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Modal parameter identification for a roof overflow powerhouse under ambient excitation

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Abstract

Modal parameter identification is a core issue in health monitoring and damage detection for hydraulic structures. For a roof overflow hydropower station with a bulb tubular unit under ambient excitation, a complex unit-powerhouse-dam coupling vibration system increases the difficulties of modal parameter identification. In this study, in view of the difficulties of modal order determination and the noise jamming caused by ambient excitation, along with false mode identification and elimination problems, the ensemble empirical mode decomposition (EEMD) method was used to decrease noise, the singular entropy increment spectrum was used to determine system order, and multiple criteria were used to eliminate false modes. The eigensystem realization algorithm (ERA) and stochastic subspace identification (SSI) method were then used to identify modal parameters. The results show that the relative errors of frequencies in the first four modes were within 10% for the ERA method, while those of SSI were over 10% in the second and third modes. Therefore, the ERA method is more appropriate for identifying the structural modal parameters for this particular powerhouse layout.

Keywords: Hydraulic structure; Order determination; Ensemble empirical mode decomposition; Singular entropy; Eigensystem realization algorithm; Bulb tubular unit

1. Introduction

In general, the reduction of hydraulic structural strength and stiffness results from the effects of design loads, working conditions, and unexpected external factors such as earthquakes. Hence, structural damage will occur during the structure's service life, affecting the safety and stability of its operation. Therefore, this type of damage must be considered in structural health monitoring. Recently, the topic of vibration-based structural health monitoring has attracted considerable interest. This type of monitoring offers the possibility of obtaining more accurate and objective information with respect to the deterioration and damage of instrumented structures. With damage, the structural dynamic properties will change. This can be reflected in the modal parameters. Therefore, obtaining modal parameters with accurate techniques is a key prerequisite for monitoring the structural operation conditions (Darbre et al., 2000).

Traditionally, modal parameter identification is carried out through the frequency domain- or time domain-based methods (Ibrahim and Pappa, 1982; James et al., 1996; Brinker et al., 2001; Schoukens et al., 1998). The latter can avoid errors caused by data conversion and increase the identification accuracy, because it deals directly with measured response signals, without going through the Fourier transform (FT) process

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(Kim, 1998). Thus, it has been widely used in modal parameter identification of hydraulic structures, large-scale machines, and aerospace structures. Zhang et al. (2007) extracted the components of free-decay response of a powerhouse from its vibration signals after its dynamic loads were suddenly released with the random decrement technique and identified the modal parameters of the powerhouse in China's Lijiaxia Hydropower Station. Li and Lian (2009) used the genetic algorithm to identify the modal parameters of the powerhouse in China's Qingtongxia Hydropower Station. Lian et al. (2009) used the eigensystem realization algorithm (ERA) to identify dynamic characteristics and damage scenarios of China's Yingxiuwan Hydropower Station sluice after strong seismic shocks with flood discharge excitation, as well as the operational modal parameters of the Three Gorges left guide wall during the flood season. Döhler and Mevel (2013) obtained modal parameters of the Z24 Bridge with a multi-setup subspace identification algorithm and determined the first ten mode shapes by estimating the covariances of modal parameters.

In the time domain-based methods, the ERA (Juang and Pappa, 1985; Juang, 1994) and the stochastic subspace identification (SSI) method (Peeters and Roeck, 2001; Han et al., 2010) are mostly used for structural modal parameter identification (Fu, 1990; Hong et al., 2001; Döhler et al., 2013; Cheng and Zheng, 2014). The system order necessary to obtain the correct modal properties with comparable efficiency and accuracy varies depending on the system identification method. As a result, it is important to understand the advantages and disadvantages of each method and determine the most appropriate method to implement in different applications. Lew et al. (1993) compared four methods: the ERA (Juang and Pappa, 1985), the ERA using data correlation (ERA/DC) (Juang et al., 1988), the Q-Markov cover theory (Anderson and Skelton, 1988), and an algorithm proposed by Moonen et al. (1989). It was concluded that the ERA/DC is the best identification method of the four for input-output data. Petsounis and Fassois (2001) compared the identified modal parameters using four stochastic methods, including the prediction error method (PEM), the two-stage least squares (2SLS) method, the linear multi stage (LMS) method, and the instrumental variable (IV) method, based on the autoregressive moving average (ARMA). However, the necessity of input and output data for the ERA decreases its practical applicability in system identification for some existing structures, for which stochastic methods are preferred. Peeters et al. (1998) assessed the SSI methods, including the peak picking and poly-reference least-square complex exponential methods. The results show that the quality of the identified mode shapes from SSI is better than that of other methods. When excited only by environmental loads (such as flow-fluctuating loads and turbine-operating loads), the ERA method usually runs into several problems. The first, because of the mixed response data (including structural free vibration, forced vibration, flow fluctuation and white noise information, to name a few data types) caused by ambient excitation (Lee et al., 2002), is extraction of system-practicable free-decaying responses from one or more structural vibration responses. Second, due to noise jamming under ambient excitation, the accuracy of modal parameters derived directly from response data is poor. Thus, the response data should be pre-processed to decrease noise jamming (Li et al., 2011). The third is determination of order. With ambient excitation the system is unknown, and, therefore, its order is uncertain, leading to necessity of determining the order and which modals are true or false, so as to eliminate false ones. The SSI method can directly use the excitation response data and is less affected by noise. However, this method also requires determining order and has very strict requirements for the arrangement of measuring points.

A roof overflow powerhouse with bulb tubular units, which is a new form of hydraulic structure, has remarkable advantages over other forms under conditions of large discharges and low heads because of its high efficiency, small size, large flow capacity, and minimal engineering requirements, and it has wide application prospects. For this structure, the powerhouse is not only the support body of the bulb tubular unit but also the carrier of flow-induced vibration. A more complex vibration source is produced by the unit-powerhouse-dam coupling system with flood discharge from the surface outlet or sand-flash outlet, resulting in more excitation sources, excitation spectrums that are not smooth, and significant noise jamming. It is consequently more difficult to identify modal parameters (Lian et al., 2013). De-noising is the key to accurate modal parameter identification. In recent years, many de-noising methods have been proposed, including the wavelet technique (Chang et al., 2000), the singular value decomposition (SVD) method (Brincker et al., 2000), blind source separation (Jing and Meng, 2009), the empirical mode decomposition (EMD) method (Huang et al., 1998), and the ensemble EMD (EEMD) method (Wu and Huang, 2009). The noise reduction effect of wavelets is poor for non-stationary signals (Chang et al., 2000). Lian et al. (2009) de-noised the vibration signals of a dam using SVD. However, the noise reduction effect is unsatisfactory when the energy of noise is less than 10% or is almost equal to the energy of the useful signal (Qian et al., 2011). Therefore, this method is no longer applicable when the interference factors of the structures increase, as they do where there is a roof overflow powerhouse. The EMD method is versatile, and used in a broad range of applications for signals with nonlinear components, singular points, and irregular transient parts. However, it produces mode mixing, end effects, and stopping criterion problems, which cause a loss in useful signal (Rato et al., 2008; Sweeney et al., 2013). EEMD can not only self-adaptively decompose both nonlinear and non-stationary data, but also effectively solve the mode mixing, end effects, and termination condition problems of EMD.

In this study, two identification methods, ERA and SSI, were used to identify modal parameters of a roof overflow powerhouse under ambient excitation. In order to overcome the difficulties of practical application due to noise, system order, and false modes, we used the EEMD method to