Simulation of Ringing in Offshore Systems under Viscous Loads

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Abstract: In recent years, significant interest has been shown in identifying the nonlinear mechanisms that induce ringing in complex offshore structural systems. This high-frequency transient-type response has been observed in offshore systems, particularly in tension leg platforms (TLPs). Given the implications of this behavior on the fatigue life of TLP tendons, it is essential that ringing be considered in the overall response evaluation. This study uses a simplified structural model exposed to viscous-type loading to demonstrate several of the salient features observed in higher-order potential-type wave-induced loads. Ringing response in pitching mode caused by viscous-type loading is simulated on a cylinder piercing the water surface, and significant mechanisms reponsible for inducing ringing are delineated. Results clearly indicate that, under certain conditions, ringing-type response characteristics are captured under viscous-type loading. The cylinder characteristics are varied to ameliorate the system performance by altering the conditions conducive to ringing.

INTRODUCTION

The observation and subsequent investigation of the ringing phenomenon of offshore structural response is rather recent. Therefore a need exists for clear identification of the system characteristics and environmental conditions that lead to its onset. To distinguish between the commonly misused and interchanged terms "ringing" and "springing," some definitions are appropriate (see Fig. 1).

Springing is a steady-state response in the vertical and/or bending modes of tension leg platforms (TLPs) and gravity-based structures (GBS) because of second-order wave effects at the sum frequencies. This behavior is observed commonly in both mild and severe sea states. Ringing is the strong transient response observed in these modes under severe loading conditions triggered, presumably, by the passage of a high, steep wave event. The transient response decays to steady state at a logarithmic rate that depends on the system damping. Ringing is a rare event and has been unaccounted for in standard response analysis codes until recent experimental and full-scale observations brought it to light. This has been attributed to the higher-order loading mechanisms leading to its onset. Springing, unlike ringing, is accounted for by current response analysis codes through improved modeling of the second-order wave-structure interaction.

Studies reported in the literature [e.g., Davies et al. (1994), Jefferys and Rainey (1994), Natvig (1994), Faltinsen et al. (1995), Newman (1995)] have focused on large volume structures, which are dominated by wave diffraction inertial–type loading and minimally affected by drag forces. These loads are calculated by a slender body theory or diffraction/radiation analysis. Full-scale and model test observations (e.g., wave profiles and model behavior and validation of numerical procedures) are utilized in these studies. Natvig (1994) details a number of mechanisms that contribute to ringing such as variable cylinder wetting, wave profile, wave slapping, and added mass. With the use of a model based on slender body theory with modified Wheeler stretching, Jefferys and Rainey (1994) show encouraging agreement between model tests and theory. Davies et al. (1994) highlight the nature of loads that cause ringing based on model tests, present a time domain simulation scheme for estimating ringing response, and discuss simple guidelines for reducing the ringing response. Newman (unpublished proceedings, 1995) and Faltinsen et al. (1995) discuss second- and third-order sum frequency wave loads and their effects on ringing.

We show that viscous loads are also capable of inducing ringing response of members with large wavelength to diameter ratios, where the instantaneous moment acting on the cylinder is a quartic function of wave elevation. Ringing response in pitching caused by viscous loading is simulated on a simple pivoted cylinder that pierces the surface. The major contributing mechanisms are identified, and the system characteristics that influence the onset of ringing are delineated. Ringing behavior is observed only under very specific nonlinear sea states and loading conditions combined with system parameters conducive to large energy buildup under these circumstances.

MODEL DESCRIPTION

System Model

A simple model is adopted to demonstrate ringing (Fig. 2). The pivoted cylinder of diameter D oscillates about a fixed center of rotation (cr). The draft (dr) is always positive, and wave elevation η is positive above the mean water level. The system inertia, damping, and restoring forces are first-order functions of the system acceleration, velocity, and displacement, respectively. The equation of pitching motion is

$$(I + I_a)\ddot{\theta} + C\dot{\theta} + K\theta = M_t \quad (1)$$

where I and I_a = system and fluctuating added moment of inertia; C = system damping; K = system stiffness; θ, $\dot{\theta}$, $\ddot{\theta}$ = rotational displacement, velocity and acceleration, respectively; and M_t = moment caused by hydrodynamic loads, which is detailed later. Although the selected structural model

