Real-Time Structural Damage Detection Using Only Signals Acquired During Impact Events

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ABSTRACT

This work presents a novel, real-time, and baseline-free methodology for structural damage identification during impact events, utilizing the Hilbert-Huang Transform (HHT) to analyse acquired stress wave signals generated by the impact. The proposed technique is based on the decomposition of wave propagation modes induced by both low- and high-velocity impacts, with a focus on distinguishing between extensional (symmetric, high-frequency) and flexural (antisymmetric, low-frequency) components of the AE signals. The empirical mode decomposition (EMD) is applied to extract intrinsic mode functions (IMFs), enabling the separation and reconstruction of the fundamental wave modes. The instantaneous energy content of each mode is then calculated using HHT, and a damage index, Λ, is introduced, a dimensionless quantity that characterizes the shape and spread of the instantaneous energy spectrum obtained via HHT. Experimental validation was carried out on two sets of impact results including flat plates and complex composite structures. Impact scenarios varied from low velocity to hypervelocity regimes, using projectiles of different materials and geometries. The results demonstrate that a Λ value below a threshold corresponds to elastic impacts with no or minor deformation, while values approaching or exceeding the threshold indicate the onset of permanent damage, such as indentation, penetration, or complete perforation. For highly damaged structures, Λ values increased significantly, confirming the dominance of extensional wave components in such cases. This technique shows strong potential for real-time structural health monitoring (SHM) in aerospace and other safety-critical applications, offering high sensitivity to damage without requiring baseline signals. Furthermore, its robustness across different materials and geometries suggests wide applicability for both laboratory and operational environments.

INTRODUCTION

The continuous need to structural integrity monitoring [1]-[28] stems from the susceptibility of aircraft and spacecraft to unpredictable and impulsive loading throughout their operational life. Common sources of such loading include airborne debris during take-off and landing, bird strikes in flight, space debris, ice accretion, and tool drops during maintenance. Composite materials are highly susceptible to impact-induced damage such as fibre breakage, matrix cracking, and delamination.

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Barely visible impact damage (BVID), while initially subtle, can propagate without surface indication and potentially lead to catastrophic failure. When an impact occurs, this stress redistribution generates acoustic waves that propagate through the structure [29]. This research introduces a novel method for impact damage assessment employing the Hilbert-Huang Transform (HHT) applied to decomposed Lamb wave modes. The proposed approach collects AE signals from piezoelectric sensors fitted onto the structures under inspection, during impact events. Initially, Empirical Mode Decomposition (EMD) is performed on the acquired signals, resulting in a set of Intrinsic Mode Functions (IMFs). Because EMD relies on the local time-scale characteristics of the data, it is particularly effective for analyzing non-linear and non-stationary signals. Moreover, these IMFs are suitable for Hilbert transformation. The high-frequency (extensional) and mid-to-low-frequency (flexural) components are separated from the IMFs to yield two distinct signals. The Hilbert Transform is subsequently applied to these signals, yielding analytical forms that enable the extraction of instantaneous amplitude and phase. Subsequently, the instantaneous energy and frequency are computed. The authors previously derived an energy-based parameter that demonstrated the ability to detect damage during impact events [24]. In this paper, a new diagnostic metric is the Λ Ratio (Λ), a dimensionless quantity that characterizes the shape and spread of the instantaneous energy spectrum obtained via the Hilbert-Huang Transform (HHT). This novel parameter provides additional insight into the structural state, particularly useful for impact diagnostics. A decrease in the Λ ratio (Λ) after an impact strongly indicates structural damage, as it reflects the redistribution of vibrational energy due to stiffness loss, modal disturbance, and nonlinearities. The distinct advantage of this method lies in its ability to detect and classify damage types in near real-time without relying on baseline datasets.

