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A linearization coefficient for Morison force considering the intermittent effect due to free surface fluctuation

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ABSTRACT

For members located near the free surface, an intermittent effect caused by the free surface fluctuation makes statistical properties of fluid particle kinematics different. Therefore, a linearization coefficient of the drag force derived under the assumption that the particle velocity and acceleration follow the Gaussian process are not valid above the still water level. The present paper derives the linearization coefficient for the drag force considering the intermittent effect. Force spectra and mean values of force maxima at each location are compared between nonlinear and linearized drag force to verify the validity of the proposed coefficient. The linearization coefficients derived from fully submerged section are constant irrespective of the observation position, and it tends to underestimate both the mean values of peak forces and force spectra as the observation height increases near the free surface. The proposed linearization coefficient reflects the effect of the free surface fluctuation and improves the error between the nonlinear and linear drag with increasing observation position.

1. Introduction

Slender members have widely been used in many offshore structures such as offshore fixed wind turbines and jacket structures. In general, wave forces acting on these slender members are calculated from the Morison's equation in combination with linear random wave theory. The validity of linear random wave theory used to predict the particle kinematics in random wave field was proven at continuously submerged points by Charkrabarti (1980). However, if points of interest are located near the free surface, the particle kinematics are changed due to the intermittent effect. Wave forces act discontinuously at those points because that points are intermittently submerged due to free surface fluctuation. The phenomenon that fluid particle kinematics change by free surface fluctuation is called the intermittent effect. Tung (1975) proposed linear intermittent random wave theory that calculates particle kinematics in intermittent flow by linear random wave theory below the free surface and assuming that all properties are zero above the free surface. The probability density functions and statistical moments of particle velocity, acceleration and pressure were derived through the linear intermittent random wave theory. Anastasiou et al. (1982) indicated the importance of second-order effects in wave forces and Tung and Huang (1983, 1985) derived the probabilistic models and particle kinematics in intermittent flow using the second-order Stokes wave theory. Tung (1995) conducted a study on the magnitude of the effect of the intermittent effect and the conditions that could have a significant effect.

The Morison's equation consists of two terms. The first one is drag force which is proportional to the square of velocity and the other one is inertia force which is proportional to acceleration. Due to nonlinearity in drag force, it is difficult to calculate force spectral density. Borgman (1967) suggested force spectral density for fully submerged case. Because it is not easy to estimate force spectral density reflecting the complete form of Morison's equation as it is, a linearization coefficient was introduced to linearize nonlinear drag term in the Morison's equation. Pajouhi and Tung (1975) extended Tung's work (1975) to derive covariance function of Morison force which preserves nonlinear drag term. The force spectral density which is a Fourier transform pair of the covariance function was also derived by numerical integration of a lengthy formula in their work. Approximate form of force spectral density was also suggested to simplify formula for force spectral density. Isaacson and Baldwin (1990a, 1990b) proposed analytic formula for the probability density function of force maxima and simplified force spectral density near the free surface and verified the formula by experiments. The

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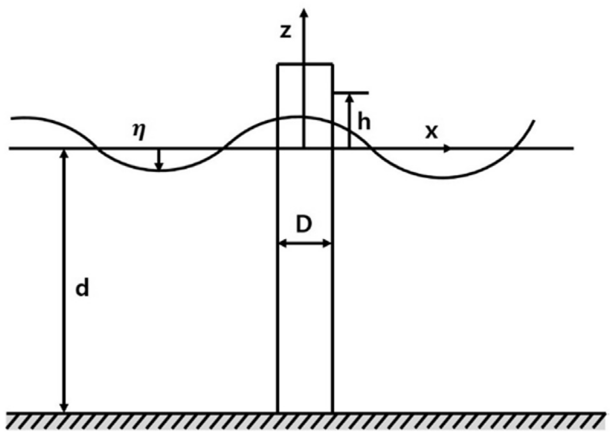

Fig. 1. Definition of coordinate system and variables.

intermittent effect was not significant below the free surface but the force spectrum was greatly reduced by the intermittent effect above the surface. Isaacson and Subbiah (1991) verified the derived theoretical model through numerical analysis in time domain and mentioned the effect of simulation time and random phase of wave on numerical analysis results.

Many researches pointed out the limitation of Borgman's linearization coefficient. Brouwers and Verbeek (1983) compared fatigue damages and extreme responses caused by nonlinear drag and linearized drag force calculated by Borgman's coefficient (1967). The linear method significantly underestimated the expected fatigue damages and extreme response when drag is dominant. An alternative approach to determine the linearization coefficient for drag force in Morison's equation was investigated by Wolfram (1999). He explained that a least-square approach used in Borgman's work was adequate if the ultimate goal was to minimize the time average of nonlinear and linearized drag force. However, in engineering point of view, truly important things are extreme response or fatigue damage, not load itself. Proposed linearization approach was to find the coefficient that could match the expectation values of force maxima of nonlinear and linearized drag force.

Existing linearization coefficients suggested by Borgman and Wolfram were estimated based on fully submerged condition. Isaacson and Baldwin (1990b) also proposed linearization coefficient in intermittent flow but it was also obtained by a least-square method that may underestimate extreme responses and fatigue damages. In this present study, the linearization coefficient in intermittent flow is investigated. The expectation values of force maxima of nonlinear and linearized drag force in intermittent flow are derived. Finally, the linearization coefficient is proposed by comparing two expectation value and is verified by numerical simulations. This paper consists of four parts. Part 2 is devoted to explain how to derive the expectation value and linearization coefficient. The procedure and results of numerical simulation is discussed in part 3. Finally, the conclusion is presented in part 4.

