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3D Finite Element Analysis of Marine Risers under Random Loads

***Rizwan A. Khan*[1]*, *Suhail Ahmad*[2]**
[1]Department of Civil Engineering, Dr B R Ambedkar National Institute of Technology, Jalandhar, Punjab, India
[2]Department of Applied Mechanics, Indian Institute of Technology, Delhi, Hauz Khas, New Delhi, India

Abstract
The dynamic response of marine risers under long crested random sea is obtained in time domain using finite element solver ABAQUS/AQUA. The response analysis is based on a simulation technique which duly considers various nonlinear effects such as relative velocity squared drag force, variable added mass due to variable submergence and nonlinearity due to large excursions. It also accounts for variable tension in the riser due to variable submergence, variable buoyancy and wave forces. Results are presented which illustrates the effects of nonlinearities, long-term drift oscillations and instantaneous motion of the vessel and current velocity on the bending stress in the marine risers. The response time histories are obtained and presented in terms of bending stress envelopes and spectra showing contribution of various harmonics which is significant because of a nonlinear system.

Keywords: *Marine risers, random waves, vessel motion, drift oscillation, dynamic response*

****Author for Correspondence*** E-mail: rizwan_iitd@yahoo.co.in

INTRODUCTION

A marine riser is a major component of offshore drilling and production systems that are a part of either fixed or floating offshore platforms. It is a slender pipe that serves as a conduit between the platform and the subsea well head. Since, a marine riser is intended to remain on station for the life of an oil field; it will be exposed to wide variety of hazards, with the potential for environmental damage and structural failure or damage to the material. The riser is excited due to waves and current actions at the site of the installation, and the imposed motions applied at the riser's top arising from the dynamic response of the production platform subjected to waves and current loading. This excitation produce significant dynamic stresses in the riser, the natural frequencies of which fall within the live range of most excitation frequencies. Generally, the deep risers have natural frequencies that lie within the dominant frequencies of the most frequently occurring sea states and consequently have large dynamic response. A realistic assessment of the loading environment on a marine riser is essential to produce a reliable and safe design. The major factors that should be taken into account are wave forces associated with the most severe operating sea state— water depth; static offset of the platform due to wind; current and slow drift; current forces on the riser and excitation due to vortex shedding.

A good number of research papers are available in various journal and conference proceedings on various aspects of dynamic response of marine risers. Atadan *et al*. [1] studied the force dynamics of the system comprised of riser, connected to a floating platform and conveying fluid, in the presence of ocean waves and ocean currents. The mathematical model of the production system is derived using the Lagrangian formulation. Shear effects based on the nonlinear elastic theory are included in the formulation. Yousun L [2] studied the force dynamics of the riser system, connected to a floating platform and conveying fluid, in the presence of ocean waves and ocean currents. Huyse *et al.* [3] have presented a static three-dimensional analytical method for drilling risers experiencing large displacements and slip at the top joint. Vessel motion has not been taken into account. Chatjigeorgiou and Mavrakos [4] studied the nonlinear dynamic response in the transverse direction of vertical marine risers/tensioned cable legs subjected to parametric excitation at the top of the structure. The dynamic model contains both elastic and bending effects. Park and Jung [5] presented a 3D numerical analysis of the lateral responses of long slender marine structure (i.e., risers and tethers) under combined, parametric and forcing excitations. The analysis is performed in time domain by finite element method, using the Newmark's constant acceleration method. Morroka *et al.* [6] studied the dynamic behavior of top tensioned marine riser in deep water through time domain simulation of its displacements and respective bending moments and stresses. Maximum and minimum envelopes for displacements and stresses along riser length are shown. Kaewunruen *et al.* [7] employed finite element method to analyse the nonlinear free vibrations of marine risers/pipes conveying internal fluids based on the energy approach.

Using the above analyses, various parametric studies have been reported on the behavior of marine risers due to dynamic excitations. However, a survey of the literature shows that there is a need for better understanding of the riser dynamics and the random wave loading. It is also seen that the effects of different nonlinearities, current velocities and vessel motions on deep water riser have not been thoroughly investigated. In view of this background, the present study focuses on investigating the effect of the following parameters on riser response (i) long-term periodic response; (ii) instantaneous vessel motion produced by random sea; (iii) current in hydrodynamic loading.