DEFINITION OF THE Λ RATIO

The Λ ratio is a frequency-domain parameter derived from the Hilbert-Huang Transform, designed to characterize the sharpness of energy concentration in response to structural impacts. It is defined as:

$$\Lambda = \frac{f_{Max\ Inst.\ Energy}}{f_{\frac{1}{\sqrt{2}}Max\ Inst.\ Energy,av}} \tag{1}$$

Where

- $f_{Max\ Inst.\ Energy}$ is the frequency at which the maximum instantaneous energy occurs (the spectral peak)
- $f_{\frac{1}{\sqrt{2}}Max\ Inst.\ Energy,av}$ is the average of the frequencies at which the instantaneous energy falls to 1/√2 of the maximum value, corresponding to the -3 dB point, commonly used in half-power bandwidth analysis.

This formulation of Λ reflects how tightly energy is localised around the frequency with higher instant energy content. The use of the 1/√2 threshold provides a standardized measure of spectral spread. By excluding energy contributions below this level, the Λ ratio becomes a robust indicator of spectral sharpness and energy dispersion, properties that tend to suddenly degrade in the presence of structural damage. The Λ ratio is sensitive to the concentration and spread of energy in the frequency domain. In a healthy, undamaged state, energy distribution is sharp and concentrated in specific natural frequencies that correspond to the structure's intrinsic modal properties, resulting in a higher Λ value. These frequencies are determined by parameters such as geometry, material stiffness, and boundary conditions, with the energy response peaking sharply around dominant modes and resulting in a narrow bandwidth. During an impact, structural damage, such as stiffness loss, local delamination, plastic deformation, or crack initiation, causes the energy spectrum to broaden or shift modal contributions, leading to a lower Λ value. The instantaneous energy spectrum, derived using Hilbert-Huang Transform, becomes broader and less concentrated after an impact, reflecting reduced spectral sharpness and increased frequency content due to structural degradation. This manifests as a widening of the energy peak, with the -3 dB point shifting to a wider frequency range as the energy takes longer to decay to 1/√2 of the peak, resulting in an increased denominator and a decreased Λ value. Thus, broader energy spread and lower Λ values indicate reduced frequency selectivity and degraded structural integrity, making the Λ ratio a quantifiable, damage-sensitive feature for impact evaluation.

HILBERT-HUANG TRANSFORM AND Λ EXTRACTION PROCEDURE

The calculation of Λ begins with decomposing the structural response signal into Intrinsic Mode Functions (IMFs) using Empirical Mode Decomposition (EMD). A function qualifies as an IMF if it satisfies two conditions: (1) the number of zero crossings and extrema are equal or differ by at most one, and (2) the mean of the envelopes defined by the local maxima and minima is zero. The EMD process is carried out through a sifting algorithm, in which local extrema are first identified, upper and lower envelopes are constructed using cubic spline interpolation, and their mean is subtracted from the signal. This iterative procedure isolates IMFs, each representing a distinct oscillatory mode at a specific time scale. The final residual, remaining after all IMFs have been extracted, represents any underlying trend or non-oscillatory component in the signal. The signal *x(t)* is thus represented as:

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \tag{2}$$

where $c_i(t)$ are the IMF and the r_n final residual. To stop the sifting [25-27], the standard deviation between successive iterations is monitored using:

$$SD = \sum_{t=0}^{T} \left[\frac{\left| h_{1(k-1)}(t) - h_{1k}(t) \right|^2}{h_{1(k-1)}^2(t)} \right] \tag{3}$$

Typically, sifting stops when SD < 0.2–0.3, or the residual becomes a monotonic function. Each IMF is then processed through the Hilbert Transform [25-27] to extract instantaneous frequency and energy values. From these, the instantaneous energy spectrum is constructed. The Hilbert-Huang Transform (HHT), which combines EMD and the Hilbert Transform, is well-suited for analyzing non-linear and non-stationary signals and can provide a more physically meaningful representation of such complex signals. After applying the Hilbert Transform to each IMF, the original signal can be reconstructed as:

$$x(t) = \Re\left\{\sum_{j=1}^{n} a_j(t)\mathrm{e}^{\left[i\int \omega_j(t)dt\right]}\right\} \tag{4}$$