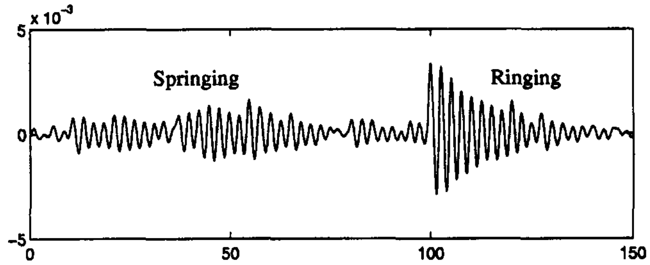

FIG. 1. Ringing and Springing Events

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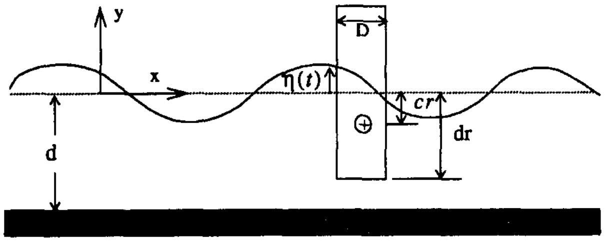

FIG. 2. Cylinder Model in Wave Train

is simple, it represents a leg of a tethered floating or bottom fixed structure in limiting cases.

The moment of inertia I of the oscillator is a function of both the total mass of the cylinder and the added mass due to water displaced by the volume of the wetted cylinder. The changing water elevation changes the effective mass of the system, and the fluctuating added mass is accounted for in a fluctuating moment of inertia term. The effective moment of inertia of the cylinder in still water is

$$I = m\frac{D^2}{16} + m\frac{l^2}{12} \tag{2}$$

where m = effective cylinder mass; and l = total cylinder length. The moment of inertia about the center of gravity will change with the added mass as a function of wave height elevation as

$$\Delta I = \Delta m\left(\frac{D^2}{16} + \frac{l^2}{12}\right), \quad \Delta m = \eta(t)\pi\rho\frac{D^2}{4} \tag{3}$$

For the system parameters used in this study, the associated natural frequency of the oscillator fluctuates about the still water value by ~8%.

The relative velocity formulation of the Morison equation was not utilized here for computational convenience. As a result, hydrodynamic damping was not included in our analysis. However, it is noted later in the paper that an increase in damping does not influence the onset of ringing phenomenon, which justifies our simplification.

In this study, we simulate ringing caused by the passage of random first- and second-order waves in a water depth of 1,000 feet. The cylinder undamped natural frequency is fixed at four times that of the peak wave frequency to avoid "quasi-ringing" events, which occurs when a portion of the input wave train contains several successive moderate amplitude waves that coincide with the structural natural frequency (Stansberg 1993).

Wave Input Model and Equivalent Moment Calculation

The JONSWAP wave elevation spectrum is applied with a peak frequency of 0.1 Hz throughout this study. The literature indicates that the onset of ringing is triggered by a sudden large amplitude wave preceded by a period of moderate wave activity. Large waves often exhibit an asymmetric wave profile, which may lead to more favorable conditions for the onset of ringing. Asymmetry about the mean water level can be modeled by a second-order wave theory. In this study, Stokes second-order random waves are simulated utilizing a quadratic transfer function (QTF) in the Volterra series framework. The QTF is derived analytically based on Stokes second-order random wave, which also is referred to as a nonlinear interaction matrix (Hasselmann 1962; Hudspeth and Chen 1979; Kareem et al. 1994). Simulation details can be found in Gurley et al. (1996). The simulated realization of the surface elevation of gravity waves exhibits non-Gaussian features with characteristic high peaks and shallow troughs.

Phase tailoring can introduce the desired wave features at the cost of being a deterministic simulation. To examine the system behavior under such a deterministic wave, a low amplitude wave train with a single large wave is generated using a constant phase in place of a random phase in a portion of the significant frequency range of the input spectrum.

Application of the Morison equation to calculate the force at the mean water level ignores the nonlinear effects of the fluctuating free surface, which is thought to be a dominant ringing mechanism. The wave kinematics up to the instantaneous water surface are used to generate moment input from both linear and second-order waves by integrating the force to the free surface and multiplying by an equivalent moment arm. The water particle velocity at the mean water level is related to the velocity profile on the wetted cylinder using modified airy stretching theory (Mo and Moan 1985).

