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Nonlinear Dynamic Analysis of Marine Risers under Random Loads for Deepwater Fields in Indian Offshore

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Abstract

The paper presents a numerical Analysis of deep water Steel Catenary Riser (SCR) under random sea loads. A finite element method is implemented in the time domain using Newmark’s-Beta method. The response analysis is based on a simulation technique which duly considers the various non-linear 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 riser due to variable submergence, variable buoyancy and wave forces. Results are presented which illustrates the effects of nonlinearities, long term drift oscillations and current velocity on the bending stress in the marine risers. The bending stress 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 non-linear system.

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1. Introduction

The Steel Catenary Riser (SCR) concept has been recently used in almost every new deepwater field development around the world. SCRs have been vital to deepwater field developments. Steel catenary risers offer a low cost alternative to conventionally used rigid and flexible risers on floating platforms and can also provide economic riser design solutions for fixed platforms. Their use has given a new dimension to oil exploration and transportation in water depths where other riser concepts could not tolerate the environmental loads or would have become costly. SCR designs are very sensitive to floating support platform characteristics to which they are typically attached. In addition to pipe stresses, the main design issue for the SCR concept is fatigue related. There are two main sources of fatigue: random wave fatigue and vortex-induced vibration (VIV) fatigue. Marine riser is excited by ocean currents, waves and the vessel motion. These excitations produce significant dynamic stresses in the risers, the natural frequencies of which fall within the range of most excitation frequencies. Generally, deep risers have natural frequencies that lie within the dominant frequencies of most of the frequently occurring sea states and, consequently have a large dynamic response. Generally three types of riser dynamic analysis are specified in the literature:

(1) deterministic steady-state or frequency domain analysis;
(2) deterministic time history analysis; and
(3) non-deterministic random vibration analysis

A good number of research papers appeared in various journals and conferences on various aspects of dynamic analysis of marine risers. Park and Jung (2002) presented a 3D numerical analysis of lateral responses of long slender marine structure (risers) under combined, parametric and forcing excitations. Averbuch et.al (2003) presented a new analytical method to evaluate displacements and stresses in SCRs subjected to static loading induced by currents. Kaewunruen et.al (2005) employed finite element method to analyze the nonlinear free vibrations of marine risers/pipes conveying internal fluids based on the energy approach. Structural model developed consists of strain energy due to axial deformation, bending, virtual work due to effective tensions and external forces, and the kinetic energy due to riser and internal fluid motions. Chatjigeorgiou (2008) dealt with the dynamic equilibrium problem of 2D catenary riser. Finite difference solution method is applied which is unconditionally stable and provides very fast convergence. The review of the literature shows that though a number of studies have been done on the dynamic analysis of riser but there is ample scope of work for analysis of riser for the Indian conditions.

In the present study a non-linear dynamic analysis of marine riser, under regular and random waves has been investigated with the emphasis on the Indian conditions. The responses are obtained using finite element solver ABAQUS/Aqua (2006) in the time domain. Riser is modeled as tensioned beam with three degrees of freedom at each node. The equation of motion has been solved considering the nonlinearities due to large deformation and time-wise variation of the submergence, buoyancy, added mass and resultant hydrodynamic loading. For random waves, sea states have been represented by the DNV version of the Pierson-Moskowitz (PM) sea spectrum which is defined by the two parameters, $H_s$ ($1/3^{rd}$ significant wave height) and $T_s$ (average time period).

2. Mathematical Formulation

The main features of the model and the assumptions are as follows:
A riser is idealized as a tensioned beam, single line, three dimensional structure undergoing motion in the plane of fluid loading caused by waves and currents in the same or opposite directions. For analysis, the riser is discretized into a number of finite beam elements (shear deformable hybrid beam element B-31H).

The bottom end of the riser is hinged and assumed to be restrained in the horizontal and vertical directions; top end of the riser is supported on a roller which allows horizontal restraint but allows movement in the vertical direction.

It is assumed that no buoyancy tanks are provided along the riser length.

2.1 Equation of motion

With the above assumptions for the analysis of the riser system, the equation of motion for the resultant multi-degree-of freedom system is given as

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

(1)

where \([M]\) is the consistent mass matrix, \([C]\) is the damping matrix, \([K]\) is the system stiffness matrix and \(\mathbf{F}(t)\) is the time- dependent random hydrodynamic loading. \(\ddot{\mathbf{x}}, \dot{\mathbf{x}}, \mathbf{x}\) are the vectors of structural acceleration, velocity and displacement respectively.

The stiffness matrix \([K]\) is made 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 added mass effect. The latter is considered for the submerged part of the riser up to still water level (SWL).

