# CHAPTER 12

# HHT-BASED BRIDGE STRUCTURAL HEALTH-MONITORING METHOD

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A new Hilbert–Huang transform (HHT)-based method for nondestructive instrument structure health monitoring is developed. When applied to bridges, this new method depends on a transient test load and simple data collection. The essense of the method is the newly developed HHT for nonstationary and nonlinear time series analysis, which consists of the empirical mode decomposition and Hilbert spectral analysis. The final decision on the health of the bridge structure is based on two criteria. The first criterion detects the nonlinear characteristic of the intra-wave frequency modulations of the bridge response, which usually appears during comparisons of light with heavy loads. The second criterion detects the frequency downshift as an indication of structural yield. This new method enjoys many advantages: no *a priori* data required, simple data collection, minimum traffic disruption, and precise and nuance quantitative answers. The result of a case study is presented, which establishes the feasibility of this new approach for structural health monitoring.

## 12.1. Introduction

With the inevitable aging of civil infrastructures, structural health monitoring has become an urgent problem worldwide (Chang 1997, 1999, 2001). To safeguard the safety performance of a bridge, regular inspections are essential (see, for example, Mori and Ellingwood 1994a,b). At the present time, the inspection method is primarily visual: a technician has to go through a bridge to examine each member and certify its safety. This method is subjective and flawed, lacking rigorous and objective standards. For example, for a bridge deteriorating from fatigue or aging, the damage is not clear-cut at any time. Therefore, any call is judgmental. Furthermore, using this method for complicated bridge structures is not feasible: some members might be located at positions too awkward to access; the members might require too much time to inspect; and the damage might be too subtle to be detected visually. Because of these limitations, the visual-inspection results are known to be not totally reliable, yet we are forced to rely on them today.

According to Doebling et al. (1996, 1998), an ideal inspection method would have to satisfy the following conditions:

(1) be robust, objective, and reliable,

(2) be able to identify the existence of damage,
(3) be able to locate the damage,
(4) be able to determine the degree of damage, and
(5) be able to provide data to estimate the remaining period of service.

The visual inspection method certainly fails the first requirement, and thus creates uncertainties in the remaining four conditions. These requirements lead us to conclude that non-destructive inspection methods that employ precise scientific sensors coupled with rigorous data analysis would be clearly preferred if available. Developing alternatives for the visual inspection method has been the central theme of the research in the Bridge Management Program, Turner-Fairbank Highway Research Center of the Federal Highway Administration (Chase and Washer 1997). A large program of research and development in new technologies for the nondestructive evaluation of highway bridges has been initiated. The objectives are to locate, quantify, and assess the degree of damage in bridges. Although various technologies, such as infrared thermography, ground-penetrating radar, acoustic emission monitoring, eddy current detection and others have been developed and are feasible, none of them is really practical. The difficulties of these systems are many. The first difficulty is due mainly to their limited field of view. One would have to locate the damage first before using the sophisticated imaging devices to examine it in detail. For a complicated structure, locating the damage is difficult enough. Secondly, the more daunting task involves evaluating the damage in terms of structural safety. Relating what can be measured in terms of structural safety is an almost impossible task without dynamic tests. As a result, even with the advances made by these sophisticated and esoteric techniques, their complexity and expense prevent their routine use. The data used routinely in bridge management today are still based almost entirely upon the unreliable visual-inspection methods, followed by expensive static load testing. The only viable alternative lies in the structural damage identification and health monitoring from changes in the bridge's vibration characteristics (Salawu 1997; Farrar et al. 1999), but past efforts to use vibration as a structural health-monitoring tool have met with great difficulties, mainly because of the lack of a better data-analysis method. The New Nondestructive Instrument Bridge Safety Inspection System (Huang 1998a) is based on such a new data-analysis method: the Hilbert–Huang transform (HHT), which consists of empirical mode decomposition (EMD) and the Hilbert spectral analysis (HSA) developed by Huang et al. (1996, 1998d, 1999, 2003) and Wu and Huang (2004). This new data-analysis method immediately found applications in a wide variety of geophysical engineering and biomedical problems (Huang 1998b,c; 1999). The details of the specific application to bridge-safety inspection have been described in a patent filed by Huang (1998a).

For bridge-safety inspection, Huang (1998a) proposed to use a transient load and to examine the nonlinear characteristics in the bridge vibration data to identify the damage. Huang et al. (1998d) clearly pointed out that, for a faithful representation of the nonlinear and nonstationary data, a different approach other than Fourier or Fourier-type wavelet analysis is needed. Huang's (1998a) approach is based on Huang et al.'s (1998d) newly developed HHT, which was designed specially for nonlinear and nonstationary data analysis. This new method requires two steps for analyzing data: the first step is to use the EMD method, with which any data can be decomposed, according to the characteristic scales, into a number of intrinsic mode functions (IMFs). In this way, the data are expanded in a basis derived from the data. The second step, the HSA, is to apply the Hilbert transform to the IMF components and construct the time-frequency-energy distribution, designated as the "Hilbert spectrum." In this form, the time location of events will be preserved, for the frequency and energy defined by the Hilbert transform has intrinsic physical meaning at any point. Huang (1998a) used precisely these characteristics of this new data-analysis method. Before presenting the new method, it will be instructive to review the present state-of-the-art methods used for bridge inspection.

## 12.2. A review of the present state-of-the-art methods

The approach of using dynamic response and vibration characteristics for nondestructive structural damage identification is the theoretical foundation of instrumental safety-inspection methods. This approach has also been the mainstream of research for more than thirty years (Natke et al. 1993; Chang 1997). Doebling et al. (1996, 1998) and Salawu (1997) have reviewed the available literature on this approach, and Farrar and Doebling (1997, 1998) and Felber (1997) have reviewed the practical problems associated with it. In principle, each structure should have its proper frequency of vibration under dynamic loading. The value of this proper frequency can be computed based on the elasticity properties of the structure (see, for example, Clough and Penzien 1993 or Chopra 1995).

Sound as this argument is, the dynamic instrument inspection has never worked successfully. The reasons are many: first, the precision sensors needed to measure the detailed dynamic response of the structure under loading are lacking. Secondly, historical data about individual bridges do not exist. Thirdly, proper data-processing methods to process the structural response have not been developed. Finally, the sensitivity of the structure in global response due to the local damage is unknown, and this problem is further gravitated by the large built-in safety factor. For example, damage of up to 50% of the cross-section locally can result in only a few percentages of vibration-frequency change. Such a small frequency shift, when processed by using the conventional methods, would be totally lost in the inevitable noise in all real situations. In the final analysis, many of the difficulties can be alleviated if the data-processing method can be made more versatile to handle vibration signals from highly transient loads and nonlinear responding waveforms. This problem will be addressed presently.

According to the traditional approach, the proper frequency can be computed only through Fourier analyses, from which the time domain data are reduced to purely frequency domain results. In this approach, the data have to be assumed as stationary and linear. Under such a restriction, if one has a perfect record of the undamaged structure as a reference, one will be able to detect the change of the proper frequency and its harmonics, but such a result still will not reveal the location of the damage. In what follows, a review of the state-of-the-art data-analysis methods, loading conditions, and use of the transient load will be presented. As the data-processing method is the driving force in determining the testing conditions, including the sensor types and their deployment schemes, and loading strategy, these problems will be examined first.

