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Dynamic Specification Determination using System Response Processing and Hilbert-Huang Transform Method

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Abstract
Signal processing and system characterization using vibration measurement tools have been an essential topic of research in recent decades. One of the critical methods in signal processing is the Hilbert-Huang transform (HHT). This method has the potential to overcome the limitations of other methods, such as Fourier transform or a wavelet transform. In this paper, we use empirical mode decomposition (EMD) and Hilbert transform to characterize the system. Initially, the intrinsic mode function (IMFs) of the structural acceleration responses were obtained by the empirical mode analysis method, and the combination of these functions was calculated by HHT of natural frequency and system attenuation ratio. To illustrate the performance of the proposed method, the acceleration responses of an eight-story structure have been demonstrated, and the effect of different loading and measurement noise on the system determination has been investigated. The results show that the HHT calculates the system specifications very accurately and the effect of measurement noise and loading type will have little effect on the system determination.

Keywords: Signal processing, Hilbert-Huang Transform, Intrinsic Mode Functions, system determination

1. INTRODUCTION

The subject of structural health monitoring is one of the most important engineering subjects in the world. The reason is that structures need to be investigated after natural disasters and other incidents that may cause them damage, and the location and extent of the damage must be evaluated. Several types of damage can weaken a structure such as puncturing, cracking, scaling, delaminating, etc. Therefore, different methods for structural health monitoring have been developed, such as i) Visual confirmation [1], ii) Destructive and non-Destructive tests [2] and iii) Determining the damaged structure modal analysis parameters through analysis of vibration signals [3]. The signal analysis method for structural health monitoring is more accurate and less expensive, which is why it is more popular with engineers and researchers; this method determines the modal analysis parameters by following the changes in the structure's dynamic characteristics such as frequency, damping ratio, etc. This category includes methods such as Fourier analysis, wavelet transform (WT), Wigner Ville distribution (WVD), and Hilbert-Huang transform (HHT). The signal processing-based system identification also has a wide range of applications in the electrical and mechanical actuators like BLDC motors and reaction wheels [4, 5]. The system identification is a fundamental part of the fault detection process for the safety of the designed tools and products. Izadi et al. [6] provide a method for fault detection in the primary actuator for attitude control in a three-axis satellite. The static and dynamic imbalance in the structure of the RW is isolated by using the time and frequency domain.

In the more basic methods of signal processing, such as Fourier transform, when a signal passes through the Fast Fourier Transform (FFT), it transforms into a collection of harmonics in the frequency domain [7]. The information gathered from the harmonic domain provides essential clues for detecting anomalies. The frequency behavior of a healthy structure plays a crucial role in the fault detection process. In [6], the application of the FFT method in the FDIR process is shown. One of the limitations of such methods is their inability to process the signal in the time domain. Therefore, to overcome the drawbacks of the Fourier method, the time-frequency analysis methods were introduced. One of the essential methods of time-frequency analysis is wavelet analysis. The primary purpose of this method is to transform a signal to a specific scale and time. This method creates a uniform time-frequency domain; however, due to using the limited mother wavelet, this method is also fundamentally flawed. Even with the fundamental flaws, wavelet analysis is one of the best methods of time-frequency analysis and is suitable for determining the parameters of engineered structure's modal analysis that have been excited by random loads [8, 9]. Due to the faults of previous methods, Huang developed the Hilbert-Huang method [10] for analyzing the structures in time-frequency and the related non-linear signal analysis.

In some scenarios, special sensors have been used that can remotely sense the structures' behavior and send it to a remote server for further processing [11]. Compressed sensing method also is used in heterogeneous traffic networks in order to compress the big data which is going to be transferred by a cloud data or wireless [12]. Ghadami et al. [13] and Bao et al. [14] have used compressive sensing for efficient and fast health monitoring of structures. In compressive sensing, what we sense from the signal is much smaller than the actual signal; therefore, there would be less power consumption [15, 16]. This method may cause losing some quality of the signal, but on the other hand, it is also capable of enhancing the signal, meaning it can reduce the effects of the noise specially in nonlinear fuzzy systems [17,18]. Recent techniques in the recovery of compressive sensing can enable us to improve the quality of the signal [19]. In compressive sensing, the sparsifying dictionary can be a Fourier dictionary or wavelet dictionary; these dictionaries can also be used for doing the health-monitoring process in the compressed domain [20].

