signal excitation for probing the structure [3]. In the AE method, stress waves are structure-born and produced internally by defects during loading of the structure. Most classical ultrasonic techniques require high-frequency external excitation and often use longitudinal and shear wave modes for interrogation [4]. Other NDE techniques, such as guided waves, which travel in thin plates (aka. Lamb waves), have emerged as a promising technique for inspecting structures. Due to their propagation characteristics, Lamb waves can be used as a means to detect both superficial and internal flaws in a structure [5, 6, 7, 8].

Despite the growing number of techniques studied in search of better SHM techniques, a large majority of methods are based on frequency domain (modal) analysis of vibration data [9]. The most serious limitation of the modal analysis is that it depends on the global deformation of the entire structure. Consequently, deformation as a result of local damages can be detected only in higher modes; however, to determine mode shapes of the higher modes, a larger number of sensors must be used to collect the necessary data. Even with good reference data, the noise from real systems and measurements can cloud the picture and make it difficult to detect and locate damages with high sensitivity. In pursuit of better damage

detection algorithms, researchers have investigated several other methods including time domain analysis [10, 11, 12, 13], wavelet transform [14], and Hilbert-Huang transform (HHT) [15].

The HHT is a relatively new approach for joint time-frequency analysis of signals, including nonlinear and nonstationary cases [16]. The key part of HHT is the ‘empirical mode decomposition’ procedure, in which a complicated signal can be decomposed into a finite and often small number of ‘intrinsic mode functions’ (IMFs). Essentially, the procedure is to identify the intrinsic oscillatory modes in the data empirically by their characteristic time scales and then decompose the data accordingly. After the data has been decomposed into IMFs, the second step is to apply the Hilbert transform to each IMF, which produces instantaneous phase (frequencies) as functions of time. The final presentation of the results is shown as a magnitude-frequency-time distribution, designated as the Hilbert spectrum. This means that the instantaneous frequency and energy defined locally is obtained, rather than the global frequency and energy defined by the Fourier transform. Also, Fourier analyses are valid for problems involving linear systems with periodic or stationary response. However, Fourier analysis has little physical meaning for nonlinear systems and/or nonstationary responses.

The HHT method has been used by several researchers for SHM. Kunwar et al [15, 16, 17, 18] presented the health monitoring of an experimental bridge model using Hilbert-Huang transform of transient vibration data. Here the Hilbert spectrum, marginal Hilbert spectrum, and instantaneous phase examination of transient vibration measurements showed that the method can detect and locate damage successfully. Vincent et al. [17] compared HHT with a wavelet analysis for damage detection for a three-story shear building, modeled as a simple 3 DOF system. It was concluded that the HHT method seems to be more promising for quantifying the damage level. Yang et al. [19] performed numerical simulations to show that the damage time instants can be identified through the spikes in the signal using the HHT analysis method. Xu and Chen [20] presented an experimental investigation for a multi-level structure with the first level connected to springs that were released suddenly to simulate damage. Pai et al. [21] extracted system nonlinearities and time-localized transient response to impulsive loading using the HHT. They showed that the HHT can aid in the accurate extraction of intrawave amplitude and phase modulations, different orders of nonlinearity, and time instants of impact loading on a structure. Chen et al. [22] used HHT for early damage detection in composite wing box structures and showed that accurate results were obtained in spite of the presence of noise.

This paper investigates damage detection in polymer matrix composite beams through analysis of vibration data using the HHT. Three beams with a length of 90.2 cm, width of 7.6 cm, and thickness of 3.8 mm for each configuration of $\{0_{20}\}_T$ were fabricated using carbon prepreg. Damage was introduced by placing Meguir’s® mold release wax close to the tip of the beams at midplane (10th ply) of the beams. The test beams were instrumented with five high temperature accelerometers and a shaker table was used to excite the beams in vibration over a frequency sweep at three temperatures. Frequency-time representations, also known as Hilbert-Huang spectrums are

presented. It is shown that because of the unique capability of HHT to analyze nonlinear and nonstationary signals, the presence and location of damage may be correctly predicted.