### 12.2.1. *Data-processing methods*

As discussed by Huang et al. (1998d), using the Fourier analysis method for nonlinear and nonstationary data involves fundamental problems, yet for lack of alternatives, it is still used extensively, although seldom in its bare form as in Basseville et al. (1993) and Hanagud and Luo (1997). Fourier analysis, however, appears in almost all other data-analysis methods such as the Wigner-Ville distribution, modal, wavelet, and even Hilbert analyses, as will be discussed later. In fact, the frequency determination from any data is almost always based on Fourier analysis, yet it is physically meaningful only for linear and stationary data. All real structures are seldom linear, especially when the structure is damaged to the extent where the response could be plastic. The lack of a nonlinear and nonstationary signal-processing method has made the random-vibration approach inconclusive as a method for nondestructive tests of bridges and other structures. Detailed summaries of the lessons learned from the Fourier approach are given by Salawu and Williams (1995a,b), Farrar and Doebling (1997) and Felber (1997). The applications of these Fourier-based methods are summarized as follows:

**Modal analysis**: The modal-analysis method was proposed as an adaptive approach for analyzing stationary random data (see, for example, Pandit 1991). When applied to analyzing deformations of a structure, the modes involved have been reduced drastically. Stationarity (or homogeneity) is assumed. This assumption should not be a serious problem for the lower modes. The most serious limitation is that the modal analysis depends on the global deformation of the whole structure. Consequently, deformation due to the local damages can be detected only in higher mode variations, but to determine the mode shape of the higher modes, a large number of sensors must be used to collect the necessary data. Even with the detailed data, the sensitivity is still low for local damages, due to the ubiquitous noise problem. As a result, this method is not very sensitive to the existence of damage (Farrar and Doebling 1997).

Recent developments, however, have alleviated some of the difficulties mentioned above. For example, Kim and Bartkowicz (1997) proposed a method with limited instruments; Stubbs and Kim (1996) suggested a method to infer the reference state from measured data; Vakakis (1997) proposed nonlinear normal mode expansion; and Fahy (1994) and Doebling et al. (1997) suggested an energy-based method to improve damage location. All these improvements notwithstanding, the real test of bridges and large structures by using modal analysis still presents great problems (Alampalli et al. 1997; Juneja et al. 1997). Even with good reference data, the noise from the real system and measurements can still cloud the picture and render the detection and location of the damage difficult. Another serious drawback of modal analysis is its requirement for prior analytical or test data of the undamaged state as a reference. Usually, such data are not available. The main problem when using modal analysis to locate damage is the requirement for the higher mode of deformation, which requires very detailed deformation measurements from many sensors. Therefore, this method is quite expensive and complicated to implement. Furthermore, noise removal and simplification of the structural deformation to a finite number of modes both present problems (Kim and Stubbs 1996). To overcome them, modal analysis is usually conducted jointly with Wigner-Ville distribution methods, or wavelet analysis as well.

**Wavelet analysis**: The wavelet analysis method is an adaptive window Fourier analysis (see, for example, Chui 1992); therefore, it can accommodate nonstationary but not nonlinear data (Dalpiaz and Rivola 1997). It is well known that the discrete wavelet is not useful for extracting special features from data. On the other hand, the continuous wavelet suffers redundancy and can hardly give quantitative results. Furthermore, wavelet analysis is still a Fourier-type transform; therefore, its use makes sense only when the data are from linear systems. Any nonlinear distortion of the waveform will require harmonics to be involved. Harmonics are mathematical entities with no physical meaning. Another problem of the wavelet approach is the uncertainty principle: the fundamental flaw of continuous wavelet analysis is the conflicting requirement of localization (with a narrow window) and frequency resolution (with a wide window) as discussed by Huang et al. (1998d). Even with these flaws, wavelet analysis has been used by Surace and Ruotolo (1994), Staszewski et al. (1997), Basu and Gupta (1997), Al-Khalidy et al. (1997), and Hou et al. (2000) to detect damage in various structures. Due to the poor frequency resolution, this detection method suffers a serious signal-to-noise ratio problem (Al-Khalidy et al. 1997). One possible usage of the wavelet analysis is to detect the singularity on the signal due to a sudden change of signal properties. Such changes, however, are rare in the bridge-damage problem.

**Wigner-Ville distribution**: The Wigner-Ville distribution was thoroughly discussed by Cohen (1995). Brancaleoni et al. (1993) and Feldman and Braun (1995) have tried to use it in damage detection with some limited success. As Wigner-Ville distribution is also Fourier-based, it suffers all the shortcomings of the Fourier analysis. Furthermore, its result is not strictly local; therefore, its ability to identify the location of the damage is also limited.

**Neural network**: Application of the neural network technique found application in damage detection as early as 1991, by Wu et al. (1991). Many investigators have extended the application, such as Tsou and Shen (1994), Manning (1994), Pandey and Barai (1995), and Barai and Pandey (1995, 1997). Most of these applications train the program to construct the reference modes or to reduce the noise in the data (Barai and Pandey 1995); therefore, this application is still mode-based. Any drawbacks of modal analysis cannot be fully eliminated and can be only partially ameliorated. For a true solution, a method that can produce localized analysis as well as accommodate nonlinear variation in the data must be found. The Hilbert transform certainly fits these requirements, but it also has limitations. These will be discussed in the following section.

**Hilbert transform**: The application of the Hilbert transform to nonstationary data was proposed long ago (see, for example, Bendat and Perisol 2000). Its application in damage identification has been tried by Feldman (1991, 1994a,b), Feldman and Braum (1995), Braum and Feldman (1997), and Feldman (1997). In all these studies, the signal was limited to a "monocomponent" condition, i.e., without the superposition of any smaller, riding waves, and the signals had to also be symmetrical with respect to the zero-mean. Thus, the applications were limited to cases of simple free vibrations. Although Prime and Shevitz (1996) and Feldman (1997) used Hilbert transforms to identify some of the nonlinear characteristics through the frequency modulation in a nonlinear structure, the limitations imposed on the data properties render the method of little practical use in both identifying and locating the damage. Among all the Hilbert transform applications, the most relevant one was due to Brancaleoni et al. (1993) who has employed a transient load over a damaged bridge. Confronted by the limitations of a straightforward application of the Hilbert transform to arbitrary data (as discussed by Huang et al. 1998d), Brancaleoni et al. resorted to filtering of the data to separate the data into different modes. As the filtering process is Fourier-based, it alters the nonlinear properties of the data drastically. Thus, the filtering method renders the results questionable. The real value of the Hilbert transform had to wait until Huang (1996) and Huang et al. (1996, 1998d) introduced the empirical mode decomposition (EMD) method as a pre-processing step, to be discussed presently. Before discussing the EMD method, another limitation of the present bridge-inspection method, the loading conditions, will be discussed.

### 12.2.2. *Loading conditions*

Because the previous data-processing methods are limited to mainly linear and stationary processes, the loading conditions will have to be designed to produce datasets tailored to fit the available analysis methods. As reviewed by Salawu and Williams (1995a,b), two loading conditions are frequently used: free and forced vibrations.

**Free vibrations**: In the free-vibration test, the structure is not under any live load other than the one that triggers the vibrations at the beginning, and is free of load thereafter. That load can be an impulse or residual vibrations from a transient loading. The free vibrations of bridges are usually assumed to be linear but with time-varying amplitude. The global mean frequency can be determined to a high degree of accuracy with Fourier analysis, yet without a reference state from a healthy bridge, the frequency from the free vibration is not very informative. The traditional vibration analysis might work under special conditions when a structure becomes highly nonlinear due to damage. Then the Fourier analysis will show many harmonics as indicators of the nonlinear deformation of the vibration waveforms. Even then, for lack of the phase information of the harmonics, the various harmonics cannot be uniquely used to reconstitute the data; therefore, it will be impossible to determine the damage scenario or the degree of damage. Furthermore, the Fourier-based analysis also makes vibration analysis unable to determine the locations of the damage, for vibration analysis works only in frequency space.

**Forced vibrations**: In forced vibrations, the structure is under some loading throughout the period of vibration, which can be due to artificial or ambient forces. Ambient forces include those from the traffic, the wind, and earthquakes. All these loads are assumed to be linear and stationary, an assumption that is hardly ever true: since the wind force is ever fluctuating and is proportional to the squared velocity, this force is certainly neither linear nor stationary. The ground motions from earthquakes are never stationary; for a strong earthquake, these motions cannot only be nonstationary, but also highly nonlinear. One of the loading conditions is a special artificially-induced vibration from a point source of a vibrator. The data from such a condition, though relatively easy to interpret, are hard to generate effectively, for the application points are usually different from the unknown damage location (Felber 1997). Therefore, the force will not produce diagnostic data as effective and sensitive as the date produced by the forces that are applied just at the damaged spot. Whenever the ambient loads are uniformly applied to all the structure, the load will certainly visit all the damage locations, but the loading conditions are not controllable, and the nonstationary properties also make the data analysis difficult. Furthermore, the signal-to-noise ratio becomes a critical issue: if a light load is considered as in microseisms, the response is not sensitive to the local damage. Only under a large load will the deformation be larger, and the responses nonlinear, but then, the random nature of the loading condition will make the signal (from the damage) and noise (from the ambient load) ratio too low to reveal the damage clearly.

