APPLICATIONS OF COMMON REAL-TIME IDENTIFICATION OF DYNAMIC CHARACTERISTICS FOR OFFSHORE STRUCTURES

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Abstract

The dynamic behavior of offshore structures becomes complex due to the effect of the combination of marine environmental and operational conditions. There are some damages and failures that need to be detected early to establish a suitable maintenance strategy. Therefore, the online structural health monitoring (SHM) system has been investigated and developed continuously to ensure safety performance by timely warning. The SHM requires a suitable real-time identification of dynamic characteristics of offshore jacket structure. This article presents a discussion of the advantages, disadvantages, and development trends of existing real-time identification systems and techniques commonly applied to offshore jacket structures. The main identifications in the real-time domain methods including the Short-Time Fourier Transform (STFT), Wavelet Transform (WT) and Hilbert Huang transform (HHT) techniques in predicting dynamic characteristics were also discussed and evaluated. Meanwhile, HHT is the most suitable identification method for real-time identification methods in SHM of offshore jacket structures.

Keywords: *Offshore structure; dynamic characteristic; real-time identification; Hilbert Huang transform (HHT).*

1. Introduction

In recent years, health monitoring systems of fixed offshores and wind turbine engineering have received more attention from researchers and engineers. They provide owners and maintenance organization with useful advice in order to ensure the safety of operations and to reduce economic losses. The fixed jacket structure has been widely used in supporting the offshore platforms or wind turbine power [1]. However, the offshore structures are usually faced with a complex marine environment including waves, currents, wind and/or machine operation. In order to ensure their safety during service life, structural health monitoring (SHM) of offshore structures has been improved by developing the real-time warning system.

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SHM systems are typically based on the identification of dynamic characteristics including the natural frequency, modal damping and modal shape. The identifications are based on the combination of the structural response vibration measurement and signal processing algorithm [2]. The structural responses such as acceleration, velocity, and displacement are measured at site, and then processed by signal techniques to predict the variation of dynamic characteristics due to the structural deterioration, damage and scouring of the pile foundation... Mangal *et al.* [3] and Nichols [4] used the impulse and relaxation method to identify the natural frequencies of offshore platform. Hillis and Courtney [5] applied the response vibration measurement based on the bicoherence method to investigate the change in offshore structure stiffness. Mojtahedi *et al.* [6] combined the fuzzy logic system, model updating method and vibration measurement analysis to detect the nonlinearity behavior of the offshore jacket structure. These researches applied simple signal processing technique DFT (Discrete Fourier Transform) and FFT (Fast Fourier Transform) in a frequency domain. These techniques are difficult to apply to the online SHM.

Recently, some researches improved advantaged real-time identifications of dynamic characteristics for the offshore structures to meet the requirements of online SHM [7]. For the real-time prediction to be conducted in the online SHM, the dynamic characteristics must be identified and performed in the time domain. The modal parameters of structure varying over time are identified by some signal processing techniques including a Short-Time Fourier Transform (STFT), a Wavelet Transform (WT) [8-11], and a Hilbert Huang transform (HHT) [12-16]. Sherif *et al.* [17] applied the WT technique to detect the damage of structure varying in time and Min and Sun [18] also used the wavelet method to obtain instantaneous modal parameters of structure. Liu [19] used the HHT to determine the dynamic characteristics of the offshore platform in the time domain. Trung [20] and Trung *et al.* [21] proposed the improved HHT method using the decomposition techniques of vibration signals including EEMD (Ensemble Empirical Mode Decomposition) and iEEMD (improved Ensemble Empirical Mode Decomposition) to predict the modal parameters of fixed offshore structure under wave condition.

As a result, signal processing algorithms used for current SHM systems have many processing methods, however, their processing results are in the frequency domain, have no continuity over time, or only remove noise terms and then transmit directly, without the step of identifying the structural parameters [7, 22, 23]. Therefore, this paper summarized and evaluated some advanced signal processing methods used in the real-time identification of dynamic characteristics of offshore jacket structures. It could be convenient for engineers and experts to collect and develop a suitable method for establishing the online SHM.

