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DAMPING ESTIMATION OF ENGINEERING STRUCTURES FROM AMBIENT VIBRATION DATA

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Abstract. *Damping is a mechanism that dissipates vibration energy in dynamic systems and plays a key role in dynamic response prediction, vibration control as well as in structural health monitoring during service. In this communication a time domain and a time-scale domain approaches are used for damping estimation of engineering structures, using ambient response data only. The use of tests under ambient vibration is increasingly popular today because they allow to measure the structural response in service. In this paper we consider two engineering structures excited by ambient forces. The first structure is the 310 m tall TV tower recently constructed in the city of Nanjing in China. The second example concerns the Jinma cable-stayed bridge that connects Guangzhou and Zhaoqing in China. It is a single tower, double row cable-stayed bridge supported by 112 stay cables. Ambient vibration of each cable is carried out using accelerometers. From output data only, the modal parameters of the structure are extracted using a subspace method and the wavelet transform method. Usually the Morlet wavelet is considered when the wavelet transform is applied to free response of signals. In this communication the free response of ambient vibrations is obtained using the random decrement technique and a new analyzing wavelet function is investigated. The extraction of modal parameters is based on the ridge of the wavelet transform.*

Keywords: *Subspace identification method, wavelet transform, modal parameters, ambient vibration*

1. Introduction

Modal parameters identified from the measured data can reflect the dynamic characteristics of a vibrating system and often serve as input to model updating, health monitor or damage diagnosis. To identify the modal parameters of a system, both the excitation force and the response of the system should be measured and the frequency response function between the excitation and the response need to be calculated. In laboratory cases this experimental modal analysis method is effective and practical. However, for large and heavy structures, expensive and very strong exciting equipment is needed and the testing process may damage the mechanical structure. The last ten years, more attention was paid to so-called ambient excitation structures. The structural response is measured to freely available natural forces such as wind, traffic, waves and micro earthquakes. Obviously, the excitation force cannot be measured and is not available as input measurement. The mechanical system is subject to an uncontrolled, unmeasured and non-stationary excitation. The advantage of using ambient forces is that they are more representative for the true excitation to which a structure is subjected during its lifetime. Hence, the need arises to identify modal parameters in the real operational conditions, from output only measurements. In this paper the modal parameters of structures are extracted from output-data only using subspace methods [1-3] and the wavelet transform [4-5]. Two examples using real data are presented in the communication. The first experiment concerns the TV tower in the city of Nanjing in China [6]. This tower is 310 m high and the acceleration response of the structural system measured under ambient conditions is used to identify its dynamic characteristics. The second experiment concerns the Jinma cable-stayed bridge that connects Guangzhou and Zhaoqing in China [7]. It is a single tower, double row cable-stayed bridge supported by 112 stay cables. Ambient vibration of each stay cable is carried out using accelerometers and results are compared using subspace methods and the wavelet transform technique.

2. Subspace identification

The method assumes that the dynamic behaviour of a structure excited by ambient forces can be described by a stochastic state space model

$$z_{k+1} = \mathbf{A}\, z_k + w_k \quad \text{state equation} \tag{1}$$

$$y_k = \mathbf{C}\, z_k + v_k \quad \text{observation equation} \tag{2}$$

where y_k is the (mx1) vector of observations, w_k, v_k are white noise terms representing process noise and measurement noise together with the unknown inputs; z_k the (nx1) is the internal state vector; **A** the (nxn) state matrix describing the dynamics of the system and **C** the (mxn) output matrix, translating the internal state of the system into observations. The modal parameters of a vibrating system are obtained by applying an eigenvalue decomposition to **A**. The eigenfrequencies and damping ratios are obtained from the eigenvalues and the mode shapes are obtained by pre-multiplying the eigenvectors with **C**. Define the (mfx1) and (mpx1) future and past data vectors as $y^{+}_{k} = (y'_k, y'_{k+1}, \ldots, y'_{k+f-1})'$ and $y^{-}_{k} = (y'_k, y'_{k-1}, \ldots, y'_{k-p+1})'$ and the (mfxmp) covariance matrix between the future and the past as:

$$\mathbf{H} = \mathbf{E}\left[y^{+}_{k} y^{-'}_{k-1} \right] = \begin{bmatrix} \mathbf{R}_1 & \mathbf{R}_2 & . & \mathbf{R}_p \\ \mathbf{R}_2 & \mathbf{R}_3 & . & \mathbf{R}_{p+1} \\ . & . & . & . \\ \mathbf{R}_f & \mathbf{R}_{f+1} & . & \mathbf{R}_{f+p-1} \end{bmatrix} \tag{3}$$