The most effective loading condition should be the one with a transient load. This is equivalent to a point source applied to every load-bearing part of the structure. The data obtained from such a load, however, are certainly nonstationary. If the loading is up to the designed standard, the deformation of the damaged bridge should be linear. If the structure is damaged, the load-bearing capacity will decrease. Under such conditions, the structure will behave nonlinearly. Thus, a moving design load might produce nonlinear and nonstationary data for a damaged structure, a problem that the present available methods are unable to handle.

### 12.2.3. *The transient load*

Given all the shortcomings of the available methods, Huang (1998a) proposed a totally different approach: use a transient load and record the dynamic response, and then analyze the data by using the newly invented Hilbert spectral analysis (Huang 1996; Huang et al. 1998d). This method is designed for both nonstationary and nonlinear data.

Huang's (1998a) approach is based on the following two observations:

(1) When a bridge suffers structural deficiency, the stress-strain relationship will go beyond the linear limit. Then, we can visualize that the vibration waveform should be deformed. As discussed by Huang et al. (1998d), this nonlinear deformation will show up as an intra-wave frequency modulation.
(2) The response of the structure will be the strongest if the load is applied directly at the damaged location. This result is a logical consequence of the influence line, which represents the influence of the loading at any given point of the structure from the load applied at any other point of the structure.

The justifications of these claims are briefly summarized as follows: any structure under a design load should respond linearly and elastically. Under loading, the structure should reveal its proper frequency as well as free vibration. When the structure is damaged, its strength will decrease. Such a structure, even under the design load, will have an abnormally large deformation and behave nonlinearly. The nonlinearity could be the consequence of the non-elastic response of the material, or could be due to the non-uniform cross-section of the load-bearing members that suffered damage. Because of the unique capability of the Hilbert–Huang transform for analysis of transient and nonlinear signals, the precise location of the damage can be determined from the time domain variations of the vibration characteristics without any *a priori* knowledge of the damage location.

With these observations in mind, the ideal method to detect damage at an unknown location will be a transient load, which will visit every point of the bridge. When this load is directly over the damage point, the response will be strongest. This loading condition can be easily implemented with a moving vehicle. Unfortunately, until now, such a loading condition has been actively avoided because no proper method has been available for analyzing the data obtained from this condition. With the invention of the HHT technique, the transient data are no longer a problem. Before proceeding further, the problems associated with nondestructive structural health-monitoring methods should be considered.

Limited by the data-analysis methods, the structural vibration data were always assumed to be linear and stationary. These assumptions are not true, especially when the structure is damaged. Even if one assumes that one has a complete knowledge of the structure, in fact, any knowledge will be limited and only empirical. Even if the complete design plan is available, the anomalies introduced in construction would make such a design plan an approximation at best. Because of the lack of complete knowledge of the structure, any model is also an approximation. When measurements of the structure are made, further limitations are imposed by the number of sensors available, accessibility to the structure everywhere, and noise in the data from other sources. Finally, the unbridgeable gap between the damage response and the damage scenario must be mentioned, as well as the low sensitivity of damage to loadings, and the fussiness of damage thresholds. All these difficulties point to a need to change the damage-detection paradigm. No perfect solution exists for the myriad problems, but an attractive alternative is now available: the HHT-based nondestructive method, which, though having not solved all the problems, has certainly ameliorated most of the difficulties listed here. As the HHT method is a central part of this approach, a brief summary is given below.

## 12.3. The Hilbert–Huang transform

As discussed by Huang et al. (1996, 1998d), the HHT method is necessary to deal with data from both nonstationary and nonlinear processes. Contrary to almost all the previous methods, this new method is intuitive, direct, and adaptive, with the basis of the decomposition based on and derived from the data. HHT consists of two parts: the empirical mode decomposition (EMD) and the Hilbert spectral analysis (HSA). Details of this procedure can be found in Huang et al. (1998d, 1999).

With the EMD's initial processing, any data can be decomposed into a finite set of intrinsic mode functions (IMFs). These IMF components are usually physically meaningful, for the characteristic scales are defined by the physical data. Additionally, we can also identify a new use of the IMF components, that of filtering. Traditionally, filtering is carried out in frequency space only, but applying any frequency filtering when the data are either nonlinear or nonstationary is very difficult, for both nonlinear or nonstationary data cause these methods to generate harmonics of all ranges in order to match the nonlinear shape and nonstationary occurrence of the data. Therefore, any filtering will eliminate some of the harmonics, and this result, in turn, will cause deformation of the data filtered. Using IMF, however, a time domain filtering can be devised. For example, a low pass filtered result of a signal having $n$-IMF components can be simply expressed as

$$x_{lk}(t) = \sum_{j=k}^{n} c_j + r_n \, ; \tag{12.1}$$

a high pass result can be expressed as

$$x_{hk}(t) = \sum_{j=1}^{k} c_j \, ; \tag{12.2}$$

and a band pass result can be expressed as

$$x_{bk}(t) = \sum_{j=b}^{k} c_j \,. \tag{12.3}$$

The advantage of this time domain filtering is that the results preserve the full nonlinearity and nonstationarity in the physical space. This Hilbert–Huang transform method has been used recently by an increasing number of investigators for structural health monitoring (Liu 1999; Yang et al. 2002, 2003a, 2003b, 2003c, 2004). The HHT approach will also be demonstrated here for health monitoring of a bridge structure, but before providing the details, the damage-detection criteria must first be clarified.

## 12.4. Damage-detection criteria

Limited by the previous data-analysis methods, the past practice of damage identification was based primarily on modal analysis, as seen in the work of Doebling et al. (1996, 1998d), for example. The problems with modal analysis are as listed above. Here, the ability of the HHT to determine the instantaneous frequency precisely will be utilized. Furthermore, the ability of the HHT to distinguish between the linear vs. the nonlinear vibrations will also be used. This ability is crucial for the success of the HHT approach.

As the HHT can clearly define nonlinearly deformed waveforms, this definition will be used as the first indication of the existence of damage. The following approaches will be shown:

(1) comparing the fundamental frequencies of the new and the current structure,
(2) comparing the fundamental frequencies of the healthy and damaged structure, and
(3) comparing the fundamental frequencies of light and heavy loadings.

All structures are designed to perform in the elastic limit. Therefore, the structure should behave linearly under the design load when it is newly finished and healthy. If such data are available, the data could serve as a valuable reference. In most cases, such data are not available, and using an old and healthy structure as a reference will also be impossible, as will be discussed presently. A new and practical approach introduced here is to utilize the differences between the linear and nonlinear responses. Doing so is critical, for the HHT can be used to identify nonlinear distorted waveforms. To take advantage of these characteristics of structure, both light and heavy loading on the structure will be used to generate different responses. If the structure is healthy, the response should be linear and have clean symmetrical sinusoidal waveforms irrespective of the loading conditions, as long as the load is within the design limit. If the structure is damaged, the response of the structure will then be different: under a light load, the structure might still behave linearly;

once the stress increases, however, the damaged structure might behave nonlinearly. Then the vibration waveforms will be distorted, and the distortion will give intra-wave frequency modulation. The consequence is a broadening of the marginal Hilbert spectrum. The nonlinear behavior of the structure is a clear warning sign of structural defficiency. Appropriate actions should be taken: limiting loads or speed, for example, might be necessary.