Mathematical Formulation

A nonlinear 3D dynamic analysis of marine riser has been carried out in the time domain using finite element solver ABAQUS/AQUA as shown in figure 1 [8]. The riser is modeled as tensioned beam with six degrees of freedom at each node (three translations and three rotations). 3D shear deformable B31 Timoshenko beam elements have been used for modeling the marine riser. The bottom end of the riser is hinged and the top end is restrained in horizontal direction. The analysis includes nonlinearities due to large deformation; time-wise variations of submergence; buoyancy added mass and drag force.

Equation of Motion

The equation of motion for the resultant multi-degree of freedom system is given as:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{F(t)\} \qquad (1)$$

Where $[M]$ is the consistent mass matrix; $[C]$ is the damping matrix; $[K]$ is the system stiffness matrix; $\{F(t)\}$ is the time-dependent random hydrodynamic loading; $\{\ddot{x}\}$, $\{\dot{x}\},\{x\}$ are the vectors of structural acceleration, velocity and displacement, respectively. The stiffness matrix $[K]$ is made up of both elastic and geometric stiffness matrices corresponding to the degrees of freedom. The consistent mass matrix $[M]$ for the complete riser is made up from the assembly of the element mass matrices in global coordinates. The elemental mass matrix consists of two parts— one due to the mass of the element and the other due to added mass effect. The latter is considered for the submerged part of the riser up to still water level (SWL). The damping matrix is not explicitly known but is assumed to be a linear combination of $[M]\&[K]$, so that the knowledge of the modal damping ratio is sufficient for obtaining the dynamic response of the riser.

Treatment of Dynamic Loading

The sources of dynamic loading considered in this study consist of hydrodynamic loading due to random wave and current. The hydrodynamic loads $\{F(t)\}$ has two components *viz*. drag force and inertia force which depend on the velocity and acceleration with respect to the riser as well as the velocity and accelerations of the water particle and currents. The hydrodynamic load per unit length on the riser at any instant of time is determined by using Morison's equation:

$$f_i = \frac{1}{2}\rho_w C_D D\left(\dot{U}_i - \dot{x}_i + V_{c_i}\right)\left|\dot{U}_i - \dot{x}_i + V_{c_i}\right| + \rho_w \frac{\pi}{4} D^2 C_M \ddot{U}_i - m\cdot\ddot{x}_v \tag{2}$$

where m is the mass of the riser per unit length and is given by:

$$m = \frac{\pi}{4}\left(D^2 - D_i^2\right)\rho_s + \frac{\pi}{4}D_i^2\rho_o + \frac{\pi}{4}D^2\rho_w\left(C_M - 1\right) \tag{3}$$

where $\dot{U}_i, \ddot{U}_i$ are the water particle velocity and acceleration, $\dot{x}_i$ is the velocity of the riser at point 'i' for any instant of time and $\ddot{x}_v$ is the acceleration of the vessel imparted to the top of the riser at the same time. Other variables are defined in Table 1.

Representation of Random Waves

The sea surface is assumed to be Gaussian ergodic process and the surface elevation is assumed to be a super position of infinite small harmonic waves having randomly distributed phases. The spectral density of the sea surface elevation is a representation of the energy content of different harmonics present in it and is completely characterized by significant wave height H_s, average time period T_z. The DNV version of the Pierson–Moskowitz (P–M) sea surface elevation spectrum is used here.

$$S_{\eta\eta}(f) = \frac{H_s^2 T_z}{8\pi^2}(T_z f)^{-5}.\exp\left[-\frac{1}{\pi}(T_z f)^{-4}\right] \tag{4}$$

where f is the frequency in cycles/sec, H_s is the significant wave height in m, T_z is the zero up crossing period in sec, and $S_{\eta\eta}(f)$ is the PM (single-sided) sea surface elevation spectrum.

