A Review on Vibration of Marine Platform Risers

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Abstract

The riser is one of the key equipment in a floating drilling platform, but also one of the weakest components of vulnerability. With the development of the marine oil and gas drilling in the deep water, the forces on the platform riser has become complicated increasingly. With the increase of water depth, the riser dynamics is becoming more and more important. In order to determine accurately the strength, dynamic stability and fatigue life of risers, It is only way to analyze exhaustively the vibration characteristics and the dynamic responses of the riser in the deep water. Through the analysis and discussion on present literatures, the research results of the platform riser vibration in the domestic and international are summarized, which focus on mainly the two aspects of vibration characteristics and dynamic responses. The suggestions for the future study are made in the end; the following questions should be paid more attention. (1) The roles of the various load factors on the riser must be taken into account integrated and systematically. (2) The boundary conditions of the marine platform riser must be handled correctly. (3) The dynamic influence of the marine seismic vibrations on the platform riser must be considered. (4) The contact interaction between the drill string and drilling riser must be investigated. (5) The real-time monitoring on-site for dynamic response of marine platform riser must be carried out as soon as possible.

Key words: marine platform, riser; vibration, review

Introduction

The riser is one of the key equipment in a floating drilling platform, but also one of the weakest components of vulnerability. Because there is high pressure moving liquid in its internal, there is the drift of the floating body and there are sea wind, wave, as well as ocean current on its external, the riser is in a very complex marine environment. Due to a riser system damaged under the enormous complex external forces, a lot of marine drilling operations are interrupted, not even to recover to drilling; causing the failure of drilling engineering and a great loss. With the water depth increases, a series of new problems about the riser is appeared. The marine platform riser system is the emphasis and difficulty problem in the design of the marine oil equipments, due to the variety of loads, the complexity of the drilling process, the large non-linear deformation of the riser structure and the uncertainty analysis methods, as well as the abstract of the actual dynamic responses and so on.

The mechanical analysis of the marine platform riser is an important subject in the marine engineering at all times. With the water depth increases, the effect of the dynamic factors on the riser is more and more significant, so as the principles and methods of dynamics analysis have been put forward. For the vibration problems of marine platform risers, a lot of achievement has been made by a number of domestic and foreign experts and scholars. In this paper, these literatures are summarized, analyzed and discussed, which focus on mainly the two aspects of vibration characteristics and dynamic responses.

1….Vibration characteristics

The dynamic responses of the different structure are different under the same dynamic loads, and the responses are directly related with the natural frequencies of the structure. The natural frequencies and mode shapes must be calculated in order to forecast the dynamic properties of the structure. Therefore, the analysis of the natural frequencies and mode shapes is a major content of the dynamic analysis of the marine riser. Serious side wear of the riser may be caused by the resonance of drill string, when the lateral vibration natural frequency of the riser closes to the rotary speed of the drill string in the process of marine drilling. When the lateral natural frequency of the riser closes to the release frequency of turbulence induced by the current, the vortex vibration will occur, that is to say, the riser is a "lock", in which the fatigue life of the marine riser is reduced significantly. Therefore, the accurate calculation of the riser lateral vibration natural frequencies is of great significance for selecting drilling parameters reasonably, avoiding no normally damaged, forecasting vortex-induced response and fatigue life.

In the literature [1], the mathematical basis and numerical data for determining natural frequencies are given for marine drilling risers operating in water depths up to 600 ft. An approximate mathematical solution is also given and. is compared with the exact mathematical solution based on this analysis. The approximate formulation gives good engineering results and is somewhat easier to use. Riser frequencies are affected by several parameters，however, not all are easily varied on location. Tensioning and drilling-mud density can be varied on location, and both significantly affect natural frequency. Riser tensioning increases natural frequency and is analogous to the tuning of stringed musical instruments. Like the windings on bass-fiddle strings, drilling mud adds mass but not stiffness and, thus, reduces natural frequency. Mode shapes are non-trigonometric. As a result, bending is greatest nearer the lower end, where tension is the smallest. Points of inflection are possible near the top where the tension is greatest. These points are dynamically equivalent to ball joints.

