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Study on nonlinear dynamic characteristics inherent in offshore jacket platform using long-term monitored response of ice-structure interaction

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ABSTRACT

This paper proposes a method to structurally identify inherent dynamic characteristics based on long-term monitored acceleration data of nonlinear offshore platforms under sea-ice excitation. Not all the inherent characteristics can be excited due to the randomness of ice loading and its limited bandwidth. However, the long-term monitored data can reflect most of the conditions of sea-ice excitation. The change of natural characteristics of the platform under ice loads can be identified by analyzing of long-term monitored data. A nonlinear system of two-degree-of-freedom (2DOF) is simulated to identify dynamic characteristics and verify the effectiveness of the proposed method. The method is applied to analyze the acceleration data caused by ice-induction at a jacket platform in Liaodong Bay. The inherent characteristics of the structure can be identified and its variation under different ice-load intensities is summarized.

1. Introduction

Most jacket platforms in Liaodong Bay are aging ones. Wind and waves weakly affect platform safety whereas ice loads can cause sustained vibration of platform during the winter, affecting the structural safety and comfort. For the in-situ platforms, the previous damage may cause changes to the mass and/or stiffness distribution of the structural system, and consequently the modal properties, such as natural frequencies and mode shapes [1]. Therefore, to monitor the structural health of the jacket platforms in Liaodong Bay during winter, it is necessary to monitor the response of the structure under ice loads, and identify the inherent dynamic characteristics of the structure to judge whether there is any abnormal change. In the field of Structural Health Monitoring (SHM), natural frequencies and mode shapes were identified from the operational modal analyses to assess the structural health of the large bridges [2]. On the basis of the inverse vibration technology, Haeri et al. [3] presented a new method for SHM of offshore jacket platforms which only utilized the first few modal properties. In fact, large-scale offshore structures are nonlinear dynamic systems, and their inherent characteristics vary. The variation and its range of inherent dynamic characteristics (extracted from the long-term monitored data) can be used as the basis for SHM under ice loads. Meanwhile, the natural frequencies of the platform distribution in the bands of ice loads in the design process can be avoided, as the data can reflect most of the conditions and frequency bands of ice loads.

There have been many related studies on the modal analysis of offshore platforms. Kianian et al. [4] developed a promising methodology of effectively selecting frequency points to detect the structural damage. The modal frequency was identified by numerical simulation of a two-dimensional jacket platform. Mangal et al. [5] identified vibration parameters using impulse and relaxation methods to monitor the integrity of offshore structures. An experimental investigation on a laboratory model of a jacket platform verified the effectiveness of the method. However, modal properties of the in-situ offshore structure would be significantly different from those of the model. Li et al. [6] performed a field step-relaxation test of a jacket-type offshore platform to identify the modal parameters from the generated free-vibration response data. However, considering the difficulty of exciting offshore platforms in the field using artificial methods, only responses under

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environmental loads, such as wind, waves and ice, could be used to estimate modal parameters of the in-situ structures.

Only based on structural responses can we analyze structural dynamic characteristics under environmental excitation. Yi et al. [7] proposed a least square-based frequency domain decomposition method by incorporating the least square method and conventional frequency domain decomposition method. Additionally, dynamic tilting angle responses were utilized to extract a few lower modal properties of a jacket-type offshore structure under tidal excitation. In connection with the non-stationarity of the monitored data for the huge offshore structure, Tang et al. [8] presented a modal analysis through the unilateral moving average and Random Decrement (RD) technology to construct a free response signal. Monitored data of the Floating Production Storage and Offloading (FPSO) single-point mooring structure was analyzed by this method. Considering measurement noises interference, Liu et al. [9] put forward a modal parameters identification method by reconstructing a new response consisting of only lower-order frequencies of interest, and applied it to the sea test of a jacket platform under ice excitation in Liaodong Bay. Liu et al. [10] further pointed out that an offshore platform should be considered to be a time-varying system due to time-varying environmental loadings. They presented a time-series reconstruction method to identify weak modal parameters of the offshore platform in the time domain. Ku et al. [11] extracted free vibration response of the dynamic system from the RD signature of the acceleration response, and achieved the modal parameter identification of a linear dynamic system. To identify the accurate modal damping ratio for the non-stationary structural responses, Tang et al. [12] proposed a modal identification method based on stationary filter-time frequency independent component analysis. Then the damping ratio was more accurately identified through analysis of prototype measurement data of FPSO single point mooring system. In a recent study, Nord et al. [13] used a stochastic state-space model to identify the natural frequencies of a lighthouse structure under different ice conditions, in which ice excitation was randomized.

