Direct Observations of Non-Stationary Bridge Deck Aeroelastic Vibration in Wind Tunnel

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Abstract:

It is useful to study directly the general motion of the bridge deck due to ambient wind excitations, especially for the purpose of monitoring the "aeroelastic status" of the structure. In the general motion, a sustained or exponentially modified sinusoidal oscillation is not available and the linear time invariant system assumption as is required by the flutter derivative model (e.g. [1]) is jeopardized. Besides, the existence of uncontrollable factors under operational conditions may also bring about the time varying features. As will be show in this paper, the non-stationarity in the general motion is usually stronger than expected, which may cast a doubt on current practices of applying stationary techniques on ambient vibration analysis. Therefore, it is suitable to have reliable signal processing techniques to pre-examine the measured ambient responses before processing them. In this paper, a joint time-frequency study is carried out, via wind tunnel experiments, on the aeroelastic vibration of a rigid sectional model. Hilbert transform combined with empirical mode decomposition method is used. Instantaneous frequency domain properties of aeroelastic vibrations are obtained. Time dependant features of the interactive system are revealed. The result of this study indicates that, as far as the experiment in this paper is concerned, the non-stationarity is stronger in the vertical and rotational motion than in the lateral motion.

Key Words: Bridge aeroelasticity, Time-frequency analysis, Hilbert transform and Empirical mode decomposition

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Symbols

$a(t)$	Amplitude of an analytical signal
A	Rotational displacement
$A(\tau, n_i)$	Amplitude of an intrinsic mode function
$C_i(t)$	An intrinsic mode function
$E(t)$	Energy of a wave
$h_{ik}(t)$	Variables
H	Vertical displacement
$m_i(t)$	Local mean of a signal
$n_i, \langle n \rangle_t$	Instantaneous frequency (IF) and weighted averaging IF
P	Lateral displacement
$r_i(t)$	Residue signal
SD	Standard deviation
$t, t_1, t_2,\ \tau$	Time
$X(t), Y(t), Z(t)$	Signal
$\theta(t)$	Angular phase
Δ_t^2	Bandwidth

Abbreviations

DOF	Degree of freedom
EMD	Empirical mode decomposition
IMF	Intrinsic mode function
IF	Instantaneous frequency
MBW	Mean bandwidth
MIF	Mean instantaneous frequency
PCIF	IF of Principal component
WAIF	Weighted averaging instantaneous frequency

Tables

Figures

1 Introduction:

With the increasing number of cable-supported bridges in service, it is of practical importance to have systematic methods to monitor the "aeroelastic status" of the bridges under its working condition, i.e. to monitor the interaction between the self-excited wind forces and the bridge deck motion. This gives rise to a problem of interpreting the ambient response of the bridge directly.

Although the experimentally identified flutter derivatives [1] are the major engineering tool to formulate the interactive wind forces, they are very difficult to be fitted directly to ambient response measurements even in the simplest case, i.e. the sectional model experimental case. The reason is that the flutter-derivative model is based on a sustained or exponentially modified sinusoidal motion, therefore, the study of general motions of the bridge deck due to ambient wind excitations must depend on indirect numerical procedures (e.g. [2]) after flutter derivatives has been identified separately under sustained or exponentially modified sinusoidal condition.

In order to monitor the aeroelastic behavior of a bridge, we need to study the same problem in the reverse order, i.e. start from studying the general motion to understand the interaction mechanism. In this case, the vibration is deformed from a pure sinusoidal type to a more general oscillatory one, for which the frequencies are not constant making reduced frequencies also changing within one wave. Because the flutter derivatives are functions of reduced frequencies, the time invariant linear relationship between the interactive forces and the deck motion is no longer valid. The interactive system is then time varying and the general motion nonstationary.

Besides, under many operational conditions, the uncontrollable factors, such as the changes in wind speed and directions, may also bring about nonstationary features.

It is needed, therefore, to have a reliable method to pre-examine the experimental data for non-stationarity before processing them because the available theories of bridge aeroelasticity mainly focus on the stationary phenomena. Overlooking the existence of non-stationarity may lead to a biased interpretation of the problem under investigation.

It seems, however, there is a lack of effective tool to analyze the nonstationary aeroelastic vibration. Current experimental methods for studying general motions, for example, output covariance analysis (e.g. [3]), inevitably average the parameters over too long a time interval to study the instantaneous properties of the aeroelastic problem. Time domain frequency independent state-space equation expressions (e.g. [4]) of the self-excited wind forces are ultimately based on the transformation of flutter derivatives from frequency to time domain, therefore has the same restrictions as has been placed on flutter derivative model. The breach of the restriction will call for the direct experimental observation of the non-stationarity of the general aeroelastic motion, for which the frequency has to change from time to time.

Although the major concern in bridge aeroelasticity is the aerodynamic damping, due to complexity in the non-stationary cases, the authors would like to focus on the frequency changes only at current stage and leave the study of aerodynamic damping for later studies. The objective of this paper is to identify some of the characteristic problem in the direct observation of the general aeroelastic vibration and explore some of the available tools for the possibility of applying them for understanding the phenomenon.

2 Instantaneous Frequency (IF) and Empirical Mode Decomposition (EMD)

There are several ways to define instantaneous frequency. The most frequently used one is by the Hilbert transform. For an arbitrary time series, $X(t)$, its Hilbert Transform, $Y(t)$, is

$$Y(t) = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{X(t')}{t - t'} dt' \tag{1}$$

where P is the Cauchy principle value.