The Hilbert-Huang method is a combination of Empirical mode decomposition (EMD) and Hilbert transform (HT), which determines the characteristics of the system and detects structural damage by calculating the intrinsic mode functions (IMF) which are resulted from EMD and transforming each IMF using HT. Bahar and Ramezani [21] introduced a new method using HHT to reduce the mathematical limitation of Hilbert spectrum analysis. To reduce the effects of the frequency noise of the IMFs, they introduced an extra parameter. The capabilities of the proposed method were evaluated through two models, a standard model with three degrees of freedom under a random vibration and a fifteen-story structure under limited vibration. Cheraghi et al. [22] studied the characteristics of the vibrating plastic pipes with piezoelectric sensors through an HHT [23,24]. In the end, the laboratory experiment showed a satisfactory result, which was comparable with finite element analysis [25].

In this study, the dynamic characteristics of an eight-story structure with acquisition noise and different loads will be investigated through a Hilbert-Huang Transform. In the next sections, first the HHT and then the numerical experiment will be explained briefly.

2. HILBERT-HUANG TRANSFORM

The Hilbert-Huang transform is an important signal processing method and is made up of two parts. The first part is the EMD in which the signal is decomposed into small components called IMF. This method is based on the remaining residue, as can be seen in (1).

$$x(t) = \sum_{j=1}^{n} C_j(t) + r_n(t) \qquad (1)$$

where Cj are the n IMFs and rn is the residue. The second part of HHT is the Hilbert transform. After the IMFs are calculated through EMD, each of them is then transformed through a Hilbert transform as in (2).

$$y(t) = HT[x(t)] = \frac{1}{\pi} P \int_{-\infty}^{+\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (2)$$

where P is the Cauchy constant. In the EMD is combined with HT the result is called Hilbert-Huang Transform. The signal that goes through HT can be written as (3).

$$Z(t) = x(t) + iy(t) = A(t)e^{i\theta(t)} \qquad (3)$$

$$A(t) = A.e^{iwt}, \theta = \omega t - \alpha \qquad (4)$$

where A and θ can be calculated using (4) and are the Hilbert's amplitude and phase angle.

$$\omega(t) = \frac{d\theta(t)}{dt} \qquad (5)$$

and ω in Eq. (5) is the Hilbert frequency.

3. DIAGRAM OF SYSTEM'S DYNAMIC CHARACTERISTICS ANALYSIS USING HILBERT-HUANG TRANSFORM

In Figure 1 a diagram of the phases of determining the dynamic characteristics is shown.

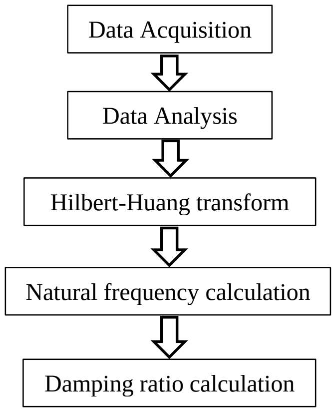

Figure 1: A diagram of the phases of the system's dynamic characteristic determination process using HHT.

4. NUMERICAL SIMULATION

To evaluate the performance of the system's dynamic characteristics determination using HHT an eight-story structure with non-shear walls and non-classic damping matrix has been used. The structure's stiffness matrix has been calculated through finite element method. The characteristics of the eight-story structure's model sections are demonstrated in Figure 2 and Table 1.

The time-domain results of the structure have been acquired for every floor for different loads. In this study, the phases of the system's dynamic characteristics determination will be performed for the third floor.

The time-domain results of the structure have been acquired for every floor for different loads. In this study, the phases of the system's dynamic characteristics determination will be performed for the third floor. Based on the frequency values of the Fourier transform, the output of the third floor which is close to the frequency values of the system (eight-story structure), the third floor's output is considered to be the main output. Also, to analyze the effects of the noise in the performance of this method, some noise has Characteristics of The Structure For 8 Degrees of Freedom has been added to the sensor's outputs. Finally, the results of the EMD method and HHT have been compared with FFT (Picking Method), and the error has been calculated.

