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Operational modal analysis for Canton Tower

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Abstract. The 610 m high Canton Tower (formerly named Guangzhou New Television Tower) is currently considered as a benchmark problem for structural health monitoring (SHM) of high-rise slender structures. In the benchmark study task I, a set of 24-hour ambient vibration measurement data has been available for the output-only system identification study. In this paper, the vector autoregressive models (ARV) method is adopted in the operational modal analysis (OMA) for this TV tower. The identified natural frequencies, damping ratios and mode shapes are presented and compared with the available results from some other research groups which used different methods, e.g., the data-driven stochastic subspace identification (SSI-DATA) method, the enhanced frequency domain decomposition (EFDD) algorithm, and an improved modal identification method based on NExT-ERA technique. Furthermore, the environmental effects on the estimated modal parameters are also discussed.

Keywords: operational modal analysis (OMA); Canton Tower, vector autoregressive models (ARV) method; environmental effects; structural health monitoring (SHM)

1. Introduction

According to (Farrar and Worden 2007), structural health monitoring (SHM) is defined as the process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructures. It is clear that the modal properties (i.e., natural frequencies, damping ratios and mode shapes) play an important role in the SHM study. For example, in vibration-based damage assessment, the modal properties from both the undamaged and damaged structures can be used to update the structural model in order to locate and quantify the damage. Besides this, with the help of the modal properties, an updated and reliable structural model can also benefit the model-based load reconstruction study, e.g., the method in (Niu *et al.* 2011a). In structural control design, an appropriate tuning frequency of tuned mass damper (TMD) has a close relation with the structural modal frequencies (Ni *et al.* 2009). The above mentioned three points, to some extent, can reflect the importance of modal properties. It is known that the operational modal analysis (OMA), or named as output-only modal analysis, can identify the modal characteristics using only the response measurements of structures in their operational conditions subject to ambient or natural excitation (Zhang *et al.* 2005).

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The Canton Tower, formerly called Guangzhou New Television Tower (GNTVT), has a total height of 610 m, including a 454 m high main tower and a 156 m high antenna mast, and is currently considered as the landmark of the Guangzhou city in southern China. It serves for the functions of TV and radio transmission, sightseeing, cultural entertainment, and offers an orbital Ferris wheel, a ceremony hall, observatory decks, 4D cinemas, revolving restaurants, skywalk, etc. In November 2010, the Canton Tower also took part in broadcasting the Asian Games hosted by Guangzhou. To maintain the safe and reliable operation of the Canton tower, researchers from the Hong Kong Polytechnic University extended their practice and experiences gained in developing structural health monitoring (SHM) systems for bridges to high-rise structures, and have designed and implemented a long-term SHM system for the Canton Tower (Ni *et al.* 2011). Meanwhile, to ensure and improve the comfort of people staying in this tower, a hybrid mass damper (HMD) control system is installed on the main tower and two tuned mass dampers (TMDs) are suspended on the antenna mast to mitigate the wind-induced vibration (Ni and Zhou 2010).

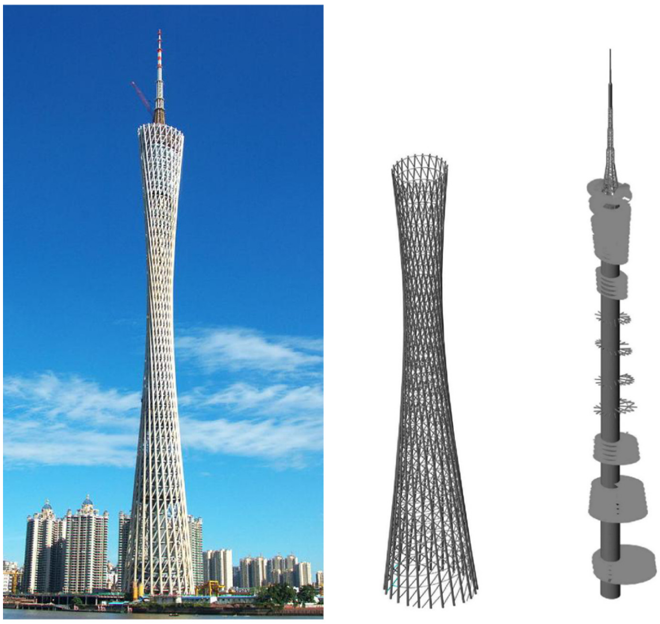
Under the auspices of Asian-Pacific Network of Centers for Research in Smart Structures Technology (ANCRiSST), an SHM benchmark problem for high-rise structures is being developed by taking the instrumented Canton Tower as the host structure (Ni *et al.* 2012, Xia *et al.* 2009). The benchmark study task I is output-only system identification and FE model updating. At present, a set of 24 hour field measurement data and a reduced-order FE model for the Canton Tower have been available (Lin *et al.* 2010). This paper focuses on the output-only system identification part using the available field measurement data.

In 2010, Kraemer and Fritzen applied vector autoregressive models (ARV) method for the study of dynamic characteristics of offshore wind energy plants (Kraemer and Fritzen 2010a, Kraemer and Fritzen 2010b). In this contribution, the ARV technique is also adopted in the operational modal analysis for the Canton Tower. The organization of this paper is as follows. In Section 2, a short description of the field measurement data is provided. In Section 3, the principles of the ARV method are briefly reviewed. In Section 4, the identified natural frequencies, damping ratios and mode shapes are presented and compared with the available results presented by different research groups (Chen *et al.* 2011a, Chen *et al.* 2011b, Faravelli *et al.* 2010a, Faravelli *et al.* 2010b, Loh *et al.* 2011, Niu *et al.* 2011b, Niu *et al.* 2011c, Ye *et al.* 2011). In Section 5, the environmental effects on the identified modal parameters are discussed. Finally, the conclusions are given.

2. Field measurement data for OMA

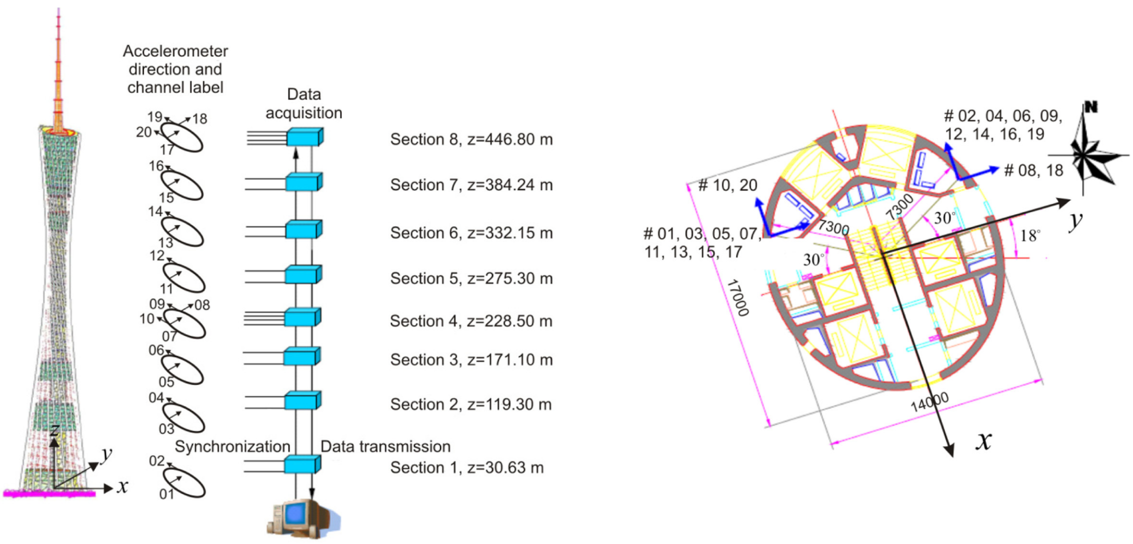
The 454 m high main tower of the Canton Tower has a tube-in-tube geometry, consisting of a reinforced concrete inner structure and a steel lattice outer structure, as shown in Fig. 1. The 156 m high antenna mast mounted on the top of the main tower is a steel spatial structure. Detailed dimension and configuration description can be found in (Ni *et al.* 2009). In Task I of this benchmark problem, twenty uni-axial accelerometers (Tokyo Sokusin AS-2000C), an anemometer (RM Young, 05103L) and a thermocouple (PT1000) were employed from the designed SHM system. The positions and measurement directions of these sensors are illustrated in Figs. 2 and 3.