$X(t)$ and $Y(t)$ form a complex conjugate pair, so we can have an analytical signal:

$$Z(t) = X(t) + iY(t) = a(t)e^{i\theta(t)}, \tag{2}$$

where $a(t) = [X^2(t) + Y^2(t)]^{0.5}$, $\theta(t) = \arctan[\frac{Y(t)}{X(t)}]$.

Essentially, equation (1) defines the Hilbert transform as the convolution of $X(t)$ with $1/t$;

therefore, it emphasizes the local properties of $X(t)$. In equation (2), the polar coordinate expression further clarifies the local nature of this representation: it is the best local fit of an amplitude and phase varying trigonometric function to $X(t)$. With the Hilbert transform, the instantaneous frequency is defined as

$$n(t) = \frac{1}{2\pi}\frac{d\theta(t)}{dt} \tag{3}$$

In principle, the instantaneous frequency given in equation (3) is a single value function of time. At any given time, there is only one frequency value; therefore, it can only represent one component, hence the signal must be 'mono-component' or narrow banded. In the sense of practical data processing, in order to obtain meaningful instantaneous frequency, additional restrictive conditions have to be imposed on the data: (1) in the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one to make sure the data is narrow banded; and (2) at any point, the local mean value of the signal is zero.

Generally, the recordings of bridge deck response to ambient wind excitations will not satisfy these two conditions. Therefore, the empirical mode decomposition (EMD) procedure [5] is used to decompose the original recordings into series of intrinsic mode functions (IMF), which will meet these conditions individually.

The nature of the EMD is a series of processes shifting the signal $X(t)$ by its local mean $m_1(t)$, i.e.

$$X(t) - m_1(t) = h_1(t) \tag{4}$$

This operation repeats. In this process, the $k-1^{th}$ result, $h_{1(k-1)}(t)$, is used as the signal to calculate the k^{th} result, $h_{1k}(t)$, i.e.

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

It is required by the EMD method that the shifting process should not be applied too many times to avoid obliterating the physically meaningful amplitude fluctuations. The standard deviation computed from two consecutive shifts, i.e.

$$SD = \sum_{t=0}^{T} \left[\frac{\left| h_{1(k-1)}(t) - h_{1k}(t) \right|^2}{h_{1(k-1)}^2(t)} \right] \tag{6}$$

should fall between 0.2 and 0.3 for 1024 data points. Therefore, in this paper, the standard deviation is set to $n*0.2$ to $n*0.3$ for $n*1024$ data points.

When $h_{1k}(t)$ meets the aforementioned two conditions, it is named the first IMF, i.e.

$$C_1(t) = h_{1k}(t). \tag{7}$$

The first IMF is then removed from the original signal to produce the first residue signal $r_1(t)$, i.e.

$$X(t) - C_1(t) = r_1(t). \tag{8}$$

The first residue signal is then used as the signal for second round of shifting to obtain the second IMF: $C_2(t)$. This process continues until n IMFs are found and the residue signal is the mean trend or constant. The original signal is then expressed as

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

Instantaneous frequencies can be calculated for each IMF by using equation (1-3).

According to Huang et al [5], the IMFs identified in such way form a complete and orthogonal basis for the signal decomposition. Because the procedure is empirical, it is adaptive to individual data sets, and has superiority over other fixed structured time-frequency method, such as wavelet decomposition.

The intrinsic mode functions in the EMD method may not always have physical meaning. They may just appear as numerical phenomena. Therefore, for a recording full of uncertainties, such as a general motion of the bridge deck due to ambient wind excitations, not all the IF corresponding to the IMFs may represent a physical aeroelastic state. This study will use Hilbert Transform and EMD in a "conservative" way, not looking into all the details that can be obtained.

3 Direct Observation of General Aeroelastic Motions

The general aeroelastic motions in this study are the free vibrations of an elastically supported rigid sectional bridge deck model due to ambient wind excitations.

In the experiment, a partially streamlined box girder section (Figure 1) was suspended on a three-dimensional suspension system (Figure 2). The natural frequencies of the suspension system under no-wind condition are 4.18, 5.66 and 3.20 Hz in vertical, rotational and lateral directions respectively. Wind was then applied. The typical turbulence intensity was less than 2%, therefore, the oncoming flow was considered smooth. Even so, the bridge started to response when the wind speed increased. This is because not only the small fluctuations in the oncoming flow, but also the signature turbulences generated by the bluff model itself serve as sources of excitation [6]. Laser displacement sensors were used to record the displacement time histories of vertical rotational and lateral motions. The sampling rate was relatively high, i.e. 200 Hz, to allow reasonable averaging of instantaneous frequencies over a period of time without losing the concentration of the identified frequencies in time domain.

Three recordings of the general vibration due to ambient wind excitations were made at wind speeds of 17.5m/s, 14m/s and 10m/s. Each recording lasts for 5 minutes. Because the EMD procedure is a little time consuming, 5000 data, spanning for 25 seconds, were selected from the 5 minutes recordings for analysis with EMD method.

Because the EMD procedure would normally pick up noise as first several IMFs, which are apparently not meaningful signals for this study, the original recordings were de-noised using wavelet packets before being subjected to EMD. A segment of the recordings and the de-noised signals are shown in figure 3. In the figure, label H (m), A (m) and P (m) are vertical, rotational and lateral displacement in meters respectively. It can be seen the de-noised procedure produces very good approximations of the original signal. The de-noised procedure should be conducted very carefully, since it may deform the signal and affect the instantaneous frequency identification.