If the damage is more severe, the stiffness of the structure might be permanently changed. In that case, the fundament frequency will change. To take the full advantage of the linear and nonlinear response under different loading conditions, a frequency ratio test must be done. A frequency ratio measurement can be defined as follows: let $\omega$ denote the frequency of a bridge, and $\omega_0$ denote the frequency when the bridge is new; then the frequency ratio $S$ is defined as

$$S = \frac{\omega}{\omega_0}\,. \tag{12.4}$$

According to Nishimura (1990),

$$\begin{array}{ll} 0.85 \le S \le 1.00 & \textit{safe} \\ 0.70 \le S \le 0.85 & \textit{caution} \\ 0.00 \le S \le 0.70 & \textit{detailed inspection} \end{array} \tag{12.5}$$

The rationale is simple: according to the beam theory, the fundamental frequency of the beam is proportional to the squared-root of the stiffness of the beam. Therefore, when the frequency ratio drops to 0.70, the stiffness should have reduced to 49%, a condition that certainly warrants a detailed inspection. Under such conditions, the original safety factor is reduced to unity.

As reasonable as these criteria are, they are unfortunately practically useless, for the frequency records for the mint state are available for few, if any, bridges. For bridges, a saving grace is that there are usually repeated spans, and all the spans are unlikely to suffer the same damage simultaneously. To utilize this fact, Li and Yen (1997) proposed a modification of the frequency ratio by using $\omega_0$ as the frequency for a healthy, old but undamaged span. They also modified Nishimura's criteria to read

$$\begin{array}{ll} 0.90 \le S \le 1.00 & \textit{safe} \\ 0.80 \le S \le 0.90 & \textit{caution} \\ 0.00 \le S \le 0.80 & \textit{detailed inspection} \end{array} \tag{12.6}$$

This modification is reasonable, for all structures will soften slightly with age. Given the lack of data for a bridge in its mint state, using the slightly lower $\omega_0$ and, therefore, a reduced ratio criterion is a logical alternative. Further research should be conducted to give this modification quantitative validation. In summary, the variation of the instantaneous frequency will be used here to detect damage, for the variation of the instantaneous frequency can arise from the following two causes.

First, the variation is due to the nonlinear behavior of the bridge; damage will cause a change of stiffness of the structure. This damage may or may not be over the linear elastic limit, but the sudden change of stiffness will cause the vibrational waveform to deform or the frequency to decrease, and the results will introduce either intra-wave frequency modulations or frequency downshift. These are critical indicators of local structure damage. As discussed by Huang et al. (1998d) these intra-wave frequency modulations are a clear indication of nonlinear oscillations.

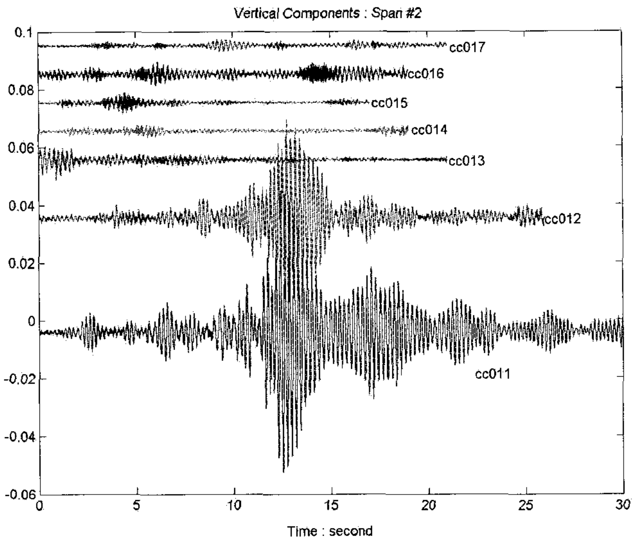
Second, the transient characteristic of the load can help us to locate the damaged spot. After the initial variation of the frequency due to the transient response when the test load first arrives on the bridge, the rest will be a forced vibration. As the test load passes along the bridge, this load will visit all the points, including the damaged spots, where the response should be the strongest as the test load moves over the damaged spots. Therefore, the first time the frequency goes nonlinear, or when it is below the free oscillation value, damage is indicated. The damage location is thus found from the time record and is identified when the testing load passes over the damaged location. This result is another crucial discriminator for damage detection.

### 12.5. Case study of damage detection

To demonstrate the use of the HHT analysis, Huang (1998a) used the deflection of a bridge under a transient load through computer simulation. The case studied was a simply supported bridge with a span of 8.5 m subjected to various damages under the standard design load. Clearly, the damaged bridge under the design load revealed the nonlinear characteristics of structural yielding at precisely the starting point when the load was over the damaged spot. From this time on, the period of oscillation of the damaged bridge was much longer than that of the undamaged bridge. This result was true also for the free oscillation after the truck had passed across the bridge. Fourier analysis of these data produced the spectra, which also showed the damaged bridge with a frequency down shift (indicating the increasing of the oscillation period). Since Fourier analysis totally lacks time information, there was no way one could determine the location of the damage from the Fourier analysis.

By considering a real bridge case study, the ability of this new approach with real measurements over a bridge with live transient loads can be demonstrated. This example also serves to show that data from a simple accelerometer can also be used for detecting damage. This demonstration will further show that HHT results can provide critical information for damage identification.

A bridge in southern Taiwan was selected for a field test. This bridge is a two-lane pre-stressed concrete girder bridge with 12 spans each 30 m in length. The girders are simply supported between piers, but the bridge deck is continuous with 15 cm reinforced concrete over three spans. There is a construction joint at every three spans.



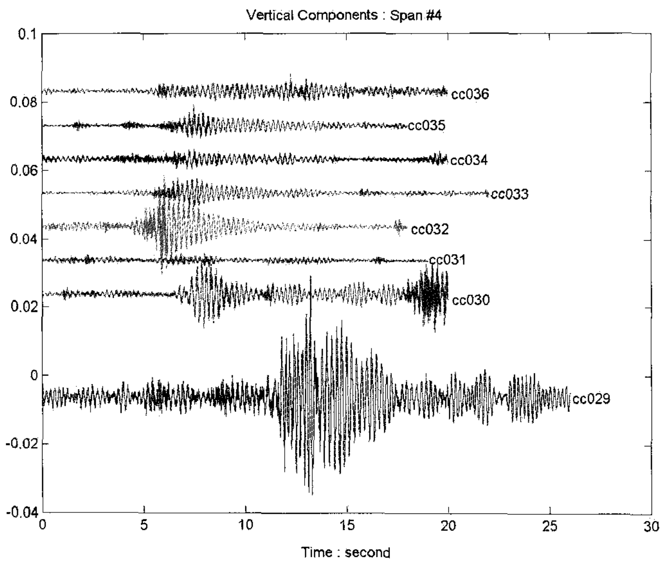




**Figure 12.1**: The raw vibration data collected with an accelerometer at the mid-span. (a, top) From Span 2. (b, bottom)

During this test, a tri-axial force balance Kinemetrics EpiSensor accelerometer was used. For the bridge deck, the sensor was installed at the mid span; for the piers, the sensor was installed on the pier cap. This sensor has an extended bandwidth of DC to 200 Hz with a user-selected full-scale recording range covering $\pm 0.25$ to $\pm 4$ g. The output was field selected and set at the $\pm 2.5$ V range.