The acceleration, wind direction and wind speed were measured with sampling frequency 50 Hz, and the temperature was sampled every minute (1/60 Hz). The field measurement data available for the OMA were recorded permanently during 24 hours from 18:00 h on January 19, 2010, to 18:00 h



(a) (b) (c)

Fig. 1 (a) Canton tower, (b) outer steel structure, and (c) inner concrete structure (Source: The Hong Kong Polytechnic University)



(a) (b)

Fig. 2 (a) Positions of accelerometers and data acquisition system and (b) measurement directions of acceleration and channel labels (Source: The Hong Kong Polytechnic University)

on January 20, 2010. More detailed information on the field measurements and sensor specifications are presented in (Lin *et al.* 2010).

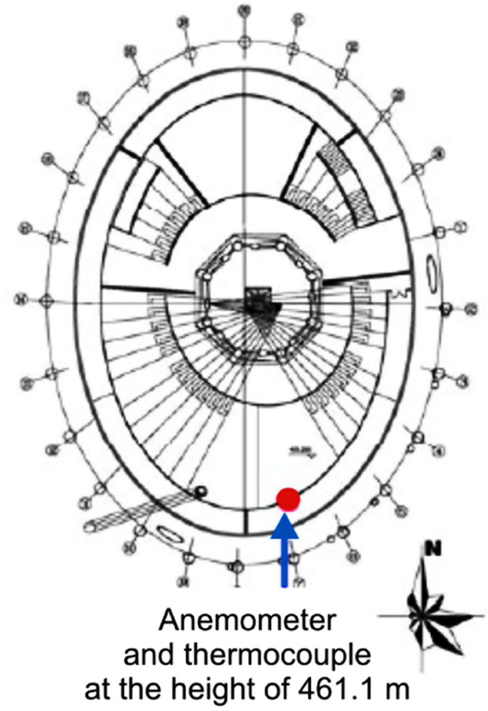


Fig. 3 Positions of the anemometer and the thermocouple (Source: The Hong Kong Polytechnic University)

3. Vector autoregressive models (ARV) method

The measurements obtained at equally spaced time instants k can be modeled by an arbitrary order vector autoregressive model (ARV) of the following form

$$\boldsymbol{y}_k = \boldsymbol{b} + \sum_{l=1}^{p} \boldsymbol{A}_l \boldsymbol{y}_{k-l} + \boldsymbol{\varepsilon}_k \tag{1}$$

where $\boldsymbol{y}_k$ denotes the measurement vector from m sensors at time instant k, p is the order of this AR model and $\boldsymbol{A}_1, \ldots, \boldsymbol{A}_p \in R^{m \times m}$ are coefficient matrices. $\boldsymbol{b}$ is an intercept vector. $\boldsymbol{\varepsilon}_k$ is assumed to be an uncorrelated zero mean random vector, representing the residual between real measurements and the model at time instant k. Assuming $\boldsymbol{b}$ is a zero vector, the p-th order AR model (AR(p)) can be transformed to a state space form as in Eqs. (2(a) and (b)) with expressions in Eqs. (3)-(6).

$$x_{k+1} = \boldsymbol{A}_d \boldsymbol{x}_k + \boldsymbol{w}_k \tag{2a}$$

$$\boldsymbol{y}_k = \boldsymbol{C}\boldsymbol{x}_k \tag{2b}$$

$$\boldsymbol{x}_k = \left[\boldsymbol{y}_k^T \boldsymbol{y}_{k-1}^T \ldots \boldsymbol{y}_{k-p+1}^T\right]^T \in \boldsymbol{R}^{(mp) \times 1} \tag{3}$$

$$A_d = \begin{bmatrix} A_1 & A_2 & \dots & A_{p-1} & A_p \\ I & 0 & \dots & 0 & 0 \\ 0 & I & \dots & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & \dots & I & 0 \end{bmatrix} \in R^{(mp)\times(mp)} \tag{4}$$

$$w_k = \begin{bmatrix} \varepsilon_{k+1}^T & 0 & \dots & 0 \end{bmatrix}^T \in \boldsymbol{R}^{(mp)\times 1} \tag{5}$$

$$\text{and } C = \begin{bmatrix} I & 0 & \dots & 0 \end{bmatrix} \in \boldsymbol{R}^{m\times(mp)} \tag{6}$$

The robust calculation of the autoregressive coefficient matrices takes advantage of the ARFIT MATLAB package (Neumaier and Schneider 2001, Schneider and Neumaier 2001). Then the dynamical characteristics of the investigated structure can be extracted by solving the eigenvalue problem of the discrete state space system matrix A_d

$$A_d = \Psi \Lambda \Psi^{-1} \tag{7}$$

where Λ is a diagonal matrix of associated discrete-time eigenvalues $\lambda_{p,i}^d$ (i=1,⋯,mp) and Ψ contains the corresponding eigenvectors $\Psi_{p,i}$ (i=1,⋯,mp) in its i-th column. Using Eq. (8), $\lambda_{p,i}^d$ can be transformed to its continuous-time counterpart

$$\lambda_{p,i}^c = (\ln \lambda_{p,i}^d)/\Delta t \tag{8}$$

where Δt is the sampling time. The corresponding natural frequency $f_{p,i}$, damping ratio $\zeta_{p,i}$ and complex mode shape $\varphi_{p,i}$ (i=1,⋯,mp) can be calculated using Eqs. (9)-(12).

$$\lambda_{p,i}^c, \lambda_{p,i}^{c\,*} = -\zeta_{p,i}\omega_{p,i} \pm j\omega_{p,i}\sqrt{1-\zeta_{p,i}^2} \tag{9}$$

where $\lambda_{p,i}^{c\,*}$ is the complex conjugate of $\lambda_{p,i}^c$.

$$f_{p,i} = \left|Im(\lambda_{p,i}^c)\right|/(2\pi) \tag{10}$$

$$\zeta_{p,i} = -Re(\lambda_{p,i}^c)/\left|\lambda_{p,i}^c\right| \tag{11}$$

$$\varphi_{p,i} = \begin{bmatrix} \mathbf{0}_{m\times m} & \mathbf{0}_{m\times m} & \dots & I_m \end{bmatrix}_{m\times(mp)} \Psi_{p,i} \tag{12}$$

In order to separate the physical modes from the spurious ones caused by noise and numerical errors, the percentage frequency difference f_{diff}, the percentage damping ratio difference d_{diff} and the modal assurance criterion (MAC) value between the modal properties from the AR(p) model and those from the AR($p-1$) model are adopted, and the following three criteria are introduced

$$\text{(a) } f_{diff} = \frac{|f_{p,i} - f_{p-1,j}|}{f_{p-1,j}} \le f_{tol} \tag{13}$$

$$\text{(b)}\ d_{diff} = \frac{|d_{p,i} - d_{p-1,j}|}{d_{p-1,j}} \le d_{tol} \tag{14}$$

$$\text{(c)}\ MAC = \frac{|\varphi_{p,i}^{T} \varphi_{p-i,j}^{*}|^2}{\varphi_{p,i}^{T} \varphi_{p,i}^{*} \varphi_{p-1,j}^{T} \varphi_{p-1,j}^{*}} \ge MAC_{tol} \tag{15}$$

where $p \ge 2$, (i=1,⋯,mp), j=1,⋯,$m(p-1)$, $\varphi_{p,i}^{T}$ is the transpose of $\varphi_{p,i}$, and $\varphi_{p,i}^{*}$ is the conjugate transpose of $\varphi_{p,i}$.

