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Structural Modal Identification of tall Buildings based on Variational Mode Decomposition and Energy Separation Algorithm

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SUMMARY:
Accurate estimation of modal parameters (i.e., natural frequency, damping ratio) of tall buildings is of great importance to their structural design, structural health monitoring, vibration control, and state assessment. Based on the combination of variational mode decomposition, smoothed discrete energy separation algorithm-1, and Half-cycle energy operator (VMD-SH), this paper presents a method for structural modal parameter estimation. A numerical study of a four-story frame structure is conducted using the $Newmark-\beta$ method, and it is found that the relative errors of natural frequency and damping ratio estimated by the proposed method are much smaller than those by traditional methods. Furthermore, the proposed method is employed to estimate modal parameters of a full-scale tall building utilizing acceleration responses. The identified results verify the applicability and accuracy of the developed VMD-SH method, which provides an alternative effective tool for the modal identification of high-rise buildings.

Keywords: Modal parameter identification, Variational mode decomposition, Energy separation algorithm

1. GENERAL INSTRUCTIONS

Currently, accurate identification of structural modal parameters from field-measured structural dynamic responses is critical to provide useful guidance for the wind-resistant design of buildings and structures. There are different signal processing techniques proposed for modal parameter identification of civil structures, such as the wavelet transform (WT), empirical wavelet transform (EWT) (Xin et al., 2019), and Hilbert-Huang transform (HHT) (Han et al., 2014). However, the performance of the WT depends highly on the selection of the wavelet function. As a derivative of the WT, the EWT sometimes fails to adaptively divide an acceleration spectrum with many burr points. Besides, the first step of the HHT requires empirical mode decomposition, which brings several inevitable problems such as mode mixing, ending effect, and spurious mode. In general, the above-mentioned methods are inadequate for the decomposition of mixed signals in different aspects. In response to the above situation, Dragomiretskiy and Zosso (2013) proposed the variational mode decomposition (VMD) method, which can effectively decompose the mixed signal with high-level noise into several independent modal components, thus adopted as the modal decomposition method in this paper.

After successfully obtaining each single-frequency component of the mixed signal, it is vital to determine modal parameters of each component accurately. The Hilbert transform (HT) is a common and effective method for estimating the frequency and amplitude envelope of amplitude modulation and frequency modulation (AM-FM) signals. However, the HT has a serious ending effect affecting the accuracy of identified modal parameters (Lv et al, 2017). To overcome this problem, an alternative approach to identify natural frequencies, namely the discrete energy separation algorithm-1 (DESA-1) developed by Potamianos and Maragos (1994), is employed here. As for the estimation of damping ratio, previous studies (Huang et al., 2007) have shown that half-cycle energy operator (HCEO) has advantages such as stronger anti-noise ability, higher precision, and better stability, which is a more accurate method than the classical HT.

In this paper, the VMD, SDESA-1, and HCEO will be integrated for the modal parameter identification, abbreviated as VMD-SH. Section 3 compares the VMD-SH with other traditional methods in modal parameters estimation of a simulated four-story frame structure to verify the validity of the proposed method. To check the applicability of the VMD-SH method further, the measured acceleration responses of a tall building are analysed in Section 4.

2. PROCEDURE OF THE COMBINED VMD-SH APPROACH

The procedure of the integrated VMD-SH method is illustrated in Fig. 1. The measured acceleration responses are firstly decomposed by the VMD into several single-mode components. Then, the free decay response of each mono-component is obtained by using the natural excitation technology (NExT) (Han et al., 2014). Finally, the SDESA-1 technique is employed to determine the natural frequency from each free decay response, while, the damping ratio of each component is estimated by the HCEO technology.

