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SYSTEM IDENTIFICATION OF LONG-SPAN BRIDGES VIA SYNCHRO-SQUEEZED ADAPTIVE WAVELET TRANSFORM BASED OPTIMIZED MULTIPLE ANALYTICAL MODE DECOMPOSITION

Hongya Qu[1], Mwenda Lomthundzi[1], Yan Xu[1] and An Chang[1]

[1] Department of Bridge Engineering, Tongji University
1239 Siping Rd. Shanghai 200092, China
e-mail: hqu@tongji.edu.cn, lomymwenda@outlook.com, 05203@tongji.edu.cn, ox@tongji.edu.cn

Abstract

In this study, a new system identification method, synchro-squeezed adaptive wavelet transform based optimized multiple analytical mode decomposition (SSAWT-oMAMD), is proposed and introduced. The SSAWT adaptively adjusts the wavelet parameters, which provides the optimal representation over the entire time-frequency plane and minimizes the energy dispersion. In this way, SSAWT yields the time-frequency representation that is close to actual signal characteristics. Then, SSAWT is utilized as the preprocessing for oMAMD method, which is to determine bisecting frequencies with high accuracy. The oMAMD is then applied to the structural health monitoring signals, for denoising, decomposition, and identification. The proposed SSAWT-oMAMD is first verified with various analytical and numerical examples, and the identification accuracy of the complex time-varying systems are generally within 5%, demonstrating the effectiveness of the method. Based on SSAWT-oMAMD, shake table test of a scaled cable-stayed bridge model is then carried out. The parameters of the implemented viscous damper are identified with the SSAWT-oMAMD algorithm, and damage progression of the bridge structure is also identified with the algorithm through damping and stiffness coefficient. It is proved that the proposed SSAWT-oMAMD is effective in identifying key features of the bridge system under earthquake loading based on basic structural health monitoring data, which further facilitates the resilience evaluation of bridge damage subjected to earthquake loading.

Keywords: Signal Processing, System Identification, Structural Dynamics, Seismic Response, Shake Table Test.

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1 INTRODUCTION

Signal processing typically includes two categories: representation and decomposition. For signal representation, it transforms the viewing angle of a signal, which includes but not limited to Wigner-Ville distribution [1], short-time Fourier transform [2], and wavelet transform [3]. To further improve time-frequency resolution of conventional wavelet transform, synchro-squeezed wavelet transform is proposed [4]. Adaptation algorithm [5] is then proposed to formulate synchro-squeezed adaptive wavelet transform (SSAWT) [6], which provides the optimal time-frequency representation of the signal. For signal decomposition, some typical decomposition methods include: filters [7], empirical mode decomposition [8], Hilbert vibration decomposition [9], and analytical mode de-composition (AMD) [10]. Empirical mode decomposition is one of the most popular method for decomposition of signal with time-varying characteristics. AMD retains the capability of time-varying signal decomposition with high accuracy.

A number of cable-stayed bridge has been constructed in recent years, and some of these bridges are located in earthquake-prone zones. Shake table tests are carried out by limited research works, which includes structural response analysis under non-uniform excitation [11]; comparison of various isolation devices in cable-stayed bridge [12]; the effect of viscous damper on seismic performance [13]. In addition, there is only a few studies that focus on the system identification of cable-stayed bridge under earthquake load [14-18]. Therefore, it is necessary to perform parameter identification of cable-stayed bridge components during an earthquake with shake table test, in order to understand the seismic behavior or even damage progression.

In this study, synchro-squeezed adaptive wavelet transform based multiple analytical mode decomposition (SSAWT-MAMD) is proposed, to perform the system identification of a 1/20-scale cable-stayed bridge model. Based on the numerical and experimental study of cable-stayed bridge, it is demonstrated that the SSAWT-MAMD algorithm is capable for identification of nonlinear behaviors of bridge structural components.