4. OMA results

It is known that the monitoring data segment length should be long enough to reduce the noise effects, while more data, on the other hand, lead to longer computation time. In accordance with the choice in (Faravelli *et al.* 2010a, Faravelli *et al.* 2010b), 1 h is selected as the time interval in this paper for each data segment. However, the originally provided 24 measurements of 1 h duration are not used directly for the present study but first decomposed into 70 overlapping data sets of 1 h duration with a 20 min shift, as shown in Fig. 4.

The reason for such an operation is to improve the continuity of the one hour mean wind speed and the one hour mean temperature in later environmental effect discussion. For a comparison of

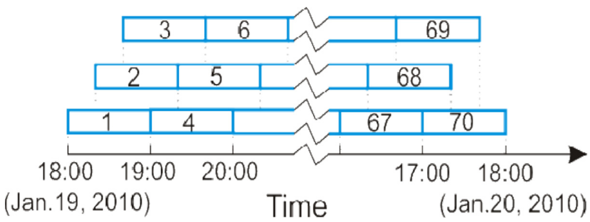


Fig. 4 20 min shift data operation

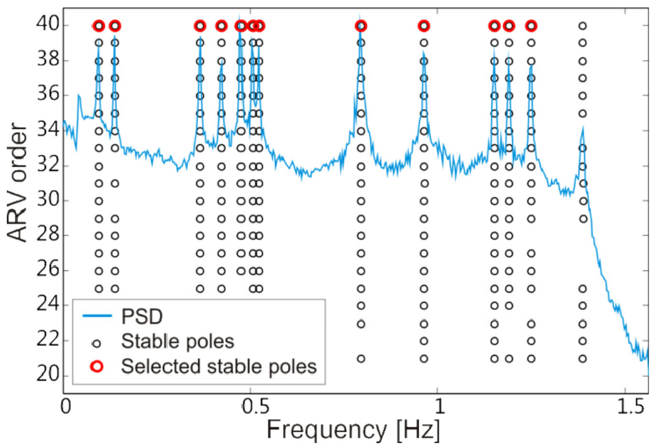


Fig. 5 Stabilization diagram for data set no. 61

Table 1 Identified natural frequencies and damping ratios

Mode Nr.	Natural frequency f [Hz]	CV of identified f	Damping ratio ζ [%]	CV of identified ζ
1	0.0936	0.0030	0.68	0.7228
2	0.1384	0.0021	0.39	0.5095
3	0.3659	0.0021	0.34	0.4724
4	0.4238	0.0008	0.20	0.3520
5	0.4747	0.0007	0.12	0.8658
6	0.5055	0.0011	0.17	0.3027
7	0.5224	0.0008	0.19	0.4954
8	0.7953	0.0013	0.26	0.7801
9	0.9648	0.0015	0.27	0.4011
10	1.1505	0.0005	0.13	0.4609
11	1.1909	0.0005	0.12	0.6020
12	1.2507	0.0009	0.15	0.2338

the identified modal parameters with those already available results from other research groups, only the first 12 modes of the Canton Tower are of interest in this paper. To select the stable poles and construct the stabilization diagram, following tolerance values are used in Eq. (16)

$$f_{tol} = 1\%, \ \zeta_{tol} = 10\% \ \text{ and } \ MAC_{tol} = 0.99 \tag{16}$$

According to the modal frequency range provided by the reduced-order FE model of the Canton Tower (Lin *et al.* 2010), the first 12 modes are within 1.3 Hz, so the acceleration measurements are downsampled by a factor of 16 to decrease the computation effort. As an example, the stabilization diagram for the data set no. 61 is shown in Fig. 5.

The mean values and CV (Coefficient of Variation) values of the identified natural frequencies and damping ratios are listed in Table 1. As a verification, the results from the ARV technique are also compared with those obtained using the data-driven stochastic subspace identification (SSI-

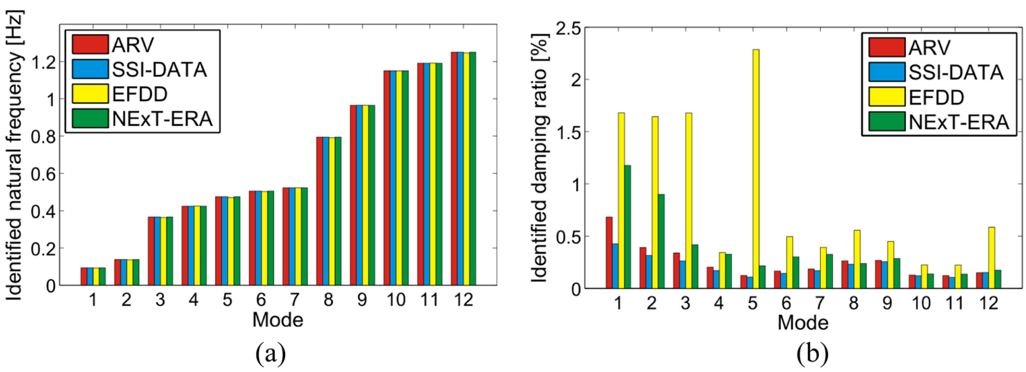


Fig. 6 Comparison of the results from the ARV, the SSI-DATA, the EFDD and the NExT-ERA: (a) Identified natural frequencies and (b) identified damping ratios

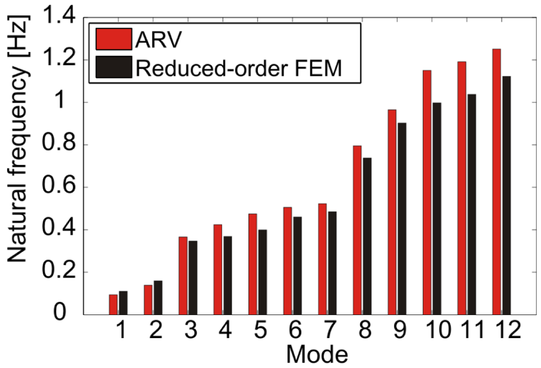


Fig. 7 Comparison of the identified natural frequencies with those of the FE model