2. Structural health monitoring using identification of dynamic characteristics

In general, a typical online SHM system using the dynamic response measurement is shown in Fig. 1. The measurement method includes:

1) Onsite measurement system: The measurement system includes sensors, data acquisition and data storage. The sensors are installed in some suitable locations in the offshore structure to measure the acceleration response. Then, the acquisition equipment received and transformed the response data. The data could be recorded in the computer storage, as shown in Fig. 1.

2) Operator center: The operator center is located on land to receive the data from onsite measurement system by internet connection. The response signal data would be processed and evaluated by using the processing algorithms such as STFT, WT and HHT to identify the dynamic characteristics of offshore structures in time domain. The processed data is recorded and arranged in the website server, as shown in Fig. 1.

3) Online monitoring system: The online monitoring system is an internet-connected device system including the computer and smartphone controlled by engineers, owners and interested persons. They could monitor the structural technical status by the performance of dynamic characteristics of the offshore structure, as shown in Fig. 1.

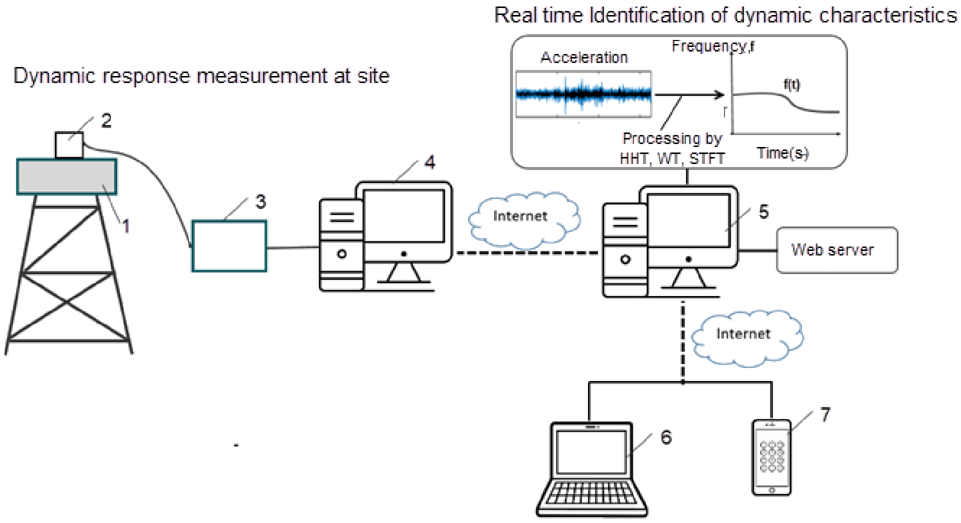


Fig. 1. Online structural health monitoring (SHM) for the offshore structure:

1) Topside of jacket structure; 2) Accelerometer, 3) Acquisition equipment; 4) Computer at offshore site; 5) Computer in land; 6) Personal computer; 7) Smart phone.

A decisive step for the online health monitoring infrastructure is to identify dynamic characteristics such as natural frequencies, modal shapes, and damping ratio from vibration measured responses. The change of fundamental natural frequencies, modal shape and damping ratio is a basis to evaluate the deterioration of the offshore structures in general.

Deterioration of structural properties is predicted by changes in the fundamental natural frequency of structure has been the driving force in SHM. Loan and Dodds [24] used changes in resonant frequencies, modal shapes, and response spectra to determine damage to the offshore platform. Frequency changes of 10% to 15% were observed when structural damage occurred near the water level. Depending on the deterioration, the effect of local damage and others, the changes in natural frequency of offshore structure may vary during service life.

Variation of modal shape could be used to locate damage with acceptable accuracy. However, it is unknown whether this method can be applied to real structures because the number of modal shapes and natural frequencies that can be reliably determined experimentally is quite limited. Carrasco *et al.* [25] studied the modal strain energy for damage determination and demonstrated that the modal strain energy method performs very well for detecting the damage locations, and failures of structures.

The damping ratio is also one of the dynamic characteristics of offshore structures. The damping coefficient of the offshore structure is combined by the structural modal damping, viscous fluid damping and radiation damping (wave making damping) [26]. The effect of the damping is significant to the vibration response of the offshore structure. The damping ratio is predicted by the half-power bandwidth technique of the peak picking method [27].