where **E** denotes the expectation operator, **H** is the block Hankel matrix (a block band counter diagonal matrix) formed with the (mxm) individual auto covariance submatrices $\mathbf{R}_i = \mathbf{E}[y_{k+i}\, y'_k] = \mathbf{C}\mathbf{A}^{i-1}\mathbf{G}$, with $\mathbf{G} = \mathbf{E}[z_{k+1}\, y'_k]$. The sample covariance matrices calculated from data y_k, $k = 1, 2, \ldots, N$

$$\hat{\mathbf{R}}_i = \frac{1}{N} \sum_{k=1}^{N-i} y_{k+i}\, y'_k \quad ; \qquad i = 0, 1, \ldots, p+f \tag{4}$$

are used to construct an estimated block Hankel matrix $\hat{\mathbf{H}}$. In order to estimate the model coefficients, two matrix decompositions of the block Hankel matrix are employed: the singular value decomposition and the factorization of $\hat{\mathbf{H}}$ into its observability and controllability matrices. The singular value decomposition of $\hat{\mathbf{H}}$ is $\hat{\mathbf{H}} = \hat{\mathbf{U}}\hat{\mathbf{\Sigma}}\hat{\mathbf{V}}'$ with $\hat{\mathbf{U}}'\hat{\mathbf{U}}$ and $\hat{\mathbf{V}}'\hat{\mathbf{V}}$ identity matrices and $\hat{\mathbf{\Sigma}}$ a diagonal matrix of singular values. The second factorization of the block Hankel matrix into its (mfxn) observability and (nxmp) controllability matrices, **O** and **K** is :

$$\mathbf{H} = \begin{bmatrix} \mathbf{C} \\ \mathbf{CA} \\ \vdots \\ \mathbf{CA}^{f-1} \end{bmatrix} \begin{bmatrix} \mathbf{G} & \mathbf{AG} & \ldots & \mathbf{A}^{p-1}\mathbf{G} \end{bmatrix} = \mathbf{O}\,\mathbf{K} \tag{5}$$

The two factorisations of the estimated block Hankel matrix can be equated to give :

$$\hat{\mathbf{H}} = \hat{\mathbf{U}}\hat{\mathbf{\Sigma}}\hat{\mathbf{V}}' = \left(\hat{\mathbf{U}}\hat{\mathbf{\Sigma}}^{0.5}\right)\left(\hat{\mathbf{\Sigma}}^{0.5}\hat{\mathbf{V}}'\right) = \hat{\mathbf{O}}\,\hat{\mathbf{K}} \tag{6}$$

implying $\hat{\mathbf{O}}^{\#} = \hat{\mathbf{\Sigma}}^{-0.5}\hat{\mathbf{U}}'$ and $\hat{\mathbf{K}}^{\#} = \hat{\mathbf{V}}\hat{\mathbf{\Sigma}}^{-0.5}$, where $\hat{\mathbf{O}}^{\#}$ and $\hat{\mathbf{K}}^{\#}$ are pseudo-inverses.

To estimate **A**, it is necessary to introduce a time shifted block Hankel matrix $\overleftarrow{\mathbf{H}}$, obtained by shifting a block column or a block row. We have then

$$\overleftarrow{\mathbf{H}} = \mathbf{O}\,\mathbf{A}\,\mathbf{K} \tag{7}$$

The estimate of **A** is obtained by applying the pseudo inverses of $\hat{\mathbf{K}}$ and $\hat{\mathbf{O}}$ again, yielding

$$\hat{\mathbf{A}} = \hat{\mathbf{O}}^{\#}\hat{\overleftarrow{\mathbf{H}}}\hat{\mathbf{K}}^{\#} = \hat{\mathbf{\Sigma}}^{-0.5}\hat{\mathbf{U}}'\hat{\overleftarrow{\mathbf{H}}}\hat{\mathbf{V}}\hat{\mathbf{\Sigma}}^{-0.5} \tag{8}$$

Using properties of the product of eigenvalues, we note that $\hat{\mathbf{A}}$ and $\hat{\mathbf{H}}^{\#}\hat{\overleftarrow{\mathbf{H}}}$ have the same eigenvalues and to obtain the modal parameters of a vibrating system we can extract the eigenvalues of the product $\hat{\mathbf{H}}^{\#}\hat{\overleftarrow{\mathbf{H}}}$. In order to select the physical modes stabilisation diagrams for both eigenfrequencies and damping ratios are used with a modal assurance criterion [8]. Results using subspace identification are presented in section 4.