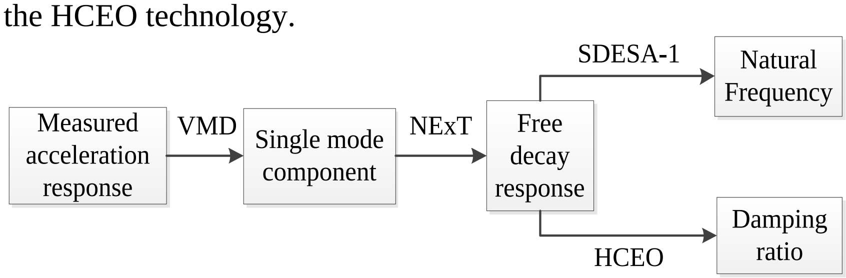

Figure 1 The identification procedure of modal parameters by VMD-SH

3. NUMERICAL STUDIES

The adopted building model is a Four-story frame structure. The weight of each floor $m_1 = m_2 = m_3 = m_4 = 17.51 kN \cdot s^2/mm$, and stiffness $k_1 = 350.24, k_2 = 175.12\ and\ k_3 = k_4 = 105.07 kN/mm$ are set for each floor. The theoretical center frequency of each mode can be obtained as shown in Table 1. The acceleration responses of the floors under the simulated wind force excitation on the fourth roof can be obtained by the $Newmark - \beta$ method. After employing VMD on the original acceleration signal to get single-mode components, each free decay signal is then obtained by the NExT. Subsequently, by performing the SDESA-1 and HT method on the free decay signals, the estimated constant frequency f_n is obtained by taking the mean of time-varying frequency, and the modal damping ratio ξ of each component is calculated by the HCEO, HT, and improved HT (IHT). The results are listed in Table 1. All three approaches can accurately extract the natural frequency. The VMD-SH and VMD-IHT have higher accuracy in natural frequency identification, and the relative error (RE) is within 1%. Meanwhile, the maximum RE of natural frequencies obtained by the VMD-HT is 2.34%. In terms of the damping ratio, the maximum relative error by the VMD-SH is under 3.20%, but the ones by the VMD-HT and VMD-IHT reach 17.50% and 10.00%, respectively. This highlights the good performance of the VMD-SH method in structural modal identification.

Table 1. Estimated and theoretical values of modal parameters including the natural frequency f_n, damping ratio ξ and relative error (RE)

Mode	Theoretical values		VMD-SH		VMD-HT		VMD-IHT	
	f_n (Hz)	ξ (%)	f_n (Hz)/ RE(%)	ξ (%)/ RE(%)	f_n (Hz)/ RE(%)	ξ (%)/ RE(%)	f_n (Hz)/ RE(%)	ξ (%)/ RE(%)
1	0.1774	1.6	0.1787/ 0.73	1.57/ 1.88	0.1757/ 0.96	1.41/ 11.88	0.1788/ 0.79	1.52/ 5.00
2	0.4753	1.18	0.4764/ 0.23	1.16/ 1.69	0.4642/ 2.34	1.35/ 14.41	0.4727/ 0.55	1.25/ 5.93
3	0.6803	1.32	0.6787/ 0.24	1.28/ 3.03	0.6748/ 0.81	1.56/ 18.18	0.6785/ 0.26	1.44/ 9.09
4	0.9492	1.6	0.9466/ 0.27	1.55/ 3.13	0.9425/ 0.71	1.88/ 17.50	0.9471/ 0.22	1.76/ 10.00

4. MODAL PARAMETER IDENTIFICATION OF A REAL HIGH-RISE BUILDING

4.1. Introduction of the monitored building

Saige Plaza building is a hybrid steel pipe and concrete structure with 72 floors above ground and 4 floors below ground, located in Shenzhen, China, as shown in Fig. 2(a). From May 15 to May 20, 2021, the Saige building and the masts experienced significant vibration. To investigate the cause of this phenomenon, eight triaxial force balance accelerometers (Kinemetrics ETNA2, Fig. 2(b)) were installed on site to obtain synchronous acceleration responses of the tall building. The accelerometers were placed every four floors and along the two orthogonal axes of the building plan, and measuring points are all placed at the corner of the corner tube, as shown in Fig. 2(c).

