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Hilbert-Huang Transform (HHT) transient analysis of composite panel undergoing high-velocity impact†

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Abstract

Fast Fourier transform (FFT) has been widely used to analyze distribution patterns of frequency components in dynamic response signals. Given a stationary dynamic response signal, a fixed frequency distribution pattern can be obtained efficiently using FFT. If the system of concern is not stationary, however, the frequency distribution pattern varies with time, and the variation in that pattern cannot be effectively determined via FFT. To overcome this weakness, time-frequency dual-domain signal analysis methods such as wavelet transform and Hilbert-Huang transform (HHT) have been introduced. HHT has been shown to be particularly effective in analysis of non-stationary signals obtained from non-linear as well as linear systems. In the present study, the transient characteristics of a composite panel undergoing high-velocity impact were investigated. The composite panel, along with the colliding bullet, were modeled using the finite element method. To verify the reliability of the analysis model, an impact experiment was carried out, which proved that the model provides reliable, similar-to-experimental results.

Keywords: Composite panel; High-velocity impact; Transient characteristic; Hilbert-Huang transform; Experimental verification

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1. Introduction

The transient characteristics of the protection panels of land vehicles have received sustained research attention. During the past few decades, several researchers have investigated the dynamic behavior of protection panels undergoing impact, in order to enhance their impact energy absorption characteristics. In investigating energy absorption characteristics, the first steps should be to obtain the transient responses of the panel undergoing high-velocity impact and to examine them using a signal analysis method.

In early studies, fast Fourier transform (FFT) was the most widely employed method for analyzing the distribution of frequency component distributions in a signal. To use FFT effectively, however, the signal of concern must be stationary. Unfortunately, signals obtained from dynamic analysis are often non-stationary and even non-linear. To address this issue, time-frequency dual-domain analysis methods, which can simultaneously provide time and frequency information for a signal by mapping the one-dimensional signal to a two-dimensional time-frequency plane, were introduced.

Wavelet transform is one such time-frequency dual-domain analysis method finding wide application in analysis of transient signals. However, the commonly used Morlet wavelet suffers many of the same shortcomings as FFT, and provides physically meaningful interpretations only for linear phenomena. When wavelet transform methods are applied to non-linear problems, the result often exhibits border distortion, energy leakage [1], and other undesirable phenomena that make interpretation difficult. To overcome these shortcomings, an alternative time-frequency dual-domain analysis method was introduced, namely Hilbert-Huang transform (HHT) [2, 3]. HHT consists of two main processes: Empirical Mode Decomposition (EMD) and a Hilbert transform. The EMD decomposes the random signal into several mono-component signals called intrinsic mode functions (IMFs). HHT possesses several advantages over wavelet transform, including high resolution and the capacity not only to handle large data sets but also, and most attractively, to analyze non-linear signals. HHT has thus been widely adopted in many practical applications, such as identification of underwater noises [4], wear detection in gear systems [5], earthquake motion recording [6], geophysical science [7], non-linear structural dynamics [8] and mechanical signal interpretation [9].

Since determination of the dynamics of a panel undergoing high-velocity impact is a long-standing problem, a great amount of research (see, for instance, Refs. [10-17]), both

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experimental and analytical, has been performed. Most of the previous work, however, focused on plastic deformation of a panel during impact. Penetration, in particular, was the most widely studied subject in this previous work. Additionally, in some previous studies, analysis models for composite structures were developed. However, the transient frequency response characteristics of structures undergoing impact were rarely investigated.

The purpose of the present study was to develop a reliable analysis model and to investigate the time-varying frequency response characteristics of a multi-layer composite panel undergoing high-velocity impact. The structural system was modeled using a non-linear finite element method to obtain impact analysis results. To verify the accuracy and reliability of the finite element model, these analysis results were compared with experimental results. The comparison was performed using time-frequency dual-domain signals obtained using HHT. Incidentally, to show the superiority of HHT over wavelet transform, time-frequency dual-domain results also were obtained using wavelet transform, and these were compared to those for HHT.