The total applied moment M is a combination of four components listed in the following equations. There are three combinations of the four moment expressions applied for three different combinations of the wave elevation and center of rotation

$$\eta > 0, \quad \eta > cr \Rightarrow M = M_1 + M_2 + M_3 \tag{4}$$

$$\eta < 0, \quad \eta > cr \Rightarrow M = M_2 + M_3 \tag{5}$$

$$\eta < 0, \quad \eta < cr \Rightarrow M = M_4 \tag{6}$$

The time-dependent moments in the foregoing equations (M_i) acting on the cylinder are calculated from the water particle velocity using the Morison drag term $M = LF_lR$, where F_l is the viscous force per unit length on the cylinder $F_l = 1/2\rho C_d D|u|u$; ρ, C_d, and u are the fluid density, coefficient of drag, and water particle velocity, respectively; L is the fluctuating wetted cylinder length; and R is the fluctuating equivalent moment arm. The four moment expressions are (Gurley and Kareem 1996)

$$M_1 = \frac{1}{2}\rho C_d D\eta\left(\frac{\eta}{2} - cr\right)u_{mwl}|u_{mwl}| \tag{7}$$

$$M_2 = \sum_{i=1}^{na}\frac{1}{2}\rho C_d D u_i|u_i| dl\left((na - i)dl + \frac{dl}{2}\right), \quad n_1 = \begin{pmatrix} 0, \eta > 0 \\ \eta, \eta \le 0 \end{pmatrix}$$

$$\cdot dl = (n_1 - cr)/na \tag{8}$$

$$M_3 = -\sum_{i=1}^{nb}\frac{1}{2}\rho C_d D u_i|u_i| dl\left((i - 1)dl + \frac{dl}{2}\right) \quad dl = (dr + cr)/nb \tag{9}$$

$$M_4 = -\sum_{i=1}^{nb}\frac{1}{2}\rho C_d D u_i|u_i| dl\left((i - 1)dl + \frac{dl}{2} - \eta\right)$$

$$\cdot dl = (dr + \eta)/nb \tag{10}$$

where u_{mwl} = water particle velocity at the mean water level. The cylinder below the mean water level is discretized to calculate the local force per unit length due to the exponentially decaying velocity profile. The portion below the mean water level and above cr is divided into na parts, and its moment contribution is given in the foregoing equation as M_2. The portion below cr is divided into nb parts, and its moment contributions are given by M_3 and M_4. The u_i is the local water particle velocity at the ith discrete portion of the cylinder, and dl is the length of the discretized section.

System and Input Parameters

System parameters that help control the onset of ringing are investigated. A lower center of rotation increases the percentage of the passing wave, which contributes to the positive or ringing inducing moment. Increasing the draft increases the negative or "restoring" moment from the portion of the wave acting beneath the cylinder center of rotation.

Inclusion of force in the variably wetted portion of the cylinder results in the quartic relation between applied moment and wave elevation. A second-order correction to linear wave trains is applied to generate waves with steep peaks and shallow troughs. These nonsymmetric profiles lead to skewed water particle velocity profiles, with higher probability of occurrence in the extreme tail region than in corresponding Gaussian waves. Both non-Gaussian waves and free surface integration are considered to simulate ringing in this study. Phase tailoring is used to simulate single large amplitude waves. The waves that lead to ringing then may be used as a part of the design checking procedure to explore the possibility of ringing.

RESULTS

Nonlinear Wave Effects

Fig. 3 shows a Gaussian wave field and the cylinder response (graphs 1 and 2) and the same wave field with the second-order contribution added and the resulting response (graphs 3 and 4). The nonlinear wave input triggers ringing whereas the linear wave input does not. The response to nonlinear waves is positively skewed because of the skewness in water particle velocity and has a high kurtosis because of the ringing events. Both the skewness and the kurtosis lead to problems associated with extreme response and fatigue of ocean systems.