Simulation of Top Vessel Motion

To adequately simulate the vessel motion, a model have been adopted which includes terms representing mean vessel offset from the well bore, long term drift, i.e, modeling the response of the positioning system and the instantaneous response of vessel motion to irregular waves. The proposed vessel motion model is similar to those given by Sexton and Agbezuge [9] represented as

$$S_v(t) = S_o + S_L \sin(\omega_1 t - \alpha_1) + \sum_{n=1}^{n} S_n \cos(K_n S_v(t) - w_n t + \beta_n + \alpha_n) \tag{5}$$

where S_o is the static offset; S_L, ω_1, α_1 are the long-term drift motion amplitude, frequency and phase, respectively; S_n, and α_n are obtained from Response Amplitude Operator (RAO) curve corresponding to the component frequency $w_n = 2\pi/T_n$ used in the simulation of sea surface elevation above. Iteration is required to determine the value of $S_v(t)$ at a given time and $S_v(t)$ appears on both the sides of Eq. (5).

Time domain solution

The equation of motion as given in Eq. (1) is solved in the time domain using a step-by-step integration procedure. Time histories of the marine riser stresses and displacements in x, y and z directions, together with the top tension are generated by the time integration method described earlier. For all the response quantities the structure is initially assumed to be at rest. For the hydrodynamic and structural damping present in the system, initial conditions die out roughly in 5–10 cycles, i.e, for a time of 5T$_o$–10 T$_o$ sec, where T$_o$ is the period of marine riser vibration in the mode of vibration under consideration. The time histories are obtained at a time interval of $\Delta t = T_o/10$. This time interval yields sufficient accuracy in the step-by-step integration procedure adopted here using Newmark's-β scheme. The root mean square (RMS) response is obtained from the response time histories after discarding an initial length of the time histories to eliminate the effect of nonstationarity. The spectrum of the response quantities are obtained by direct Fourier transform of the response histories using FFT developed by Cooley and Turkey [10]. This version of the Fourier transform algorithm requires ordinates of the time history to be equal to 2^N. No spectrum was obtained from the time history of ordinates less than 2048. The raw spectrum obtained from the time history is smoothened by a standard procedure.

Numerical Study

A marine riser as shown in Figure 1 has been chosen for the numerical study. The applied tension at the top of the riser is considered as variable. Riser properties are given in Table 1. The first five frequencies of the riser for an applied tension are shown in Table 2.

Table 1: *Marine Riser Specifications.*

Riser Tension (T)	$=3 \times 10^6$ N
Water depth (H)	=920.5 m
Riser length (L)	=920.5 m
Outer diameter of riser	=0.406 m
Inner diameter of riser	=0.374 m
Effective outer diameter	=0.66 m
Mass density of steel	$=7850$ kg/m^3
Mass density of water	$=1025$ kg/m^3
Coefficient of drag (Cd)	=0.7
Coefficient of Inertia (Cm)	=2.5
Current velocity (Vc)	=1.5 m/sec
Modulus of elasticity	$=2.07\times10^{11}$ N/m^2

Table 2: *Natural Frequencies of the Riser.*

Riser length (m)	**Top tension (kN)**	**Natural frequencies (cycles/s)**				
		Mode 1	**Mode 2**	**Mode 3**	**Mode 4**	**Mode 5**
920.5	3000	0.045	0.081	0.121	0.162	0.203

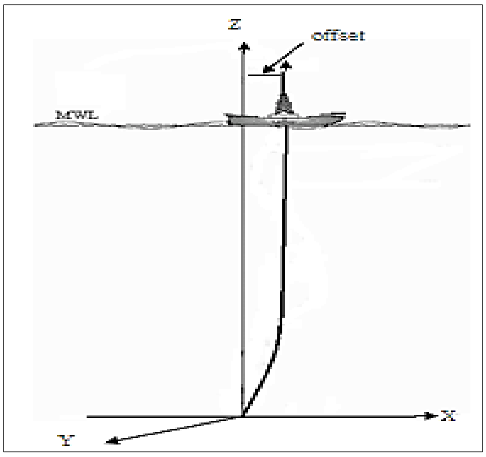

Fig.1: *Marine Riser.*

Dynamic responses are obtained for random waves, with and without current. Four different wave period/ wave height combination are selected for irregular waves; namely 20 m/15 sec, 15 m/15 sec and 15 m/10 sec. These combinations are chosen in order to study the behavior of the risers under extreme near resonating and nonresonating dynamic excitations. The long crested sea states are represented by DNV version of the P-M spectrum defined by the two parameters— H_s (significant wave height) and T_z (zero crossing period). Combination of H_s and T_z used in the example are 20 m/15 sec and 15 m/15 sec. These sea states adequately cover the condition of significant dynamic excitation. For the time domain analysis using step-by-step integration procedure, the response time histories are obtained for sufficient length of time. So, the response attained their steady state values. The initial part of the time history of response has been excluded to remove the effect of transient nonstationary phase.