A record of the vertical motion at wind speed of 17.5m/s and its IMFs are shown in figure 4. The EMD procedure produces 6 IMFs and a residue signal. The residual is shown in the upper plot in darker color together with the original displacement time history. The main body of the recording is contained in IMF No.2 and 3.

It can be observed that the IMF no.1 is a pulse like signal. Between the pulses, the small amplitude parts are actually noise components which have not been removed totally by the de-noise procedure. This may only indicate at the time when the pulses occur, the signal is relatively cleaner than at other times. If an IMF contains only noise, it can be safely deleted. This IMF, because of the meaningful components in it, needs to be included. The noise components so introduced will not be a problem as they are small in amplitude and can be dealt with in the following procedures.

The residue signal in the upper plot of figure 4 is the “left over” of the EMD process. It equals the difference between the displacement time history and the summation of the IMFs. If the EMD process continues, it will generate more IMFs and a less fluctuating residue. As a matter of fact, if the residue fluctuates in considerably lower frequency than the main frequency, it should be considered as the time dependent equilibrium position of the oscillation. In this case, the EMD process should be stopped otherwise we will lose some useful information about the changes of equilibrium position, which is an indication of non-stationarity.

The residues of vertical, rotational and lateral displacement at wind speed of 17.5m/s are shown in figure 5 together with respective time history and the instantaneous average wind speed. From this figure, it can be observed that the vertical and rotational movements change their equilibrium position more frequently than the lateral movement. This is an indication that the non-stationarity is stronger in the vertical and rotational motion than in the lateral motion.

The IMFs are then subjected to Hilbert transform for instantaneous frequencies. The Hilbert transform of the IMF no. 2 and 3 of the vertical displacement time history is shown in Figure 6. The role of the Hilbert transform may be explained as follows: while sampled data are comprised of pure real numbers, it is treated as a set of complex numbers for the purpose of signal processing. For the imaginary component of the signal to be zero, according to signal processing theory, each positive frequency must be canceled by a corresponding negative frequency. The Hilbert transform essentially subtracts out just negative frequencies, which means the resulting signal becomes complex. When graphed in a complex plane, the resulting signal will tend to follow a loopy but locally circular path as shown in Figure 6. The first derivative of the polar phase angle with respect to time is instantaneous frequency.

A segment of Instantaneous frequencies so identified for all the IMFs of the vertical displacement time history are shown in Figure 7. It can be observed that there are independent frequencies for each IMF. The first IMF shows the largest dispersal among the IMFs. This is because the fist IMF still carries some noises although the signal has already been de-noised before hand. Other IMFs show clear frequency trends changing with time.

4 Weighted Average Instantaneous Frequency

Normally, other signal analysis methods would treat a changing instantaneous frequency as a series of waves with constant frequencies. One wave begins where another wave ends. This is referred to as inter-wave frequency modulation. The Hilbert transform also allows this, through having multiple IMFs, but by having instantaneous frequency value for each point, it allows for a new interpretation: changing frequencies within one IMF represents an intra-wave frequency modulation.

However, due to the highly uncertain factors in the turbulence and the interaction mechanism under investigation, also due to the unclear physical meaning of individual IMF, it is not safe to run into such a delicate conclusion. At current stage, we would rather to focus on the overall frequency for all IMFs in one direction, instead of one IMF. For the vibration in individual directions: vertical, rotational and lateral directions, there should be mainly one predominant frequency, which may be changing from time to time. Therefore we define the weighted average instantaneous frequency (WAIF) using the instantaneous energy in each IMF as a weight.

As shown in Figure 8, for all the IMFs in the given time window with width of $2w$ centered around time t, $t_1 = t - w$, $t_2 = t + w$, $t = \frac{t_2 + t_1}{2}$, the total energy in the window is the integration over time $\tau \in [t_1, t_2]$ of the summation of the square of all the IMF amplitude $A(t, n_i)$ with instantaneous frequency of n_i, i.e.

$$E(t) = \int_{t_1}^{t_2} \sum_i \left| A(\tau, n_i) \right|^2 d\tau \, . \tag{10}$$

The WAIF at time t is the first order moment of instantaneous frequency

$$\langle n \rangle_t = \frac{\int_{t_1}^{t_2} \sum_i n_i \left| A(\tau, n_i) \right|^2 d\tau}{E(t)} \, . \tag{11}$$

The WAIF bandwidth is defined as:

$$\Delta_t^2 = \int_{t_1}^{t_2} \sum_i (n_i - \langle n \rangle)^2 \frac{\left| A(\tau, n_i) \right|^2}{E(t)} d\tau \, . \tag{12}$$

Therefore, we assume there is only one predominant frequency in each direction and the effect of the existence of other frequencies in smaller amplitude is taken into consideration by the computation of the bandwidth. The averaging window width in this study corresponds to five times of the sampling interval.

The computed WAIFs of the general motion in 3 directions of the bridge deck model at wind speed of 17.5m/s are shown in Figure 9. The bandwidth is also shown in the figure by dotted symbols. From the figures, we have several observations:

1. The highly fluctuating part (the thin continuous line) does not necessarily indicate the non-stationarity of the interactive system. The reason is as follows: a delta function type of input force could spread the energy of the response signal in the frequency domain at the time when the force is applied. In this case, scattered instantaneous frequencies will be identified. No-interactive part of the wind forces may performs in this way, causing the signal to deform and generating fluctuations in the instantaneous frequencies.