3. Real time techniques

The success of online SHM is based on the identification of dynamic characteristics of the offshore structure in real time. The accuracy of identification and performance of the dynamic behavior of the structure depends on the quality of the signal processing algorithm from the vibration response of the structure in a time domain. Therefore, this section proposes some main signal processing techniques for identifying the dynamic characteristics varying over time.

3.1. Short-time Fourier transform

The STFT is based on the Fourier transform (FT) algorithm. To identify the instantaneous frequency of structure using STFT, the identification procedure is conducted as follows:

1) The measured response vibration signal at site is divided into short segments in a narrow time.

2) Then each divided segment is processed by FT and performed by a window size. Fig. 2 shows the identified time-frequency segments by FT, specified by windowed segments.

3) All of the windowed segments by FT are simultaneously combined in a time domain using the Eq. (1). As a result, the instantaneous frequency of the structure is established by windowed segments.

Nasser [28] proposed the equation to identify the instantaneous frequency as follows:

$$\begin{cases} X_{STFT}[m,n] = \sum_{k=0}^{L-1} x[k]g[k-m]e^{-j2\pi nk/L} \\ x[k] = \sum_{m}\sum_{n} X_{STFT}[m,n]g[k-m]e^{-j2\pi nk/L} \end{cases} \quad (1)$$

where $x[k]$ denotes an original signal and $g[k]$ denotes an L-point windowed segment function. The STFT of $x[k]$ can be interpreted as the Fourier transform of the product of $x[k]$ and $g[k–m]$, as shown in Eq. (1). Fig. 2 illustrates the function of STFT by taking Fourier transforms of a windowed segment signal.

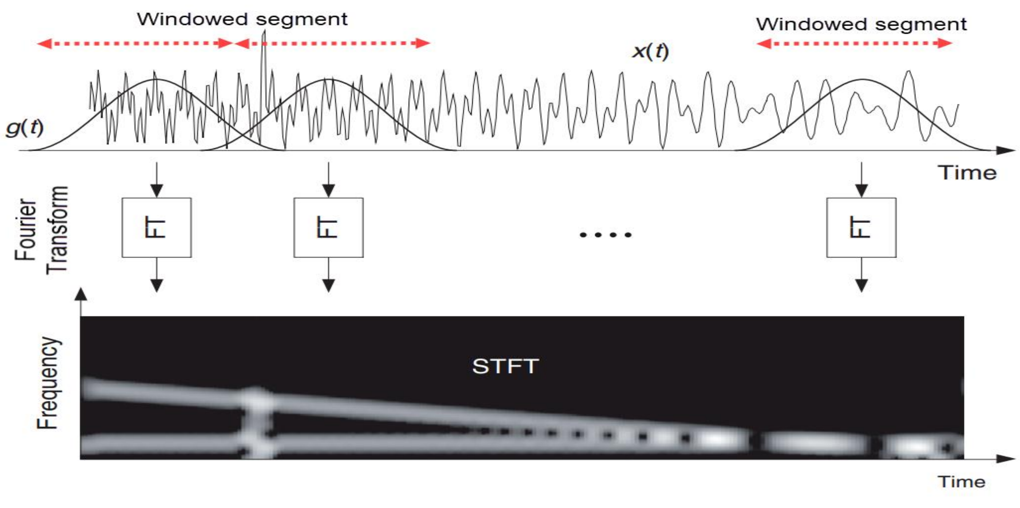


Fig. 2. Frequency in time domain by using STFT technique [16].

In STFT, the selection of windowed segment has an important role. The segment should be narrow enough to ensure that the processing signal is suitable for stationary data of the FT algorithm. However, the narrow windowed signal segment does not contain good information of structure in the frequency domain. Otherwise, if the selected segment is in a long band, performance of frequency in time domain becomes unclearly. This is a limitation of STFT in processing the vibration signal of the offshore structure in a nonstationary condition.

3.2. Wavelet transform

Wavelet transform is an advanced time-frequency analysis technique and designed for non-stationary time signals of linear systems in recent two decades. Wavelet analysis requires an advanced STFT method with adjustable time-varying windows. WT represents signals with energy-concentrated functions instead of sized window segment functions which are used in STFT [10, 11, 29].