2.2 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 \(\mathbf{F}(t)\) has two components viz. drag force and inertia force which depend on the velocity and acceleration w.r.t 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:

\[
f_i = \frac{1}{2} \rho w C_D \left( \dot{U}_i - \dot{x}_i + V_c \right) \left| \dot{U}_i - \dot{x}_i + V_c \right| + \rho w \frac{\pi}{4} D^2 C_M \dot{U}_i - m \cdot \ddot{x}_i
\]  

(2)

where \(m\) is the mass of the riser per unit length and is given by
\[ m = \frac{\pi}{4} \left( D^2 - D_i^2 \right) \rho_s + \frac{\pi}{4} D_i^2 \rho_o + \frac{\pi}{4} D^2 \rho_w (C_M - 1) \] (3)

in which \( \dot{U}_i, \ddot{U}_i \) 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.

2.3 Simulation of random waves

The sea surface is assumed to be Gaussian ergodic process and the surface elevation is assumed to be a superposition of infinite small harmonic waves having randomly distributed phases. The spectral density of the sea surface elevation is represented by the DNV version of the Pierson-Moskowitz (PM) sea spectrum, which is given by

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

Where, \( f \) is the frequency in cycles/s, \( H_s \) is the significant wave height in m, \( T_z \) is the zero up crossing period in sec, and \( S_{qq}(f) \) is the PM (single-sided) sea surface elevation spectrum. The random waves and the corresponding water particle kinematics are simulated by wave superposition techniques from their respective spectra.

3. Numerical Study

For the present numerical study a riser configuration for the semi-submersibles for Krishna Godavri (KG) field in East Coast of India in water depth of 1800 m signifying long riser is considered. The height of the still water level (SWL) above sea bed is considered same as the length of the riser. It is assumed that the riser is connected to the vessel by a heave compensating device which allows the free vertical movement of the connecting point with the passage of wave. The riser properties are given in Table 1. The first fifteen frequencies of the riser for the given cases are shown in Table 2.

Dynamic responses are obtained for regular and random waves, with and without current. The extreme storm analysis is performed using 100 year extreme storm waves for two different combination of wave height and wave period; namely 20.7m/14.4sec, 17.67m/13.25sec. These combinations are chosen in order to study the behavior of the risers under extreme near resonating and non resonating dynamic excitations.
Table 1 Riser Data Specifications

| Parameter                              | Value          |
|----------------------------------------|----------------|
| Water depth (H)                        | 1800 m         |
| Riser length (L)                       | 2485 m         |
| Outer diameter of riser                | 0.429 m        |
| Inner diameter of riser                | 0.407 m        |
| Effective weight (W<sub>e</sub>)       | 1.1320 kN/m    |
| Top Tension                            | 1.2*W<sub>e</sub>*L |
| Mass Density of Steel                  | 8200 kg/m³     |
| Mass Density of Water                  | 1025 kg/m³     |
| Coefficient of drag, C<sub>d</sub>     | 1.0            |
| Coefficient of Inertia, C<sub>m</sub>  | 1.0            |
| Current velocity, V<sub>c</sub> (at top) | 1.4 m/sec     |
| Current velocity, V<sub>c</sub> (at bottom) | 0.0 m/sec    |
| Modulus of elasticity                  | 2.07 ×10¹¹ N/m² |
| Service Life                           | 20 Years       |

Table 2 Risers Natural Frequencies

| S. No. | Mode Number | Natural Frequencies (rad/sec) |
|--------|-------------|------------------------------|
|        |             | (rad/sec)                    |
| 1      | 1           | 0.0884 0.0884                |
| 2      | 2           | 0.1617 0.1617                |
| 3      | 3           | 0.1737 0.1737                |
| 4      | 4           | 0.2408 0.2408                |
| 5      | 5           | 0.3092 0.3092                |
| 6      | 6           | 0.3225 0.3225                |
| 7      | 7           | 0.4012 0.4012                |
| 8      | 8           | 0.4485 0.4485                |
| 9      | 9           | 0.4827 0.4827                |
| 10     | 10          | 0.5643 0.5643                |
| 11     | 11          | 0.5776 0.5776                |
| 12     | 12          | 0.6454 0.6454                |
| 13     | 13          | 0.7084 0.7084                |
| 14     | 14          | 0.7280 0.7280                |
| 15     | 15          | 0.8108 0.8108                |

For irregular waves the combination of the significant wave height and wave period used in the present study are 11.13m/10.67 sec and 9.5m/9.86 sec. These sea states adequately cover the probable conditions of significant dynamic excitation for the given region. The current profile along with the depth is assumed to be triangular with a velocity (V<sub>c</sub>) of 1.4m/sec near the sea surface reducing linearly to zero at the sea bed.
3.1 Effect of random wave on riser response

To study the effect of long crested random sea on deepwater risers two different combinations of significant wave height and zero crossing period (Hs, Tz) are chosen. Figure 2 shows the RMS bending stress plot for random sea, Hs and Tz as 9.5m/9.86 sec respectively.