In the literature [2], the vibration analysis of marine risers is investigated by combining the dynamic stiffness method with the WKB theory, which assumes that the coefficients in the differential equation of motion are slowly varying. The WKB-based dynamic stiffness matrix is first derived and the frequency-dependent shape function is expressed implicitly. Next the natural frequencies are found by equating to zero the determinant of the global dynamic stiffness matrix, which is obtained by following the procedure of the conventional finite element method. Finally, two examples of non-uniform risers are analyzed, and the results are compared to show the efficiency of this method.

In the literature [3], an investigation emphasizing on nonlinear free vibrations of marine risers/pipes to determine the nonlinear natural frequencies and their corresponding mode shapes is presented in this paper. Based on the virtual work-energy functional of marine risers/pipes, the structural model developed consists of the strain energy due to axial deformation, strain energy due to bending, virtual works due to effective tension and external forces, and also the kinetic energy due to both the riser and the internal fluid motions. Nonlinear equations of motion coupled in axial and transverse displacements are derived through the Hamilton’s principle. To analyze the nonlinear free vibration behaviors, the system formulation has been reformed to the eigenvalue problem. The nonlinear fundamental frequencies and the corresponding numerically exact mode shapes are determined by the modified direct iteration technique incorporating with the inverse iteration. The significant influences of the marine riser’s parameters studied on its nonlinear phenomena are then illustrated here first. Those parameters demonstrate the nonlinear effects due to the flexural rigidity, top tensions, internal flow velocities, and static offsets.

In the literature [4], considering the 3D loads, the dynamics characteristics of the drilling riser in deep water are calculated with the 3D dynamics model and using finite element method. It is shown that the influence of the top tension on the natural frequency of the riser is obvious, the natural frequencies of the riser increases as the top tension increases, the higher order frequency of the riser in conventional working condition is close to the common frequency of sea waves, for which more attention should be paid while designing and operating. The natural frequencies of the riser can be changed in a certain range by adjusting the top tension of the riser to prevent the resonance between the riser and sea waves.

In the literature [5], assuming the riser is a small deformation beam subjected on uniform top tension, the simplified formula for calculating the natural frequencies of the riser is derived on basis of the energy conservation principle. By analyzing an example, it is shown that the results calculated with the simplified formula proposed in this paper are agreement with those in relevant literatures; the simplified formula can meet the needs of actual engineering. So, the simplified formula could be recommended as the formula calculating the natural frequency of the marine riser. The simplified formula can not be used in deep water, because the riser is large deformation caused by the loads of the marine environment and the initial offset of the drilling ship. Since the simplified formula is based on the idealized model of riser and elastic strain theory that is the small deformation of the riser is assumed and the tension is uniform, the simplified formula presented in this paper is only fit for a certain range water depth. It is verified that the simplified formula is of high precision under the conditions of the water depth less than 600 m. In addition, this article also discussed the effect of throttle and well killing pipelines outside the riser on the natural frequency of the riser, which can’t be ignored, otherwise, the values calculated of the natural frequency are larger. The top tension is the most sensitive and most important parameters among the parameters influencing the natural frequency of the riser. Therefore, the natural frequency of riser can easily changed by regulating the riser top tension which is one of the effective measures to prevent and suppress riser vortex vibration in practice.

In the literature [6], the software Shear 7 is adopted to analyze the vortex induced vibration (VIV) performances of the risers with no buoyancy module, staggered buoyancy modules and fully arranged modules respectively, and also the natural frequency of riser is analyzed quantitatively. It is shown that the natural frequency decreases with the increase of the buoyancy modules, the natural frequency of the riser with fully arranged modules can be reduced to 45 percent compared with that without buoyancy module.

In the literature [7], the bending deformation equation of the riser expressed by triangular series equation is established based on energy method. The natural frequency of the riser system is calculated by Rayleigh method. The self-vibration performance and character are analyzed for risers with different size and in different water depth through engineering cases. The lateral vibration frequency of the rise coincides with the rotary speed of drill string in a large frequency range for the offshore exploration at present; thus, the resonance may be caused in the drilling process, which will lead to excessive wear for risers. Therefore, more attention to choose the reasonable rotary speed of drill string must be paid so as to avoid resonance zone.

In the literature [8], considering the internal flowing fluid and the external environmental loads, the lateral vibration differential equation of a marine riser is derived. Discretization is made with Hermite interpolation function and the program of computing the dynamics properties of a marine riser has been written.