3. The wavelet transform

3.1. Definitions

The wavelet transform gives time and frequency information about the analyzed data. The wavelet transform of a signal $x(t)$ is defined as [9]

$$W_{\psi}\left[x\right](a,b)=\langle x,\psi_{a,b}\rangle=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}x(t)\psi^{*}(\frac{t-b}{a})dt \tag{9}$$

where $\psi(t)$ is an analyzing function called mother wavelet, a is the dilatation or scale parameter defining the analysing window stretching and b is the translation parameter localising the wavelet function in the time domain. The WT represents the correlation between the signal $x(t)$ and a scaled version of the function $\psi(t)$ and the idea of the WT is to decompose a signal $x(t)$ into wavelet coefficients using the basis of wavelet functions. The decomposition is obtained locally at different time windows and frequency bands. The size of the time window is controlled by the translation parameter b while the length of the frequency band is controlled by the dilatation parameter a. Hence, one can examine the signal at different time windows and frequency bands by controlling translation and dilatation.

Since the wavelet transform is a linear representation of a signal, it follows that the WT of P signals is

$$W_{\psi}\left[\sum_{i=1}^{P}x_i\right](a,b)=\sum_{i=1}^{P}W_{\psi}\left[x_i\right](a,b) \tag{10}$$

this property is convenient for the analysis of multi-component signals.

A number of different analyzing functions have been used in the wavelet analysis. One of the most known and widely used is the Morlet wavelet defined in the time domain as [4,5,9]

$$\psi(t)=e^{\frac{-t^2}{2}}e^{j\omega_o t} \tag{11}$$

where ω_o is the wavelet frequency. The dilated version of the Fourier transform is

$$\hat{\psi}(a\omega)=\sqrt{2\pi}e^{-\frac{1}{2}(a\omega-\omega_o)^2} \tag{12}$$

In practice the value of ω_o is chosen $\omega_o=2\pi/\sqrt{2\log(2)}$ which meets approximately the requirements of admissibility condition [9]. Note that $\hat{\psi}(a\omega)$ is maximum at the central frequency $\omega_c=\omega_o/a$ and the Morlet wavelet can be viewed as a linear bandpass filter whose bandwidth is proportional to $1/a$ or to the central frequency. Thus, the value of the dilatation parameter a at which the wavelet filter is focused on the wavelet frequency can be determined from $a=\omega_o/\omega_c$.

For a given value of the dilatation parameter a the spectrum of the Morlet wavelet has a fixed bandwidth. If the analysed frequency is important the dilatation parameter becomes small and the spectrum of the Morlet wavelet function is wide. There is then a bad spectral resolution. An alternative is to modify the Morlet wavelet function by introduction of a parameter N which controls the shape of the basic wavelet : this parameter balances the time resolution and frequency resolution of the Morlet wavelet. The modified Morlet wavelet function used in this paper is :

$$\psi(t)=e^{\frac{-t^2}{N}}e^{j\omega_o t} \tag{13}$$

with $N>0$ and whose dilated version of its Fourier transform is :

$$\hat{\psi}(a\omega)=\sqrt{N\pi}e^{-\frac{N}{4}(a\omega-\omega_o)^2} \tag{14}$$

The wavelet filter central frequency is $\omega_c=\omega_o/a$ and gives then a relation between the scale parameter a and the central frequency of the modified Morlet wavelet.

When N tends to infinity the modified Morlet wavelet tends to $e^{j\omega_o t}$ which has the finest frequency resolution allowing a better resolution of closely spaced modes, but at the expense of time resolution. Indeed, increasing N will increase the frequency resolution but it decreases the time resolution. So, there always exists an optimal N that has the best time-frequency resolution for a certain signal localized in the time-frequency plane. This modified Morlet wavelet function offers a better compromise in terms of localization, in both time and frequency for a signal, than the traditionally Morlet wavelet function. The optimal value of N is obtained by minimizing the entropy of the wavelet transform [10].