For its flexibility in choosing the window length, wavelet analysis provides details and approximations of the temporal signal at many levels and retains the instantaneous properties of the signal series with the spectrum decomposition of frequency in a time domain.

The WT is an integral of the analyzed signal $x(t)$ and the initial wavelet function [30] as follows:

$$w(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty}x(t)\Psi^{*}\left(\frac{b-t}{a}\right)dt \tag{2}$$

where a, b are temporal scale and location parameters; $w(a,b)$ is the wavelet coefficient which represents the comparison between the original wavelet expansion and shift and the signal at time b and scale a. $\Psi^{*}\left(\frac{b-t}{a}\right)$ represents a complex conjugate function (mother wavelet) and is chosen to serve as a prototype for basis functions (son wavelet) in the process, as described in Fig. 3. Fig. 3 shows some functions used for this purpose such as Gaussian, Mexican Hat, Haar, and Morlet functions. The distribution of wavelet coefficients in the time-frequency plane can be used for time-frequency analysis.

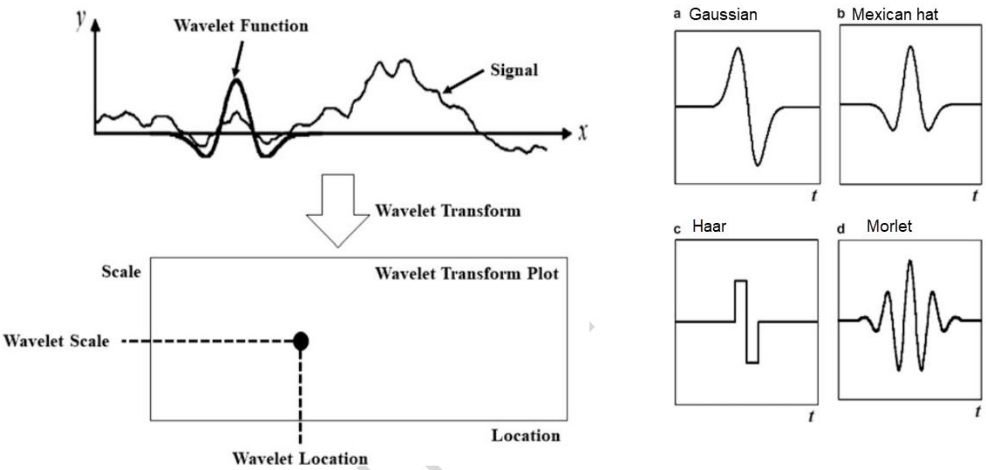


Fig. 3. Wavelet function transformation [17].

Three are some main steps to determine the instantaneous natural frequency of structure using the WT method:

1) Based on the length of measured vibration response and noises, select the suitable son wavelet functions: Gaussian, Mexican Hat, Haar, and Morlet. The Morlet function is suggested in this study due to its capabilities in time-frequency localization.

2) Using Eq. (2) to decompose the vibration response signal into wavelet coefficient $w(a,b)$ based on the selected son wavelet functions.

3) Based on the processed response signal by WT, determine time-varying amplitude and phase angle parameters. The instantaneous frequency and damping of the structure are identified based on these parameters.

Actually, WT is more interesting in analyzing the non-stationary signals than STFT. It could collect short windows at high frequencies and long windows at low frequencies, so WT had good resolution and high performance for visualization. However, the limitation of WT is suitable to the process of linear signal series. The vibration responses of the offshore structure are usually complicated due to the ultimate effect of the marine environment, the response is a non-stationary and nonlinear data.

3.3. Hilbert Huang Transform using empirical model decomposition technique

Hilbert Huang transform method is one of the most advanced signal processing techniques in processing the nonstationary and nonlinear data series. It is a combination of the EMD and Hilbert spectral analysis (HSA) [22, 23, 31].

a) Empirical Mode Decomposition

Huang *et al.* [12] introduced a new sifting process method named EMD. The EMD is used to decompose the vibration signal into a series of band-limited quasi-stationary signals called IMFs. IMFs are in the narrow band passed signals which are suitable to the Hilbert transform in the processing procedure. The process for obtaining each IMF is called the sifting process, which is described as follows:

1) Specify all the local extrema, and then connect all the local maxima by a cubic spline as the upper envelope. Repeat the procedure for the minima to produce the lower envelope. The upper and lower envelopes should cover all the data. If the mean is designated as m_1, the difference between the data and m_1 is the first component h_1, then:

$$h_1 = x(t) - m_1 \tag{3}$$

where h_1 is an IMF, the mean m_1 is given by the sum of local extrema connected by the cubic spline.