The effects of internal flow velocity and the top tension of the riser on dynamics characteristics are discussed. It is indicated that the natural frequency of the riser is decreased with the increase of the internal flow velocity, while the increase of the top tension can counteract this effect.

In the literature [9], the effect of the damping term is taken into account in the analysis of dynamic characteristics in this paper. The differential equation for the response of the vortex induced vibration (VIV) of the riser considering the effect of the internal flowing fluid and the external marine environmental condition is derived. Then the dynamic equation is solved by the complex mode method to obtain the natural frequencies of the risers with damping, and the MATLAB calculating program is written. It is given by the results that: (1) The natural frequencies of the riser with the damping are slightly smaller than those without it. The effect of damping on the dynamic characteristics is relatively small compared with the length of the riser and the internal flow velocity. (2) With the increase of the internal flow velocity, the first order natural frequency of the riser gradually decreases, when it decrease and close to the vortex shedding frequency, the "lock" phenomenon is prone to cause, which will lead to the fatigue damage. Fortunately, the internal flow velocity is small ($V_c < 10\,\mathrm{m/s}$) in general marine engineering, thus, the effect of the internal flow velocity on the natural frequencies of riser is small. (3) The length of the riser imposes great impact on the natural frequency of the riser; the natural frequency drastically reduces along with the increase of the length of the riser.

Based on the above analysis, the main factors affecting the lateral vibration natural frequency of the rise are listed as following:

(1) The top of tension of the riser: The top tension affects significantly the natural frequency of the riser. The natural frequency of the riser increases with the increase of the top of tension. The natural frequency of the marine riser system can be changed in a certain range by adjusting the top tension, so as to prevent the resonance between the marine riser and sea waves. It is worth noting that the high-frequency of the conventional riser is close to the common frequency of wave.

(2) Drilling mud density: with the increase of the drilling mud density, the quality of the riser system will increase, and the stiffness is same, so that the natural frequency of the riser systems will decrease.

(3) The internal flow velocity of the riser: With the increase of the internal flow velocity, the first order natural frequency of riser gradually decreases. When the natural frequency decrease and close to the vortex shedding frequency, the "lock" phenomenon is prone to cause, which will lead to the fatigue damage. Fortunately, the velocity of internal flow in the riser is small ($V_c < 10\,\mathrm{m/s}$) in general marine engineering, thus, the effect of the internal flow velocity on the natural frequencies of riser is small.

(4) The internal liquid damping of the riser: the natural frequencies of the riser with the damping are slightly smaller than those without it. The effect of damping on the dynamic characteristics is relatively small compared with the length of the riser and the internal flow velocity.

(5) The length of the riser: The length of the riser imposes great impact on the natural frequency of the riser. The natural frequency drastically reduces along with the increase of the length of the riser.

(6) The buoyancy modules: the natural frequency decreases with the increase of the buoyancy modules, the natural frequency of the riser with fully arranged modules can be reduced to 45 percent compared with that without buoyancy module.

(7) Throttle and well killing pipelines outside the riser: the effect of throttle and well killing pipelines outside the riser on the natural frequency of riser can't be ignored. Otherwise, the values calculated of the natural frequency are larger.

2 Dynamic responses

Earlier scholars put forward the dynamic models in analytical solution to study the force and strength of the marine riser, assuming that the speed of the water particles is the steady-state sine wave. Lateral displacement of the same cycle was obtained using steady-state solution and the dynamics response model was gained through the change of the Harmonic Functions. However, this method is impractical due to the simplifying the model and the complexity of solving the equations. At present, the numerical solution is mostly adopted for dynamics analysis of the riser. One way is to establish the fourth-order non-linear partial differential equations of the riser, and then to solve the dynamics equations using the method of the numerical integration or numerical difference. Another way is to use the finite element method. The methods of riser dynamic response analysis include three types: the rule wave analysis in time-domain (certainty analysis in time-domain), the irregular wave analysis in time-domain (random vibration analysis in time-domain) and frequency domain analysis. Now, the time-domain analysis is mostly adopted for the riser vibration response analysis.