3.2. Application of the wavelet transform to modulated signals

Consider the case of a signal $x(t)$ modulated in amplitude :

$$x(t) = A(t)\cos(\varphi(t)) \tag{15}$$

if $x(t)$ is assumed to be asymptotic, the WT of $x(t)$ can be obtained by means of asymptotic techniques and can be expressed as [4,5]

$$W_\psi\left[x\right](a,b) = \frac{\sqrt{a}}{2}A(b)e^{j\varphi(b)}\hat{\psi}^*\left(a\dot{\varphi}(b)\right) \tag{16}$$

the point indicating a derivative. The dilatation parameter can be calculated in order to maximize $\hat{\psi}^*\left(a\dot{\varphi}(b)\right)$, that is using the Morlet wavelet (or the modified Morlet wavelet) for the dilatation $a(b) = \omega_o / \dot{\varphi}(b)$. The wavelet transform is essentially concentrated in a neighbourhood of a curve given by $a(b)$.

Consider now the free response of a viscously damped single degree of freedom system:

$$x(t) = Be^{-\zeta\omega_n t}\cos(\omega_d t + \chi_o) \tag{17}$$

with B the residue magnitude, ω_n the undamped natural frequency, $\omega_d = \omega_n\sqrt{1-\zeta^2}$ the damped natural frequency, ζ the viscous damping ratio. If the system is underdamped, that is if the damping ratio is smaller than 1, (in general $0<\zeta<<1$, so $\omega_d \simeq \omega_n$) the signal $x(t)$ can be considered asymptotic, and therefore the results obtained previously can be used considering :

$$A(t) = Be^{-\zeta\omega_n t} \tag{18}$$

$$\varphi(t) = \omega_d t + \chi_o \quad \Rightarrow \quad \dot{\varphi}(t) = \omega_d \tag{19}$$

The wavelet transform of the damped sinusoid is :

$$W_\psi\left[x\right](a,b) = \frac{\sqrt{a}}{2}Be^{-\zeta\omega_n b}e^{j(\omega_d b+\chi_o)}\hat{\psi}^*\left(a\omega_d\right) \tag{20}$$

For a fixed value a_o of the dilatation parameter the logarithm of the wavelet transform amplitude is

$$\ln\left|W_\psi\left[x\right](a_o,b)\right| = -\zeta\omega_n b + \ln\left(\frac{\sqrt{a_o}}{2}B\left|\hat{\psi}^*\left(a_o\omega_d\right)\right|\right) \tag{21}$$

Thus the decay rate $\sigma = \omega_n\zeta$ of the signal can be estimated from the slope of the straight line of the logarithm of the wavelet transform modulus. The wavelet transform phase is given by :

$$\mathrm{Arg}\left(W_\psi\left[x\right](a_o,b)\right) = \omega_d b + \chi_o \quad \Rightarrow \quad \frac{d}{db}\mathrm{Arg}\left(W_\psi\left[x\right](a_o,b)\right) = \omega_d \tag{22}$$

and the plot of $\frac{d}{db}\mathrm{Arg}\left(W_\psi\left[x\right](a_o,b)\right)$ should be constant in time and equal to the damped natural frequency ω_d .

The damping ratio and eigenfrequency estimation procedures, based on the wavelet transform presented above, can be extended to multi degrees of freedom systems by selecting the right value of the dilatation parameter a_i corresponding to the mode of interest. Consider now the free response of a P degrees of freedom system :

$$x(t)=\sum_{i=1}^{P} B_i e^{-\zeta_i \omega_{ni} t}\cos(\omega_{di} t+\chi_{oi}) \tag{23}$$

where B_i is the residue magnitude, ζ_i is the damping ratio, ω_{ni} the undamped natural frequency and ω_{di} the damped natural frequency associated to the i-th mode. From equation (20), the wavelet transform of the multi degrees of freedom system is :

$$W_\psi\left[\sum_{i=1}^{P} x_i\right](a,b)=\sum_{i=1}^{P}\frac{\sqrt{a}}{2}B_i e^{-\zeta_i\omega_{ni}b}e^{j(\omega_{di}b+\chi_{oi})}\hat{\psi}^*\left(a\omega_{di}\right) \tag{24}$$

The wavelet transform is a signal decomposition procedure working as a filter in the time-frequency domain: it analyzes a signal only locally at windows defined by the wavelet. Thus, multi-degrees of freedom system can be decoupled into single degrees of freedom. For a fixed value of the dilatation parameter ($a=a_i$), which maximizes $\hat{\psi}^*\left(a\omega_{di}\right)$, only the mode associated with a_i gives a relevant contribution in the wavelet transform, while all the other terms are negligible. Thus the wavelet transform of each separated mode i = 1, 2,…, P becomes:

$$W_\psi\left[x_i\right](a_i,b)=\frac{\sqrt{a_i}}{2}B_i e^{-\zeta_i\omega_{ni}b}\hat{\psi}^*\left(a_i\omega_{di}\right)e^{j(\omega_{di}b+\chi_{oi})} \tag{25}$$