   The changing trend lines (thick continuous lines) of the identified WAIF may be more important than the highly fluctuating part in observing the non-stationarity. These trend lines are computed by wavelet regression estimation tools. The basic wavelet used is db4 and the decomposition level is four.

Because the WAIF is computed by using all the IMFs in the respective directions, it reflects the both intra-wave and inter-wave amplitude changes with respect to time. If the main component of the signal changes from one IMF to another, which may have different frequency, the trend line may also change accordingly. The trend line might reflect non-stationarity more reliably.

2. Generally speaking, the changes in the vertical and rotational motion are more frequent than in the lateral motion. This phenomenon also indicates, as do the changing equilibrium position, the non-stationarity is stronger in the vertical and rotational direction than in the lateral motion.

3. The changes in frequency are also observed to correlate, to some extent, with the changes in the equilibrium position shown in Figure 5. For example, between the time of 5 and 10 seconds, the equilibrium position of the vertical motion is relatively stable; accordingly, the vertical WAIF is also stable during this period of time. On the other hand, between the time of 10 and 20 seconds, the vertical equilibrium position changes more frequently; the vertical WAIF also experiences a bumping trend line. This might suggest one of the major factors affecting the instantaneous frequency is the unsteady equilibrium. However, more detailed research is needed to investigate the problem.

4. The bandwidths reach high values compared to the IF values at some time. The bandwidth in the lateral direction is generally smaller than those in the other two directions. A wide bandwidth indicates the signal is multi-component while a narrow bandwidth indicates the signal is mono-component. In the former case, there is relatively more energy exist in the frequency other than the main frequency. It is still not clear what are the factors affecting the distribution of the energy among IMFs and why there are low frequency IMFs as has been shown in the Figure 7. Generally speaking, the bandwidth is smaller in the lateral direction than in the vertical and rotational directions.

According to these observations, it can be concluded that in the analysis of the general aeroelastic motion, especially the rotational and vertical motions, non-stationarity should not be neglected. In order to interpret the direct measurement data, factors introducing non-stationarity must be identified. Current observations are not enough for detailed analysis of the nonstationary aeroelastic motion but it reveals the potential of the time-frequency analysis in tracking the time dependent features of the general aeroelastic motion.

5 Comparison of Stationary and Nonstationary Cases

Above observations show the time varying nature of the aeroelastic system under general motion. In order to compare these results with those from time invariant methods, frequencies from output covariance of the general motions are also identified from the same experiment [6]. Refer to reference [3] for more details of the procedure. The output covariance corresponds to the averaging scenario over the data length. Therefore, there is no time varying feature can be captured by it.

From Table 1, it can be observed that the mean instantaneous frequencies (WAIF), especially the rotational and vertical frequencies, are consistently lower that the corresponding frequencies identified from the output covariance for all the wind speed in the experiment. This is due to the presence of low frequency IMFs, e.g. IMF no. 4, 5, 6 in the vertical displacement as can be seen in Figure 7. The presence of large mean bandwidth (MBW) values in Table 1 also confirms the existence of large amount of energy in different frequencies other than the main frequency. The smaller values of mean bandwidth of the lateral motion suggest that this part of motion is affected very weakly. Consequently, the discrepancy between the lateral WAIF and the frequency from output covariance is small.

The origin of these low frequency IMFs is not clear at current stage and needs to be investigated in future studies. They do not affect the identification by output covariance for the reason that during the identification, the system order, i.e. the degree of the freedom of the rigid model, is fixed to 3 or 6 in the case of a state space representation. Information other than these 3 DOFs are screened out by the fixed order [6], which is the usual practice in identifying the flutter derivatives. The measurement of vertical and rotational displacement might carry some information that has been overlooked. This needs further investigation.

It is also noticed in Figure 4 that between the times of 5 and 10 seconds, the signal is relatively mono-component. The second IMF is the major part and other IMFs account for a very small fraction of the signal energy. This means, from the time of 5s to 10s, a single IMF approximates the vertical displacement. This part of the second IMF is the principal component of the signal within this slot of time. Similar principal components can be observed in vertical displacement time history at different wind speed as well. Rotational displacements seem very transient and it is very hard to find such stable principal components, suggesting they are not mono-component at most of the time. On the other hand, the displacements in lateral direction are relatively more mono-component than vertical movement and the principle components are easier to find. Some of the IFs of the principal components (PCIF) are also given in Table 1. From this numbers, it can be seen the PCIFs are close to the frequency obtained by stationary method, indicating the importance of the principal component of the IMFs in analyzing the nonstationary aeroelastic vibration. However, at current stage, it seems impossible to control the decomposition process to have stable principal components.

Despite the unsolved problems, the comparison of stationary and nonstationary methods mentioned in this paper reveals the shortcomings of both cases. The former is lack of the ability to track the time dependent properties, the latter needs to be improved to have more physically meaningful IMFs.

6 Conclusions

In order to monitor the aeroelastic status of a cable-supported bridge, it is necessary to study the general motion of the bridge deck in wind directly. Under this circumstances, the interactive system is time varying and the general motion is nonstationary. This will raise challenges for analyzing the monitoring data. Despite some problems, the non-stationarity of the general aeroelastic motion is studied by Hilbert Transform supplemented by empirical mode decomposition. The time varying nature of the interactive system, especially the vertical and rotational components of the motion, is not negligible. To some extent, the changes of trend lines of the instantaneous frequency seem to correlate with the changes of the unsteady equilibrium positions.