This expression represents a 3-D representation of the amplitude as a function of frequency and time, known as the Hilbert spectrum *H(ω,t).* Here*, n* is the total number of Intrinsic Mode Functions (IMFs) obtained via Empirical Mode Decomposition (EMD), $a_j(t)$ the instantaneous amplitude of the j-th IMF, derived from the analytic signal derived via the Hilbert Transform, $\omega_j(t)$ is the instantaneous angular frequency of the j-th IMF, defined as $\omega_j(t)=d\theta\backslash dt$, where $\theta_j(t)$ is the instantaneous phase and $\Re\{\cdot\}$ denotes the real part of the complex-valued expression inside the brackets. The frequencies corresponding to the maximum energy and to $1/\sqrt{2}$ of that maximum are identified, and the Λ ratio is calculated using the defined formula. This approach allows Λ to capture both localized and global variations in the vibrational energy distribution, making it a reliable indicator for assessing structural condition. By applying HHT, instantaneous frequency variations induced by an impact can be identified, offering a clearer representation of damage onset and characteristics. In the case of structural health monitoring (SHM), this method can be used to assess whether damage has occurred following an impact, such as from bird strikes or tool drops. The adaptability of HHT allows for real-time assessment without the need for baseline data, making it highly effective for on-the-fly impact detection in composite and metallic structures.

RESULTS AND DISCUSSION

In this section, the results from the experimental campaign and retrieved data from [28] and [29] are discussed, highlighting the key insights gained.

COMPOSITE PLATE

The impacts on the composite plates were carried out at high velocities; the first did not cause perforation, while the other two resulted in structural perforation. The acquired signals and velocity for the three impacts are shown in Figure 1.

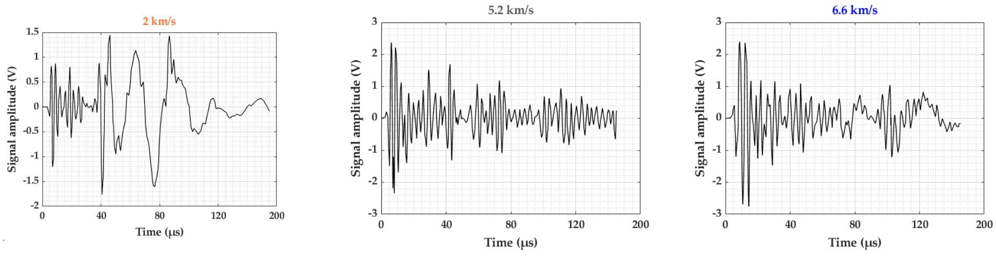

Figure 1. Signals acquired from impact tests on a composite plate at different speeds.

In the first plot (i.e., impact velocity of 2 km/s), the flexural component is predominant compared to the extensional one, but both are clearly excited by the impact, with the extensional mode characterised by higher frequency components. The amplitudes of the two modes are almost comparable, as shown in Figure 1. As the impact velocity increases to a level that induces perforation of the sample, the propagation modes change, and the extensional component becomes predominant, while the flexural part decreased substantially. This trend is consistent in both penetrating impacts, as depicted in Figure 1. Damage analysis was executed using the method introduced for decomposing the impact signals into extensional and flexural components. The bar chart, shown in Figure 2 displays the Λ values corresponding to three structural conditions: No Penetration, Penetration 1, and Penetration 2. This visual evidence shows that Λ is a sensitive and effective indicator of structural condition, as derived from Hilbert-Huang Transform (HHT) analysis. The chart reveals a progressive increase in Λ values, rising from approximately 1.2 in the No Penetration case to around 1.3 for Penetration 1, and peaking at about 1.8 in Penetration 2. This clear trend demonstrates that Λ responds to the severity of impact-induced damage. As the level of penetration increases, the vibrational energy distribution within the structure shifts accordingly, a change effectively captured by the decreasing Λ values. These results confirm that Λ is not only effective at detecting the presence of damage but also capable of assessing its severity. The significant decrease in Λ from Penetration 1 to Penetration 2, - 60%, highlights the non-linear progression of structural degradation and underlines the importance of using adaptive techniques like HHT to capture such variations. From the output data of the evaluated Hilbert spectrum, the damage descriptor Ξ, introduced in a previous work from the authors [24] and defined as

$$\Xi = \frac{E_{i,max,extensional}}{E_{i,max,flexural}} \tag{5}$$

was calculated and is reported in Figure 3. The rationale behind mentioning Ξ is to validate the results obtained with the novel introduced parameter Λ.

