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Identification of the excitation and reaction forces on offshore platforms using the random decrement technique

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ABSTRACT

This paper describes a method to identify the parameters of the dynamic model of a fixed offshore platform subjected to wind-generated random waves using its stationary response. The structure is modeled as a single degree of freedom system. The parameters identified are the damping coefficient, the natural frequency, and the excitation. In addition, the moment and force acting on the foundation are also identified. The method uses the random decrement signature as a tool to identify the parameters in the equation of motion. Excellent agreements were obtained between the predicted and actual values of the parameters as well as for the reaction and moment at the platform's foundation. The method can be applied without any interruption to the operation of the offshore structure. The method is easy to apply, and uses inexpensive motion measurement instruments. The estimated force and moment can be used as a tool for an on-line foundation check.

1. Introduction

Early detection of fatigue cracks occurring in offshore platform members is critical to the safe, efficient, and economic operation of the platform. Several approaches have been suggested to rationalize inspection of offshore platforms using reliability-based methods (Onoufriou, 1999; Pillai and Prasad, 2000) and damage detection techniques (Viero and Roitman, 1999). Offshore platforms subjected to random waves are usually modeled as multi-degree of freedom systems. The forces caused by the random waves can excite certain vibratory modes corresponding to frequencies near or equal to wave frequencies. A number of vibration-based damage detection techniques have also been suggested (Budipriyanto et al., 2007). Other methods which depend on the measurement of the vibratory response of structures only can also be used e.g. operational modal analysis technique (Brincker et al., 2001).

The random decrement (RD) technique has been successfully applied to multi-degree of freedom systems to predict early damage occurrence (Zubaydi et al., 2000). The Random decrement is an averaging technique that can be used to extract the free decaying response of a vibrating body from its random excited stationary response. It was first introduced by Cole (1968) to identify the damping of an aerospace structure using stationary random response. The Random decrement can be obtained without a prior knowledge of the excitation forces under the assumption that the forces are zero mean, stationary Gaussian random process. Owing to its efficiency and simplicity in processing vibration measurements and the lack of requirements for input excitation measurements, the method is applied extensively to detect damage in civil and offshore structures (Yang et al., 1980, 1984; Zubaydi et al., 2002; Budipriyanto et al., 2007). The method can also be used to identify mode shapes and frequencies of multi-degree of freedom systems (Ibrahim and Mikulcik, 1977). Vandiver et al. (1982) showed that the random decrement can be obtained from the auto-correlation function by multiplying the auto-correlation function by the threshold or triggering level. Haddara (1992) extended the random decrement technique to nonlinear systems. Zubaydi et al. (2000, 2002) and Budipriyanto et al. (2007) used the random decrement signature to identify the damage in the side shell of a ship.

2. Equation of motion

The response of a single degree of freedom linear system is governed by the following basic dynamic equation:

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

where m stands for the total virtual mass, c for the damping, k for the stiffness, t for time, and $F(t)$ is the external force. The total

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Nomenclature

c	damping coefficient (N s/m)
f_r	natural frequency (Hz)
d	logarithmic decrement
$F(t)$	excitation force (N)
H_s	significant wave height (m)
k	stiffness (N/m)
m	mass (kg)
ODE	ordinary differential equation
$P(Y,t\|Y_o)$	conditional probability density
RD	random decrement
T_z	average zero up crossing period (s)
x, $\dot{x}$, $\ddot{x}$	displacement (m), velocity (m/s) and acceleration (m/s^2), respectively
x_s	triggering level
δ	Dirac delta function
ζ	non-dimensional damping coefficient
μ_1, μ_2	mean values of displacement and velocity, respectively
v_{11}, v_{22}	the variance of displacement and velocity, respectively
σ^2	variance
ψ_o	variance of excitation
ω_o, ω_d	undamped and damped natural frequencies (rad/s), respectively

virtual mass is the sum of the physical and the hydrodynamic added mass of the system.

Eq. (1) can be normalized with respect to the total virtual mass, m as

$$\ddot{x}(t)+\frac{c}{m}\dot{x}(t)+\frac{k}{m}x(t)=\frac{F(t)}{m} \tag{2}$$

or

$$\ddot{x}(t)+2\omega_o\zeta\dot{x}(t)+\omega_o^2x(t)=f(t) \tag{3}$$

where ω_o is the natural frequency (rad/s), ζ is the damping ratio, $f(t)$ is the force per unit total virtual mass, and $x(t)$ is the response of the system. A dot over the derivative indicates differentiation with respect to time.