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Table 1 Comparison of the Output Covariance and Instantaneous Cases

<table>
<tr><td colspan="2">Wind Speed</td><td colspan="3">10 m/s</td><td colspan="3">14 m/s</td><td colspan="3">17.5m/s</td><td colspan="3">0m/s</td></tr>
<tr><td colspan="2">Directions</td><td>H</td><td>A</td><td>P</td><td>H</td><td>A</td><td>P</td><td>H</td><td>A</td><td>P</td><td>H</td><td>A</td><td>P</td></tr>
<tr><td>OC</td><td>Frequency (Hz)</td><td>4.26</td><td>5.50</td><td>3.22</td><td>4.19</td><td>5.39</td><td>3.24</td><td>4.09</td><td>5.11</td><td>3.22</td><td>4.18</td><td>5.66</td><td>3.2</td></tr>
<tr><td rowspan="3">HT</td><td>WAIF (Hz)</td><td>3.9</td><td>4.3</td><td>3.1</td><td>3.9</td><td>3.7</td><td>3.1</td><td>3.6</td><td>3.5</td><td>3.1</td><td colspan="3" rowspan="3">- Not Found</td></tr>
<tr><td>MBW (Hz*Hz)</td><td>1.6</td><td>3.2</td><td>0.8</td><td>1.6</td><td>3.0</td><td>1.0</td><td>1.6</td><td>2.4</td><td>0.4</td></tr>
<tr><td>PCIF (Hz)</td><td>4.07</td><td>-</td><td>3.1</td><td>4.03</td><td>-</td><td>3.1</td><td>4.1</td><td>-</td><td>3.1</td></tr>
<tr><td colspan="14">OC: Output Covariance; HT: Hilbert Transform;
WAIF: Weighted Averaging Instant. Frequency; MBW: Mean Bandwidth; PCIF: Principal Component IF</td></tr>
</table>

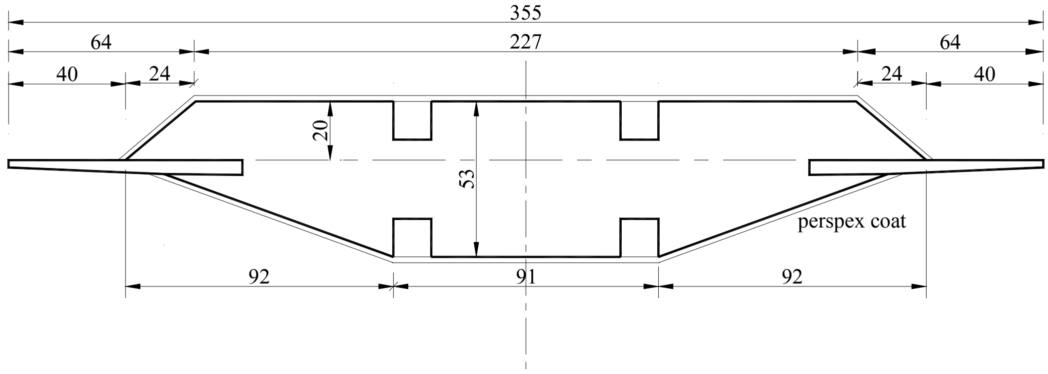

Figure 1 Streamlined Box Girder Model (Dimension mm)

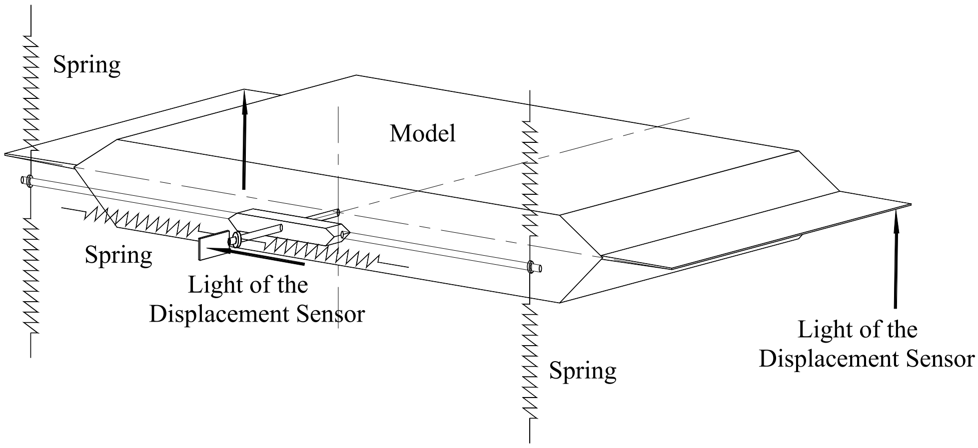

Figure 2 Setup for Vibration Test (One End)