Figure 4 describes that the data (blue) upper and lower envelopes (green) defined by the local maxima and minima, respectively, and the mean value of the upper and lower envelopes given in red.

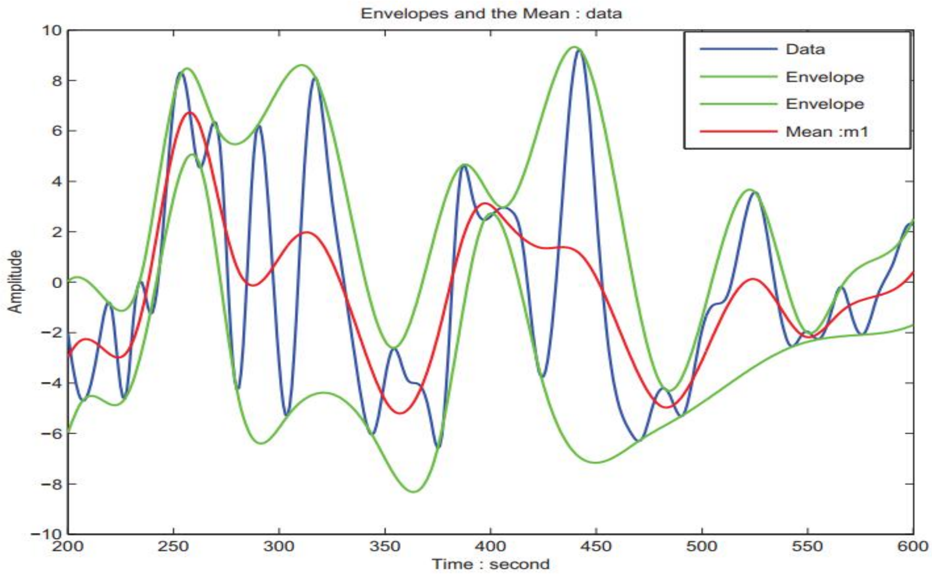


Fig. 4. The cubic spline upper and the lower envelopes and their mean, m_1 [6].

2) The sifting process is conducted to eliminate riding waves, and to make the wave profiles more symmetric. Treating h_1 as a new set of data, a new mean is obtained:

$$h_1 - m_{11} = h_{11} \tag{4}$$

After repeating the sifting process up to k times, h_1 becomes a new IMF as follows:

$$h_{1(k-1)} - m_{1k} = h_{1k} \tag{5}$$

3) After the first IMF1 is obtained, subtract c_1 from the original signal $x(t)$ and calculate the residue signal as follows:

$$x(t) - c_1 = r_1 \tag{6}$$

4) Treating r_1 as the original signal and repeat the procedure from step (1) to step (4) to obtain the other IMF (c_2, c_3,…, c_n). The process is stopped when the final residual signal $r_{n(t)}$ is a monotonic function.

$$r_1 - c_2 = r_2, \ldots, r_{n-1} - c_n = r_n \tag{7}$$

5) At the end of the procedure, the oscillation signal $x(t)$ is decomposed into n intrinsic modes $c_i(t)$ and a residue $r_n(t)$:

$$x(t) = \sum_{i=1}^{n} c_1(t) + r_n(t) \tag{8}$$

The Hilbert Transform of the i^{th} IMF segment, c_i is determined by:

$$h_i(t) = \frac{1}{\pi} PV \int \frac{c_i(\tau)}{t-\tau} \tag{9}$$

where *PV* denotes the Cauchy principal value, and its analytic signal.