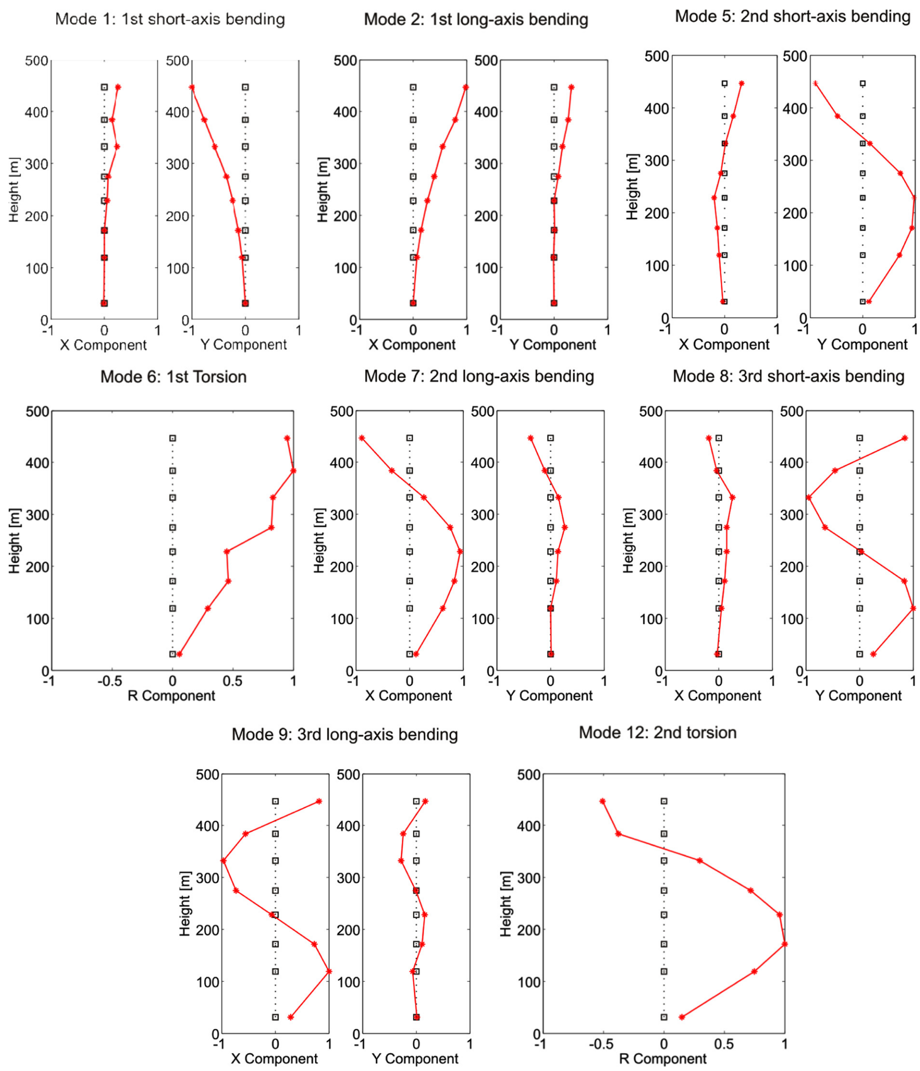


Fig. 8 The extracted mode shapes of the main tower (□ · · · · : Ref.; —✱—: Mode shape)

DATA) method (Faravelli *et al.* 2010a), the enhanced frequency domain decomposition (EFDD) algorithm (Ye *et al.* 2011), and an improved automatic modal identification method based on NExT-ERA (Ye *et al.* 2011). The comparison bar plots are shown in Fig. 6.

As shown in Fig. 6, the indentified natural frequencies from these four methods have a quite good accordance with each other. However, big differences are noticed for the identified damping ratios, especially for the lower modes. Compared to the damping ratios from the EFDD and the NExT-ERA, the values from the ARV and the SSI-DATA show a relatively good agreement. Furthermore, Fig. 7 gives the comparison of the identified natural frequencies with those of the reduced-order FE model in presented in (Lin *et al.* 2010). It can be seen that there are still some differences, especially for modes 10, 11 and 12.

The identified mode shapes of the main tower, not including the antenna mast, are plotted in Fig. 8. It is observed that a sudden change appears in some lower bending modes, e.g., in the *x*-component of mode 1 and the *x*-component of mode 8. Such kind of sudden changes are also noticed in the identified mode shapes when using the SSI-DATA method implemented in the MATLAB toolbox MACEC and in the study results presented in (Loh *et al.* 2011, Ye *et al.* 2011). However, the mode shapes calculated from the tower model do not show such sudden changes (Lin *et al.* 2010). One explanation given to this is that the vibration modes are nonproportionally damped due to the special tube-in-tube geometry of the tower (Ye *et al.* 2011).

5. Environmental effects on the identified modal parameters

Another interest of this paper is to investigate the environmental effects on the identified modal parameters so that some reference information can be provided for later damage identification study.

The 1 h mean wind velocity and wind direction are plotted in Fig. 9, where 0 degree wind direction corresponds to the north. The corresponding wind rose diagram is given in Fig. 10. It can be seen that after 2 a.m. on January 20, 2010, the wind direction becomes relatively stable. Therefore, to reduce effects from varying wind directions on the modal parameters, only measurements after 2 a.m. on January 20, 2010 were used in the study between wind speed and modal parameters. The discussion on the correlation between the temperature and the modal parameters considers all measurement data. In order to eliminate the effects of outliers, robust regression analysis technique has been applied in the following study by using the MATLAB function *robustfit*.

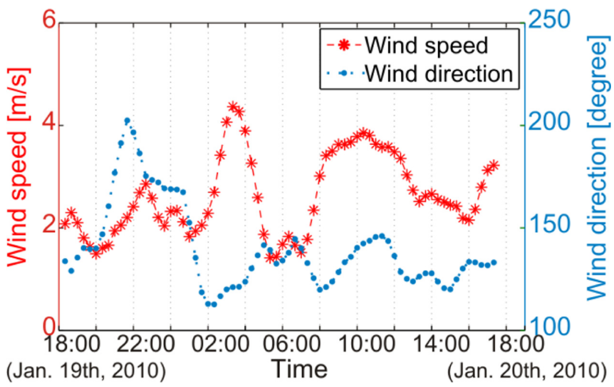


Fig. 9 1 h mean wind speed and wind direction

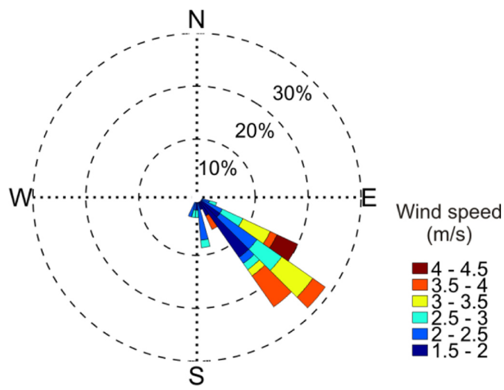


Fig. 10 Wind rose diagram

5.1 Natural frequency vs. temperature

Fig. 11 clearly reveals that the natural frequencies of the first 12 modes decrease as the temperature increases. This result agrees well with that presented in (Faravelli *et al.* 2010a). Assume the straight-line fit model has the form in Eq. (17)

$$f_i = \beta_0 + \beta_1 T \tag{17}$$

where f_i is the i-th natural frequency, T is the ambient temperature, β_0 and β_1 are the regression coefficients. The values of β_0 and β_1 for the first 12 modes are listed in Table 2.