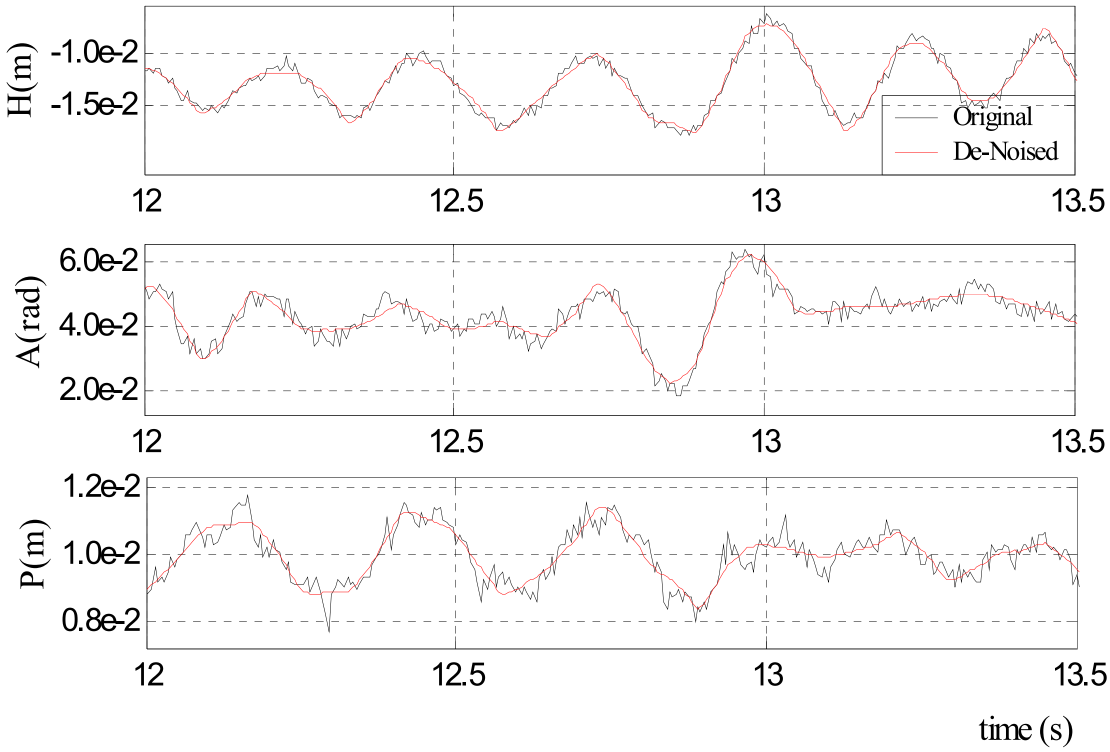

Figure 3 Original recordings and de-noised signals

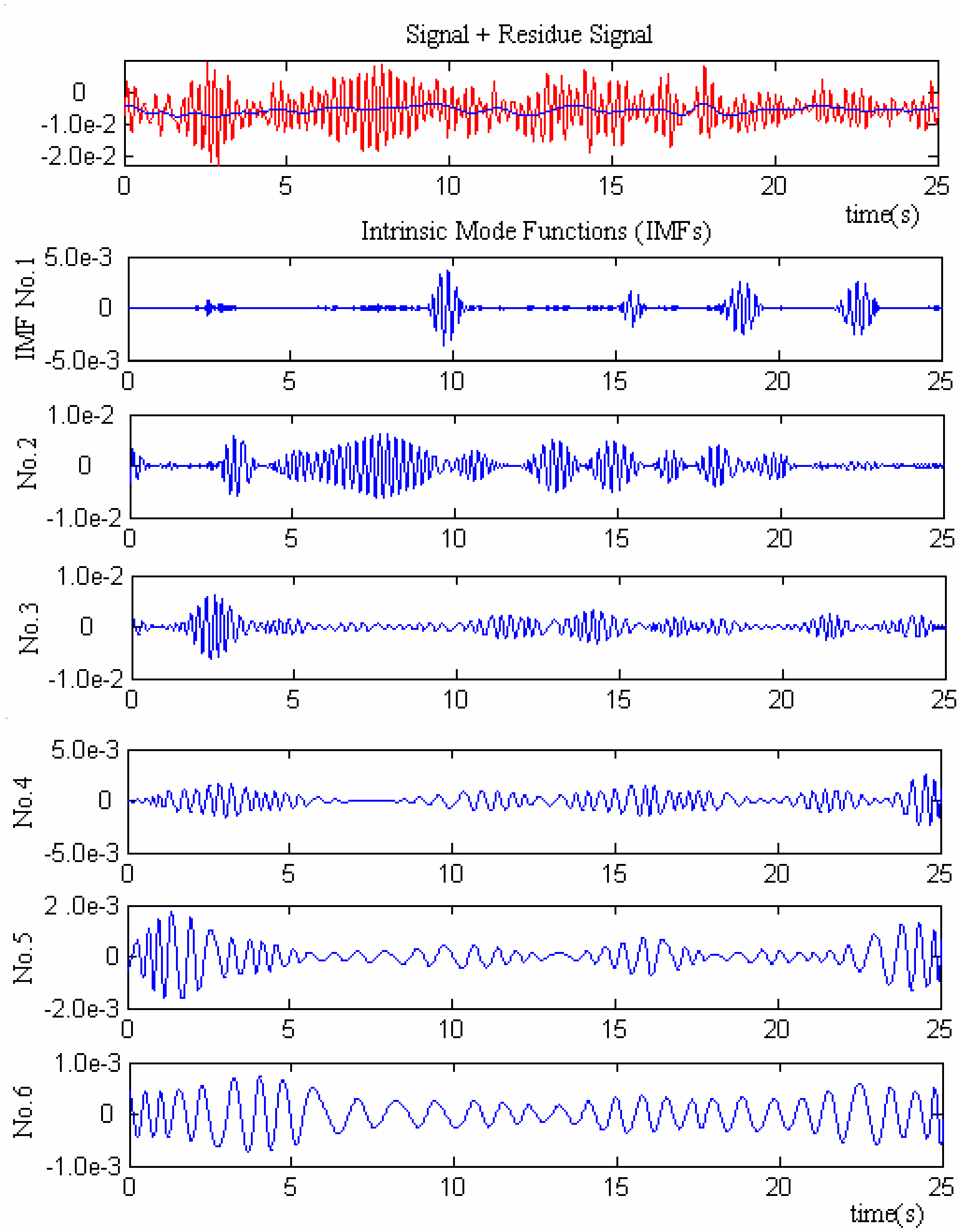

Figure 4 Vertical Displacements, Intrinsic Mode Functions and Residue Signal