The instantaneous frequency, $\omega_i(t)$, for each IMF component can be defined as follows:

$$\omega_i(t) = \frac{d\theta_i(t)}{dt} \tag{10}$$

4. A study case using the Huang Hilbert transform

The HHT is the most suitable technique to identify the complex natural frequencies of the offshore structure during wave condition. Its advantages have been proved by many previous researches [19, 20]. Therefore, this section briefly describes a study case suggested by self-author *et al.* [21] using HHT to identify the fundamental natural frequency of fixed offshore structures in a time domain.

4.1. Vibration test

A vibration test was conducted on the test model of four legged-steel fixed jacket offshore structure in wave tank, as shown in Fig. 5.

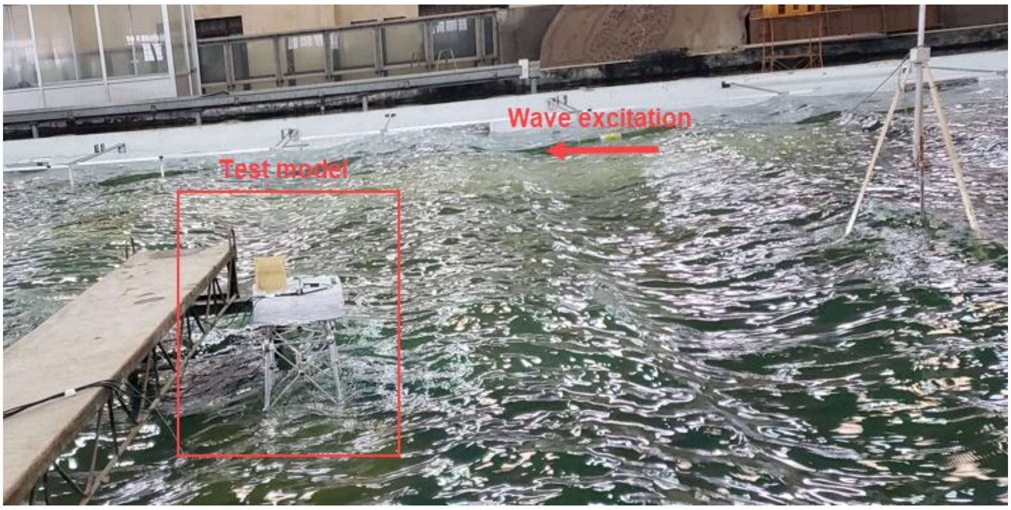


Fig. 5. The vibration test of offshore structure in the wave tank [10].

The tubular beams of the jacket structure were made of acrylic material and the topside of the superstructure was made of concrete. The test used the similarity law of 1/60 for the length scale and 1/65 for the Young modulus scale. The test model was excited by a regular wave in the wave tank. The accelerator sensors were installed at the top of the test model to receive a good vibration response from the structure. The accelerometers were connected to acquisition system to record and perform the response data.

4.2. Results

The original acceleration time history was recorded at the topside of the test model of offshore structure, as shown in Fig. 6.

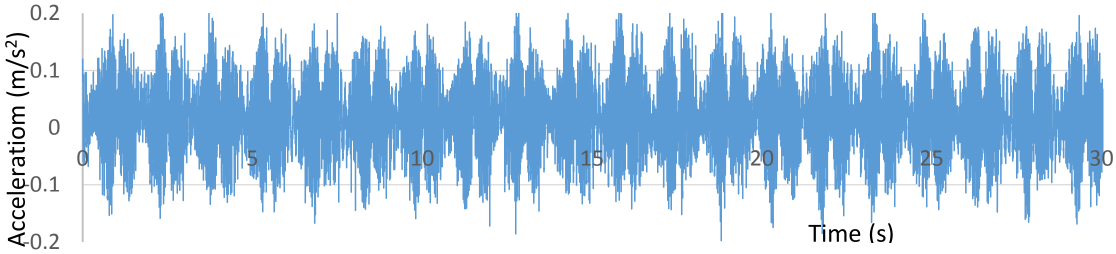


Fig. 6. Original acceleration response time history measured at the topside of test model under a sine wave [10].