The test loads employed were the regular traffic flow with vehicles of various sizes and speeds. The procedure of the test was to wait for a single vehicle to

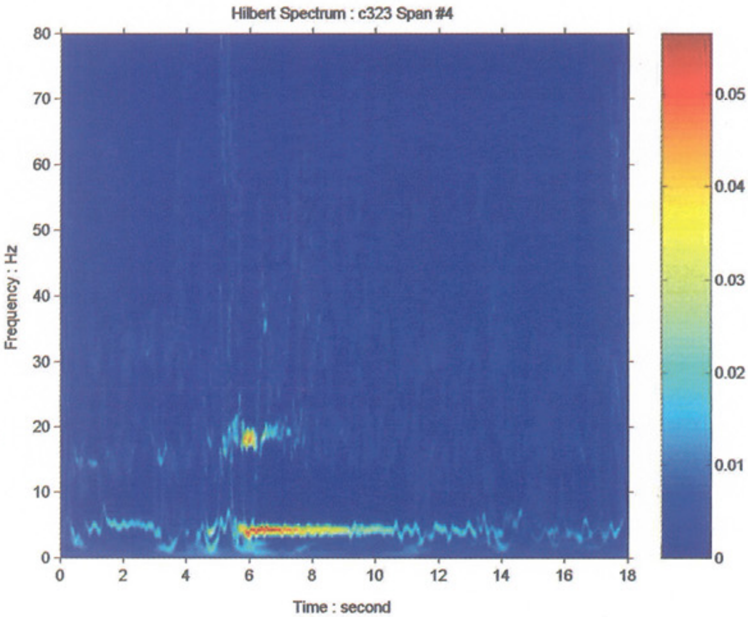



**Figure 12.2**: An example of the Hilbert spectra for the acceleration data for span 2.

pass by and record the vibration generated by it. By recording the various sizes of vehicles, a comparison of the bridge vibration characteristics under different loading conditions could be made. Figures 12.1a–c give the recorded vertical component of the acceleration as recorded by the accelerometers located at the middle of span numbers 2, 3 and 4. The recorded acceleration signals vary over a large range. In fact, the signal from a small light car is not even as big as the noise of the large heavy truck. Light or heavy, all transient vehicles triggered the bridge system's vibration signals. This result could have been realized only as a consequence of the transient loading. According to the linear vibration theory, if the loading is stationary, the system should respond with the frequency of the forcing function.

An example of the Hilbert spectrum for the heavy loads over span number 4 is given in Fig. 12.2. This figure reveals that the strongest bridge responses under the transient loads are concentrated around the 4 Hz range. Although concentrated around 4 Hz for this load, the energy distribution is diffused under the heavier loads, indicating the onset of intra-wave frequency modulations. The diffusing of energy is more obvious in the marginal spectra to be discussed next.

According to the beam theory, the response frequency should be a function of the elastic modulus and the moment of inertia of the cross-section of the beam. When the reaction of the beam is linear, the elastic modulus, or the ratio of stress-strain, should be constant. If the beam suffers any damage, it will become softened; i.e., the beam will deform more than the undamaged span under the same load. Thus,

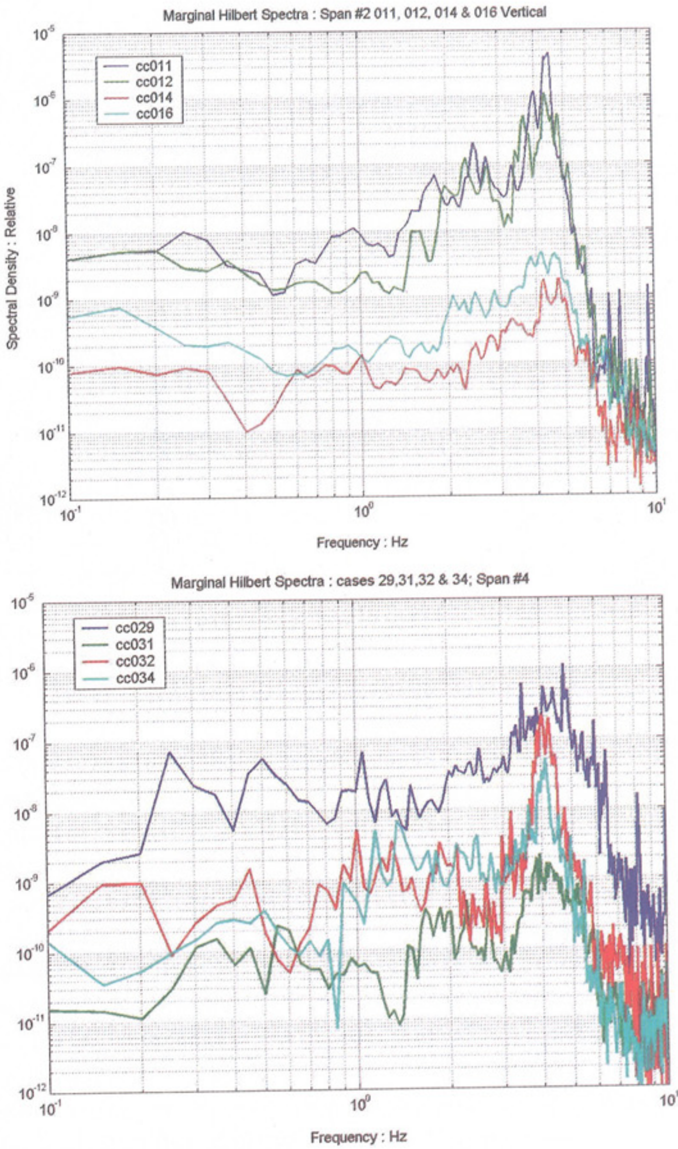



**Figure 12.3**: The marginal Hilbert spectra for the acceleration data. (a, top) Span 2. (b, bottom) Span 4.

the reaction becomes nonlinear. Based on these considerations, the determination of whether the reaction of a structural beam is or is not linear should be possible by examining the reaction of the beam under varied loading conditions. When the load is light, the structure will usually react linearly. If the structure is sound, the reaction of the beam should be linear even under a heavy load as long as the loading

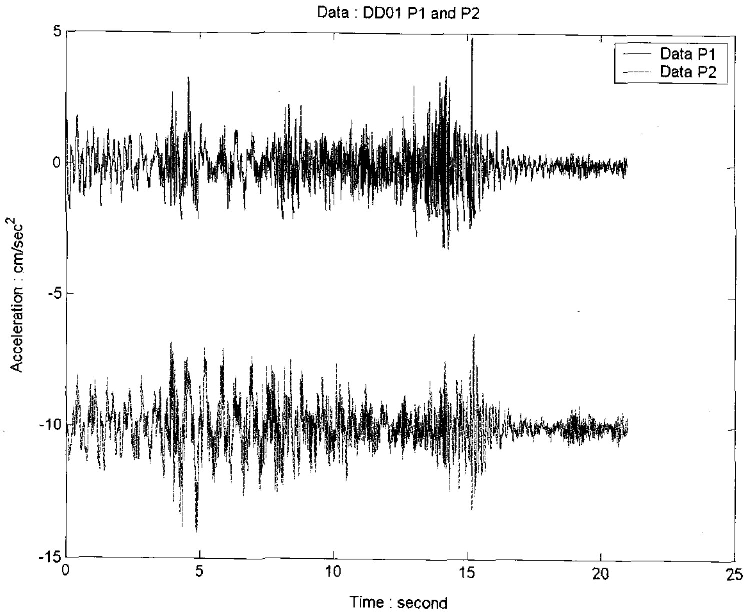



**Figure 12.4**: The raw vibration data collected with an accelerometer at the pier caps #1 (top) and #2 (bottom) under a heavy load. The "P2" data has been offset by −10.

is within the design limit. On the other hand, if the structure is damaged, the beam will become softened permanently or yield exceedingly under heavy loads. Then the reaction will vary according to the loading condition: the reaction might be linear under a light load, but become nonlinear under a heavy load.

Following these observations, the Hilbert spectra of the beam under different loads for the two representative spans can be examined. The results of the marginal spectra for spans 2 and 4 are shown in Figs. 12.3a–b. Figure 12.3a for span 2 is clearly linear under all the loads. For span 4, the peak of the energy is still centered around 4 Hz. Only under the heaviest load, does the spectral form widen slightly, indicating a nonlinear reaction by the onset of intra-wave frequency modulations: this reaction indicates the deformation of the vibration waveform under the heavy load. As the central value stays at the same location, the structure should still be sound, although it is under extreme stress, and care should be paid to its operational condition. Perhaps a limitation on load and/or speed should be considered.