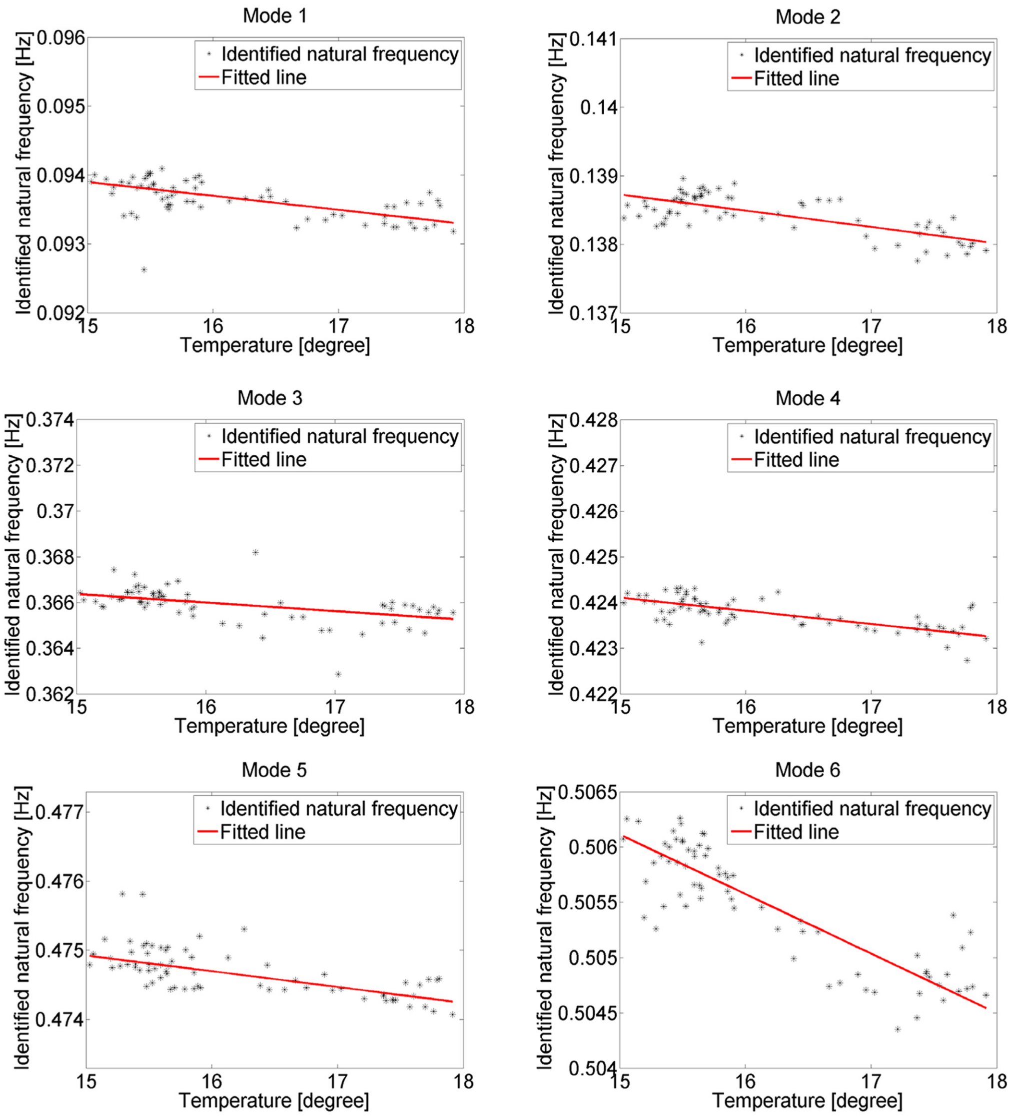


Fig. 11 Changes of natural frequencies with respect to the ambient temperature

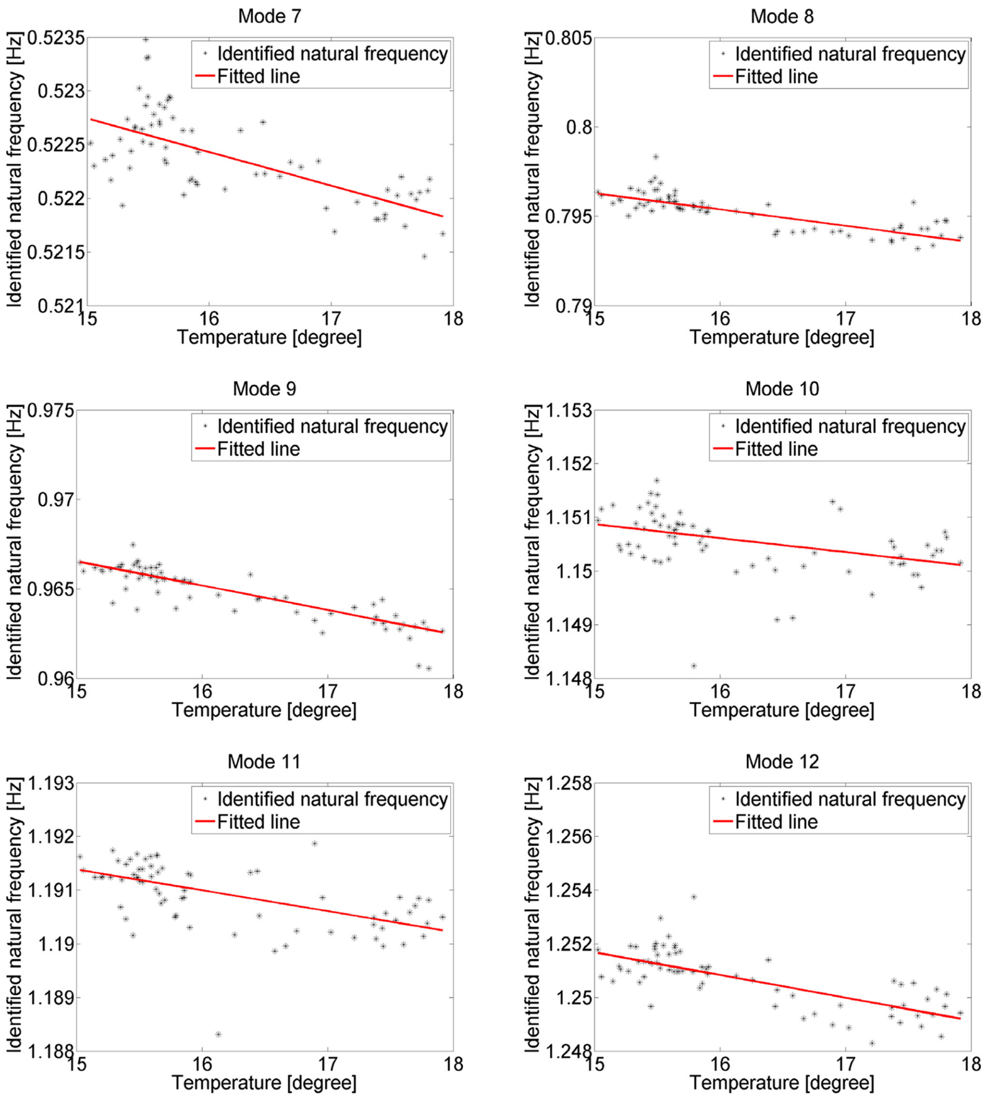


Fig. 11 Continued

Table 2 Correlation between the natural frequency and the ambient temperature

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6
β_0	0.0969	0.1423	0.3720	0.4284	0.4784	0.5142
β_1 (10^{-4})	-2.0285	-2.3705	-3.7537	-2.8865	-2.2902	-5.3893
	Mode 7	Mode 8	Mode 9	Mode 10	Mode 11	Mode 12
β_0	0.5274	0.8100	0.9871	1.1548	1.1972	1.2644
β_1 (10^{-})	-3.1320	-9.1326	-0.0014	-2.6042	-3.8919	-8.4954