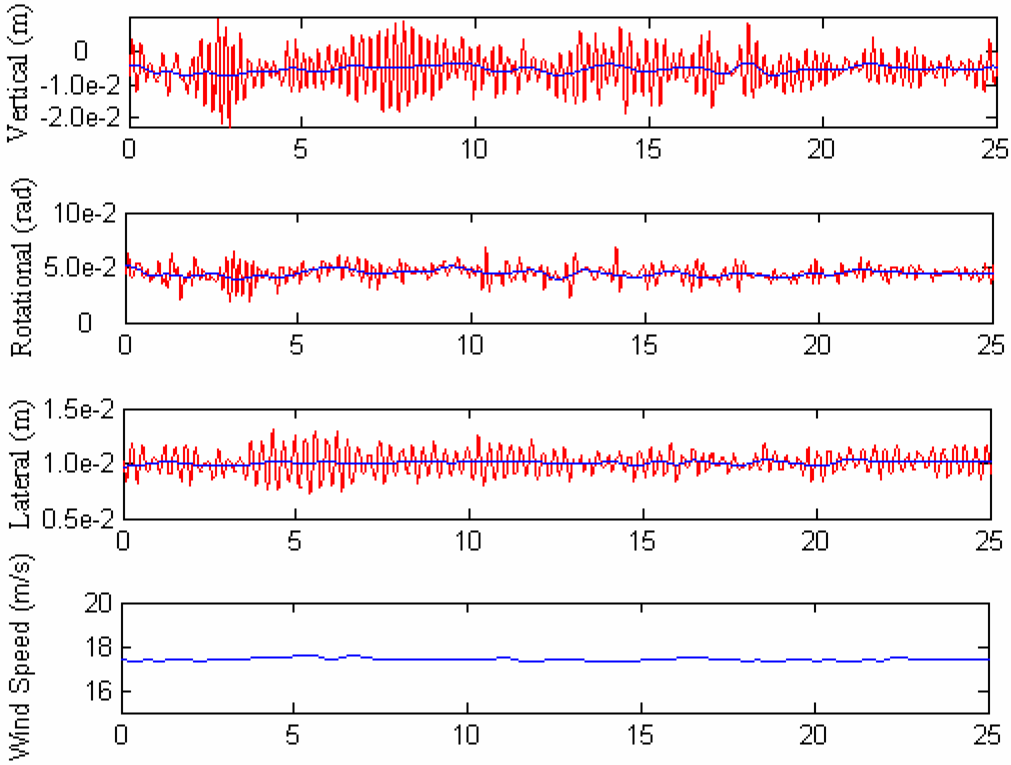

Figure 5 Changing Equilibrium Position

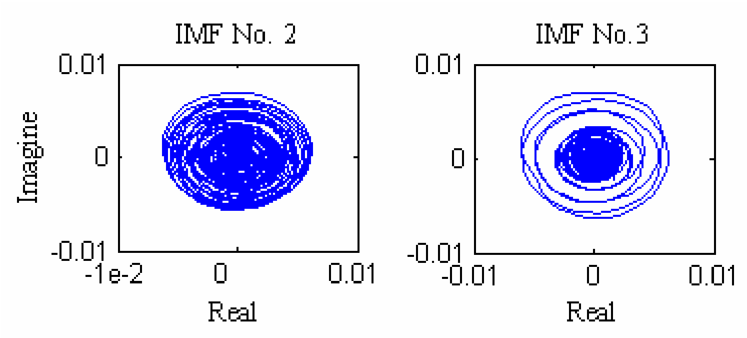

Figure 6 Hilbert Transform of IMF No. 2, 3 of Vertical Displacement

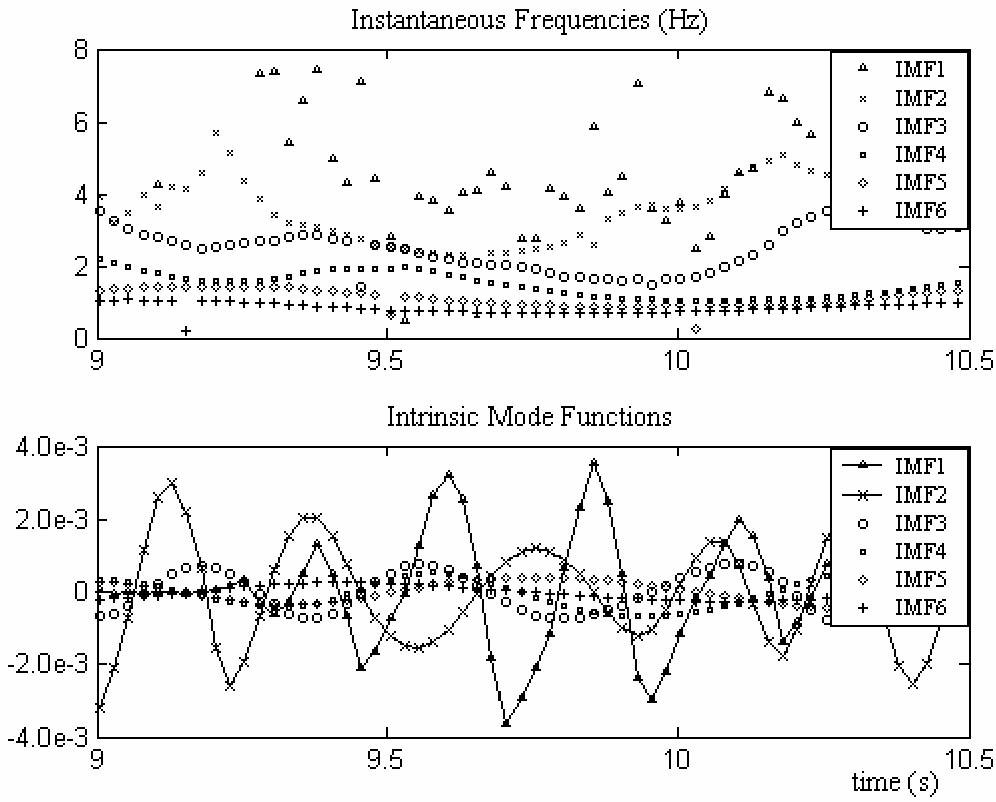