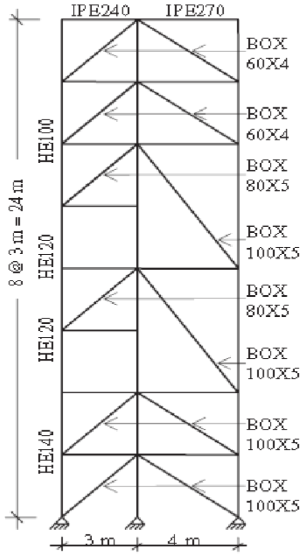

Figure 2: Characteristics of the two-dimensional sections of the structure with eight degree of freedom.

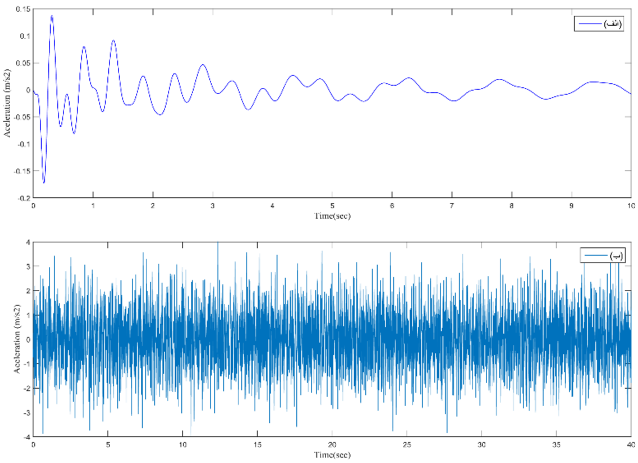

Figure 3: Output of the acceleration of the third floor (a) free vibration (b) forced vibration resulted from random load on the first floor.

To perform the signal processing steps and algorithms, MATLAB software has been employed.

Table 1: Characteristics of The Structure For 8 Degrees of Freedom.

Story	1	2	3	4	5	6	7	8
Floor mass (Ton)	70	55	40	55	40	60	60	55
Structure frequency (Hz)	0.60	2.02	2.81	3.91	5.50	6.37	7.89	9.66
Structure damping	0.01	0.032	0.044	0.062	0.087	0.1	0.12	0.15

5. DETERMINATION OF SYSTEM'S NATURAL FREQUENCY BASED ON HILBERT-HUANG TRANSFORM

5.1. Determination of system's frequency through instant frequency

Since the natural frequency range of the structure is not known in the system identification process, the Fourier transform of the responses is used to approximate the structural frequency range. Based on the result values of P.P.M method and its comparison to the frequency values of the structural theory shown in Table 2, it is found that the third-floor response has the necessary properties of the structural characteristics.

Table 2: Comparison of structure's natural frequency values using P.P.M method for the third floor

	Story	1	2	3	4
Frequency	Theory	0.607	2.027	2.815	3.919
	P.P.M	0.611	2.014	2.871	3.907

By specifying the frequency range of the first four modes, one can obtain the natural frequency value of each mode by the Hilbert's instant frequency method. To eliminate the effect of other modes, the response of the third floor must be refined in each frequency mode and the values of the intrinsic modal function for each mode must be calculated. The acceleration response of the third floor should be refined in each mode according to the frequency of the system. According to Table (2), natural frequency of the structure in first class is 0.607 Hz so that the acceleration response, $x(t)$, of the third floor of the structure is in the frequency range of $0.3 < \omega < 1.8$ which is processed by Band Pass Filter. After a refinement on the third-floor response, the filtered response is obtained in the specific frequency range so that Figure 4 shows the refined response for third in free vibration mode in the range of $0.3 < \omega < 1.8$.

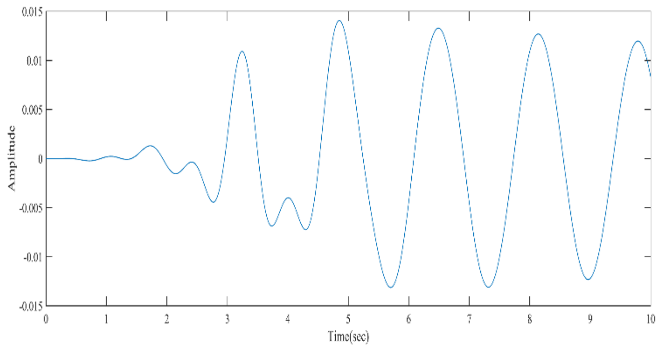

Figure 4: Refined response for the third floor in free vibration mode in the range of $0.3 < \omega < 1.8$.