2. Derivation of linearization coefficient in intermittent flow

2.1. Linear intermittent random wave theory and the probabilistic density function of force maxima

2.1.1. Linear intermittent random wave theory

The linear random wave theory (LRWT) has been verified in a number of studies for its accuracy in predicting particle kinematics at a fully submerged point. The surface elevation derived from the LRWT follows a zero-mean Gaussian process and could be expressed as a wave spectrum in frequency domain. Particle velocity and acceleration at $x = 0$ are linearly proportional to the surface elevation and its derivative as Eq. (1)–(3).

$$\eta(x,t) = \frac{H}{2}\cos(\omega t) \tag{1}$$

where η : *surface elevation*, H : *wave height* ω : *angular frequency* t : *time*

$$u(z,t) = \frac{H}{2}\omega G(z)\cos(\omega t) = u_0 G(z)\cos(\omega t) = \omega G(z)\eta \tag{2}$$

where *u: horizontal particle velocity, d: water depth,* $u_0 = \frac{H}{2}\omega$ *: velocity amplitude* $G(z) = \frac{\cosh(k(z+d))}{\sinh(kd)}$ *where* $z \le 0$, *otherwise* $G(z) = \frac{1}{\tanh(kd)}$, k = wave number

$$a(z,t) = \frac{\partial u}{\partial t} = -\frac{H}{2}\omega^2 G(z)\sin(\omega t) = -u_0\omega G(z)\sin(\omega t) = \omega G(z)\dot{\eta} \tag{3}$$

where a : *horizontal particle acceleration*

However, in the vicinity of the free surface, the particle kinematics are discontinuous due to the surface fluctuation. Tung (1975) proposed the linear intermittent random wave theory to express particle kinematics in intermittent flow as described in Fig. 1. This approach estimates particle kinematics near the free surface by comparing the surface elevation (η) and observation position (h). When η is larger than h, which means that the observation point is immersed, particle kinematics are calculated based on LRWT and otherwise all properties are assumed to be zero. The particle velocity (u') and acceleration (a') in intermittent flow derived from the linear intermittent random wave theory are expressed as Eq. (4) mathematically.

$$u'(z,t) = u(z,t)Y(\eta(t)-h),\ a'(z,t) = a(z,t)Y(\eta(t)-h) \tag{4}$$

where *Y: Heaviside function,* $[Y(x) = \begin{cases} 0, & x < 0 \\ 1, & x \ge 0 \end{cases}]$

The probability density functions of the particle velocity ($p(u')$) and acceleration ($p(a')$) at h are expressed by Tung (1975) as Eqs. (5) and (6).

$$p(u') = [1 - Q(b)]\delta(u') + \frac{1}{\sigma_u}Z\left(\frac{u'}{\sigma_u}\right)Q\left(\frac{b - \frac{ru'}{\sigma_u}}{\sqrt{1-r^2}}\right) \tag{5}$$

where σ_u : the standard deviation of particle velocity at h, $\delta(x)$: *Dirac delta function* $r = \frac{1}{\sigma_\eta\sigma_u}\int_0^\infty S_{u\eta}(\omega)d\omega = \frac{1}{\sigma_\eta\sigma_u}\int_0^\infty \omega G(z)S_\eta(\omega)d\omega$ (the cross-spectral density between u and η) σ_η : the standard deviation of elevation$b = \frac{h}{\sigma_\eta}$, $Z(\lambda) = \frac{1}{\sqrt{2\pi}}exp\left(-\frac{\lambda^2}{2}\right)$, $Q(b) = \int_b^\infty Z(\lambda)d\lambda$

$$p(a') = [1 - Q(b)]\delta(a') + \frac{1}{\sigma_a}Z\left(\frac{a'}{\sigma_a}\right)Q(b) \tag{6}$$

where σ_a : *the standard deviation of particle acceleration at h*

The Q in above equations is the probability that the surface elevation exceeds the observation height. When the observation point is always submerged, Q goes to unity and the probability density function of u' and a' become Gaussian distribution like fully submerged case. Pajouhi and Tung (1975) derived spectral density functions for particle velocity, acceleration and pressure in intermittent flow by extending Tung's work (1975) as Eqs. (7) and (8).

$$S_{u'}(\omega) = \left[\omega G(z)Q(b) + \frac{\sigma_u}{\sigma_\eta}rbZ(b)\right]^2 S_\eta(\omega) = |H_{u'}(\omega)|^2 S_\eta(\omega) \tag{7}$$

where $S_{u'}(\omega)$: *spectral density of particle velocity in intermittent flow* $S_\eta(\omega)$: wave spectrum, $H_{u'}(\omega)$: transfer function for particle velocity

$$S_{a'}(\omega) = \left[-i\omega^2 G(z)Q(b)\right]^2 S_\eta(\omega) = |H_{a'}(\omega)|^2 S_\eta(\omega) \tag{8}$$

where $H_{a'}(\omega)$: *transfer function for particle acceleration*