Two types of vessel motion are considered long term drift oscillation and the instantaneous response of the vessel to random waves. The long term drift oscillation is modeled by a harmonic motion whose amplitude (S_L) is taken as 3 m and the period is varied to suit different case studies. The phase angle between the drift motion and the wave is taken as zero. The current profile along the depth is assumed to be triangular with a velocity (V_c) of 1.5 m/sec at the top.

Effect of vessel motion on riser response

Both type of vessel motion, i.e., long-term drift motion and instantaneous motion due to random waves, are investigated. In Figure 2, the envelopes of maximum bending stresses obtained 15 m/15 sec random wave and the combined motion (same wave and vessel motion 3 m/15 sec) are presented. The significance of the vessel motion on riser response is well depicted in the figure. Not only do the stresses at the top of the riser become maximum, but considerable stresses are also produced in the middle of the riser. It is clear from the figure that long term drift motion of the vessel produces stresses far in excess alone. In the present case, the maximum response produced by combined effect of wave and vessel is about 2.5 times that produced by the wave alone. In Figure 3 the results are shown for riser under 20 m/15 sec wave and 3 m/15 sec vessel motion. In this case the main contribution to the response is from the first two modes of the structures. The ratio of the maximum stress produced by the combined effect of wave and vessel to that of wave alone is about 2.1. It can also been seen in the power spectral density (PSD) of the stresses (Figures 4 & 5) as the maximum energy content of the wave plus vessel is much higher as compared to that of long crested sea alone.

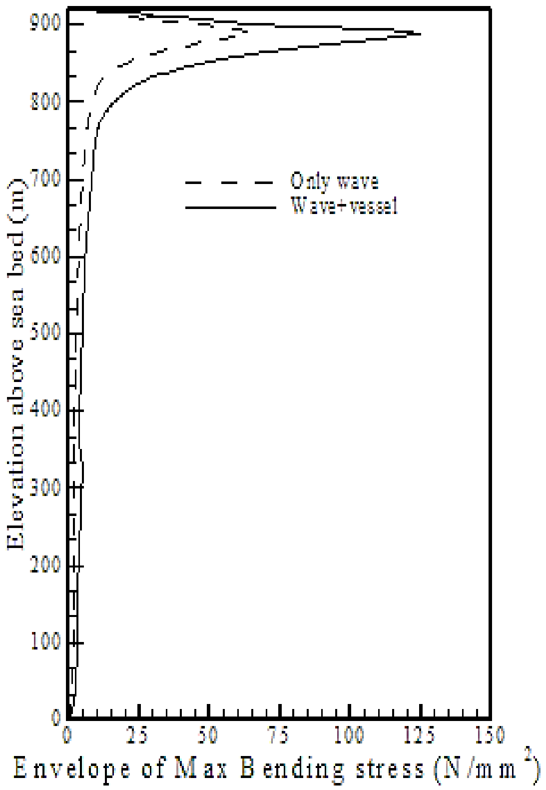

Fig. 2: *Effect of Vessel Motion on response of Long Riser for Random Sea State. (H=920.5, L=920.5, T=3000 kN, Hs=15 m, Tz=15 sec, S_L=3 m).*