The refined response is then combined with the experimental modal decomposition and the first inherent mode function is obtained which will be quite like the modal response of the

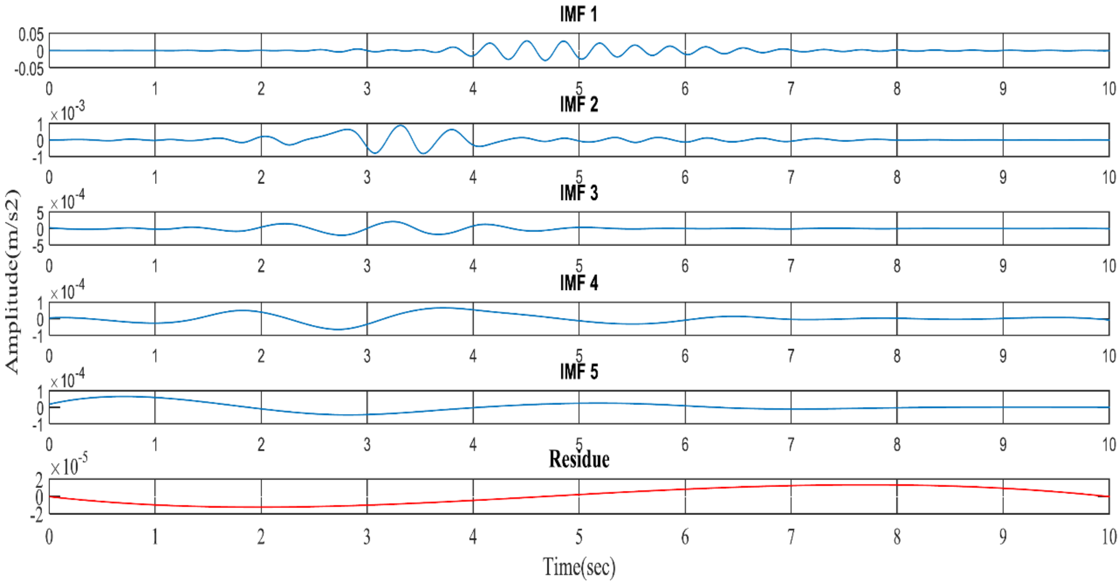

Figure 5: Filtered signal response of the third-floor inherent mode functions.

same mode. All the previous steps should be done for all frequency ranges in order to calculate the values of their inherent mode functions for each range. At this point, the Hilbert transform is applied to any existing inherent mode function. By performing the Hilbert transform for each modal response, an analytical signal is produced with the help of equation (3) so that it is possible to draw the Annie Hilbert frequency. Because after a while, the system frequency reaches an almost constant and stable frequency, the stable part of the instantaneous frequency curve can be considered as the natural frequency of the system so that by drawing the instantaneous frequency for specific modes, natural frequencies in each mode will be obtained. In figure (6), the instantaneous frequency is plotted through time and the value of natural frequency for the first class of the structure is obvious.

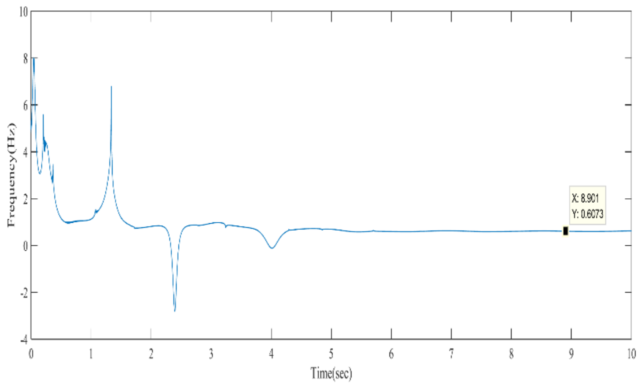

Figure 6: The instantaneous frequency of the first intrinsic mode function of the third-floor refined signal response.