4.2. Modal parameter identified by VMD-SH

Based on the measured data of 8 measuring points at the floors of 45 and 72, concerned modal estimates for assessing the safety and serviceability of the skyscraper are provided in Fig. 3. The results show that structural frequencies estimated by the presented VMD-SH method agree well with those obtained by VMD-IHT and are slightly greater than the values given by VMD-HT. As for the damping ratio, although its estimations for the components with the relatively low signal-to-noise ratio (i.e., modes T1 and T2) present some uncertainty when utilizing different identification methods, estimated damping ratios of IMFs with high signal-to-noise ratio for modes X1, Y1, X2 and Y2 in Fig. 3 almost keep constant and are independent of the method used, verifying the effectiveness of VMD-SH in the estimation of modal parameters from the field-measured structural responses of high-rise buildings.

5. CONCLUSIONS

This paper investigates the validity of the proposed VMD-SH method in the modal parameter estimation of high-rise buildings. The VMD-SH approach is comprised of the VMD, the SDESA-1, and the HCEO method. The validity of the VMD-SH for multi-modal systems was examined by identifying the modal parameters of a simulated four-story frame structure. It is proved that the VMD-SH, VMD-HT, and VMD-IHT can all effectively estimate the modal natural frequency. However, in terms of damping ratio, the VMD-SH estimates show better accuracy than the VMD-HT and VMD-IHT estimates. The VMD-SH was also employed to identify the modal parameters of the high-rise building utilizing the field-measured acceleration records. The estimates of natural frequencies and damping ratios of a tall building by the VMD-SH are generally not affected by the mode mixing and ending effect. The estimated frequency values are almost consistent, while the damping estimation for the component with the low signal-to-noise ratio shows uncertainty when adopting different identification methods.

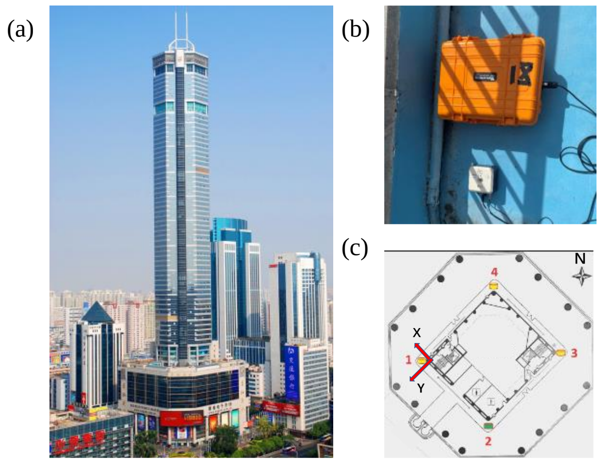

Figure 2 (a) Monitored tall building, (b) accelerometers, and (c) arrangement of accelerometers

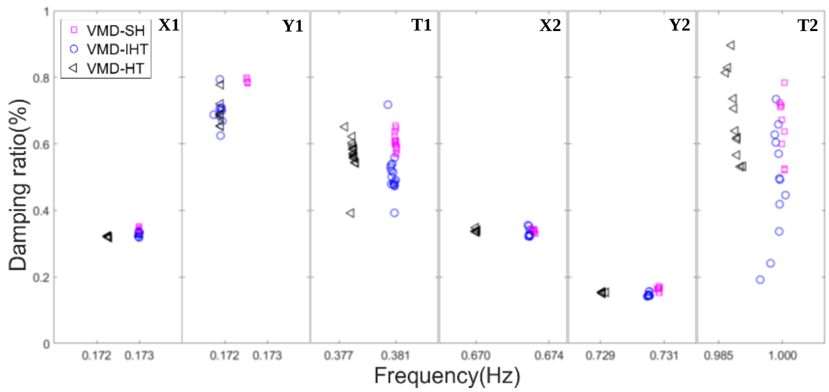

Figure 3 Modal parameters of the monitored skyscraper.

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