Next, the test for the piers will be demonstrated. The data obtained when a heavy truck passed over the bridge are given for both pier 1 and 2 in Fig. 12.4. These data do not indicate any drastic difference between the different piers. Figures 12.5a–b show the Hilbert spectra of the two piers under an identical heavy load. Notice the time-frequency variation with the energy concentrated around 1.5 Hz. At around 5 s after the onset of data taking, a very high energy density in both the spectra appears. These densities represent the time when the load is over the

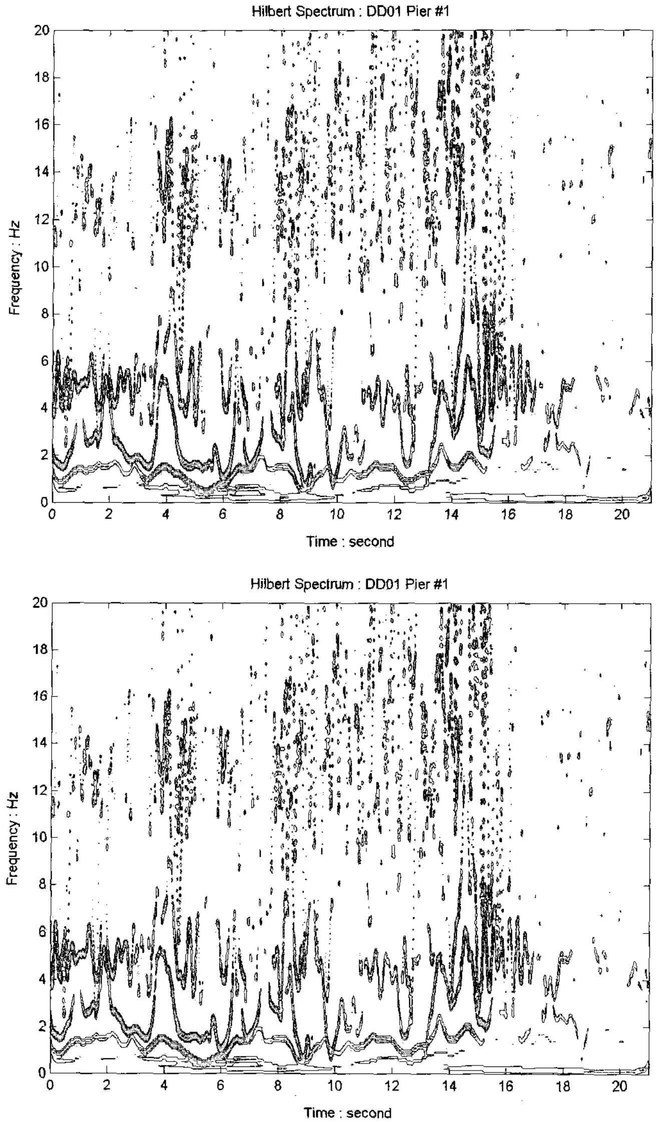



**Figure 12.5**: The Hilbert spectra for the acceleration data. (a, top) Pier 1. (b, bottom) Pier 2.

pier. On careful examination of the frequency difference, one can detect the slight decrease of frequency for pier number 2 relative to pier number 1. The difference shows up even more clearly when we examine the marginal Hilbert spectra together with the Fourier spectra in Fig. 12.6. The Fourier spectra reveals no substantial difference between the two piers. The spectra might have small amplitude changes, but unfortunately, amplitude is not a good discriminator for problems. The Hilbert marginal spectra, however, shows drastic changes: the peak frequency for pier 2

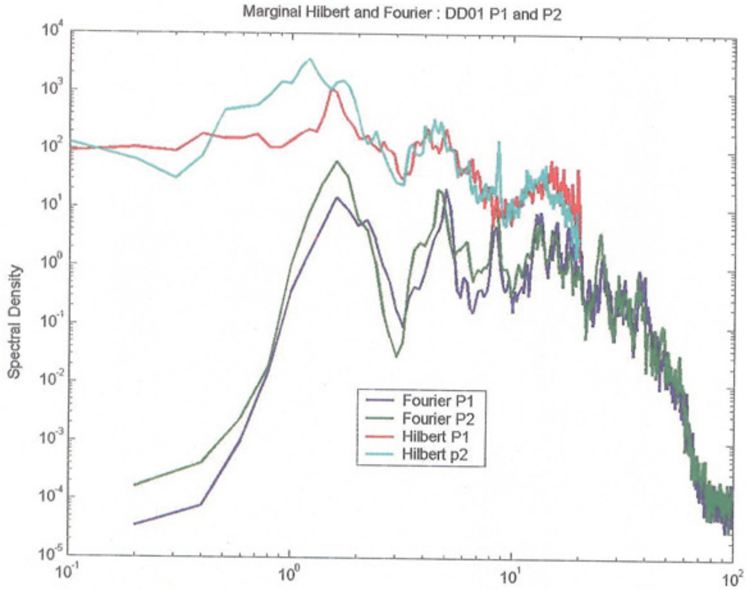



**Figure 12.6**: The marginal Hilbert and the Fourier spectra from the acceleration data collected at the pier caps. Note the frequency downshift revealed from the Hilbert spectra, but not in the corresponding Fourier spectra.

is at 1.2 Hz, while that for pier 1 is at 1.6 Hz, a clear downshift of the vibration frequency and a clear indication of softening of the structure. As the frequency is proportional to the square root of the stiffness of the structure, the ratio of 1.6 Hz to 1.2 Hz indicate that the stiffness has changed in proportionality from 16 to 9, a reduction of almost 50%. Assuming that pier 1 is healthy but not in mint condition, the frequency ratio is only at 0.75, a value already under the empirical criterion set by Li and Yen (1997) and Li et al. (2003). Visual inspection of the pier, as shown in Fig. 12.7, indeed found the piling of pier 2 exposed through erosion, a common problem of bridges in Taiwan, where rivers are short and riverbeds are steep, so that the rains coming with typhoons always produce torrential flash floods. The reduction of the stiffness for pier 2 is a serious condition, warranting immediate remedial actions. Bridge scouring is also a serious problem in many locations, which contributes to many a bridge failure. The collapse of the Kaoping Bridge in 1990 is an example.

## 12.6. Conclusions

The HHT method for structural health monitoring introduced here is both new and practical. The case study serves to illustrate the idea of data collection for safety inspection: use a constant speed transient load that will pass through the bridge to produce forced and free vibrations. This case study is of one of the simplest bridges