5.2. Determination of natural frequency and damping ratio of the system based on phase curve method and instantaneous amplitude curve

In this section, after obtaining the refined responses of each mode and passing it through the EMD method, its IMFs ($x_j(t), j = 1, 2, 3, 4$ which $x_j(t)$ represent the inherent mode function) will be derived. The analytical signal results from the combination of the first IMF of each mode with HT. At this point from Eq. (4) and Eq. (3) the instantaneous amplitude and phase value will be extracted. The demonstration of the phase angle curve θ_j is based on the time in the second unit. An area of the phase curve that is regular and uniform is selected, and a straight line is drawn using the least-squares fitting. Finally, the slope of the fitted straight line will be the same natural frequency of the system in the defined mode. This issue is demonstrated in Figure 7. After calculating the instantaneous amplitude, its logarithmic curve in the time domain is plotted (Figure 8). In a specific region, the slope of this curve will be equal to the multiplication of damping and the frequency. Therefore, the damping ratio obtains from the slope of this region.

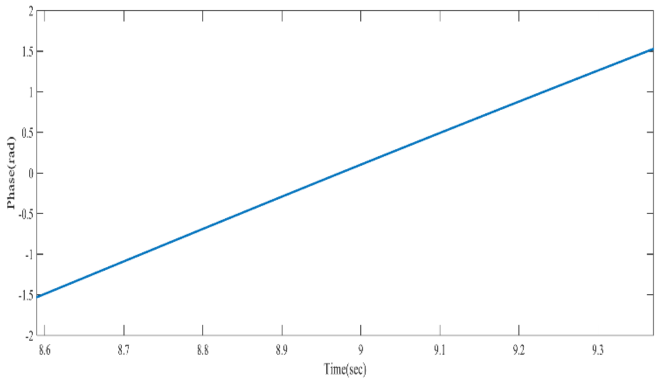

Figure 7: Phase curve of the first IMF of the third-floor refined response signal

Previous steps have been performed in the third-floor free vibration mode for the first four modes and the results are summarized in the following tables. Results are analyzed by considering 17 percent and 15 percent measurement noises in responses. In Table 3, the dynamic properties of the structure for free vibration mode are calculated from two methods of instantaneous frequency and phase curve for frequency and instantaneous amplitude. The numbers in parentheses indicate the error of the Hilbert-Huang method compared to the theoretical values. The results show the accuracy of the Hilbert-Huang method in comparison with the M.P.P method and the main values of the natural frequency of the structure.

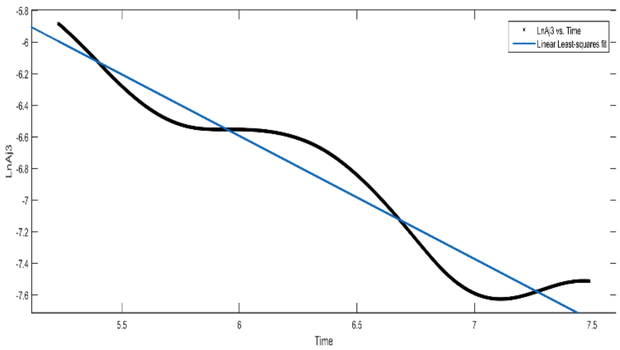

Figure 8: Least squares fit to the logarithmic instantaneous amplitude of the first IMF of the third-floor refined response signal.

The average error rate of the Hilbert-Huang method is less than 0.3 percent in the natural frequency. Also, the error rates for the damping ratio of the Hilbert-Huang method are less than 0.3 percent.

Table 3: Dynamic properties of the structure for free vibration mode without measurement noise

Mode Num.	Systems' Natural Frequency (rad/sec)				Systems' Damping Ratio	
	Theory	P.P.M	HHT (IF)	HHT (phase)	Theory	HHT (Amplitude)
1	3.81	3.84 (0.56)	3.82 (0.24)	3.81 (0)	0.0095	0.0095 (0)
2	12.71	12.65 (0.4)	12.73 (0.59)	12.76 (0.43)	0.0318	0.0316 (0.51)
3	17.64	18.03 (2.18)	17.62 (0.1)	17.63 (0.08)	0.0441	0.0440 (0.23)
4	24.62	24.54 (0.3)	24.61 (0.65)	24.46 (0.65)	0.0615	0.0613 (0.39)
Average Error Value		**0.86**	**0.23**	**0.29**		**0.28**

Tables 4 and 5 show the dynamic properties of the system with 17 percent and 15 percent measurement noises respectively. The results show that the amount of noise in the time domain responses has little effect on determining the dynamic values of the system. So that the calculated average error value of natural frequency in the 17 percent measurement noise case is less than 0.4 percent and for the 15 percent case the average error percentage is less than 0.5. Also, the average error value of the damping ratio determined at the 10 and 15 measurement noise cases are 0.25 and 0.24 respectively.