2. Hilbert-Huang Transform (HHT)

HHT, as already mentioned, is widely known for its effectiveness in analysis of non-stationary and non-linear signals. And employing HHT for signal analysis, again, entails two steps. First, the signal is decomposed into several mono-component signals using the EMD method. For each mono-component signal, the time derivative of the instantaneous phase $\phi(t)$ obtained from the Hilbert transform is the instantaneous frequency $\omega(t)$. Second, the well-known Hilbert transform is applied to these decomposed signals. If the original and the transformed signals are denoted as $x(t)$ and $y(t)$, the Hilbert transform (see Ref. [2]) can be defined as

$$y(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \ . \tag{1}$$

Then, the analytical signal $z(t)$ is obtained as

$$z(t) = x(t) + iy(t) = \alpha(t)e^{i\phi(t)} . \tag{2}$$

Here,

$$\begin{aligned} \alpha(t) &= \left[x^2(t) + y^2(t)\right]^{1/2} \\ \phi(t) &= \arctan\left[y(t)/x(t)\right] \end{aligned} \tag{3}$$

where $\alpha(t)$ and $\phi(t)$ are the instantaneous amplitude and phase, respectively. If $x(t)$ is a mono-component signal, the time derivative of the instantaneous phase $\phi(t)$ is the instantaneous frequency $\omega(t)$. The frequency can then be obtained as

$$\omega(t) = \frac{d\phi(t)}{dt} \ . \tag{4}$$

However, in practical applications, most signals are multi-component; thus $\omega(t)$ in most cases cannot be obtained directly via Hilbert transform. To obtain instantaneous frequency information from signals arising in practical contexts, Huang et al. [2] introduced EMD, by which a signal can be represented as the sum of several mono-component IMFs. An IMF satisfies two conditions: (1) in the entire data set, the number of extrema and the number of zero crossings must differ by at most one; and (2) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero. The EMD process can be summarized as follows:

(1) Interpolate the local maxima by cubic spline lines to form the upper envelope of the signal $x(t)$.

(2) Interpolate the local minima by cubic spline lines to form the lower envelope of $x(t)$.

(3) Calculate the mean $m(t)$ of the upper and lower envelopes.

(4) Calculate $h(t)$ by the equation

$$h(t) = x(t) - m(t) ; \tag{5}$$

if $h(t)$ satisfies the two conditions mentioned previously, the first IMF $c_1(t)$ can be obtained as

$$c_1(t) = h(t) \ . \tag{6}$$

(5) $r_1(t)$ is defined as

(7)

$$x_2(t) = r_1(t) ; \tag{8}$$

now, $x_2(t)$ is the signal to be decomposed. Repeat steps (1) through (5) until a residue $r_n(t)$ is obtained that does not satisfy the IMF conditions. Once n IMFs have been obtained, the original signal $x(t)$ can be recovered by using the IMFs as follows:

$$x(t) = \sum_{i=1}^{n} c_i(t) + r_n(t) \ . \tag{9}$$

3. Experimental condition and FE modeling

The given dimensions of the integrated composite panel under consideration were 500 mm × 500 mm × 38.7 mm. The materials and thicknesses of the layers of the panel are listed in Table 1. An aluminum bullet of 10 mm radius and 50 mm length was fired at a velocity of 474 m/s towards the center of the panel, as shown in Fig. 1. The green structure in the figure represents the composite panel, and the red line indicates the direction of impact. The analysis conditions are summarized in Table 2, while the material properties of the composite

Table 1. Thicknesses of composite panel layers.

Structure	Materials	Thickness [mm]
Composite panel layers	S2 Glass	8.00
	Rubber	15.0
	Aluminum Foam	3.00
	Aluminum	12.7

Table 2. Parameters for experiment and FE analysis.

Test parameter	Value
Impact velocity	474 m/s
Time step	0.02 ms
Simulation time	10 ms
Sampling frequency	50000 Hz

Table 3. Material properties of panel layers and bullet.