The random excitation $f(t)$ is assumed to satisfy the following conditions:

$$\begin{aligned}\langle f(t)\rangle &= 0\\ \langle f(t)f(t+\tau)\rangle &= \psi_o\delta(\tau)\end{aligned} \tag{4}$$

δ is the Dirac delta function and ψ_o is the variance of the excitation.

The following change of variables is used:

$$y_1=x,\quad y_2=\dot{x} \tag{5}$$

Using the change of variables (5) in Eq. (3), one gets

$$\begin{aligned}\dot{y}_1&=y_2\\ \dot{y}_2&=-2\omega_o\zeta y_2-\omega_o^2y_1+f(t)\end{aligned} \tag{6}$$

It can be shown (Haddara, 2006) that the conditional probability density function $P(Y,t|Y_o)$ governing the vector random process, $Y(t)=\begin{Bmatrix}y_1\\ y_2\end{Bmatrix}$, satisfies the Fokker–Planck equation given by

$$\frac{\partial P}{\partial t}=-\frac{\partial}{\partial y_1}(y_2P)+\frac{\partial}{\partial y_2}[y_1\{2\zeta\omega_o y_2+\omega_o^2y_1\}P]+\frac{\psi_o}{2}\frac{\partial^2P}{\partial y_2^2} \tag{7}$$

The symbol P is used in place of $P(Y,t|Y_o)$. Solution of Eq. (7) subject to the initial condition $\lim(P(Y,t|Y_o)=\delta(t)$ as $t\to 0$ yields an expression for the conditional probability density function which governs the process $Y(t)$. Instead of solving Eq. (7), one can use it to derive expressions that describe the propagation of the mean and variance of the process, $Y(t)$ as functions of time.

3. Equations of the means and variances

By multiplying both sides of Eq. (7) by y_1 and y_2, respectively, and integrating the whole equation over the complete domain of the variables y_1 and y_2, it can be shown that (See Appendix A)

$$\begin{aligned}\dot{\mu}_1&=\mu_2\\ \dot{\mu}_2&=-\langle 2\zeta\omega_o y_2+\omega_o^2y_1\rangle\end{aligned} \tag{8}$$

where μ_1 and μ_2 stand for the mean values of the displacement and the velocity, respectively.

Multiplying Eq. (7) by y_1^2, y_2^2 and y_1y_2, respectively, and integrating the whole equation over the complete domain of the variables y_1 and y_2, we get (See Appendix A)

$$\begin{aligned}\dot{v}_{11}&=2v_{12}\\ \dot{v}_{22}&=-2\langle 2\zeta\omega_o y_2^2+\omega_o^2y_1y_2\rangle+\psi_o\\ \dot{v}_{12}&=v_{22}-\langle 2\zeta\omega_o y_1y_2+\omega_o^2y_1^2\rangle\end{aligned} \tag{9}$$

where v_{11} is the variance of the displacement, v_{22} is the variance of the velocity, and v_{12} is the covariance of the displacement and velocity. Eqs. (8) and (9) describe the means and the variances of the displacement and velocity as functions of time. These equations will be used for the identification of the parameters in the equation of motion of the offshore structure.

Eq. (8) can be combined in one equation as

$$\ddot{\mu}+2\zeta\omega_o\dot{\mu}+\omega_o^2\mu=0 \tag{10}$$

where μ is the mean value of the displacement. Eq. (10) shows that the free decay motion can be derived from the stationary random response. This is the equation of the random decrement.

4. Random decrement signature

Eq. (10) shows that the random decrement can be used to describe the free decay response of the system. The advantage of this approach is that one can obtain the free response from the stationary random response of the system. To obtain the random decrement from the stationary random response, the response is divided into a number of segments, N, each of length τ. All of these segments should have the same initial condition, $x_i(t_i)=x_s=$ constant, $i=1,\ldots,N$. The initial condition is called the triggering value. These segments will also have initial slopes with alternating signs. The ensemble average of the N segments yields the random decrement as shown in Fig. 1.

This approach can be expressed mathematically using the following equations:

$$x(\tau)=\frac{1}{N}\sum_{i=1}^{N}x_i(t_i+\tau) \tag{11}$$

where $x_i(t_i)=x_s$ for $i=1,2,3,\ldots,N$, $\dot{x}_i(t_i)\geqslant 0$ for $i=1,3,5,\ldots,N-1$, $\dot{x}_i(t_i)\leqslant 0$ for $i=2,4,6,\ldots,N$.