2 SSAWT-MAMD ALGORITHM

At given time instant τ_k over the time history of a signal, short-time wavelet transform is performed for the k^{th} short-time segment. The short-time segment ($n = (T - T_{\tau_n})/\Delta t$ in total) retains the time duration of $[\tau_k, \tau_k + T_{\tau_k}]$. The optimal center frequency (ω_c) and window length (T_{τ_k}) are determined by the adaptation algorithm. To eliminate the discontinuity of segment, adjacent edges of the transformed segments are overlapped, summed, and averaged. The adaptive wavelet transform with Morlet mother wavelet can therefore be formulated. Synchro-squeezing is finally applied, and SSAWT is defined as:

$$SSAWT\{x(t)\}(\omega, b) = \int_{A(b)} \sum_{k=0}^{n} \frac{q_k}{p_k} \frac{1}{\sqrt{2\pi\omega_c(\tau_k)/\omega}} \int_{\tau_k}^{\tau_k+T_{\tau_k}} x(t) e^{-\frac{(t-b)^2\omega^2}{2\omega_c^2(\tau_k)}} e^{-i\omega(t-b)}\, dt\, a^{-3/2} \delta(\omega_x(a,b) - \omega) da \quad (1)$$

where $\omega_c(\tau_k)$ and $a(\tau_k)$ is center frequency and scaling factor at time τ_k, T_{τ_k} is the window length, p_k is the parameter for averaging that counts the number of windowed segments spanning over τ_k, q_k is the normalization factor of each short-time segment, and $\omega_x(a,b) = -i \frac{1}{W_x(a,b)} \frac{\partial[W_x(a,b)]}{\partial b}$.

$AMD_{\omega_b(t)}[\cdot]$, decomposed low frequency component of a signal $s(t)$ with respect to the time-varying bisecting frequency of $\omega_b(t)$, is the tool for mode decomposition:

$$s(\theta)=\begin{cases}\frac{1}{2}AMD_{\omega_b(t)}[s(\theta)]+\frac{1}{2}AMD_{\omega_b(t)}\left[AMD_{\omega_b(t)}[s(\theta)]\right] & 0<\omega_b(t)<\frac{1}{4}\omega_s(t)\\ s(t)+\frac{1}{2}AMD_{\omega_b(t)}[s(\theta)]-\frac{1}{2}AMD\left[AMD_{\omega_b(t)}[s(\theta)]\right] & \frac{1}{4}\omega_s(t)<\omega_b(t)<\frac{1}{2}\omega_s(t)\end{cases} \tag{2}$$

The MAMD integrates the AMD for multiple applications for identification of nonlinear system with fast-varying components. It starts from the equation of motion of a time-varying nonlinear system:

$$\ddot{x}(t)+2h(t)\dot{x}(t)+\omega^2(t)x(t)=p(t) \tag{3}$$

where $2h(t)=2h_s(t)+2h_f(t)$ and $\omega^2(t)=\omega_s^2(t)+\omega_f^2(t)$, and the subscripts s and f indicates the slow- and fast-varying components of the coefficients.

AMD is used for the first time to denoise original signal. It is then applied for the second time to decompose the coefficients to obtain slow-varying components:

$$\omega_{s\prime}^2=AMD_{\min[\omega_{x1}(t),\omega_{x2}(t)]}\{\omega_{0x}^2(t)\} \tag{4}$$

$$2h_{s\prime}=AMD_{\min[\omega_{\dot{x}1}(t),\omega_{\dot{x}2}(t)]}\{2h_{0x}(t)\} \tag{5}$$

where $\omega_{x1}(t)$, $\omega_{x2}(t)$, $\omega_{\dot{x}1}(t)$ and $\omega_{\dot{x}2}(t)$ are the bisecting frequencies, and $\omega_{0x}^2(t)$ and $2h_{0x}(t)$ are the raw stiffness and damping coefficients mixed with both fast- and slow-varying components. The actual slow-varying components are then obtained as $\omega_s^2=\omega_{s\prime}^2+\omega_{0p}^2$ and $2h_s=2h_{s\prime}+2h_{0p}$.

By utilizing AMD for the third time, the fast-varying components with lower frequency is decomposed first, and the other is obtained afterwards:

$$2h_f=AMD_{\omega_b'(t)}\{2\tilde{h}_f\} \tag{6}$$

$$\omega_f^2=AMD_{\omega_b'(t)}\{\widetilde{\omega}_f^2\} \tag{7}$$

where $2\tilde{h}_f$ and $\widetilde{\omega}_f^2$ are the fast-varying coefficients with mixing terms, and the bisecting frequency $\omega_b'(t)$ is determined by SSAWT.