Property	Composite panel layers				Bullet
	S2 Glass	Rubber	Aluminum Foam	Alumi-num	Aluminum
Young's modulus [GPa]	29.9	1.24	68.9	69.6	68.9
Density $[kg/m^3]$	2027	1200	300	2730	2710

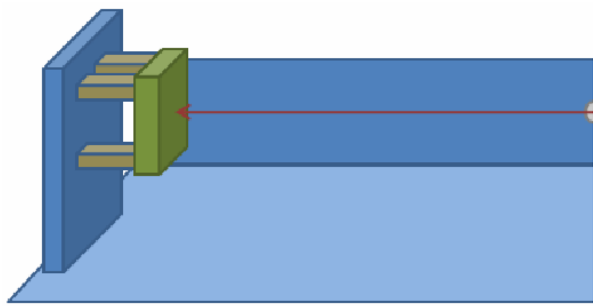

Fig. 1. Composite panel undergoing high-velocity impact.

panel layers and the bullet are given in Table 3.

The dynamic response of the panel under impact was highly non-linear, because it underwent plastic deformation. To obtain the simulation results, LS-DYNA, a commercial FE software package, was employed. The composite panel and the bullet were modeled with solid elements; to simulate the plastic deformation occurring during impact, the panel material was represented as a plastic. Fig. 2 shows the FE models of the composite panel and the bullet. The number of solid elements employed for the panel and the bullet were 16 384 and 640, respectively. The acceleration signal was measured from the rear of the panel, at a location indicated by the red dot in Fig. 3.

4. Results of analysis and experiment

Fig. 4 shows the acceleration signals obtained from the experiment and the FE analysis. Whereas these two results seem to be in reasonable agreement, only the magnitudes of the acceleration can be compared. To compare the frequencies arising in the two signals, the time-domain signals should be transformed into frequency-domain signals. Fig. 5 illustrates the results of the application of FFT to the two signals. The figure shows that the overall frequency component distribution patterns of the two signals were quite similar, even though some differences were visible in the frequency range of approximately 3 kHz to 4 kHz. Even though the FFT provides the overall distribution pattern of frequency components, it cannot provide time-varying information. In particular, transient vibration signals obtained from impact experiments constitute a typical example of a signal type for which we would

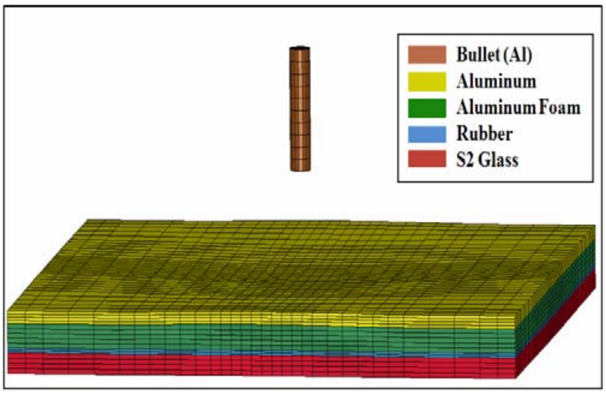

Fig. 2. FE models of bullet and composite panel using SOLID elements.

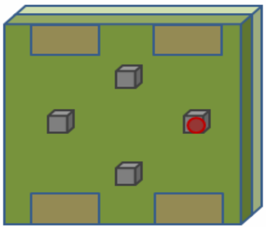

Fig. 3. Location of point where vibration signal measured.

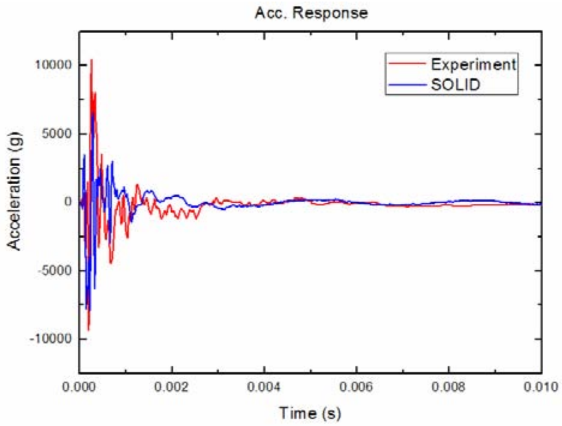

Fig. 4. Comparison of two acceleration signals.