The analysis model described in the literature [10] was formulated to analyze, both statically and dynamically, the types of marine risers presently used in floating drilling operations. This model described here provides a practical means of evaluating riser deflections and stresses resulting from static horizontal offsets of the drilling vessel, current forces, dynamic vessel motions, and wave forces. The hydrodynamic damping in the analysis model is a critical factor in limiting the riser dynamic deflections and stresses. The analysis method employs a numerical integration scheme that differs from the series solution method and the finite difference methods. The numerical integration method is particularly suited for an accurate representation of parameters that vary along the length of the riser and for efficient implementation on a digital computer. The dynamic response of the riser is a significant factor in design for all water depths, as least beyond 400 ft. The horizontal motion of the drilling vessel in waves is a major factor in determining the magnitude of riser deflections and stresses; consequently the motion characteristic of the drilling vessel in waves may be a significant factor in determining riser design. The most significant factor in extending riser design into deeper water is the increased tension required to support the riser. The tensioning requirements may exceed the practical axial load-carrying capacity of the riser as water depth approaches 2,000 ft. The addition of buoyancy to the riser appears to be a practical means of limiting the required tension to acceptable levels.

In the literature [11], an analytical method is presented to determine the effect of vortex shedding on marine risers. Formulas are given to compute riser response. An illustrative example is worked out to show that vortex shedding may cause high cyclic stresses and that the problem can be avoided by suitably adjusting the riser tension.

The literature [12] describes a method of analysis which can allow for all the effects of wind, wave, current, varying top tension, drilling vessel motion and so on as well as many kinds of "boundary conditions":-initial offset, ball joint stiffness, etc. Unlike a number of other published methods, this one takes full account of the non-linear nature of the governing equation, turning it into an equivalent set of non-linear first order ordinary differential equations which are solved numerical.

In the literature [13], the effect of a weak structural nonlinearity on the dynamical behaviors of a vertical offshore riser subjected to vortex-induced vibration is investigated. Coupling of the riser dynamics with the flow of the surrounding fluid is achieved by attaching a wake oscillator to a reduced model of the structure, which is obtained through the application of the invariant manifold technique for the derivation of nonlinear normal modes. By comparing the free responses of the linear and the nonlinear structure, it was found that the structural nonlinearity has a stiffening effect on the oscillation of the riser, which becomes more pronounced when the internal flow is incorporated into the model. Consequently, in the coupled system, the response is considerably modified for the structure as well as for the fluid variable.

In the literature [14], the differential equation for the vibration of the riser system is derived by means of functional calculus of variation. The general formula for the dynamic response can be obtained by substituting the general formula into the functional and evaluating the extreme value.

In the literature [15-16], by using the random vibration theory, the random process and random model of wave force are analyzed. Wave force is a stationary random process and its mean is zero. Transverse displacement of riser system in marine drilling is also a stationary random process and its mean is zero. The transverse random vibration of riser system is investigated by means of mode analysis and the general formulas for its correlation function and mean square response are derived. The computing program is performed; the effect of wind speed on the transverse mean square response of riser system is investigated. The numerical example shows that when wind speed is less than 10m/s, the root of mean square of the displacement is very small, may be neglect; when wind speed is more than 20m/s, the root of mean square of the displacement is approximate linearity with wind speed.

In the literature [17], considering the gap-contact condition between guide-frames and the fixed drilling unit riser subjected to wave current loads, the solution method for transient dynamic problem under the nonlinear boundary condition was discussed. By applying the finite element method, the marine riser was modeled as the beam model which was fixed under the seabed mudline at the depth of three meters, simply supported at the lower deck, and its lateral vibration was restricted by guide-frames at different elevation. Using ANSYS software, the gap-contact condition between marine riser and guide-frames was simulated by combination-40 element. The non-linear dynamic response of marine riser under one hundred-year wave-current environmental load was calculated, the displacement-time history of typical nodes and equivalent stress-time history of typical elements were also obtained, and the largest deformation and equivalent stress in the process of vibration of were then achieved successfully.

In the literature [6], the software Shear 7 is adopted to analyze the vortex induced vibration (VIV) performances of the risers with no buoyancy module, staggered buoyancy modules and fully arranged buoyancy modules respectively, and also analyze quantitatively the root mean square(RMS)displacement response of riser with buoyancy modules arranged differently. The RMS displacement increases with adding the number of buoyancy modules. The maximum RMS displacement under the fully arranged buoyancy modules is 2.66 times as large as the riser with no buoyancy module.