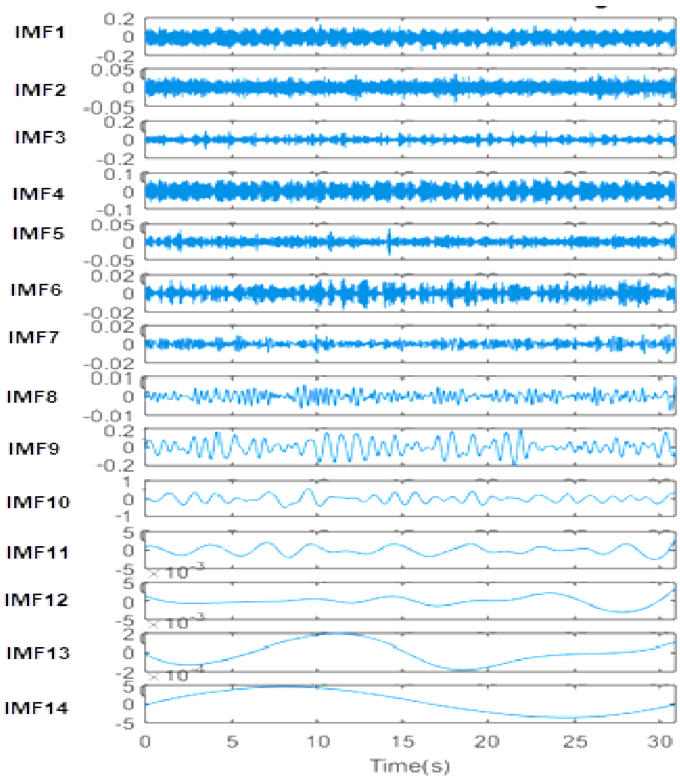
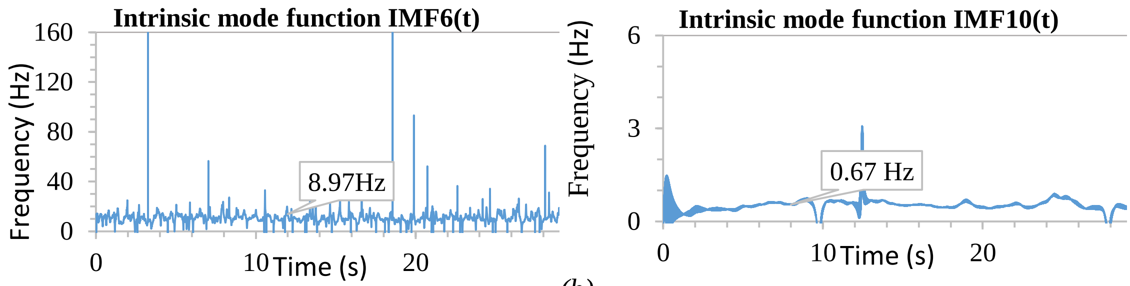


Fig. 7. Fourteen IMFs decomposed by EMD algorithm under the sine excitation [10].

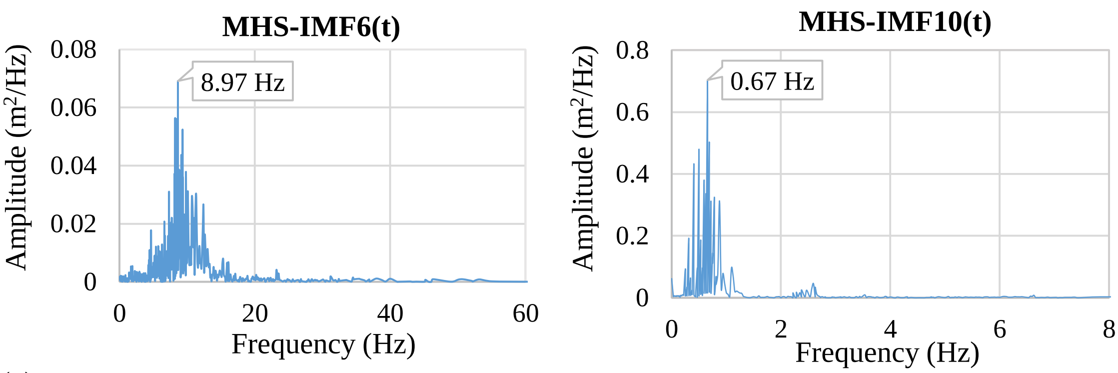
The response acceleration data would be processed by HHT to predict the natural frequency of test model. Figure 7 demonstrates fourteen IMFs [IMF1(t)-IMF14(t)] decomposed by EMD in the direction of sine wave excitation. These IMFs were arranged from the high to the low frequency band. The intrinsic mode function [IMF1(t)-IMF5(t)] is a white noise in a high frequency band. Meanwhile, the IMF6 and IMF10 contained the interested fundamental frequency range of the model test structure and the wave excitation. The rest of the IMFs were discarded since no relevant information was available.