HILBERT-HUANG TRANSFORM

The HHT method involves two distinct steps: (i) decomposition of signals into intrinsic mode functions through an empirical procedure; and (ii) Hilbert transform of the resulting Intrinsic Mode Functions (IMFs). A systematic way to extract IMFs from general signals (called the ‘sifting process’) is described in Huang et al. [16]. Rilling et al. [23] discussed issues related to the effective implementation of empirical mode decomposition (EMD) and implemented a number of algorithmic variations, including new stopping criteria. They published their code as a freeware, which has been used in this research. The EMD results in decomposition of data $x(t)$ into N intrinsic mode functions and the residue can be expressed as

$$x(t) = \sum_{n=1}^N c_n(t) + r_N(t) \quad (1)$$

Each IMF (c_n in Eq. (1)) represents the oscillation mode embedded in the data, $x(t)$. In other words, an IMF involves only one mode of oscillation, no complex riding waves are present [16]. The next step in the HHT is to apply the Hilbert transform to each IMF c_n . The Hilbert transform [24] of a real-valued time domain signal $c(t)$ is another real-valued time domain signal, denoted by $\tilde{c}(t)$, such that $z(t) = c(t) + i\tilde{c}(t)$ is an analytic signal. (The subscript in $c_n(t)$ is dropped for simplicity). The Hilbert transform can be stated as

$$\tilde{c}(t) = \int_{-\infty}^{\infty} \frac{c(k)}{\pi(t-k)} dk \quad (2)$$

We can define a magnitude function $a(t)$ describing the envelope of the original function $c(t)$ versus time and a phase function $\theta(t)$ describing the instantaneous phase of $c(t)$ versus time using $z(t) = a(t)e^{i\theta(t)}$. The Hilbert transform is general and global, but the instantaneous frequency $\omega = \frac{d\theta(t)}{dt}$ (based on the transform) is restrictive and local. The IMFs discussed previously overcome this difficulty. By performing the Hilbert transform (Eq. (2)) on the decomposed IMFs (Eq. (1)), we can express the analytical data in the following form.

$$z(t) = \sum_{n=1}^N a_n(t) \exp\left(i \int \omega_n(t) dt\right) \quad (3)$$

The expression in Eq. (3) enables us to represent the amplitude and the instantaneous frequency as functions of time in a three-dimensional space. This frequency-time distribution of the amplitude is designated as the Hilbert spectrum, $H(\omega, t)$. Because the Hilbert spectrum defines frequency locally (rather than globally as defined by Fourier transform), it has a much higher frequency resolution.

The Hilbert transform of individual IMFs gives the instantaneous phase, and the total instantaneous phase $\Theta(t)$ is obtained by a sum of the instantaneous phases for each IMF as given in Eq. (4).

$$\theta(t) = \sum_{n=1}^N \arctan\left(\frac{H[c_n(t)]}{c_n(t)}\right) \quad (4)$$

The total phase can be unwrapped from its harmonic nature to reveal a linear trend, which is used for damage identification [15]. The total phase at any point p on a structure relative to a reference point o is called the 'phase difference', which is obtained by

$$\Phi_p(t) = \theta_p(t) - \theta_o(t) \quad (5)$$

DESCRIPTION OF COMPOSITE TEST BEAMS

The material used in this study is an out of autoclave (OOA) carbon fiber prepreg (CYCOMTM-5320-1/T650 Cytec Industries). The toughened epoxy resin is typically used for OOA composite manufacturing of primary structural components. The fiber used in the prepreg is the T650 carbon fiber, with a 12K fiber tow, a fiber areal weight (FAW) of 215 gm/m². Beams of laminate configurations $\{0_{10}\}_s$ were fabricated with varying sizes of delamination damage. The damage was introduced by placing mold release wax at the midplane of the laminates at approximately and approximately 7 cm from the beam tip. This location was chosen to be midway between Accelerometers 1 and 2. Table 1 lists the laminates with their damage configurations. The test laminates were fabricated using a standard prepreg lay-up technique and cured under vacuum bag pressure for three hours at 121 °C followed by a post-cure for two hours at 177 °C. After cure, all beams were trimmed using a wet tile saw to a length of 91.4 cm (36-in.) and a width of 7.6 cm (3-in.).