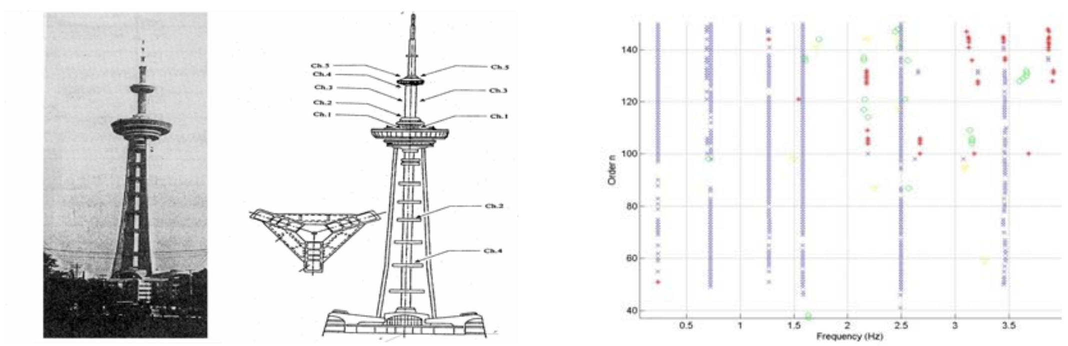
Clearly, the wavelet transform offers a decoupling of multi degrees of freedom systems into single modes. However, equation (25) is true under the assumption of vanishing $\hat{\psi}^*\left(a_i\omega_{di}\right)$ outside the interval $\left[\omega_i-\Delta\omega_\psi/a_i,\ \omega_i+\Delta\omega_\psi/a_i\right]$, that is, if none of the other frequencies of the system except ω_i and more likely if neither ω_{i-1} or ω_{i+1} belongs to the interval $\left[\omega_i-\Delta\omega_\psi/a_i,\ \omega_i+\Delta\omega_\psi/a_i\right]$. The resolution of the wavelet transform is good enough to separate the i-th mode from the neighbouring modes.

Using (25) associated with (21) and (22), it is possible to follow the amplitude and phase variations in the time domain of each modal component and to estimate the corresponding damping ratio and eigenfrequency associated to the isolated mode. This technique requires a previous choice of the value of the dilatation parameter a_i corresponding to the analyzed mode and the resolution of the wavelet transform depends on the value of this scale parameter, thus the choice of the analyzing wavelet is important.

4. Applications

4.1. The TV tower the city of Nanjing in China

Figure 1(a) shows the main structure of the TV tower in the city of Nanjing in China [6]. This tower is 310 m high and the acceleration response of the structural system measured under ambient conditions is used to identify its dynamic characteristics. The accelerometers are installed on the tower at two sets of different locations, as shown in figure 1(a), to measure the ambient vibrations of the system. The sensors at the first set of locations are concentrated on the upper part of the structure since this part is more flexible resulting in more vibration than the lower part, while those at the second set of locations are distributed along the height of the whole structure. The accelerometers are placed as close as possible to the centre of the cross section of the tower in order to minimise the response component due to torsional vibration. Acceleration records are obtained simultaneously in one direction each time, with a sampling time interval of 0.03125 second and a total recording time of approximately 600 seconds.



(a) (b)

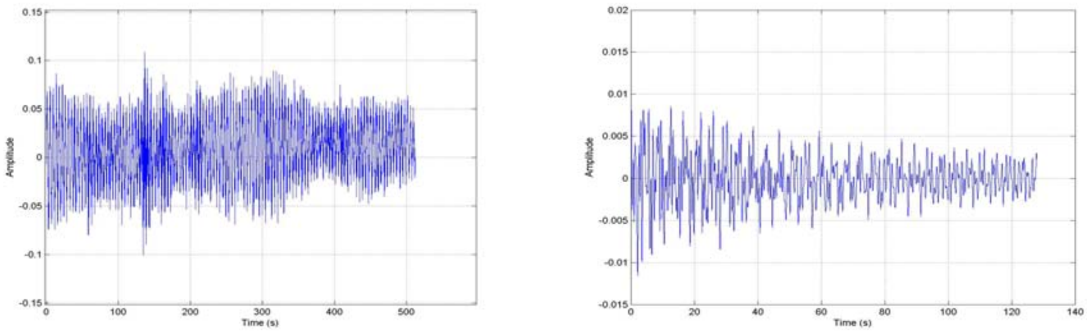
Figure 1.(a) Main structure of the tower and accelerometers locations, (b) Stabilization diagram

Figure 1(b) shows the stabilization diagram of the cable using the subspace method. From this plot we extract eigenfrequencies and damping ratios of the tower. We have used the second accelerometer of the first set of locations. The identified modal parameters for five first modes are presented in the Table 1.