Actual coefficients are thus derived from:

$$2h=2h_s+2h_f \tag{8}$$

$$\omega^2=\omega_s^2+\omega_f^2 \tag{9}$$

The SSAWT-MAMD algorithm is summarized in Figure 1.

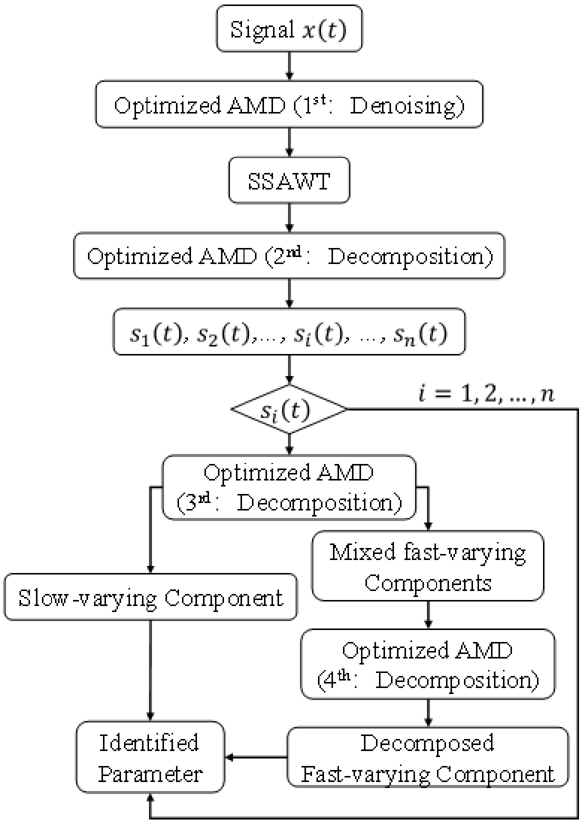
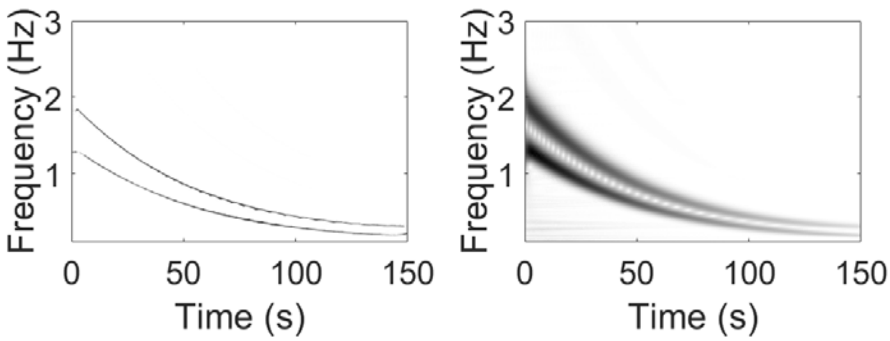


Figure 1: SSAWT-MAMD algorithm.

3 ALOGRITHM VERIFICATION WITH ANALITCAL MODEL

The effectiveness of the proposed SSAWT-MAMD algorithm is first demonstrated by two closely-spaced Duffing systems. Both systems are with the initial displacement of 100 and can be mathematically expressed as: $\ddot{x} + 0.05\dot{x} + x + 0.01x^3 = 0$ (system 1) and $\ddot{x} + 0.05\dot{x} + 3x + 0.02x^3 = 0$ (system 2).

SSAWT is performed for the time history function with Morlet mother wavelet, as shown in Figure 2. The adaptation algorithm is able to provide optimal time-frequency representation of time history function. The SSAWT result is also compared with conventional wavelet transform, and it is clearly shown in the figure that conventional wavelet transform is of thicker curves, and the two curves are interconnected with distorted representation. On the other hand, SSAWT provides clear and concentrated time-frequency representation of the two systems.



(a) (b)

Figure 2: Comparison of wavelet transforms: (a) SSAWT; (b) Wavelet transform.