Figure 7 Instantaneous Frequencies of Each IMF from Vertical Motion

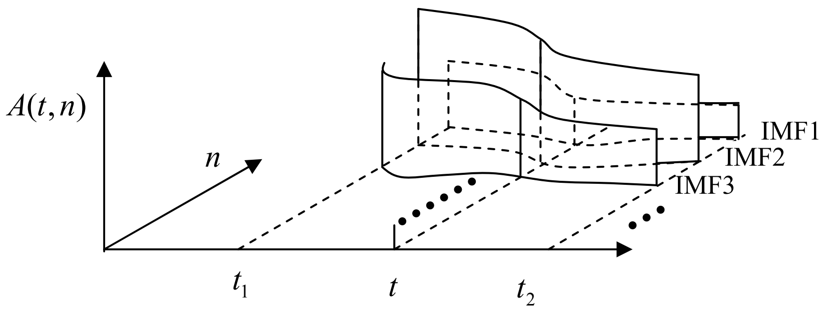

Figure 8 Definition of WAIF

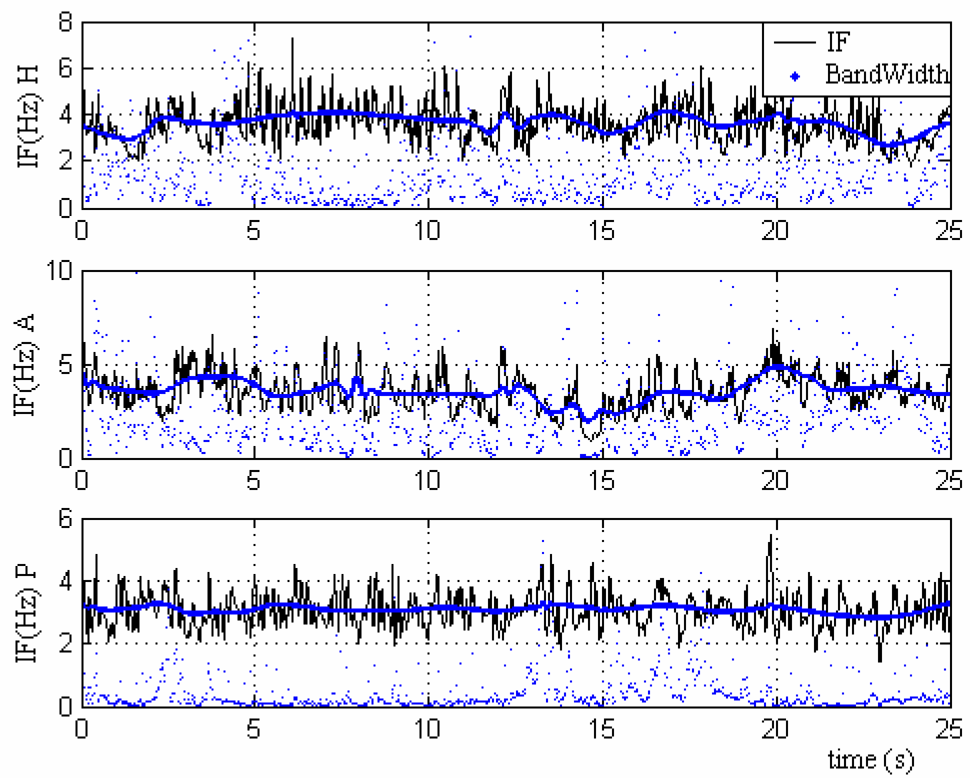

Figure 9 Instantaneous Frequencies and Bandwidth (Wind Speed: 17.5m/s)