The maximum bending stress occurs near the top of the riser and at the touch down point. At 470 m near TDP the value of maximum bending stress is found to be 84.93 N/mm². The stress further reduces nonlinearly with depth because the effect of wave forces diminishes slowly with depth. The maximum bending stress is not only at a node close to the sea surface but also near the touchdown point due to the interaction of the riser with the seabed.
The nonlinearities present in the system are duly considered and the effect of the same is observed in randomly fluctuating bending stress time history. The max bending stress time history occurs at a node close to the sea surface (Figure 3). The stresses also found to be profound near the interaction of the sea bed with the riser. This occurs due to the combination of wave loading and dynamic characteristics of the riser. The participation of various frequencies is distinctly shown in power spectral density plot (Figure 4) of the time history. Fig 4 shows that excitations are predominantly occurring at closely spaced frequencies viz. 0.538 rad/sec, 0.622 rad/sec and 0.475 rad/sec. The mean weighted frequency corresponds to 1.3Tz is 0.5087 rad/sec. Hence, the response is mainly governed by the dominant force due to the random sea state. Due to the presence of non-linearities and random load input several frequencies are excited in close proximity of the prominent peaks. These close proximities of forcing function frequencies produce beating effect in the response, as clearly visible.

Figure 4: Power Spectral Density PSD

Figure 5: RMS Bending Stress, Vc=1.4 m/s
3.2 Effect of random wave with current on riser response

A triangular current profile of maximum velocity of 1.4m/sec acts with random sea states of Hs=9.5m and Tz=9.86 sec. The RMS bending stress has been shown in Figure 5. The shape of the stress variation is not very different from the case with no current. However, maximum bending stress value in this case has reached 294.54 N/mm² while it was 271.22 N/mm² for random wave only. Response is further analyzed in terms of time history and respective spectra. Fig.6 shows the random fluctuations of bending stress where its maximum value is approximately reaching up to 263.73 N/mm². Superimposed on the same is the randomly varying stress fluctuation due to long crested simulated sea. Time history at a node with maximum bending stress shows a tendency of beating behavior.

![Figure 6: Max. Bending Stress Time History](image)

![Figure 7: Power Spectral Density PSD](image)
Although, the effect of interaction of wave and current on the riser with an offset distorts the beating behavior. Power spectral density distribution (Figure 7) of the above time history shows multiple peaks at 0.475 rad/sec, 0.538 rad/sec and 0.584 rad/sec with the higher energy content for the second and third peak. The prominent peaks occur near the mean weighted frequency 0.5087 rad/sec (1.3 Tz) implies that response is wave dominated as 0.5087 rad/sec is close to the dominant frequency of the PM spectrum. There are a couple of lower mode frequencies of the riser falling in this range as shown in Table 2.

4. Conclusions

Dynamic response of marine risers to both random waves and random waves plus current has been investigated. In the dynamic response analysis, the effects of the relative velocity squared drag term, the long term drift oscillation and the current velocity were all considered. The response was obtained in time domain using finite element package ABAQUS/AQUA. For the random sea states, the time histories of sea surface elevation, the water particle kinematics were simulated by a harmonic superposition technique. The following results can be drawn from the numerical study.

i.) For the random sea state alone response of the structure is mainly governed by the excitation force due to dominant sea state under consideration. The maximum bending stresses are found to occur near the top of the riser in the wave splash zone and near the touchdown point (TDP).

ii.) When the current velocity is added to water-particle velocity in the computation of the hydrodynamic loading, considerable change in the dynamic response of the riser may occur. The static current enhances the damping tendency of the riser. While the energy content of the frequency response goes up.

iii.) The PSD’s in cases of wave and wave with current under study shows the peak clusters. It is due to concentration of several excitation frequencies occurring closely. These frequencies are either close to the multiple of fundamental frequencies (3 times & 4 times the fundamental frequency) or the forcing frequency. Hence, shows super harmonic response.

iv.) Cluster of frequencies close to the lower modes of vibration 2nd, 3rd, 4th and 5th are mainly due to the sea states and beating phenomenon influences the response as appears in the time history and respective PSDF.

v.) Study of the responses under Hs and Tz 11.13m-10.67sec, 9.5m-9.86sec (dominant Indian conditions) establishes the basic design parameters as a result of interaction with the long riser dynamic characteristics.

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