Based on SSAWT results, time-varying bisecting frequency can be determined, and AMD is performed to decompose the two systems. For Duffing system, damping coefficient does not contain fast-varying component but stiffness coefficient. By applying MAMD, the final identification of the stiffness coefficient from Duffing system is given in Figure 3. It shows that SSAWT-MAMD can be effective for parameter identification of analytical models with fast-varying system.

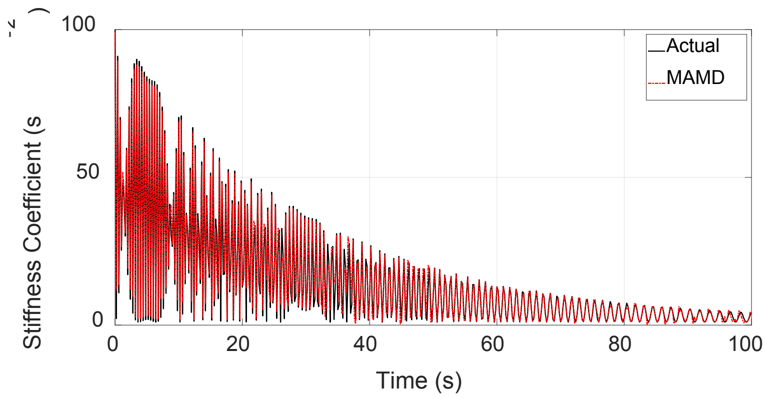


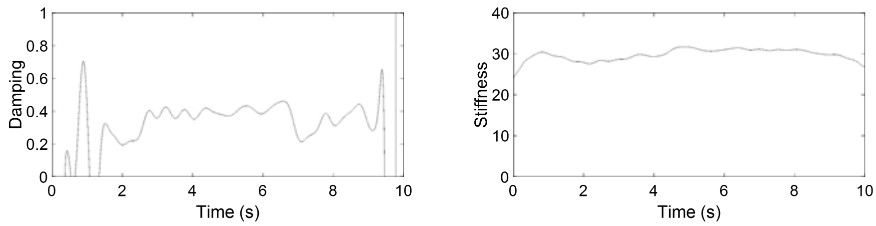
Figure 3: Identified stiffness coefficient by SSAWT-MAMD.

4 ALOGRITHM APPLICATION IN SHAKE TABLE TEST MODEL

The prototype bridge is a typical cable-stayed bridge (110 m + 260 m + 110 m). Concrete tower is 108 m tall, concrete box girder is used for the entire span, and piers of side span are thin-walled hollow-section reinforced concrete. The bridge model is scaled to 1/20 of the prototype (Figure 4), which is to investigate the nonlinear behavior of the bridge structure under seismic load. Earthquake input is a near-fault earth-quake occurred in June 28th, 1992 at Landers, California (LCN266). The PGA of the earthquake record is scaled from 0.1g to 0.4g by the step size of 0.1g.

Figure 4: Experiment bridge model.

For parameter identification of the bridge tower, the time history of acceleration at the top of the bridge tower and its SSAWT under the 0.4g (PGA) earthquake input are selected. Based on the time-frequency representation of SSAWT, the first four vibration modes can excited by the seismic load. SSAWT-MAMD it then performed, and the identified stiffness and damping of the test model under 0.4g earthquake input are shown in Figure 5. As shown in the figure, damping and stiffness of the dominant mode stays relatively constant within the time of interest (3 s to 6 s where strong earthquake motion occurs), which is in accordance with the observation from the experiment. This confirms that the bridge specimen has experienced little damage throughout the entire process of experiment.



(a) (b)

Figure 5: Identified parameter: (a) damping; (b) stiffness

5 CONCLUSIONS

In this study, SSAWT-MAMD is proposed and applied to system identification of analytical and experimental models, and the following conclusions can be drawn:

- The synchro-squeezing algorithm lowers energy dispersion and sharpens the ridgelines of the time-frequency representation.
- MAMD integrates de-noising, decomposition and identification, which effectively identifies system parameters with better accuracy.
- Clear separation of signals is presented and accurate identification of complex time-varying coefficient is achieved.
- Based on experimental results of a cable-stayed bridge model, the proposed method is effective in identifying the structural conditions.

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