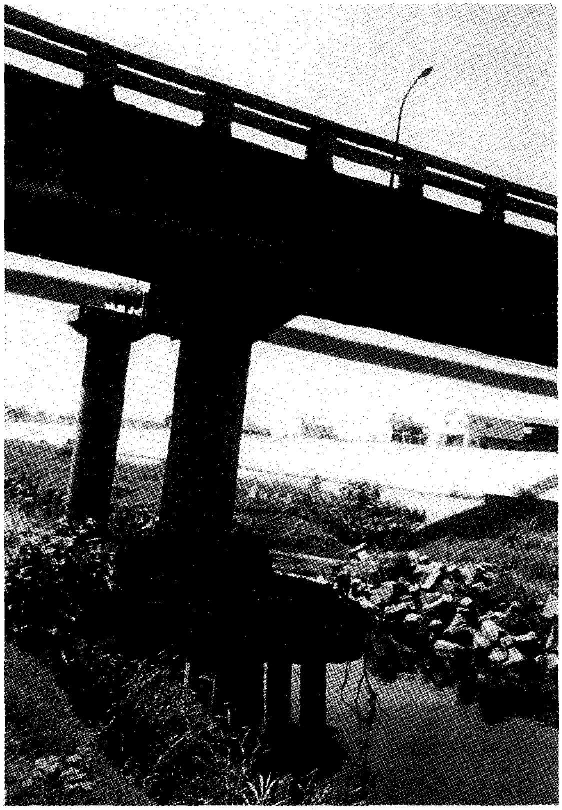


**Figure 12.7**: A photograph of pier #2. Note the pilings exposed by scouring.

in the real world. To isolate the contribution of the different structural members, the test should consist of sensors located on different parts of the bridge. With additional sensors on the piers, girders, and beams, the vibrations can be better separated than they were in the case discussed here. Future research should be concentrate along this direction. The analysis here has shown that the vibrations can be separated into different modes, and that the proper modes with structural and dynamic significance can be extracted. From this analysis, the weak structural members have been identified through either intra-wave frequency modulations or outright frequency downshifts. Therefore, the feasibility of the method has been established beyond any reasonable doubt. The present method is based on the most logical test load condition, the transient load, and the most effective data analysis method, the HHT. This method requires no special force-generating machines. The only requirement is that traffic be restricted for as long as needed for the test load, traveling at the normal speed, to pass across the bridge spans under observation. This requirement will cause only minimal traffic disruption, and the test could even be done at night or whenever normal traffic is at a minimum. The test load can be a fully loaded truck, or a roller, which is even better, for the load will be even more concentrated. The data-analysis method is the key to success, and the HHT approach used here is the most unique method and at the forefront of the research in data analysis. This approach utilizes not only the nonlinear characteristics of the response to determine the damage, but also the transient properties of the load to determine the damage location. Additionally, the free vibration frequency can be used to determine the extent of the damage. Considering the low number of the sensors required, and the efficient way of utilizing the data, the HHT presents a new, viable alternative for bridge-damage identification.

The similarity between the marginal and Fourier spectra further demonstrates the power of the Hilbert spectral analysis: it can produce whatever the Fourier analysis can and more, but Fourier-based analysis will never produce the time-frequency-energy analysis as the Hilbert spectral analysis does. Furthermore, any locally generated large amplitude vibration with a short period will be smeared by Fourier spectral analysis, as the case of pier 2 indicated. Such smearing of energy to a wide frequency range effectively obscures the frequency change of the structure. This factor is another indication that the Hilbert–Huang transform should be the method of choice.

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## References

Alampalli, S., G. Fu, and E. W. Dillon, 1997: Signal versus noise in damage detection by experimental modal-analysis. *J. Struct. Eng. (Amer. Soc. Civ. Eng.)*, **123**, 237–245.

Al-Khalidy, A., M. Moori, Z. Hou, S. Yamamoto, A. Masuda, and A. Sone, 1997: Health monitoring systems of linear structures using wavelet analysis. *Structural Health Monitoring: Current Status and Perspectives*, F.-K. Chang, Ed., Technomic, 164–175.

Barai, S. V., and P. C. Pandey, 1995: Vibration signature analysis using artificial neural networks. *J. Comput. Civ. Eng.*, **9**, 259–265.

Barai, S. V., and P. C. Pandey, 1997: Time-delay neural networks in damage detection of railway bridges. *Adv. Eng. Softw.*, **28**, 1–10.

Bacry, E., A. Arnéodo, U. Frisch, Y. Gagne and E. Hopfinger, 1991: Wavelet analysis of fully developed turbulence data and measurement of scaling exponents.

*Proc. Turbulence89: Organized Structures and Turbulence in Fluid Mechanics*, M. Lesieur and O. Métais, Eds., Kluwer, 203–215.

Basseville, M., A. Benveniste, B. Gach-Devauchelle, M. Goursat, D. Bonnecase, P. Dorey, M. Prevosto, and M. Olagnon, 1993: In-situ damage monitoring in vibration mechanics: Diagnostic and detective maintenance. *Mech. Syst. Signal Process.*, **7**, 401–423.

Basu, B., and V. K. Gupta, 1997: Nonstationary seismic response of MDOF systems by wavelet transform. *Earth. Eng. Struct. Dynam.*, **26**, 1243–1258.

Bendat, J. S., and A. G. Piersol, 2000: *Random Data Analysis and Measurement Procedures*. John Wiley & Sons, 602 pp.

Brancaleoni, F., D. Spina, and C. Valente, 1993: Damage assessment from the dynamic response of deteriorating structures. *Safety Evaluation Based on Identification Approaches*, H. G. Natke, G. R. Tomlinson, and J. T. P. Yao, Eds., Vieweg, 276–291.

Braun, S., and M. Feldman, 1997: Time-frequency characteristics of nonlinear-systems. *Mech. Syst. Signal Proc.*, **11**, 611–620.

Carmona, R., W. L. Hwang, and B. Torresani, 1998: *Practical Time-Frequency Analysis: Gabor and Wavelet Transform with an Implementation in S*. Academic Press, 490 pp.

Chang, F.-K., 1997: *Proceedings of the First International Workshop on Structural Health Monitoring*. Technomic, 801 pp.

Chang, F.-K., 1999: *Proceedings of the Second International Workshop on Structural Health Monitoring*. Technomics, 1062 pp.

Chang, F.-K., 2003: *Proceedings of the Third International Workshop on Structural Health Monitoring*. DEStech, 1552 pp.

Chase, S. B., and G. Washer, 1997: Nondestructive evaluation for bridge management in the next century. *Public Roads*, **61**, 16–25.

Chiu, C. K., 1992: *An Introduction to Wavelets*. Academic Press, 266 pp.

Chopra, A. K., 1995: *Dynamics of Structure: Theory and Applications to Earthquake Engineering*. Prentice Hall, 729 pp.

Clough, R. W., and J. Penzien, 1993: *Dynamics of Structures*. McGraw-Hill, 738 pp.

Cohen, L., 1995: *Time Frequency Analysis*. Prentice Hall, 299 pp.

Doebling, S. W., C. R. Farrar, M. B. Prime, and D. W. Shevitz, 1996: *Damage Identification and Health Monitoring of Structural and Mechanical Systems from Changes in their Vibration Characteristics: A Literature Review*. Report LA-13070-MS, Los Alamos National Laboratory, NM, 118 pp.

Doebling, S. W., F. M. Hemez, L. D. Peterson, and C. Farhat, 1997: Improved damage location accuracy using strain energy-based mode selection criteria. *AIAA J.*, **35**, 693–699.

Fahy, F. J., 1994: Statistical energy analysis–a critical overview. *Phil. Trans. R. Soc. London, Ser. A*, **346**, 431–447.

Farra, C. R., W. E. Baker, T. M. Bell, K. M. Cone, T. W. Darling, T. A. Duffey, A. Eklund, and A. Migliori, 1994: *Dynamic Characterization and Damage Detection in the I-40 Bridge over the Rio Grande.* Los Alamos Report LA-12767-MS UC-906, 153 pp.

Farrar, C. R., and S. W. Doebling, 1997: Lessons learned from applications of vibration-based damage identification methods to large bridge structure. *Structural Health Monitoring: Current Status and Perspectives*, F.-K. Chang, Ed., Technomic, 351–370.

Farra, C. R., S. W. Doebling, and D. A. Nix, 1999: Vibration-based structural damage identification. *Phil. Trans. R. Soc. London, Ser. A*, **359**, 131–149.

Felber, A., 1997: Practical aspects of testing large bridges for structural assessment. *Structural Health Monitoring: Current Status and Perspectives*, F.-K. Chang, Ed., Technomic, 577–588.

Feldman, M., 1991: Method for determination of vibratory system modal parameters using Hilbert transform. Application for Patent No. 098985, Israel, 28 July 1991.

Feldman, M., 1994a: Nonlinear system vibration analysis using Hilbert transform: I. Free-vibration analysis method, "FREEVIB." *Mech. Syst. Signal Process.*, **8**, 119–127.

Feldman, M., 1994b: Nonlinear system vibration analysis using Hilbert transform: II. Forced vibration analysis method, "FORCEVIB." *Mech. Syst. Signal Process.*, **8**, 309–318.

Feldman, M., 1997: Nonlinear free-vibration identification via the Hilbert transform. *J. Sound Vib.*, **208**, 475–489.

Feldman, M., and S. Braun, 1995: Identification of non-linear system parameters via the instantaneous frequency: Application of the Hilbert transform and Wigner-Ville techniques. *Proc. 13th Int. Modal Analysis Conf.*, Nashville, TN, 637–642.

Hahn, S., 1995: *Hilbert Transforms in Signal Processing.* Artech House, 299 pp.

