Non-LinearDynamic Response and Probabilistic Risk Analysis of Marine Risers

BY

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Dedicated

to

My Parents

CERTIFICATE

This is to certify that the thesis entitled ***"Non-Linear Dynamic Response and Probabilistic Risk Analysis of Marine Risers"***, being submitted by ***Mr. Rizwan Ahmad Khan*** to the Indian Institute of Technology, New Delhi, India, for the award of the degree of ***Doctor of Philosophy*** in Applied Mechanics, is a record of the bonafide research work carried out by him under my supervision. He has fulfilled the requirements for submission of this thesis, which is the best of my knowledge, has reached the requisite standard.

The material contained in this thesis has not been submitted in part or full to any other university or institute for the award of any degree.

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ABSTRACT

Design and analysis of marine risers has emerged as one of the biggest challenges with the extension of exploration and exploitation of offshore oil and gas to deeper waters. To produce a safe and reliable riser design, a realistic assessment of the forces is essential. Environmental and operating conditions affecting the riser include waves, current, dynamic vessel motion, top tension fluctuations and mud weight. In the upper stratum of the sea, the loads are mainly caused by waves, surface currents and platform motion. Further down, the forces are more due to current caused by the large scale oceanographic circulation. Long risers are especially susceptible to vortex induced vibration (VIV) because currents are typically higher in deepwater areas than in shallower. Furthermore, the increased length of the riser lowers its natural frequency thereby lowering the magnitude of current to excite VIV. Deepwater risers interact with significant currents and oscillate in transverse direction at much higher frequency than the fundamental bending mode. Risk and reliability assessment is, all the more, important because the structural behavior of offshore structures under deep water conditions is unpredictable and uncertain than in shallow water depth. A comprehensive literature review has exposed various unexplored aspects of riser behavior and respective objectives.

The dynamic response of marine risers has been carried out under long crested random sea. A mathematical model based on finite element idealization in ABAQUS/AQUA environment is established incorporating basic riser characteristics of longer length. Three dimensional shear deformable B31 Timoshenko beam elements have been used for modeling the marine riser. The bottom end of the riser is hinged and top end is restrained in horizontal direction. The governing equations of motion consist of

instantaneous consistent mass, system stiffness and structural damping matrices and relevant hydrodynamic force vector. The stiffness matrix is made up of both elastic and geometric stiffness components valid for nonlinear system under study. The time varying force vector consists of hydrodynamic loading due to random wave and vessel/ platform motion at the top of the riser and current forces. The response is obtained in time domain using an implicit integration solver of coupled differential equations in ABAQUS with its module Aqua, that provides an ocean environment. The associated nonlinearities due to large deformation, time-wise variation of the submergence, buoyancy, added mass and resultant hydrodynamic loading are duly considered. For random waves, sea states have been simulated by the DNV version of the Pierson-Moskowitz (PM) sea spectrum which is defined by the two parameters, H_s (1/3rd significant wave height) and T_z (average time period). The sea state is assumed to be an ergodic random process. The randomly varying sea surface elevation and the associated water particle kinematics are obtained using wave superposition technique. To adequately simulate the vessel motion, the model includes terms representing mean vessel offset from the well bore position due to current and the instantaneous response of vessel motion. The dynamic behavior of marine risers is investigated for long crested random sea incorporating various nonlinearities. Stress histories of random nature are obtained at critical riser locations. Power spectra are developed and participation of frequencies in the response are studied. Statistical characteristics of the random samples are obtained to model uncertainties involved in reliability studies. Before proceeding for the detailed study, some aspects of dynamic response are validated with the published literature.

Vortex induced vibration of slender riser is one the major design criteria for the deep-water conditions. As the shedding process is more or less harmonic, the empirical model employed considers the transverse lift force as a sinusoidal function. However, its non-linear interaction with riser undergoing small strain large deformation yields non periodic response under sheared current profiles. The response of the marine riser due to vortex induced loads is iteratively obtained in time domain under time varying axial tension. The VIV induced lift force vector in transverse direction has been obtained numerically with respect to time following an improved algorithm. The effect of multimode participation on deepwater riser response is highlighted through instantaneous response studies. Some of the results obtained by ABAQUS/AQUA are validated with the published literature.

The structural behavior of marine riser under deep water conditions is quite unpredictable and uncertain; therefore, the probabilistic risk analysis has been carried out. This is achieved by keeping in view the salient uncertainties associated with the dynamic response and limit state model adopted. Response time histories of stress reversals due to long crested random sea with and without current, together with random vessel excitation have been obtained. All major nonlinearities are incorporated. The other stress time histories due to vortex induced vibrations are also obtained to assess the long term fatigue damage. For the present study, fatigue damage estimation has been made by Palmgren-Miners rule using Bilinear S-N curve and Bilinear Fracture Mechanics approaches. Bilinear methods are less conservative as compared to conventional linear approaches. The random stress histories are modeled by the Rayleigh distribution. Twelve sea states with associated probabilities of occurrence are considered for the estimation of cumulative damage. Sea states are assumed to follow a narrow band spectrum. Non-linear limit state functions using the above two approaches have been derived incorporating the uncertainties associated with various random variables. All the important uncertainties in estimation of fatigue stress and in fatigue model have been considered. FORM and simulation based methods have been used for the reliability assessment. The riser joints are the most vulnerable failure locations and overall system reliability has thus been obtained by assuming riser as a series system. Sensitivity analyses to study the effect and participation of various random variables have been carried out. Most Probable Point (MPP) or design points have been located on the failure surfaces. The effect of service life, effect of no. of joints, effect of variation in mean values of the random variables and effect of variation in coefficient of variation values (COV)of the random variables have been studied on the parametric basis.

Finally, environmental conditions exclusively applicable to deep Indian offshore environment has been studied and complete riser dynamic and probabilistic analyses have been carried out emphasizing on Indian conditions. There are a good number of deepwater offshore sites identified for potential oil and gas reserves in Indian ocean. Environmental design conditions namely significant wave height and corresponding wave period, water depth, current profile with their probabilistic occurrences are employed. Firstly, the riser response under long crested random sea with significant wave height (H_s) and significant wave period (T_z) of 11.13m/10.67 sec and 9.5m /9.86sec respectively are obtained. These sea states adequately cover the probable conditions of significant dynamic excitation for the given region. As mentioned in the preceding sections commercial software ABAQUS has been employed to calculate the dynamic response. VIV analysis has also been carried out and requisite stress time histories are obtained for the given current profile. Finally, the reliability analysis for the probable sea states has been carried out for the cumulative fatigue damage. Commercial reliability software NESSUS has been used to carry out the reliability against fatigue limit state. The results obtained have been satisfactorily validated with the published literature and present reliability code.

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