Applied Ocean Research 76 (2018) 139–147

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

The research of soft yoke single point mooring tower system damage identification based on long-term monitoring data

Da Tang[a], Xianpeng Zeng[a,*], Deyu Wang[a], Wenhua Wu[b], Yanlin Wang[c], Qianjin Yue[c], Bingsen Wang[c], Bin Xie[d], Shisheng Wang[d], Jiaguo Feng[d]

[a] *Computer Science and Technology College, Dalian University of Technology, Dalian, 116024, China*
[b] *Fault of Vehicle Engineering and Mechanics, Dalian University of Technology, Dalian, 116024, China*
[c] *School of Ocean Science and Technology, Dalian University of Technology, Dalian, 116024, China*
[d] *China National Offshore Oil Corporation (CNOOC) Research Institute, Beijing, 100027, China*

ARTICLE INFO

Keywords:
Damage identification
Random decrement signature
Autocorrelation function
Soft yoke single point mooring (SPM) tower system
Support Vector Machine (SVM)

ABSTRACT

In this research, to identify the damage of the nonlinearity system under ambient loads, an intelligent damage identification method based on long-term monitoring data is proposed. The random decrement technique and the autocorrelation function algorithm are used to extract free decay of the structure from long-term monitoring data. The random decrement signatures, autocorrelation function, the frequency of free response and the peak points of the frequency spectrum are used as the features of the structure. These features are then input into the Support Vector Machine (SVM) to classify the current state of the system and their identification accuracy is compared. The simulation experiments results show the extracted features are capable of representing the changes of the system inherent characteristics. Finally, the proposed method is applied to the data analysis of the soft yoke single point mooring (SPM) tower system, and provide the reference for the damage identification of the soft yoke SPM tower system.

1. Introduction

Offshore platforms failures often happen due to complicated environment. Mostly of them are hidden damages and have little influence on the operation of structure. Fig. 1 shows that a soft yoke SPM tower system. The SPM tower with a soft yoke system includes an A-frame yoke, two mooring legs and a rigid steel frame that is connected to the vessel. The system is at the stern of the vessel. The system is still in service while the damage of right mooring leg has occurred. Structurally, a large gap can be seen in Fig. 1 (b) and other side has attached tightly together. The damage of the mooring leg made the mooring leg difficult to rotate. This damage will greatly shorten the life of the structure and cause serious consequences in the absence of timely detection.

Structural features recognition based on ambient loads include the random decrement technique (RDT), the natural excitation technique (NexT) and the stochastic subspace method (SSM) etc. The theory of these methods is to extract the structure inherent characteristics from the response data.

Zhong et al. [1] proposed a unified theoretical model of NexT, which can extract structural modal parameters by using displacement response for the case of either single-input or multi-input. Based on traditional SSM, Hu et al. [2] proposed the delay-index-based SSM, which can eliminate spurious modes due to non-white noise and allow the white noise assumption of ambient excitations in the traditional modal analysis methods.

However, many methods could only be applied to linearly invariant systems with stationary random loads. The situations are more complex for the real offshore platform. Firstly, the ambient loads are non-stationary. For that case, Lin and Chiang [3] extended the RDT, the amplitude-modulating function was first extracted from the response data, and then the non-stationary response was transformed into stationary one. Tang et al. [4] applied unilateral moving average to transform the non-stationary response into stationary one. Finally, the method was applied to the mode identification of the Floating Production Storage and Offloading (FPSO) soft yoke system.

In addition, many marine structures show nonlinear characteristics especially when hidden damage occurred to structure. Caldwell [5] studied the RDT for damping nonlinearity. His results showed that random decrement (RD) signatures of nonlinear system are related to corresponding displacement. Shiryayev and Slater [6] analyzed RD signatures, which were obtained from different kinds of nonlinear

* Corresponding author.
E-mail address: z_dapeng@mail.dlut.edu.cn (X. Zeng).

https://doi.org/10.1016/j.apor.2018.04.017
Received 29 November 2017; Received in revised form 17 March 2018; Accepted 30 April 2018

(a) Damage has occurred, but it is still in service

(b) The damage position of right mooring leg

Fig. 1. The diagram of FPSO soft yoke system partial damage.

systems. Compared with the linear case, the RD signatures from nonlinear systems are not same with free responses, and modal parameters are sensitive to the presence of nonlinearities. Therefore, RD signatures of nonlinear systems vary because of the change of environmental loads intensities.

In recent years, intelligent methods have been applied in more and more structural damage identification studies. A large number of data reflecting the structural characteristic are used for training; also, a classifier capable of separating damaged data from undamaged data is established. Yan et al. [7] proposed a beam structure damage identification model to identify partial cracks in supported beams on offshore platforms. Huo et al. [8] combined the cross-correlation function amplitude with the SVM for the damage detection of skeletal structures. Elshafey et al. [9] combined RD signatures and neural networks to detect damage in offshore platform under environmental loads. The proposed method could be used to detect any change in the shape of RD signatures.

In conclusion, the essence of damage identification is to analyze structure damage-sensitive features and identify the damage of structures by investigating the change of damage-sensitive features. For the soft yoke SPM tower system with nonlinearity and non-stationary ambient loads, the dynamic characteristics are varying. However, under the healthy conditions, the changes are within a certain range. Therefore, intelligent classification method can be used to investigate the changes of damage features so as to identify structural damage.