Table 1. Natural frequencies and damping ratios using the subspace method and the WT method

Modes	Subspace Method		WT Method	
	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
1	0,235	0,655	0,234	0,683
2	0.726	0.436	0,734	0,383
3	1,271	0,324	1,273	0,640
4	1,586	0,359	1,594	0,314
5	2,726	0,321	2,726	0,326

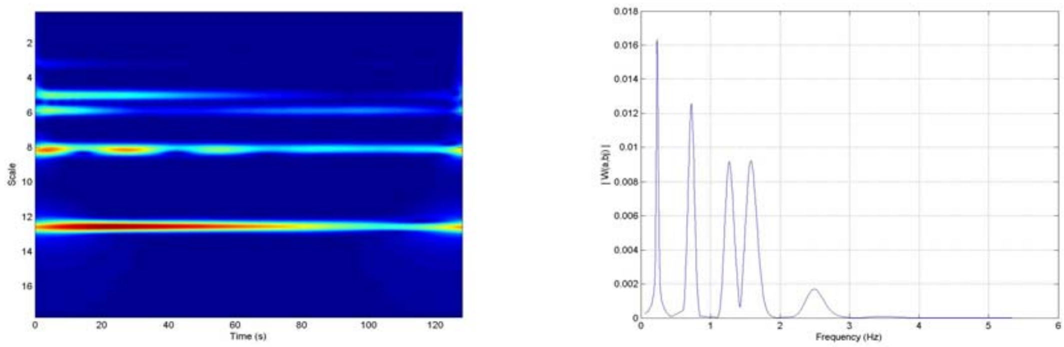
The WT estimation technique operates on the free response of the system. A method converting random responses to free decay responses is the random decrement technique [12]. Its basic concept is that the acceleration response can be decomposed into free vibration component and forced vibration component. The free vibration component can be obtained by a special averaging procedure of measurements which remove the random part, leaving its deterministic part. We apply the random decrement technique to the accelerometer number 2 to obtain its free response (see Figure 2). We apply then the WT method.



(a) (b)

Figure 2.(a) Ambient response, (b) Free response from the random decrement technique

Figure 3 shows the wavelet transform amplitude using accelerometer number 2; the five first modes are visible from this plot. The modal parameters are obtained using (21) and (22) and from the plots shown in figure 4.



(a) (b)

Figure 3.(a). Wavelet transform amplitude, (b) Determination of eigenfrequencies

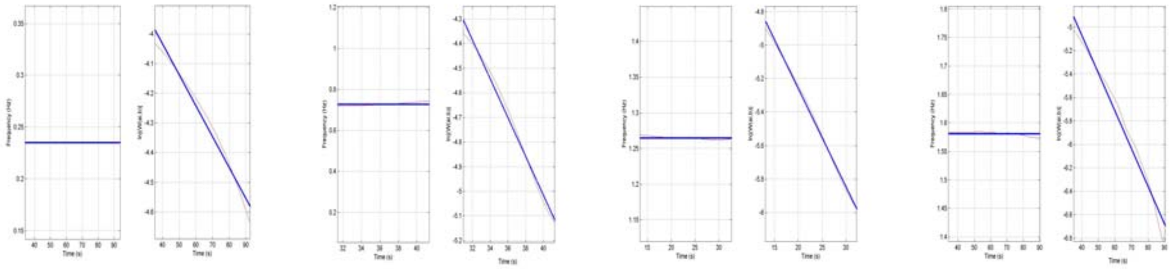
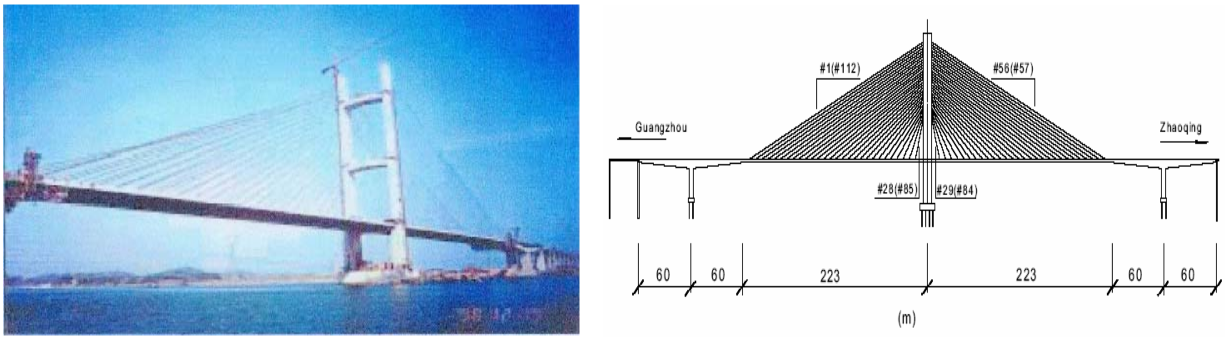