In order to consider the effect of stochastic loading, on the first floor of the structure a random load is applied. Table 6 demonstrates the natural frequencies of the structure for third floor responses with 5 percent noise on the first floor with stochastic loading. The numerical results show that the Hilbert-Huang method has good accuracy in calculating the natural frequency of the structure compared to the M.P.P method.

Table 4: Dynamic properties of the structure for free vibration mode with 10 percent measurement noise.

Mode Num.	Systems' Natural Frequency (rad/sec)				Systems' Damping Ratio	
	Theory	P.P.M	HHT (IF)	HHT (phase)	Theory	HHT (Amplitude)
1	3.81	3.84 (0.56)	3.81 (0)	3.81 (0)	0.0095	0.0095 (0)
2	12.71	12.65 (0.4)	12.81 (0.83)	12.76 (0.43)	0.0318	0.0317 (0.20)
3	17.64	18.03 (2.18)	17.69 (0.3)	17.63 (0.08)	0.0441	0.0440 (0.23)
4	24.62	24.54 (0.3)	24.57 (0.15)	24.46 (0.65)	0.0615	0.0619 (0.58)
Average Error Value		**0.86**	**0. 32**	**0.24**		**0.25**

Table 5: Dynamic properties of the structure for free vibration mode with 15 percent measurement noise.

Mode Num.	Systems' Natural Frequency (rad/sec)				Systems' Damping Ratio	
	Theory	P.P.M	HHT(IF)	HHT (phase)	Theory	HHT(Amplitude)
1	3.81	3.84 (0.56)	3.86 (0.58)	3.81 (0)	0.0095	0.0095 (0)
2	12.71	12.65 (0.4)	12.79 (0.64)	12.75 (0.37)	0.0318	0.0317 (0.20)
3	17.64	18.3 (2.18)	17.69 (0.26)	17.66 (0.12)	0.0441	0.0440 (0.23)
4	24.62	24.54 (0.3)	24.54 (0.33)	24.67 (0.24)	0.0615	0.0612 (0.55)
Average Error Value		**0.86**	**0.45**	**0.18**		**0.24**

Table 6: Dynamic properties of the structure for stochastic loading mode with 5 percent measurement noise.

Mode Num.	Systems' Natural Frequency (rad/sec)			
	Theory	P.P.M	HHT(IF)	HHT(phase)
1	3.81	3.68 (3.48)	3.83 (0.44)	3.82 (0.21)
2	12.71	12.73 (0.19)	12.0 (0.05)	12.7 (0.04)
3	17.64	17.94 (1.72)	17. 9 (0.27)	17.56 (0.46)
4	24.62	25.16 (2.20)	24.65 (0.12)	24.63 (0.07)
Average Error Value		**1.89**	**0.22**	**0.19**

6. CONCLUSION

In this study, methods for determining the dynamic properties of the system based on Hilbert-Huang transform were presented. To demonstrate the efficiency of the proposed method, an eight-floor non-shear structure was used in different loading modes with noise and the dynamic properties of the structure were obtained in the first four modes in different cases. To investigate the effects of measurement noises on the performance of the proposed methods, the 10 and 15 percent random noise in the time domain were added to the responses and the dynamic properties of the structure were obtained. Also, to compare the effect of loading type, stochastic loading with 5percent noise was applied to the first floor of the structure and natural frequency values were obtained by Hilbert-Huang method. The results showed that the type of loading and measurement noises have very little effect on the system dynamics characterization and the modal frequency values and attenuation ratio were obtained with low error percentage. According to the results of this study, Hilbert-Huang conversion can be considered as one of the most suitable tools for system frequency detection in the time-frequency domain for the structural analysis.

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