2. The analysis of damage features for soft yoke SPM tower system

Offshore platforms are subjected to non-stationary ambient loads, which include wind, wave, current, etc. These non-stationary ambient loads can cause non-stationary responses of the structure.

In addition to non-stationary ambient loads, the soft yoke SPM tower system itself is also a nonlinear system. But for a nonlinear system with random loads, it is difficult to push it into the nonlinear area [10]. Therefore, the linear system analysis methods can be used to analyze the structure, and an equivalent linearization result is obtained. However, its characteristics are not fixed, instead, they vary with the intensity of the loads.

For a linear dynamic system, the key to extract the system inherent characteristics is to obtain the free response of the structure. Both RDT and autocorrelation function are able to extract the free response of the structure from the stationary response.

The dynamic equation that describes the response of a system can be written as

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{f}(t) \tag{1}$$

In Eq. (1) **M, C, K** are respectively $n \times n$ order mass matrix, $n \times n$ order viscous damping matrix and $n \times n$ order stiffness matrix; $\ddot{\mathbf{x}}, \dot{\mathbf{x}}, \mathbf{x}$ are respectively the acceleration, velocity and displacement responses with n elements; $\mathbf{f}(t)$ is the external excitation vector added to the system.

Let $x_k(t)$ be the stochastic response of a measuring point, $x_l(t)$ be the stochastic response of another measuring point. Take $x_k(t)$ as a reference point the random decrement signatures of $x_l(t)$ is

$$d_{x_k x_l}(\tau) = (\frac{1}{N}) \sum_{i=1}^{N} \left\{x_l(t_i + \tau) \middle| x_k(t_i) = a_0\right\} \tag{2}$$

In Eq. (2), $x_k(t_i) = a_0(i = 1, 2, \dots N, a_0 \text{ is a constant})$. When two subscripts of x are the same, the RD function defined by Eq. (2) could be described as the auto RD function.

$$d_{x_k x_k}(\tau) = (\frac{1}{N}) \sum_{i=1}^{N} \{x_k(t_i + \tau)|x_k(t_i) = a_0\} \tag{3}$$

Given $t = (t_i + \tau|x(t_i) = a_0)$, Eq. (1) can be rewritten as:

$$\mathbf{M}\ddot{\mathbf{x}}(t_i + \tau) + \mathbf{C}\dot{\mathbf{x}}(t_i + \tau) + \mathbf{K}\mathbf{x}(t_i + \tau) = \mathbf{f}(t_i + \tau),\ i = 1, 2, \dots N \tag{4}$$

Merging the N equations, set $d(\tau) = (1/N) \sum_{i=1}^{N} x(t_i + \tau)$, then

$$\mathbf{M}\ddot{d}(\tau) + \mathbf{C}\dot{d}(\tau) + \mathbf{K}d(\tau) = \frac{1}{N} \sum_{i=1}^{N} \mathbf{f}(t_i + \tau) \tag{5}$$

The essence of the RDT is to convert $\mathbf{f}(t)$ into 0. Because the excitation of the offshore platform is unpredictable, $\mathbf{f}(t)$ can be only obtained according to $x(t)$. Assuming that the force is random excitations with zero mean, then $(1/N) \sum_{i=1}^{N} \mathbf{f}(t_i + \tau) \approx 0$ when N is large enough. At this point, $d(\tau)$ is the free response of the system with the triggering condition a_0.

Using the modal superposition method, the displacement for an n DOF linear dynamic system, in terms of the normal modes of the system, can be expressed by

$$\mathbf{X}(t) = \mathbf{\Phi}\mathbf{Q}(t) \tag{6}$$

where the modal matrix $\mathbf{\Phi}$ and the modal coordinates $\mathbf{Q}(t)$ are respectively, denoted by

$$\mathbf{\Phi} = [\phi_1 \quad \phi_2 \quad \cdots \quad \phi_j \quad \cdots \quad \phi_n] = \begin{bmatrix} \varphi_{11} & \varphi_{12} & \cdots & \varphi_{1n} \\ \varphi_{21} & \varphi_{22} & \cdots & \varphi_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ \varphi_{n1} & \varphi_{n2} & \cdots & \varphi_{nn} \end{bmatrix} \tag{7}$$

$$\mathbf{Q}(t) = \{q_1(t),\ q_2(t)\ \cdots\ ,\ q_n(t)\}^T \tag{8}$$

The Eq. (1) can be converted into the N coupled equations of motions as follow by Eq. (6)

$$\ddot{q}_j(t) + 2\zeta_j\omega_j\dot{q}_j(t) + \omega_j^2 q_j(t) = F_j(t)\ \ j = 1,2, \cdots n \tag{9}$$

In Eq. (9), $\varphi_j \mathrm{M} \varphi_j = 1$, $F_j(t) = \varphi_j f(t)$. The superscript * denotes the complex conjugate transpose. Eq. (9) is convoluted by $q_j(-t)$ on the both sides. According to the convolution theorems, Eq. (9) can be rewritten as:

$$\ddot{R}_{q_j}(t) + 2\zeta\omega\dot{R}_{q_j}(t) + \omega^2 R_{q_j}(t) = R_{F_j}(t)^* h_j(-t) \tag{10}$$

Assume the system is causal, then $h_j = 0$, $t < 0$, $f(t)$ is Gaussian white noise. Assume$R_{F_j} = \sigma_j{}^2\delta(t)$, and the right side of Eq. (10) is equal to zero. $R_{q_j}(t)$, $j = 1,2, \cdots n$ is the free response of the modal coordinates.