Figure 4. First four modes instantaneous frequencies and wavelet transform envelopes

Table 1 presents also the modal parameters obtained using this accelerometer by application of the wavelet transform. In generally the results are similar to those obtained by the subspace method. However the third mode presents a damping ratio slightly different. The difference comes from spurious poles which appear with the subspace identification method.

4.2. The Jinma cable-stayed bridge

The subspace method and the wavelet transform were applied to the analysis of stay cables of the Jinma cable-stayed bridge (Figure 5a, b), that connects Guangzhou and Zhaoqing in Guangdong Province, China. It is a single tower, double row cable-stayed bridge, supported by 28*4 =112 stay cables. The stay cables were excited by ambient vibrations essentially due to wind. Inputs could evidently not be measured, so only acceleration data are available. A full description of the test can be found in [7].



(a) (b)

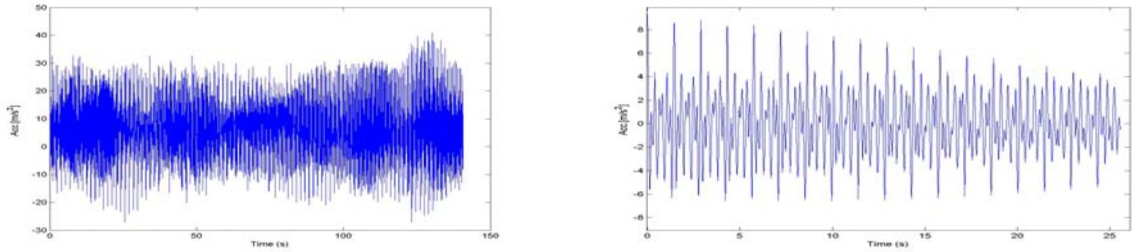
Figure 5.(a) View of the Jinma cable-stayed bridge, (b) Elevation Drawing

The subspace identification method is used to obtain modal parameters of a cable (cable number 10) and they are presented in Table 2. The instability is assessed by the Scruton number [11] defined as $S_{c,i} = \dfrac{\zeta_i \cdot \rho}{\rho_a D^2}$, where ζ_i represents the damping ratio for each mode, ρ is the mass of the cable per meter, ρ_a is the density of the air and D is the cable diameter. High values of the Scruton number tend to suppress the oscillation and bring up the start of instability at high wind speeds. Considering ρ = 66,94 kg/m, ρ_a = 1,2 kg/m^3 and D = 0,203m, the Scruton number for each mode is presented in Table 2.

Table 2. Natural frequencies, damping ratios and Scruton number using the subspace method

Modes	1	2	3	4	5	6	7	8
Frequency (Hz)	1,388	2,085	2,775	3,476	4,169	4,869	5,562	6,275
Damping ratio (%)	0,251	0,142	0,081	0,127	0,112	0,077	0,079	0,034
$S_{c,i}$	3,401	1,926	1,091	1,725	1,520	1,045	1,067	0,454

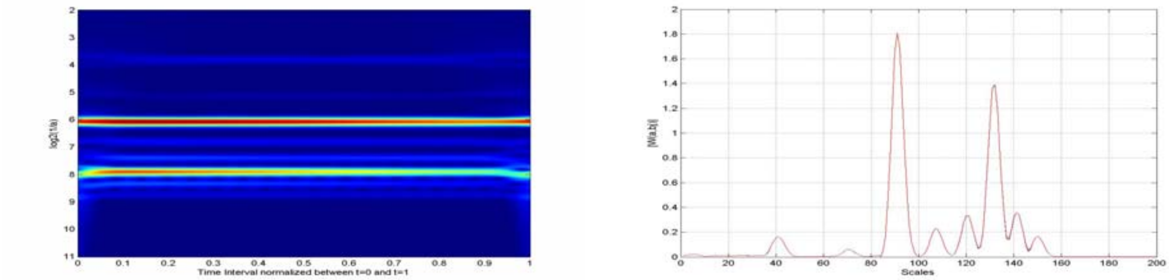
The identification procedure of modal parameters using the WT is carried out as previously. We apply the random decrement technique to the cable number 10 to obtain its free response (see Figure 6). We apply then the WT method.



