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Weak-mode identification and time-series reconstruction from high-level noisy measured data of offshore structures

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ABSTRACT

The identification of true weak modes buried in high-level, noisy, measured data from offshore structures is a practical but challenging problem because weak modes are typically eliminated as noise and rarely, yield a discrete time series. This study proposes a weak-mode identification and time-series reconstruction method for offshore structures when high-level noise is present. A theoretical development proposed in this study extends the traditional modal analysis to reconstructing the discrete time series of weak modes, thereby removing its previous limitations to only frequencies, damping ratios and mode shapes. Additionally, a second development proposed in this study makes the reconstructed time series not simply a combination of harmonic components from a Fourier transform but rather complex exponentials; the damping of the test structure is thus estimated with a better accuracy. A third theoretical development avoids variations in the results from different original signals by handling multiple signals simultaneously. The proposed approach primarily includes three steps: (1) estimate the poles and corresponding residues of high-level, noisy, measured data by converting high-order difference equations to first-order difference equations; (2) isolate the poles of weak modes by assigning multiple rough-pole windows, and subsequently extract the corresponding residues based on the row number of the isolated pole vector; and (3) identify and reconstruct the time series of the weak modes of interest in the form of complex exponentials. The most primary advantage of the proposed process in engineering applications is that the pole windows can be easily obtained and assigned from the relationship between the frequencies and their poles. Three numerical examples are studied: the first presents the detailed numerical operation of the proposed method, the second extends the proposed method from managing one signal to managing multiple signals, and the third demonstrates the advantage of the approach compared with traditional methods. The numerical results indicate that the original signals can be decomposed into multiple complex exponentials with representative poles and corresponding residues, and that the new signals representing weak modes could be reconstructed by assigning a range of frequencies in terms of their relations with the poles. To study the performance of the proposed method when applied to offshore structures such as offshore platforms and marine risers, the experimental data from the high mode VIV experiments sponsored by the Norwegian Deepwater Programme (NDP) are used firstly. The results show that two dominant frequencies corresponding to the in-line and cross-flow directions can be identified simultaneously even one mode is very weak compared with the other, and the time series of the weak mode could be reconstructed with a rough frequency window. Then sea-test data of two offshore platforms are used: one was collected from the JZ20-2MUQ offshore platform when it was excited by ice, and the other was collected from the WZ11-4D platform when it was excited by waves. The results further demonstrated that a large model order is required to estimate all poles and residues of the original noisy signals, and that the row number corresponding to a weak mode of the isolated pole matrix could be easily determined via finite element analysis or engineering experiences. Therefore, the proposed approach provides not only modal parameters, such as frequencies and damping ratios of true weak modes buried in high-level noise, but also the discrete time series of the weak mode.

1. Introduction

Considering the difficulty and occasional impossibility of obtaining an impulse response function (IRF) of offshore platforms in

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the field using artificial excitation methods, measurements under environmental excitations are usually used to estimate modal parameters of a structure, including frequencies and damping ratios. Due to the limitation of energy caused by the excitations, a challenge based on the fact that the excited true modes are often buried in relatively high-level environmental noise develops using this type of measurement; this implies that these true modes are likely to be eliminated when the singular value decomposition (SVD) technique is used.

Determining the modal parameters of a structure using measured vibration data has been called *experimental modal analysis* (EMA). Classic EMA techniques are input-output methods, that have been developed based on the measurement of vibration responses along with deterministic knowledge of the input excitation [1–4]. Conversely, beginning in the 1990s, *operational modal analysis* (OMA) has been used as a method of output-only analysis, where only the responses of a structure to ambient vibrations are measured under operational conditions with sources of vibration including wind, traffic, and earthquakes. This approach presents various advantages [5]: (a) its tests are economical and fast to perform because no equipment is required to excite the structure or simulate boundary conditions; (b) the dynamic characteristics of the complete system are obtained rather than those of only components of the system, yielding a more accurate representation of the structure; and (c) conducting these tests does not interfere with the normal use or operation of the structure. Techniques in the frequency domain (i.e., non-parametric techniques) include peak picking (PP) [6], frequency-domain decomposition (FDD) [7], and frequency-spatial-domain decomposition (FSDD)[8]. Several studies have discussed the potentials and shortcomings of previous methodologies, including Peeters and De Roeck [9] and Andersen et al. [10]. Because of the complexity of offshore platforms, a large frequency range or a large number of modes typically exist in the data; thus, implementing time-domain parametric methods could provide better estimates of the modal properties. A number of stochastic time domain system identification methods have been developed over the past decades, such as the *poly-reference complex exponential* (PRCE) method; the *Eigen-system realization algorithm* (ERA) method [11,12]; the *instrumental variable* (IV) method; the *stochastic subspace identification* (SSI) method [13–15]; and the *time-dependent auto regressive moving average* (TARMA) technique [16,17].