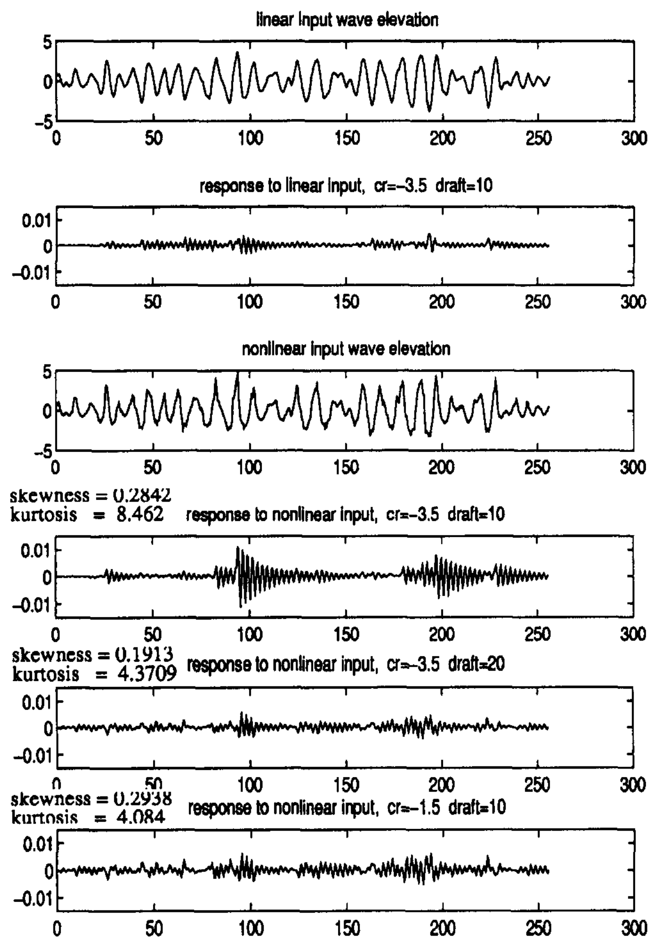

FIG. 3. Gaussian Waves and Cylinder Response (Graphs 1 and 2), Non-Gaussian Waves and Cylinder Response (Graphs 3 and 4), Response to Non-Gaussian Waves with Draft Changed to 20 m (Graph 5), and Response to Non-Gaussian Waves with *cr* Moved up to −1.5 m (Graph 6)

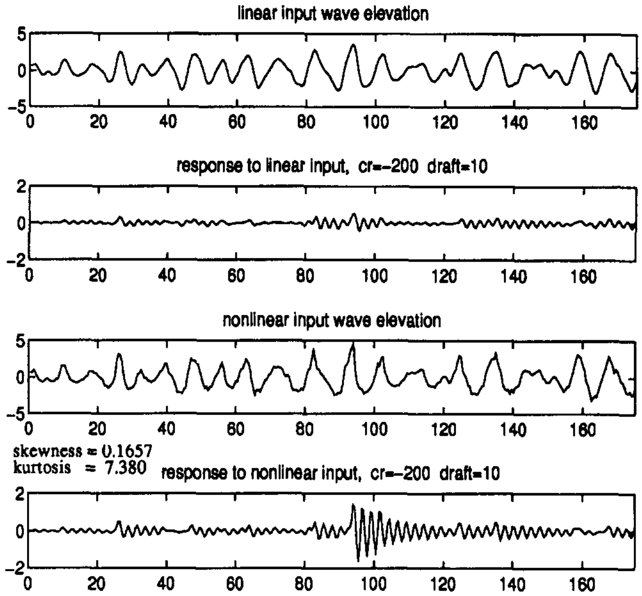

FIG. 4. Response of Cylinder to Same Wave Fields Seen in Fig. 3 (Center of Rotation at Seabed and Simulation of Bottom Fixed Structure)

It is noted that not all large waves in the non-Gaussian wave train lead to ringing. Water particle velocity is a function of frequency and wave elevation, and it is found that steeper waves lead to ringing because of a quick buildup of energy in the form of higher water particle velocity.

Cylinder Draft and Center of Rotation

At the onset of ringing the squaring of the magnitude of high water particle velocity leads to a large positive spike in the input moment. The reduction of these spikes in the input moment may be affected by providing a large offsetting negative or restoring moment. This may be accomplished by lengthening the draft of the cylinder, exposing more cylinder to forces acting below the center of rotation. Although the velocity decreases exponentially, the moment arm increases linearly with depth. Thus, even very small velocities at deep locations may contribute significantly to the restoring moment.

The ringing events observed in Fig. 3, graph 4 are not present in the response in Fig. 3, graph 5, where the cylinder has twice its previous draft (20 m). In graph 6, the cylinder response is shown with the draft back to 10 m and the *cr* raised to −1.5 m. Ringing again is eliminated effectively. The response maintains its positive skewness, as the distribution of the input water paticle velocity still is positively skewed.

Center of Rotation at Seabed

A simple bottom pivoted fixed structure can be represented by moving the center of rotation to the seabed. Here the negative moment comes from the reverse water particle velocity in the wave troughs. Fig. 4 shows that ringing occurs at the same time as for the case in Fig. 3 when the wave train is nonlinear. No ringing is observed for the Gaussian input sea state. This implies the possibility of ringing of bottom pivoted stiff systems, which also represent a special case of bottom fixed elastic structures.