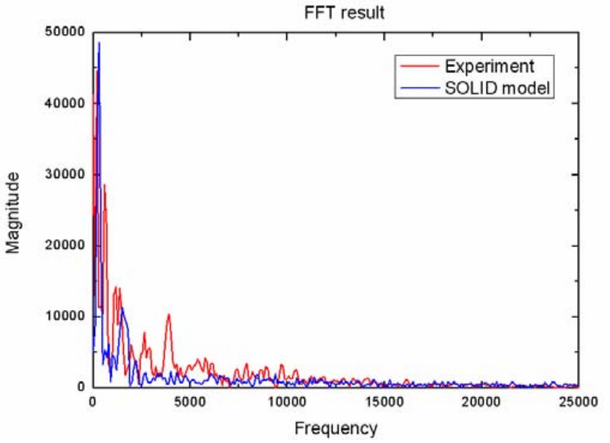

Fig. 5. Comparison of two FFT results.

like to obtain the frequency component distribution pattern but for which FFT analysis does not suffice. To obtain these time-varying frequency response characteristics, time-domain signals must be transformed into time-frequency dual-domain signals.

Figs. 6 and 7 show the results of HHT applied to transient vibration signals (acceleration) obtained from the experiment and from the FE analysis. The HHT results provide information related to the time, frequency, and power of the signal. In the figures, the horizontal axis denotes the time and the vertical axis, the frequency; the color represents the power density of the signal. It is readily apparent that the two signals have similar tendencies in the time and frequency domains. Moreover, these results show that the components with frequencies exceeding approximately 5 kHz nearly disappear within 1 ms of impact. Certainly, the frequency-wise damping characteristics of the multi-layer panel are clearly visible.

Fig. 8 shows the results of the wavelet transform applied to the acceleration response obtained from the FE simulation, using the Morlet wavelet function. As the figure shows, the wavelet transform result is not as clear as the corresponding HHT result shown in Fig. 7.

It is well known (see [1]) that wavelet transform often provides smeared results for non-linear systems, such as that shown in this plot, though it can provide good results for linear systems. Thus, for transient responses arising in non-linear systems, Hilbert-Huang transform can provide better results with improved resolution. Fig. 9 shows the frequency components below 4000 Hz in the FE simulation result. It can be seen that the energy contained in the frequency components above 500 Hz attenuates rapidly within 3 ms. By contrast, the energy contained in the low-frequency components remains high over a much longer period. These results show that the multi-layer composite panel is very effective in absorbing high-frequency components. This characteristic of the panel is very desirable, as in most cases, high-frequency vibration energy is much more dangerous to crew and equipment.

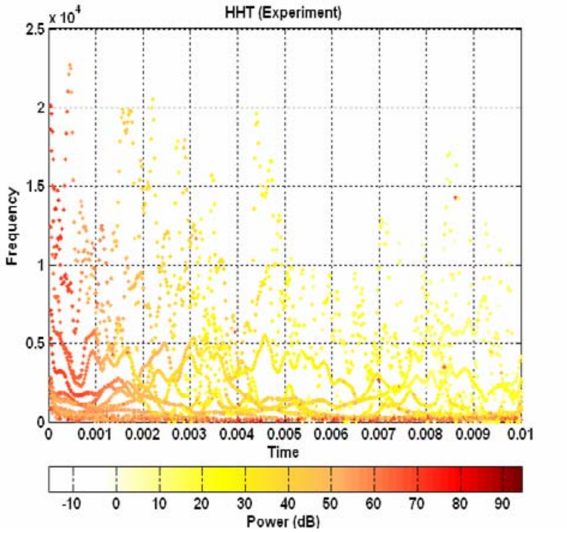

Fig. 6. HHT results of experiment.