One way to identify the weak modes of offshore platforms is to increase the model order of the system during the modal analysis to obtain a stability diagram. The stability diagrams involve tracking the estimates of frequency, damping, and possibly other modal properties as a function of the model order. The poles corresponding to a certain model order are compared to the poles of a one-order-lower model. If the modal frequency, the damping ratio and the related mode shape differences are within preset limits, the pole is labeled as stable. As the model order is increased, additional frequencies are estimated. For modes that are very active (i.e., strong) in the measured data, the modal parameters will stabilize at a very low model order; for modes that are poorly excited (i.e., weak) in the measured data, the modal parameters may not stabilize until a very high model order is chosen. When applying the above scheme to offshore platforms, it will be difficult to distinguish weak but true modes from noisy ones because high sampling rates are often preferred during data acquisition, while the fundamental frequencies are very low (e.g., the first frequency of an offshore platforms is typically near 1 Hz). To mitigate this problem, Liu et al. [18] proposed an improved modal parameter identification method by reconstructing a response consisting of only lower-order frequencies and applied this method to a real offshore jacket platform located in the northern region of Liaodong Bay, China. In Ref. [18], the lower-order modes were first isolated in the frequency domain using the fast Fourier transform (FFT) filtering, and the ERA was used for modal parameter identification from the reconstructed response consisting of the lower-order frequencies of interest. Theoretically, the assumptions of the ERA requires that the output be an impulse response function such that it cannot be used directly in a weak-mode analysis of offshore platforms excited by waves, winds and currents.

An offshore platform should be considered to be a time-varying system in a modal analysis due to the presence of time-varying environmental loadings, such as waves, winds, and currents, and operational loadings; thus, the weak modes of interest maybe discontinuous and change over time. Time-frequency analysis is an effective approach to select the duration of original signals and provide a rough estimate of the weak modes of interest. The short-time Fourier transform (STFT) [19] is one of the earliest and most basic methods used in time-frequency analysis. The basic concept of the STFT is to segment the signal and analyze each segment to ascertain the frequencies that are present within it. The wavelet transform (WT) is an advanced time-frequency analysis technique that has been designed for non-stationary time signals over the past two decades. Wavelet analysis is essentially an advanced STFT method with adjustable windows investigating various times. The S-transform [20] has become popular for use with time-frequency representations because it combines the good characteristics of both the STFT and the WT. Recently, Liu et al. [21] proposed a time-frequency and multiple-sensor assessment method and applied it to an offshore platform in the South China Sea with the goal of providing a more suitable time duration of measured signals and evaluating each sensor's contribution to the mode shapes of interest. This method can provide a more suitable time duration for further modal analysis.

In contrast to traditional modal analysis methods, this study attempts to identify weak modal parameters such as frequencies and damping ratios buried in high-level noise, and particularly attempts to obtain their time series to provide a better understanding of weak modes from the perspective of signal decomposition when multiple measurements are available simultaneously. The poles and residues of the original signals are estimated first, and then a number of pole windows are used to isolate and extract the residues of the weak modes of interest to allow the time series of the true modes to be reconstructed in the form of complex exponentials. The first numerical example is used to present the detailed numerical operation of the proposed method, the second shows how the approach manages multiple signals simultaneously, and the third demonstrates the advantage of the approach compared with traditional methods. Two real offshore platforms are used to study the performance of the proposed method by analyzing two sets of typical signals: one was collected from the JZ20-2MUQ offshore platform when it was excited by ice, and the other was collected from the WZ11-4D platform when it was excited by waves.

2. Preliminaries

2.1. Pole and residue

If the complex function y has an isolated singularity at the point z_0, then y has a Laurent series representation [22] that can be described by:

$$y(z) = \sum_{-\infty}^{\infty} r_k (z - z_0)^k = \cdots + r_{-2}\frac{1}{(z - z_0)^2} + r_{-1}\frac{1}{(z - z_0)} + r_0 + r_1 (z - z_0) + \cdots \quad (1)$$