Also, it is interesting to note that in a multiple-cylinder system, wave phase effects can either help to prevent ringing or work to enhance it.

Damping Effects

In this study the occurrence of ringing could not be prevented by increased damping. Higher structural damping applied directly or through the use of tuned mass dampers in different configurations led to an increased rate of decay of the ringing event but did not prevent its onset. In some cases added damping reduced the maximum amplitude of ringing, but the tuned mass dampers could not react quickly enough to counter sudden ringing-type responses. Based on experience with other systems, it is plausible that semiactive mass dampers may help to overcome this shortcoming because they can be mobilized instantaneously (Kareem 1995).

Grouped Waves: Phase-Tailored Design Waves

The effects of wave groupiness on the occurrence of ringing is investigated through the specification of phase within the significant energy portion of the target spectrum. In this manner the simulated wave train exhibits the desired isolated large waves, which sometimes correspond to ringing in the laboratory (Natvig 1994). An example is shown in Fig. 5. The draft and center of rotation are 10 and -3.5 m, respectively, as in Fig. 3 (graph 4). It is clear from the figure that ringing is initiated at the bottom of a passing wave trough, when the reverse water particle velocity is at a maximum. Also, it was observed in this study that groups of several large waves tend to reduce the ringing effect, which also was observed in the simulations in (Natvig 1994) involving diffraction/inertia dominated structures.

Inertial Loading

The TLPs are dominated by diffraction inertia–type loads because of their large cylinder size, although viscous loads can become important for very large wavelengths. The ringing events observed thus far have been the result of viscous loading, which results in an equivalent input moment that is a quartic function of wave height. If inertia-type loads dominate, the moment becomes a cubic function of wa' e height, because the force per unit length is a linear function of water particle acceleration. In this study, diffraction-type loads are not investigated because other studies have focused on these effects. We simply replace the viscous loading term with the inertial term in the Morison equation and find that ringing results from this cubic relationship. In Fig. 6, ringing is observed at approximately 90 s. However, the ringing observed at 200 s in the first example (Fig. 3) is not significant in this case. The ringing at 90 s is initiated with a negative peak response. The ringing here is caused by a maximum negative water particle acceleration, which is 90° out of phase with wave height elevation. In this case the nonlinear relationship between wave elevation and moment is caused entirely by integration up to the instantaneous free surface, emphasizing the importance of including the free surface effects.