5.2 Natural frequency vs. wind speed

In Fig. 12, no uniform trend is reflected. The identified natural frequencies just slightly fluctuate around their mean values. Such fluctuation might be due to the temperature changes within the 24 hours. Similar results can also be found in (AlSaleh 2010), where the dynamic properties of the Canton Tower are studied under five typhoon events, and it is reported that the natural frequencies

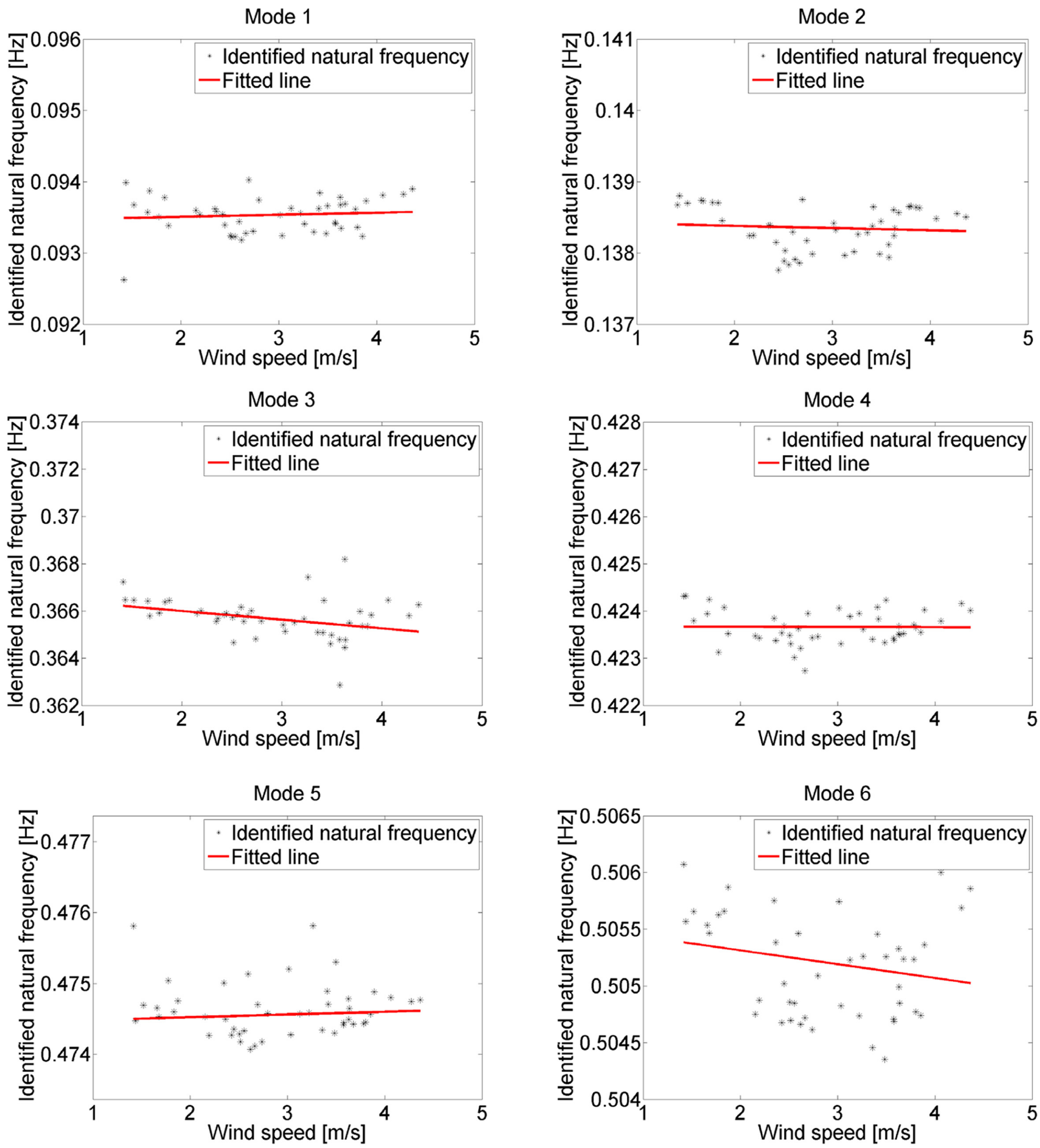


Fig. 12 Changes of the natural frequencies with respect to the wind speed

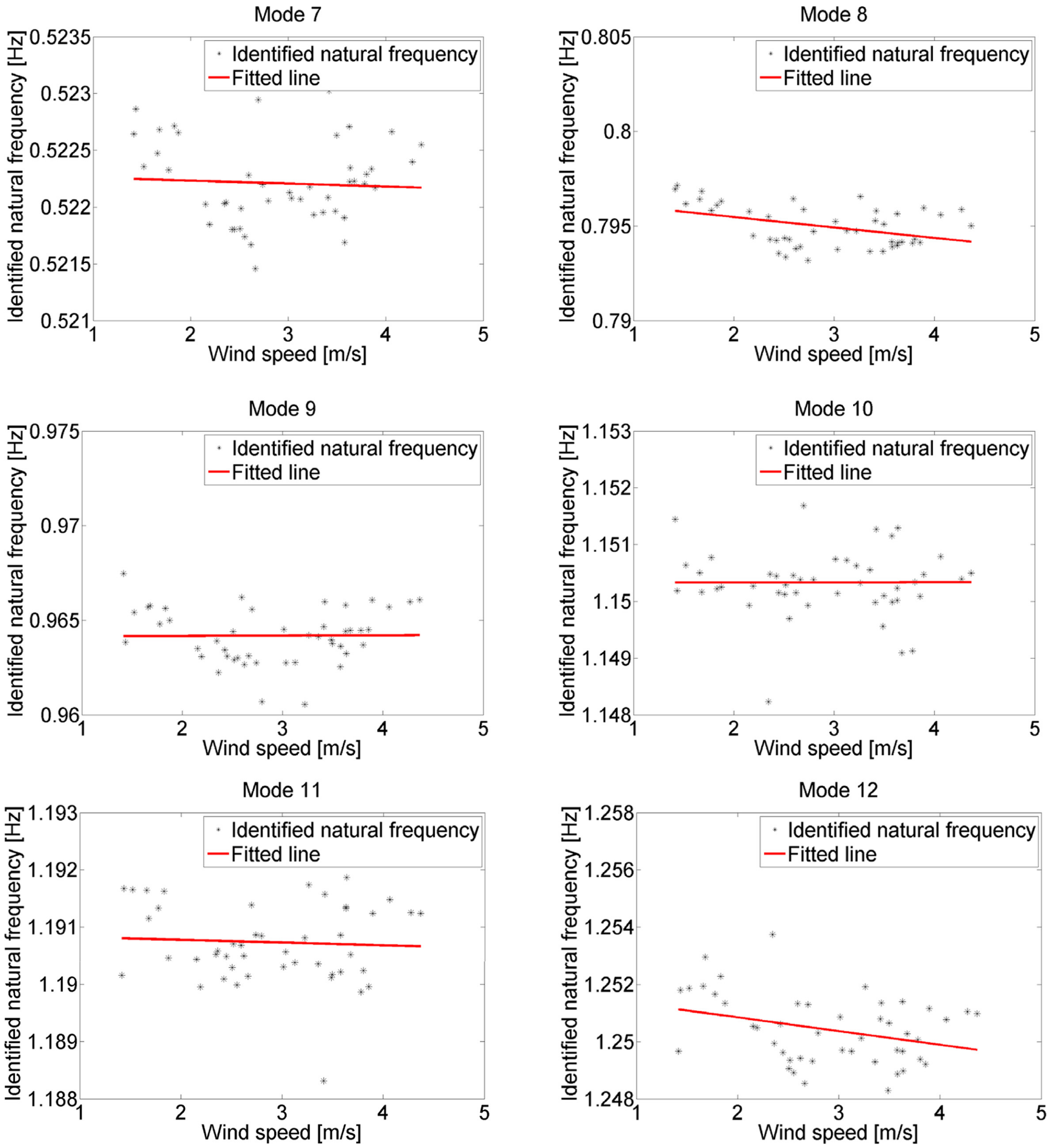


Fig. 12 Continued

of the tower under each typhoon also fluctuate slightly but do not follow a particular trend.