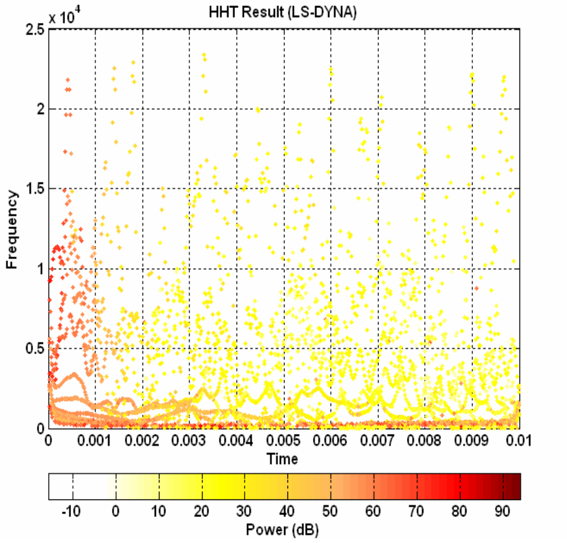

Fig. 7. HHT results of FE analysis.

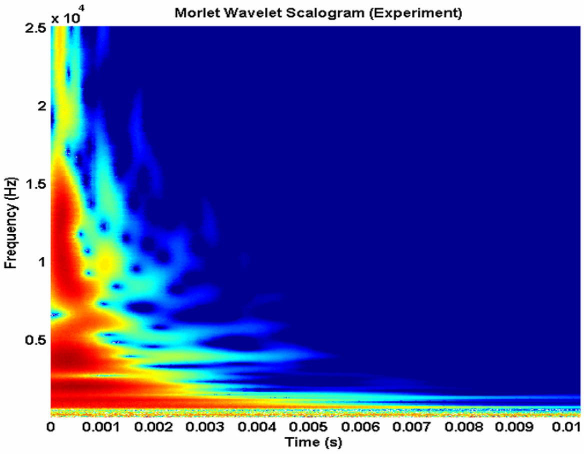

Fig. 8. Wavelet transform results for acceleration signal.

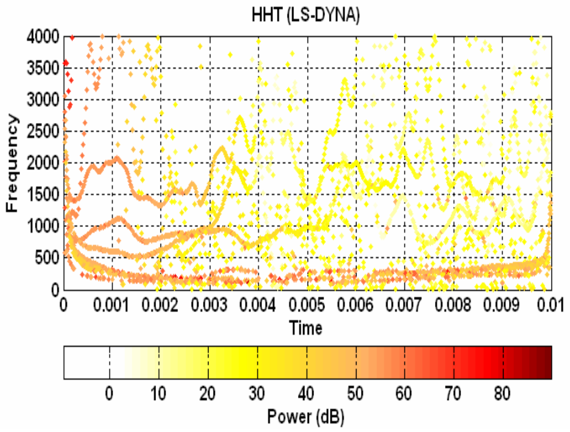

Fig. 9. HHT results under 4 kHzFE analysis.

5. Conclusions

The transient frequency response characteristics of a multi-layer panel undergoing high-velocity impact were investigated. Impact tests and an FE analysis of the panel were carried out, and the reliability of the FE analysis model was verified through a comparison study. Since such multi-layer panels undergo high-velocity impact, non-linear plastic deformation occurs. To analyze the transient frequency response characteristics of the non-linear response, Hilbert-Huang transform (HHT) was employed. The HHT results applied to the FE analysis were in reasonably good agreement with the experimental results. Using HHT, the signal characteristics could be analyzed effectively over the dual time and frequency domains. Lastly, to demonstrate the superiority of HHT over wavelet transform, the two transformed results of the impact analysis were compared, which showed that HHT indeed provides better results and with higher resolution than does wavelet transform.

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