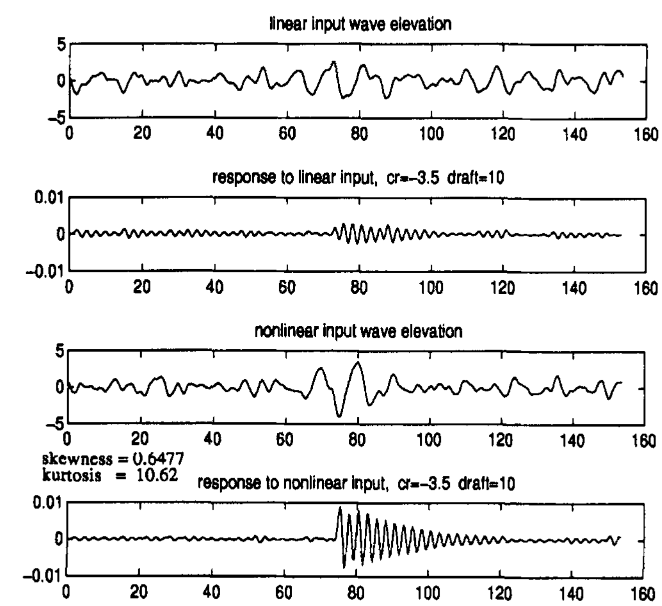

FIG. 5. Response of Linear Oscillator to Phase-Tailored Wave Train

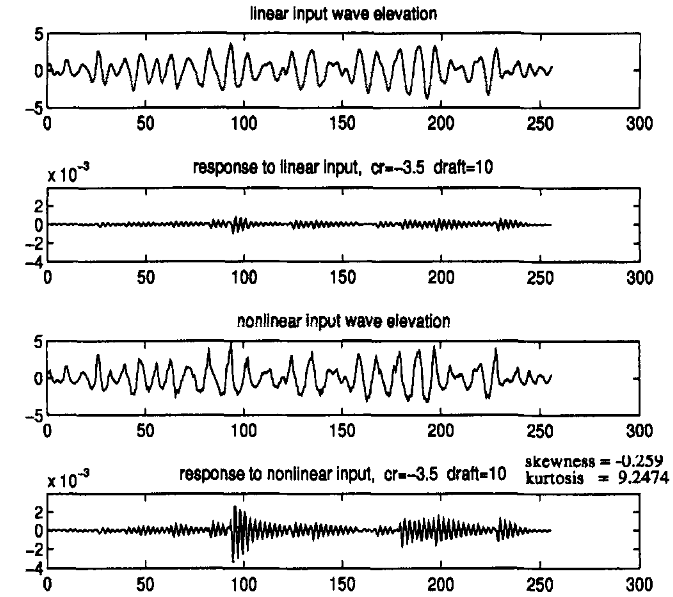

FIG. 6. Response of Linear Oscillator Using Inertial Loading Term in Morison Equation

CONCLUSIONS

A simple model is used to demonstrate the ability of hydrodynamic loads of viscous origin to promote ringing behavior in the pitching motion of a pivoted cylinder. Both the use of a second-order wave field and the integration of wave kinematics to the free surface are essential prerequisites for the occurrence of ringing. The findings of this study support the conclusions of investigations related to large volume structures, which are sensitive to inertial/diffraction–type loading.

For this pivoted cylinder system, ringing can be controlled or prevented through the modification of system parameters such as cylinder draft and the cylinder's fixed center of rotation. Ringing also occurs when the fixed center of rotation is moved to the seabed to represent a bottom pivoted stiff system, suggesting the possibility of ringing for small diameter gravity–type structures due to viscous loads under certain wave conditions. The addition of damping causes a quicker decay in ringing but does not prevent its occurrence. Inertial loading also leads to ringing in this model, as does the application of phase-tailored wave fields simulating grouped waves. In all cases, ringing was found to result from the passage of a single steep wave, not from first-order resonant effects.

APPENDIX. REFERENCES

Davies, K. B., Leverette, S. J., and Spillane, M. W. (1994). *Ringing of TLP and GBS platforms.* BOSS, McGraw-Hill, Inc., New York, N.Y.

Faltinsen, O. M., Newman, J. N., and Vinje, T. (1995). "Nonlinear wave loads on a slender vertical cylinder." *J. Fluid Mech.*, Cambridge, U.K., 289, 179–198.

Gurley, K., and Kareem, A. (1996). "Numerical experiments in ringing of offshore systems under viscous loads." *15th Int. Conf. on Offshore Mech. and Arctic Engrg.*, ASME, New York, N.Y.

Gurley, K., Kareem, A., and Tognarelli, M. (1996). "Simulation of a class of non-normal processes." *Int. J. Non-Linear Mech.*, 31(5), 601–617.

Hasselmann, K. (1962). "On the nonlinear energy transfer in a gravity wave spectrum, part I." *J. Fluid Mech.*, Cambridge, U.K., 12, 481–500.
Hudspeth, R. T., and Chen, M. (1979). "Digital simulation of nonlinear random waves." *J. Wtrwy. Port Coast. and Oc. Div.*, ASCE, 105(1), 67–85.
Jefferys, E. R., and Rainey, R. C. T. (1994). *Slender body models of TLP and GBS "ringing."* BOSS, McGraw-Hill, Inc., New York, N.Y.
Kareem, A. (1995). "The next generation of tuned liquid dampers." *Proc. of the First World Conf. on Struct. Control*, Calif. Inst. Assn. for Struct. Control, Los Angeles, Calif.
Kareem, A., Hsieh, C. C., and Tognarelli, M. A. (1994). "Response analysis of offshore systems to nonlinear random waves part I: wave field characteristics." *Proc. of the Spec. Symp. on Stochastic Dyn. and Reliability of Nonlinear Oc. Sys.*, ASME, New York, N.Y., 39–54.
Mo, O., and Moan, T. (1985). "Environmental load effect analysis of guyed towers." *J. Energy Resour. Technol.*, ASME, 107(1), 24–33.
Natvig, B. J. (1994). "A proposed ringing analysis model or higher order tether response." *Proc., 4th Int. Offshore and Polar Engrg. Conf.*, ISOPE, Golden, Colo., 40–51.
Stansberg, C. T. (1993). "Non-Gaussian properties of second-order sum frequency responses in irregular waves: a numerical study." *OMAE, Offshore Technology*, ASME, 1, 481–489.