5.3 Damping ratio vs. temperature

In Fig. 13, the changes of identified damping ratios against the ambient temperatures are presented. No uniform trend can be observed.

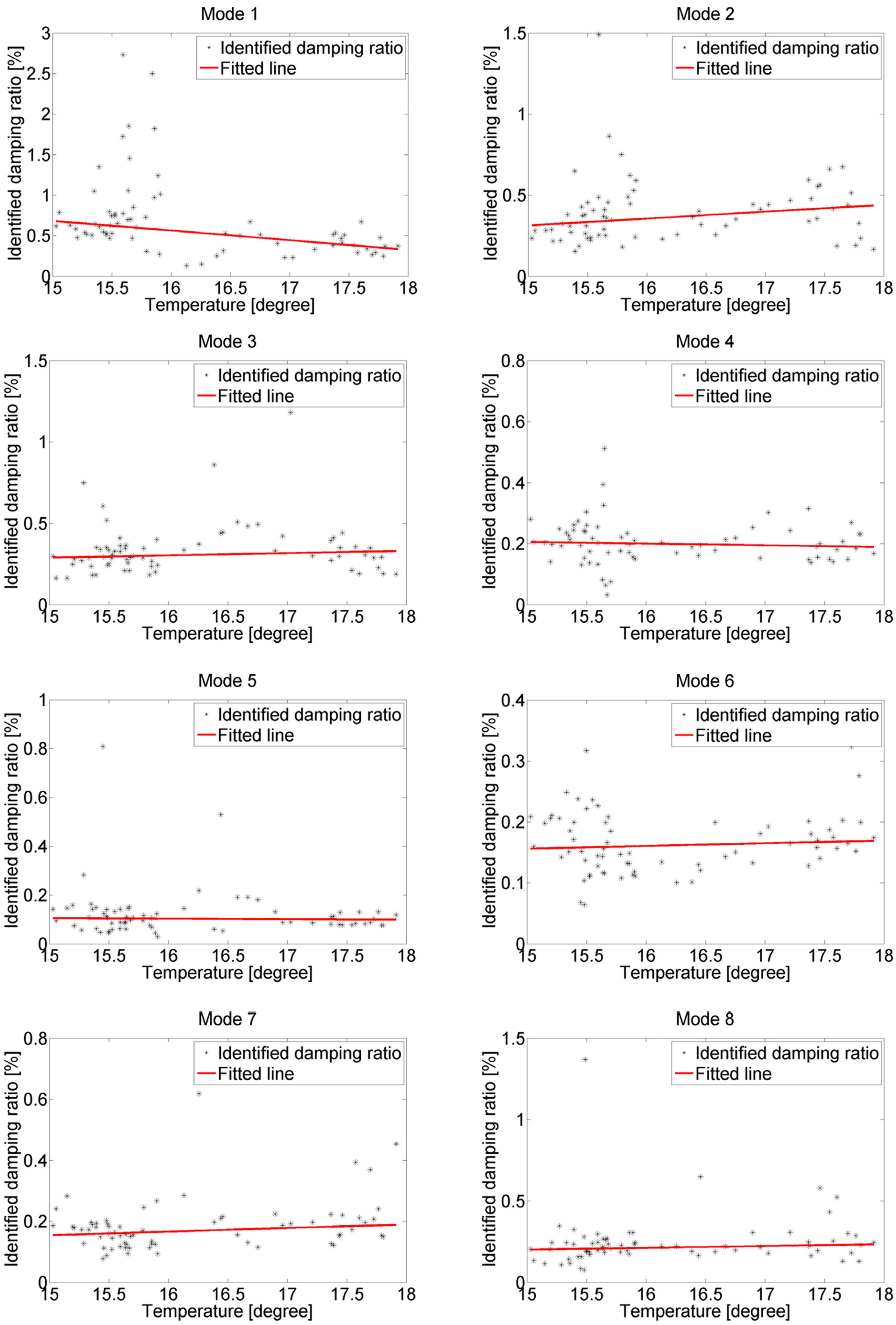


Fig. 13 Changes of the damping ratios with respect to the temperature

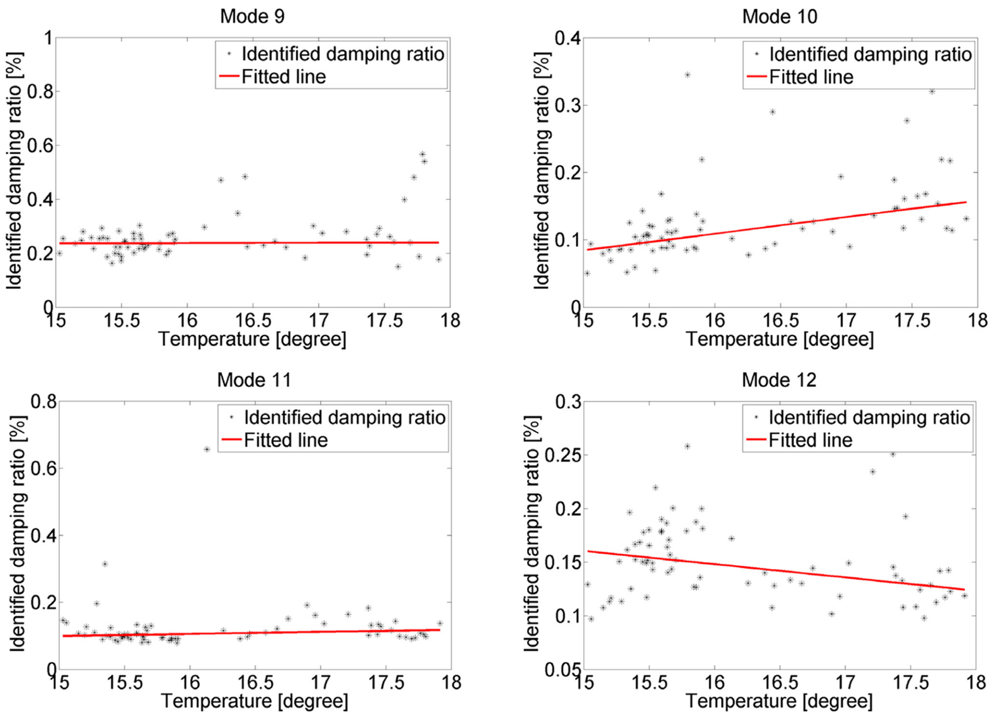


Fig. 13 Continued

5.4 Damping ratio vs. wind speed

Fig. 14 does not show a uniform trend for this case. This result is actually in common with those in (Faravelli *et al.* 2010a, Ye *et al.* 2011) and it might be due to the low wind speed during the measurement (mean wind speed of around 3 m/s during one hour at the height of 461 m). For the case that the tower is subjected to high wind loads during a typhoon events, it is reported that the identified damping ratios increase with the wind speed (AlSaleh 2010), and the damping ratios obtained under typhoon are much higher than those extracted under normal ambient excitation condition (Guo *et al.* 2011).