Figure 8 presents the instantaneous frequency of IMF6(t) and IMF10(t) obtained by using the HHT method under the sine wave. The instantaneous frequency of IMF6(t) was identified as the first fundamental natural frequency of offshore structure. The instantaneous frequency of IMF10(t) was predicted as the driven frequency of sine wave excitation. These interested IMFs in the time-domain were then transformed into the frequency domain by the marginal Hilbert spectrum technique in identifying the natural frequency value of the model test. Figure 9 describes the Marginal Hilbert spectrum of IMF6(t) and IMF10(t). By using peak picking method to determine the value of natural frequencies of test model and wave excitation.



(a) *(b)*

Fig. 8. Instataneous frequency of IMFs in cases: (a) IMF6(t); (b) IMF10(t) [10].



(a) *(b)*

Fig. 9. Marginal Hilbert spectra: (a) IMF6(t); (b) IMF10(t) [10].

The HHT is successful not only in identifying the natural frequencies of offshore structures but also in predicting the driven frequency of wave excitation in a time domain by using the EMD decomposition algorithm.

5. Conclusion

This article has collected some main signal processing techniques in identifying the real-time natural frequencies commonly applied to offshore jacket structures, including STFT, WT and HHT methods. These techniques are suitable and useful to establish the online SHM system for the offshore structure. They provide early warnings to the safety of offshore structures under the ultimate marine environment.

HHT has a good performance and is more suitable in processing the non-stationary and nonlinear response signal data of offshore structures than STFT and WT. The research suggests the Huang Hilbert transform as one of the most suitable techniques to predict the instantaneous natural frequency of offshore structure.

The HHT was successfully applied in identifying the natural frequencies of the offshore jacket structure.

It is necessary to conduct further research by experimental sites to clear this problem.

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MỘT SỐ PHƯƠNG PHÁP NHẬN DẠNG ĐẶC TRƯNG ĐỘNG THEO THỜI GIAN THỰC THƯỜNG DÙNG HIỆN NAY ĐỐI VỚI KẾT CẤU CÔNG TRÌNH TRÊN BIỂN

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Tóm tắt: Ứng xử động lực học của kết cấu công trình trên biển trở nên phức tạp do chịu ảnh hưởng đồng thời của các điều kiện môi trường biển và điều kiện sử dụng. Một số hư hỏng và phá hoại của chúng cần được phát hiện sớm để có thể xây dựng các kế hoạch bảo dưỡng phù hợp. Vì vậy, hệ thống giám sát sức khỏe kết cấu trực tuyến (SHM) đã và đang được nghiên cứu và phát triển liên tục để đảm bảo an toàn khai thác thông qua các cảnh báo kịp thời. SHM phải đòi hỏi sự nhận dạng các đặc trưng động lực học của kết cấu công trình theo thời gian thực. Bài báo trình bày về ưu, nhược điểm cũng như xu hướng phát triển của một số hệ thống và kỹ thuật nhận dạng theo thời gian thực thường dùng hiện nay. Các phương pháp nhận dạng chính trong dự đoán các đặc trưng động học bao gồm tần số dao động riêng, tỉ số cản và dạng dao động. Phương pháp đo đạc phản ứng dao động và kỹ thuật xử lý tín hiệu cũng được thảo luận và đánh giá. Mục đích của nghiên cứu là giúp kỹ sư và chuyên gia có cái nhìn toàn diện và chi tiết về các phương pháp nhận dạng theo thời gian thực của hệ thống SHM đối với kết cấu công trình trên biển...

Từ khóa: *Kết cấu công trình trên biển; đặc trưng động học; nhận dạng theo thời gian thực; đo đạc phản ứng dao động.*

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