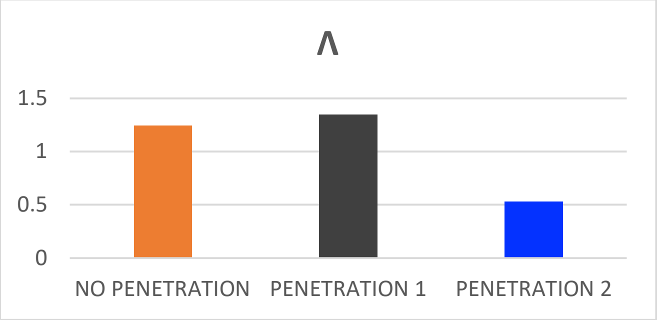

Figure 2. Λ parameter for the three impact cases.

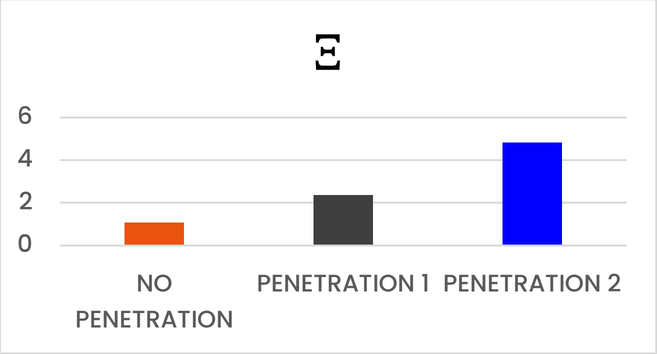

Figure 3. Ξ values for the three impact tests on CFRP plate.

As the impact velocity increases and the specimen undergoes penetration, the Ξ-parameter rises above one. This increase is attributed to changes in the modal propagation characteristics. Specifically, the extensional mode becomes dominant, as illustrated in **Error! Reference source not found.** to **Error! Reference source not found.**. The observed rise in Ξ, up to a 350% increase, correlates with the onset of severe structural damage. This observation is consistent with existing literature, which reports that during full penetration events, the flexural mode diminishes significantly while the extensional mode prevails. The results show that the behaviour of both the Λ and Ξ parameters offers a method for characterising damage during an impact and potentially its severity.

COMPOSITE BLADE

The data were retrieved from impacts on a downscaled CFRP blade with a complex stacking sequence representative of real aerospace components [29]. Two main impact scenarios were tested: one at a projectile velocity of 90 meters per second and the other at 190 meters per second. Each scenario followed a consistent sequence of pre-impact modal excitation, impact testing with the gelatin projectile, and post-impact modal analysis. An example of the applied method to decompose the signal is shown in Figure 4 where the original signal is decomposed into the extensional and flexural components. By applying the HHT approach the parameter Λ could be plotted and the results are shown in Figure 5. It can be observed how the frequency range is differently spread between impacts. From the plot, clear trends emerge regarding the structural response under different impact conditions. In the 90 m/s test, the Λ values remain relatively stable before and after impact, indicating minimal changes in the frequency response of the structure. This consistency aligns with expectations for an elastic impact, where no permanent damage is measured.

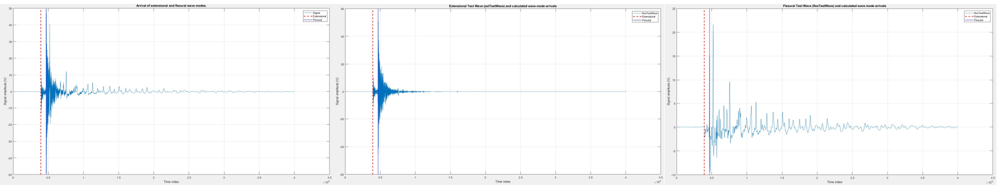
a) b) c)

Figure 4. Voltage Vs Time a) Original signal b) Extensional component c) Flexural component