A portion of the aforementioned studies are based on the assumption that the external environmental load is a stationary random signal, others assume that the environmental loads(such as wind, waves and currents) are non-stationary. But all of them were researching the modal characteristics of the linear structures. Sea-ice excitation is also non-stationary and random as its intensity and bandwidth vary. As compared to other forms of environmental load, sea-ice excitation has a stronger impact on platforms, so it can easily trigger the nonlinearity of structural responses. Therefore, it is necessary to analyze the dynamic characteristics of nonlinear platforms under ice excitation.

The identification of nonlinear structural models was regarded as a progression through detection, characterization and parameter estimation, and parameter estimation methods were classified into seven categories [14,15]. Based on the long-term prototype data of ice-induced acceleration responses, we propose a dynamic-characteristic analysis method for nonlinear offshore platforms, which is a time-frequency parameter estimation method. The free vibration response of the system is obtained from the RD signatures of acceleration responses, and then the dynamic characteristic parameters can be extracted. A simulation experiment of a 2DOF nonlinear dynamical system is carried out under excitations with different intensities and bandwidths. The effectiveness of the proposed method is verified by the recognition results. Finally, we use the method to analyze the measured acceleration response data of a jacket platform in Liaodong Bay during the ice period of 2016–2017, the inherent characteristics of the platform are identified, and the variation of dynamic characteristics under different ice-load intensities is summarized.

2. RD based method for nonlinear modal identification using acceleration responses

When random excitation acts on a nonlinear structure, a linear frequency response function is exerted due to the randomness of amplitude and phase of the excitation signal [16]. The sea-ice excitation is random, so the modal parameters of offshore platform under ice load can be identified by means of equivalent linearization.

The natural characteristics analysis of a dynamic system under environmental excitation is carried out only on the basis of system responses. The RD-based method constructs a RD signature of a dynamic system only based on the measured random response signal. Such a RD signature represents the free vibration response of the dynamic system, so that the modal parameters can be identified. The acceleration response data could be conveniently measuredduring the field monitoring of offshore platforms. This paper presents a modal analysis method based on the RD signature of acceleration responses.

The differential equation of a single DOF dynamic system is given by

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=f(t) \tag{1}$$

where m, c and$k$ are mass, damping and stiffness, respectively,$x(t)$, $\dot{x}(t)$and$\ddot{x}(t)$are displacement, velocity and acceleration responses of the system, respectively, $f(t)$ s an external force acting on the system, the displacement response$x(t)$can be expressed as

$$x(t)=x(0)a(t)+\dot{x}(0)v(t)+\int_0^t h(t-\tau)f(\tau)d\tau \tag{2}$$

in Eq. (2), $a(t)$ is the unit step response of the system, namely the free vibration of the system when initial displacement is 1 and initial velocity is 0; $v(t)$ is the unit impulse response of the system, namely the free vibration of the system when initial displacement is 0 and initial velocity is 1; $h(t)$ is the impulse response function of the system; $x(0)$ and$\dot{x}(0)$are initial displacement and initial velocity of the system, respectively.

The actual system is a causal system, then $h(t)=0$, $t<0$. Thus, when $\tau>t$, $h(t-\tau)=0$ and$\int_t^\infty h(t-\tau)f(\tau)d\tau=0$, namely $\int_0^t h(t-\tau)f(\tau)d\tau=\int_0^\infty h(t-\tau)f(\tau)d\tau$. Then Eq. (2) becomes

$$x(t)=x(0)a(t)+\dot{x}(0)v(t)+\int_0^\infty h(t-\tau)f(\tau)d\tau \tag{3}$$

Since the convolution of two signals is independent of the order, Eq. (3) can be rewritten as

$$x(t)=x(0)a(t)+\dot{x}(0)v(t)+\int_0^\infty f(t-\tau)h(\tau)d\tau \tag{4}$$

Besides, the differential of the convolution of two signals is equal to the convolution of the differential of either of the two signals and the other, thus, the acceleration response$\ddot{x}(t)$results from the double differentiation of Eq. (4) with respect to t, i.e.

$$\dot{x}(t)=x(0)\dot{a}(t)+\dot{x}(0)\dot{v}(t)+\frac{d}{dt}\left(\int_0^\infty f(t-\tau)h(\tau)d\tau\right) \tag{5}$$

$$\ddot{x}(t)=x(0)\ddot{a}(t)+\dot{x}(0)\ddot{v}(t)+\int_0^\infty \ddot{f}(t-\tau)h(\tau)d\tau \tag{6}$$

Assuming that $f(t)$ is an external random load with a mean of 0, then the displacement response $x(t)$ and the acceleration response$\ddot{x}(t)$are stationary normal processes with a mean of 0. The sample function is intercepted with the appropriate