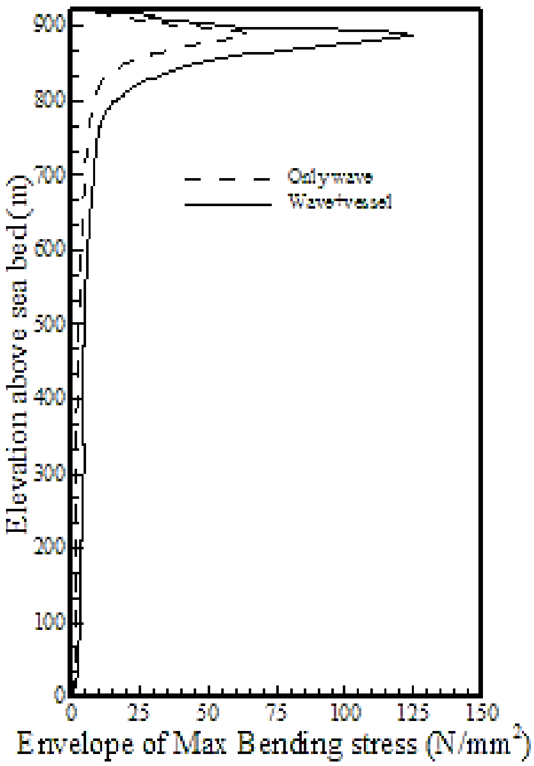

Fig. 3: *Effect of Vessel Motion on Response of Long Riser for Random Sea State. (H=920.5, L=920.5, T=3000 kN, Hs=20 m, Tz=15 sec, S_L=3 m).*