(a) (b)

Figure 6.(a) Ambient response, (b) Free response from the random decrement technique

The wavelet transform amplitude is shown in Figure 7(a) and the dilatation parameter a_i for each eigen-mode is obtained from Figure 7(b).



(a) (b)

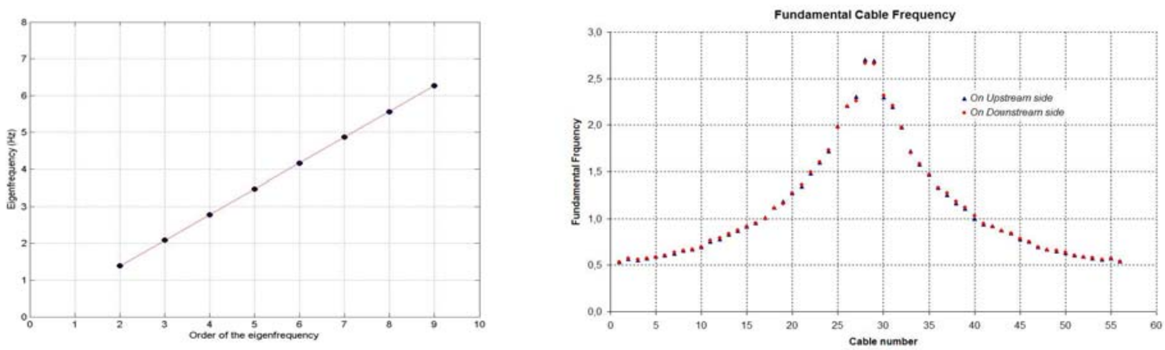
Figure 7.(a) Wavelet transform amplitude , (b) Determination of dilatation parameters

The estimated modal parameters for the eight first modes of the cable number 10 are shown in Table 3, with the Scruton number for each mode.

Table 3. Natural frequencies, damping ratios and Scruton number using the WT method

Modes	1	2	3	4	5	6	7	8
Frequency (Hz)	1,387	2,081	2,774	3,477	4,172	4,870	5,559	6,275
Damping ratio (%)	0,259	0,188	0,106	0,096	0,072	0,074	0,078	0,020
$S_{c,i}$	3,509	2,552	1,431	1,302	0,980	1,008	1,061	0,272

The fundamental frequency of the cable number 10 has been obtained using the subspace method and the WT met (gure)). W o ha Fproxi a e b ce i f_0 = 0,697 Hz. This value is obtained from the slope of the straight line. The cable tension can be estimated by the approximately expression $T = 4\rho L^2 f_0^2$, where L = 180,174 m, ρ = 66,94 kg/m. We obtain T = 4227,593 kN. This cable tension can be considered as a reference and used as an indicator for monitoring of stay cables in this cable-stayed bridge.



(a) (b)

Figure 8.(a) Fundamental cable frequency, (b) Fundamental cable frequency of all stay cables for the Jinma Bridge

Figure 8(b) shows fundamental frequencies of all stay cables (on upstream and downstream side). These frequencies vary between 0,533 Hz for the longest cable and 2,703 Hz for the shortest cable. The maximum and minimum cable forces for the Jinma bridge are then : T_{max} = 5052,073 kN (cable number 57), T_{min} = 2490,653 kN (cable number 84). These cable forces can be considered as reference tensions and used as indicators in the field of health monitoring process.

5. Conclusions

In a continuous monitoring and modal analysis process, eigenfrequencies and damping ratios of a tower can be used as reference for studying the safety comportment of this tower. A cable-stayed bridge has been studied and stay cables eigenfrequencies and damping ratios could be used to assess the health of cables of this bridge. It is shown how operational modal analysis applied to the dynamic data of stay cables provide useful information to determine cable force and the current condition of stay cables accurately. A Scruton number has been computed and used as an indicator to prevent rain-wind induced vibration. A monitoring system which records the vibrations of stay cables and a software that extracts automatically the force cables and the Scruton number is under investigation.

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