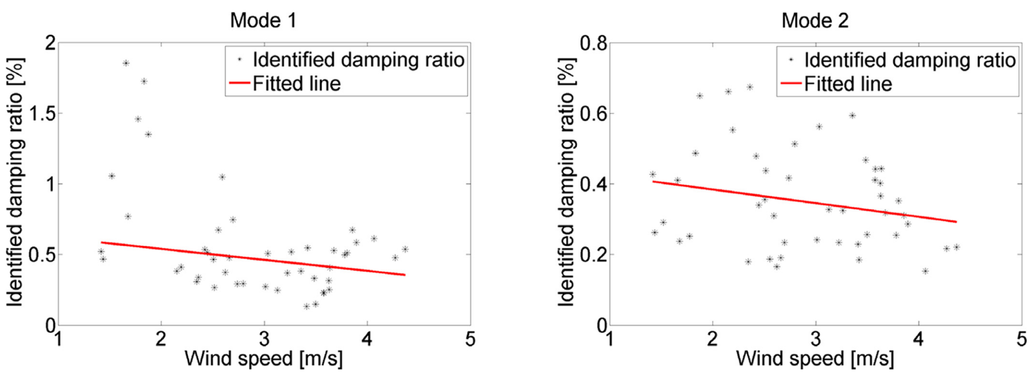


Fig. 14 Changes of the damping ratios with respect to the wind speed

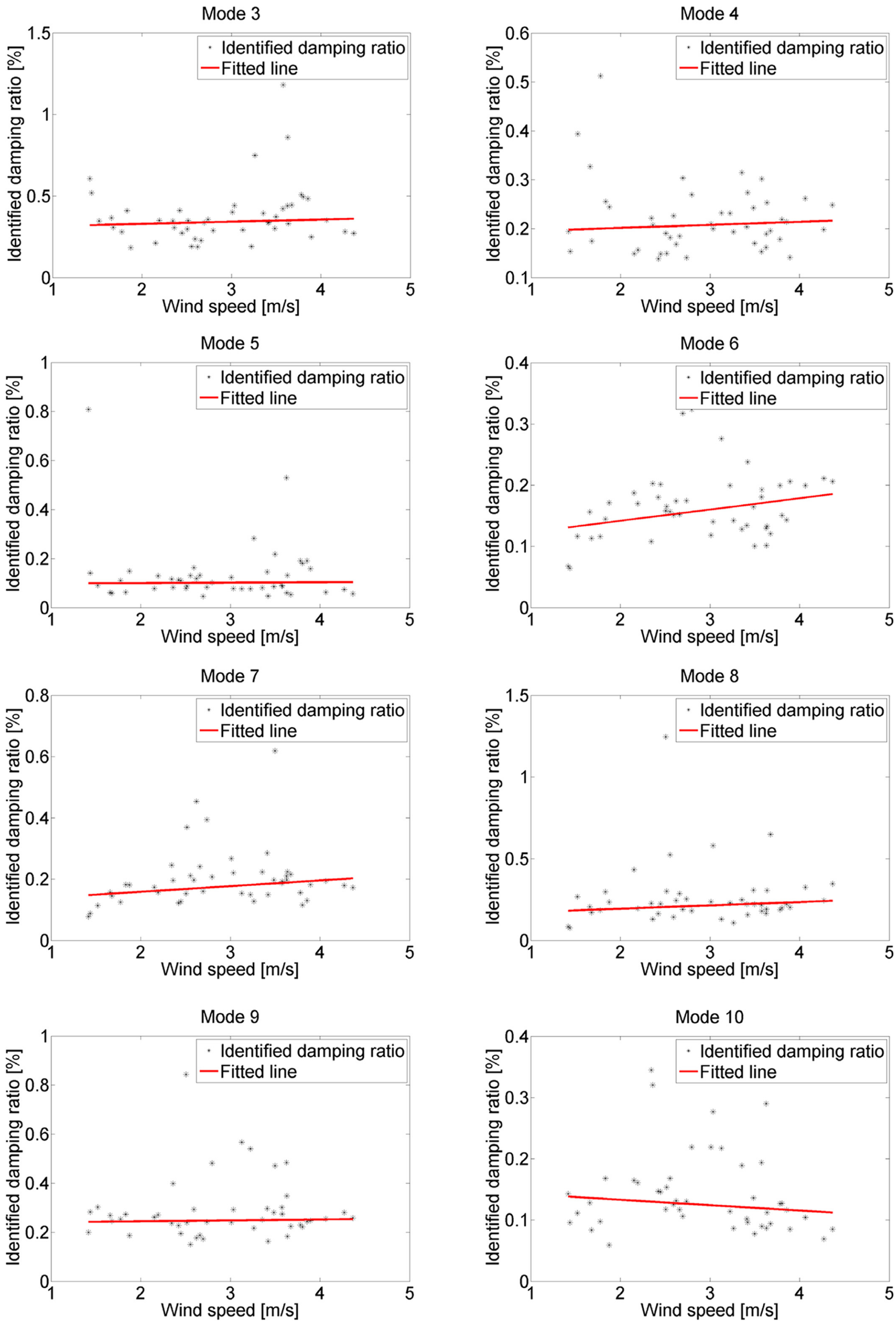


Fig. 14 Changes of the damping ratios with respect to the wind speed

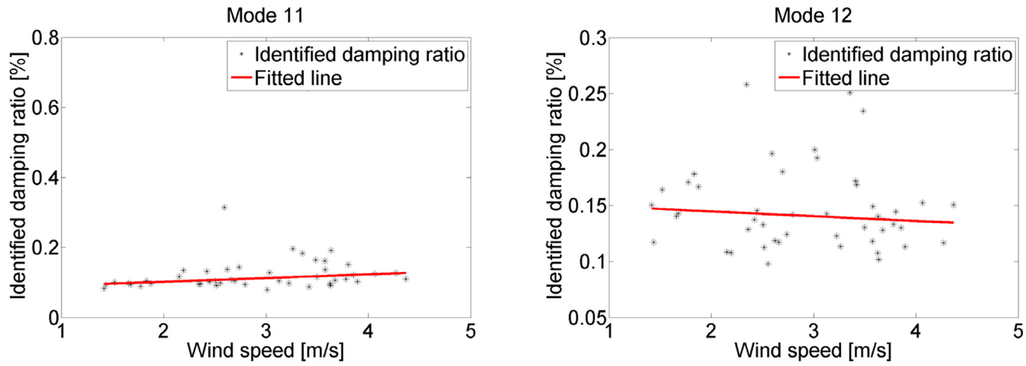


Fig. 14 Changes of the damping ratios with respect to the wind speed

6. Conclusions

In this contribution, the vector autoregressive models (ARV) method is adopted for the operational modal analysis (OMA) of the Canton Tower. The identified modal parameters (natural frequencies, damping ratios and mode shapes) are presented and compared with the available results, which are extracted by means of the data-driven stochastic subspace identification (SSI-DATA) algorithm, the enhanced frequency domain decomposition (EFDD) technique, and the NExT-ERA method. It can be concluded that the ARV method could also be considered as an efficient tool for OMA application. For the next step, the reduced-order FE model of the Canton tower will be updated according to the modal properties presented in this paper.

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