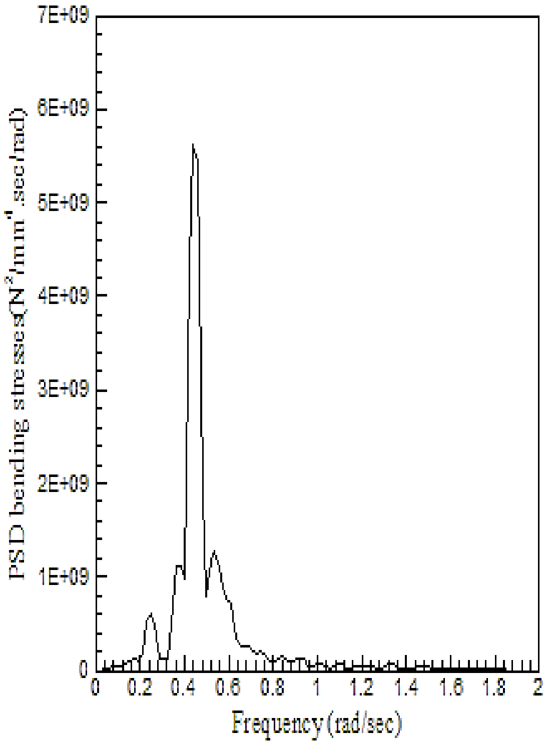

Fig.4: *PSD of the Bending Stresses Only Wave. (Wh=15 m, Wp=15 sec).*

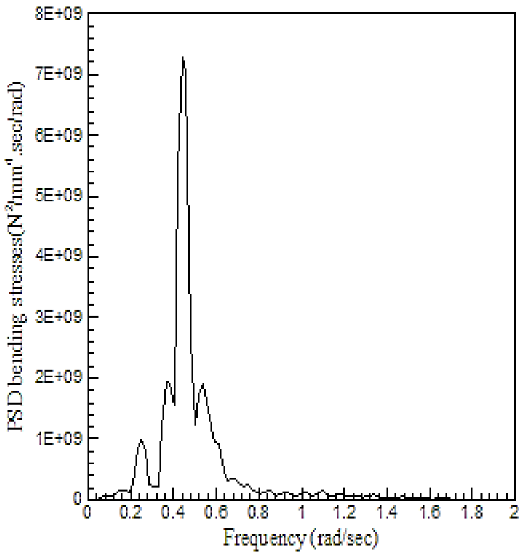

Fig.5: *PSD of the Bending Stresses Wave+Vessel Motion. (Wh=15 m, Wp=15 sec).*

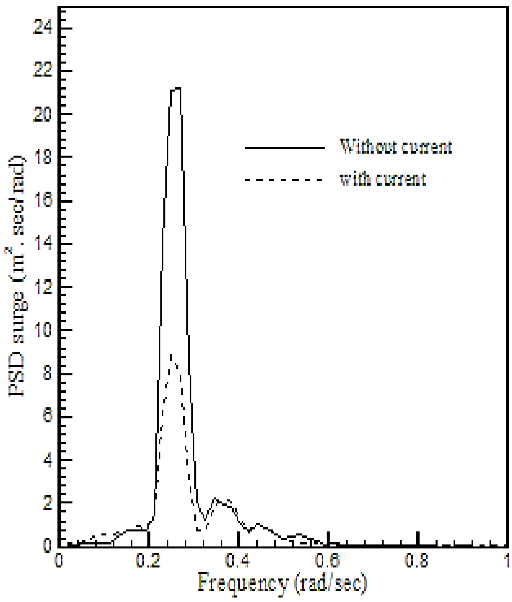

Fig.6: *Effect of Current on Surge. (Hs=20 m, Tz=15 sec).*

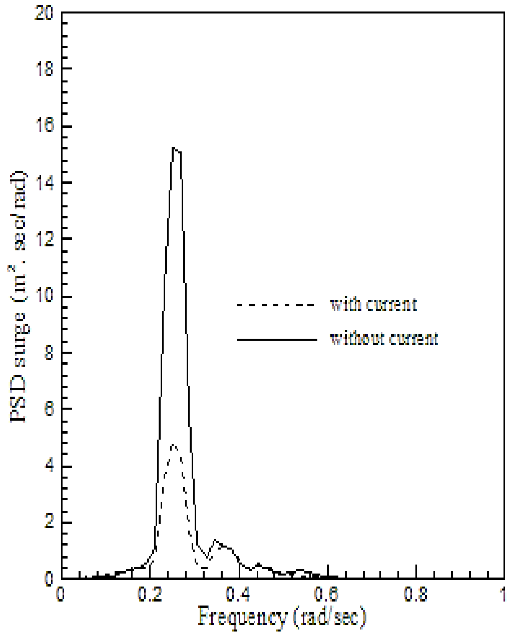

Fig.7: *Effect of Current on Surge. (Hs=15 m, Tz=15 sec).*

Effect of Current on Dynamic Response

The water particle velocity is increased by the current velocity nonvarying with time. The drag force is accordingly increased nonlinearly (Eq. 2). The current velocity does significantly influence the dynamic response. The steady drift is enhanced due to the presence of current velocity introducing a pseudo static effect. The change in the dynamic response induced by current velocity greatly depends upon the ratios of wave period to the structure's periods. When current velocity is considered in the computation of hydrodynamic forces, hydrodynamic loading gives harmonics at both even and odd multiples of wave frequency, and also at zero frequency. If the ratios are such that one of the first few frequencies of the structure nearly coincides with any of the even harmonic components of the loading, the effect of current on dynamic response is severely magnified. Current is found to increase the response considerably. This is probably due to the resonating condition described above. Figures 6 and 7 shows the effect of current on surge response in terms of PSD for cases 20 m/15 sec and 15 m/15 sec. The energy content of the current and wave induced surge is smaller than the case when the long crested sea works alone. This is probably due to the fact that the current induces a steady drift. This steady offset allows the structure to oscillate in a controlled fashion about the new mean position.

CONCLUSIONS

A dynamic analysis for irregular long crested sea is carried out in the time domain by employing a simulation of sea state by P-M spectrum. Finite Element Package ABQUS/AQUA has been used to carry out the dynamic response analysis. The effects of relative velocity squared drag term, the long-term drift oscillation and the current velocity were all considered. Time histories for various results are developed until steady state is achieved. The following result can be drawn from the numerical study:

(1) Combined vessel and wave motion results in increase in stresses near the top and in the middle of the riser. Moreover, the combined effect may produce stresses far in excess of those produced by waves alone.
(2) The ratio of the maximum stress produced by the combined effect of wave and vessel to that of wave alone is about 2.5 for the studied case.
(3) When the current velocity is added to water-particle velocity for the computation of hydrodynamic loading, considerable change in the dynamic response of the riser may result. The amount of change depends upon the ratios of wave period to the structure's periods. For the resonating conditions, addition of a small current may lead to a large change in the dynamic response.
(4) When the current velocity is added in the computation of the velocity squared drag force, the response behavior of the riser is altered significantly. It implies the significance of wave current interaction.
(5) In general, long risers are more affected by vessel motions (long-term drift) than by wave forces.

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