EXPERIMENTAL METHOD

Experimental Setup

The vibration response for all beams was acquired through the use of five uniaxial high temperature accelerometers (357B03, PCB Piezotronics). These accelerometers (A1-A5) were screw-mounted along the centerline of the beams with a 14 cm (5.5-in) spacing between the sensors, as shown in Figure 1. A shaker-table approach was used to excite the beams in vibration. The beams were clamped in the fixture in a vertical position and a 110-lb shaker unit was used to excite the beams.

Two types of vibration measurement techniques, frequency sweeps and frequency dwells at resonant frequencies, were conducted to obtain the accelerations from the six sensors. The swept sine technique was performed at a sampling rate of 500 Hz for a frequency sweep from 1 Hz to 61 Hz in 60 seconds. This was repeated for each of the test beams at three temperatures (22 °C, 91 °C and 116 °C). The setup was placed in a large oven to facilitate the

elevated temperature experiments. To obtain the modal parameters, the input force signal and the response from each sensor was recorded for later processing.

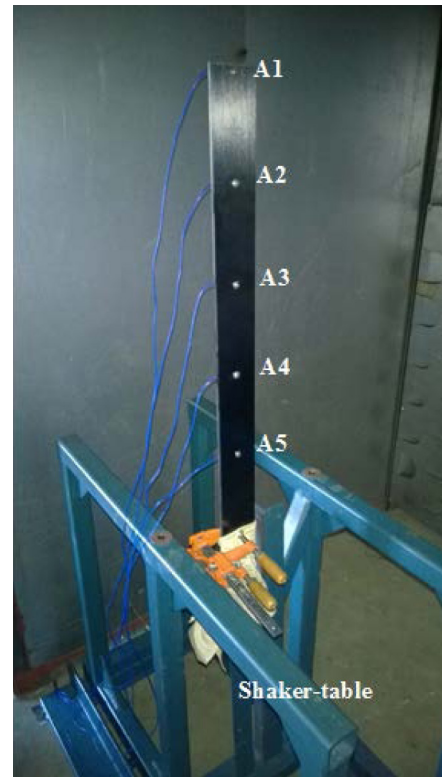


Figure 1. Experimental setup for beam vibration testing.

Data Acquisition System

Single input excitation, provided by an arbitrary waveform function generator at the specified frequencies, was used to activate the shaker amplifier (Vibration Research Corporation PA-141) and excite the 110 lb. capacity shaker unit (Vibration Research Corporation ET 140). A load cell (Interface, SMA-200 617529) and a dynamic force transducer (PCB Piezotronics, 208C02) were connected in series with the shaker to obtain the input force signal to the test structure. The open loop system records the acceleration through a LabVIEW® program.

RESULTS AND DISCUSSION

Modal Characteristics

Figure 2 shows the frequency domain data for the baseline beam at 22 °C. The peaks in this figure indicate the first two natural frequencies. Table 1 shows the first and second natural frequencies obtained from the frequency response functions of the tip accelerometers for each beam and test case at the three temperatures (22 °C, 91 °C, 116 °C). The frequencies of the beams do not change significantly with a change in temperature. This was expected since the beam consists of plies with fibers in the longitudinal direction only and the fibers have minimal temperature dependence at this range. However, a close look reveals overall decrease of the natural frequencies with increasing temperature, particularly for the baseline beam. Also, when comparing the natural frequencies of the baseline