Hanagud, S., and H. Luo, 1997: Damage detection and health monitoring based on structural dynamics. *Structural Health Monitoring: Current Status and Perspectives*, F.-K. Chung, Ed., Technomic, 715–726.

Hou, Z., M. Noori, and R. St. Amand, 2000: Wavelet-based approach for structural damage detection. *J. Eng. Mech. Div. (Amer. Soc. Civ. Eng.)*, **126**, 677–683.

Huang, N. E., 1996: Computer Implemented Empirical Mode Decomposition Method, Apparatus, and Article of Manufacture. (US Provisional Application Serial Number 60/023,411, August 14, 1996 and Serial No. 60/023,822 filed on August 12, 1996, Patent allowed March 1999.

Huang, N. E., Z. Shen, and S. R. Long, 1996: The mechanism for frequency downshift in nonlinear wave evolution. *Adv. Appl. Mech.*, **32**, 59–117.

Huang, K. 1998a: A New Instrumental Method for Bridge Safety Inspection Based on a Transient Test Load. US Patent Application Serial No. 09-210693, filed December 14, 1998; Patent No. US 6,192,758 B1 issued February 27, 2001.

Huang, N. E. 1998b: Computer Implemented Empirical Mode Decomposition

Method, Apparatus, and Article of Manufacture Utilizing Curvature Extrema, U.S. App. No. 09/082,523, filed May 21, 1998.

Huang, N. E., 1998c: Computer Implemented Empirical Mode Decomposition Method, Apparatus, and Article of Manufacture for Two-Dimensional Signals, U.S. App. No. 09/150,671, filed September 10, 1998.

Huang, N. E., Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N.-C. Yen, C. C. Tung, and H. H. Liu, 1998d: The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc. R. Soc. London, Ser. A*, **454**, 903–995.

Huang, N. E., 1999: Implemented Empirical Mode Decomposition Method, Apparatus, and Article of Manufacture for Analyzing Biological Signals and Performing Curve Fitting, U. S. App. No. 09/282,424., filed March, 31, 1999.

Huang, N. E., Z. Shen, and S. R. Long, 1999: A new view of water waves–The Hilbert spectrum. *Annu. Rev. Fluid Mech.*, **31**, 417–457.

Huang, N. E., M. C. Wu, S. R. Long, S. S. P. Shen, W. Qu, P. Gloersen, and K. L. Fan, 2003: A confidence limit for empirical mode decomposition and Hilbert spectral analysis. *Proc. R. Soc. London, Ser. A*, **459**, 2317–2345.

Juneja, V., R. T. Haftka, and H. H. Cudney, 1997: Damage detection and damage detectability–analysis and experiments. *J. Aerosp. Eng.*, **10**, 135–142.

Kim, H. M., and T. J. Bartkowicz, 1997: A 2-step structural damage detection approach with limited instrumentation. *J. Vib. Acous.*, **119**, 258–264.

Kim, J. T., and N. Stubbs, 1995: Model-uncertainty impact and damage-detection accuracy in plate girder. *J. Struct. Eng. (Amer. Soc. Civ. Eng.)*, **121**, 1409–1417.

Li, Y. F., and J. C. Yen, 1997: Vibration resistance evaluation of Chuang-Sha Bridge after erosion induced by typhoons. *Struct. Eng.*, **12**, 89–105.

Li, Y. F., W. C. Tseng, K. Huang, and T. Y. Ho, 2003: A study of ambient vibration test of bridge column by using Hilbert–Huang transform. *J. Chinese Inst. Civ. Hydr. Eng.*, **15**, 21–33.

Manning, R. A., 1994: Structural damage detection using active members and neural networks. *AIAA J.*, **32**, 1331–1333.

Mori, Y., and B. R. Ellingwood, 1994a: Maintaining reliability of concrete structures. 1. Role of inspection repair. *J. Struct. Eng. (Amer. Soc. Civ. Eng.)*, **120**, 824–845.

Mori, Y., and B. R. Ellingwood, 1994b: Maintaining reliability of concrete structures. 2. Optimum inspection repair. *J. Struct. Eng. (Amer. Soc. Civ. Eng.)*, **120**, 846–862.

Natke, H. G., G. R. Tomlinson, and J. T. P. Yao, 1993: *Safety Evaluation Based on Identification Approaches*. Vieweg, 324 pp.

Nishimura, A., 1990: Examination of bridge substructure for integrity. *Jap. Railway Eng.*, **114**, 13–17.

Pandit, S. M., 1991: *Modal and Spectrum Analysis: Data Dependent System in State Space*. Wiley-Interscience, 415 pp.

Pandey, P. C., and S. V. Barai, 1995: Multilayer perception in damage detection of bridge structures. *Comput. Struct.*, **54**, 597–608.

Prime, M. B., and D. W. Shevitz, 1996: Linear and nonlinear methods for detecting cracks in beams. *Proc. 14th Int. Modal Analysis Conf.*, Dearborn, MI, 1437–1443.

Salawu, O. S., 1997: Detection of structural damage through changes in frequency — A review. *Eng. Struct.*, **19**, 718–723.

Salawu, O. S., and C. Williams, 1995: Bridge assessment using forced-vibration testing. *J. Struct. Eng. (Amer. Soc. Civ. Eng.)*, **121**, 161–173.

Salawu, O. S., and C. Williams, 1995: Review of full-scale dynamic testing of bridge structures. *Eng. Struct.*, **17**, 113–121.

Staszewski, W. J., S. G. Pierce, W. R. Phip, and G. R. Tomlinson, 1997: Wavelet signal processing for enhanced Lamb wave defect detection in composite plates using optical fiber. *Opt. Eng.*, **36**, 1877–1888.

Stubbs, N., and J. T. Kim, 1996: Damage localization in structures without base-line modal parameters. *AIAA J.*, **34**, 1644–1649.

Surace, C., and R. Ruotolo, 1994: Crack detection of a beam using the wavelet transform. *Proc. 12th Int. Modal Analysis Conf.*, Honolulu, HI, 1141–1147.

Titchmarsh, E. C., 1948. *Introduction to the Theory of Fourier Integrals*. Oxford University Press, 394 pp.

Tsou, P. Y., and M. H. H. Shen, 1994: Structural damage detection and identification using neural networks. *AIAA J.*, **32**, 176–183.

Vakakis, A. F., 1997: Nonlinear normal-modes (NNMS) and their applications in vibration theory—An overview. *Mech. Syst. Signal Proc.*, **11**, 3–22.

Wu, X., J. Ghaboussi, and J. H. Garrett, 1992: Use of neural networks in detection of structural damage. *Comput. Struct.*, **42**, 649–659.

Wu, Z., and N. E. Huang, 2004: A study of the characteristics of white noise using the empirical mode decomposition method. *Proc. R. Soc. London, Ser. A*, **460**, 1597–1611.

Yang, J. N., S. Lin, and S. Pan, 2002: Damage detection of a health monitoring building using Hilbert–Huang spectral analysis. *Advances in Building Technology*, **2**, 1017–1024.

Yang, J. N., Y. Lei, and N. Huang, 2003a: Damage identification of civil engineering structure using Hilbert–Huang transform. *Structural Health Monitoring: The Demands and Challenges*, F.-K. Chang, Ed., DEStech, 544–553.

Yang, J. N., Y. Lei, S. Pan, and N. Huang, 2003b: Identification of linear structures based on Hilbert–Huang transform. Part I: Normal modes. *Earthq. Eng. Struct. Dynam.*, **32**, 1443–1467.

Yang, J. N., Y. Lei, S. Pan, and N. Huang, 2003c: Identification of linear structures based on Hilbert–Huang transform. Part II: Complex modes. *Earthq. Eng. Struct. Dynam.*, **32**, 1533–1554.

Yang, J. N., Y. Lei, S. Lin, and N. Huang, 2004: Hilbert–Huang based approach for structural damage detection. *J. Eng. Mech. Div. (Amer. Soc. Civ. Eng.)*, **130**, 85–95.

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