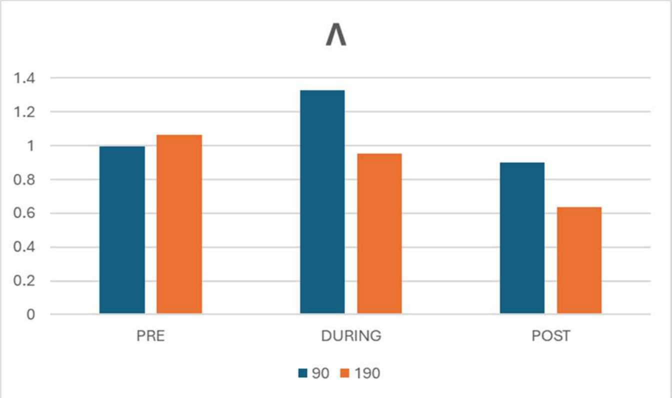

Figure 5. Λ values for the three impact tests on CFRP blade.

The frequency content remains sharply concentrated, confirming the structural integrity of the specimen. In contrast, the 190 m/s impact reveals more pronounced changes. The Λ value during the pre-impact hammer test is similar to that of the 90 m/s case, suggesting the structure was initially undamaged. During the impact, Λ decreases by approximately 10%, indicating the onset of potential damage. This reduction becomes even more significant in the post-impact hammer test, where Λ drops by nearly 40% compared to the pre-impact value. This substantial decline reflects a broadened frequency bandwidth, which is typically a result of mode scattering and energy dissipation caused by material damage such as delamination or micro-cracking. To confirm the validity of the approach, the blade was ultrasonically inspected before and after impacts at 90 and 190 km/s. These findings confirm that the high-velocity impact introduced critical damage to the structure, hence irreversible changes in the structural response of the blade, as evidenced by changes in the proposed Λ parameter.

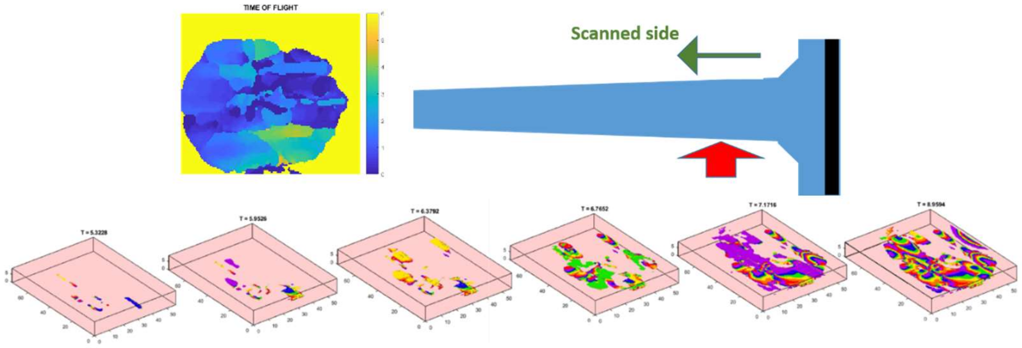

Figure 6. Phased array results for impact test at 190 km/h on the CFRP blade.

CONCLUSIONS

In this work, an alternative, baseline-free, real-time structural health monitoring (SHM) approach is proposed to enable immediate assessment of damage initiation during impact events. Unlike traditional methods that rely on pre-impact reference data, this technique allows for in-situ evaluation without requiring extensive prior baseline measurements. The method detects and characterises damage by decomposing recorded Lamb wave signals using the Hilbert-Huang Transform (HHT). Two distinct experimental datasets were analysed, each featuring varying impact scenarios and specimen configurations, to assess the robustness of the method. Central to the analysis is the introduction of a frequency-domain, damage-sensitive parameter, Λ, derived from the HHT and designed to characterise the sharpness of energy concentration in response to structural impacts. This parameter provides a reliable means of distinguishing between elastic (non-damaging) and damaging impacts. The experimental results reveal a clear increase in spectral broadening following damage, indicating a redistribution of energy across a wider frequency range. This shift reflects increased wave scattering and reduced structural integrity. These findings confirm the effectiveness of the Λ parameter as a robust, real-time indicator for detecting and characterising impact-induced damage. Future research works will involve a comprehensive experimental campaign aimed at validating the method and ascertaining statistical significance for the findings.

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