In the literature [18], the time-domain random vibration problem of the deep-water drilling riser has been studied considering the non-linearity of geometry and the related dynamic response model was established. The dynamic response of deep water drilling riser are analyzed and discussed through an example based on ABAQUS software, considering three main different boundary conditions: the platform is in the average offset, in different average off sets and under effect of first order wave force, and in different average offset during long term slow drift and under effect of first-order and second-order wave forces. The numerical example shows: (1) Under the first boundary conditions, the largest bending stress of the riser occurs between ~ 4 m under the sea level, where is dangerous point of riser fatigue. The change scope of the angle of the ball hinge installed at the bottom riser is small in the dynamic process under the invariable average offset condition of drilling platform, however, the mean value of the angle of the ball hinge is greatly affected by the average offset of drilling platform, and this value increases along with the increase of the average offset of drilling platform. Therefore, for the flexible joints angle be only needed in static analysis. (2) Under the second boundary conditions, the vibration characteristic is more complicated compared with the first boundary conditions. That is, the most bending stress is increase, the alternating amplitude of bending stress is increase, and at the same time, the vibration frequency speed up significantly. However, the amplitude and mean of the angle of the ball hinge changes little. (3) Under the third boundary conditions, that is, consider the effect of the drilling platform long-term slow drift compared with the second boundary condition, the angle of the ball hinge is seriously affected in this boundary condition. The angle changes in a certain cycle which is close to the cycle of the drilling platform long-term slow drift, and its amplitude increases with the increase of the offset of the drilling platform.

The literature [19] presents an investigation into the dynamic response of a marine riser subjected to wave and ocean current in 3-D space. The governing equation of a marine riser is given, where interaction between the marine riser and fluids with vortex induced vibration is evaluated on the basis of Matteoluca's wake oscillator model, an improvement of the Matteoluca model. Then the governing equation is discretized by using the Hermite interpolation function and the dynamic responses obtained through the Newmark method. The envelopes of displacement s in terms of various external conditions as well as the curves of transverse vortex induced vibration were then plotted. The following results are given through an example. When the wave propagation direction is in contrast to the direction of ocean current, the displacement of the riser is the largest and the direction is the most dangerous for the riser. (2) The motion of floats affects greatly the dynamic response of a riser, so that the horizontal and lifting movement must be taken when selecting boundary conditions. (3) The dynamic response of the riser is different when the damping is different. Therefore, it's unreliable to assume the damping is constant under the different outside boundary conditions. The damping factor should be correctly selected based on the coefficient of the actual lift force and the amplitude of the lateral vibration. (4) The current affects greatly the lateral dynamic response of the riser. This problem must be considered seriously.

In the literature [20], based on Biolley's wake oscillator model, the differential equation for the response of the vortex-induced vibrations (VIV) of the riser is derived and discreted with Hermit interpolation function. The effect of the internal flowing fluid and the external marine environmental condition are taken into account. The fatigue life of the marine riser is analyzed by Miner's theory. The effect of the internal flow velocity on the response of VIV and the fatigue life of the riser is analyzed. The example results show that the internal flow velocity affects greatly amplitude of the vortex-induced vibrations. When the riser nature frequency higher little than the vortex shedding frequency, the increase of the internal flow velocity will cause locked vibrations in more element of the riser, so that the response amplitude will increase. Otherwise, when the riser nature frequency is smaller than the vortex shedding frequency, the increase of the internal flow velocity will cause locked vibrations in little element of the riser, the response amplitude will reduce until the whole riser deviate the region of locked vibration, so that, the effect of the internal flow velocity should be considered in the design of risers. The influence of the internal flow on the vortex-induced vibrations of the riser can be reduced, by increasing appropriately the top tension of the riser.

In the literature [21], an iteration method between CFD analysis and structure finite element analysis is proposed. In the iteration, the fluid field and the riser response are calculated in turns. The hydrodynamic loads directly leading to vibration in the current, with the periodical lift force and drag force, are transferred from fluid field to riser. The riser movement will be defined as a function, which is used to describe the riser wall boundary of fluid control volume in the following iteration step. During analysis, CFD software FLUENT is used to analyze t he fluid field and FE software ANSYS is used to analyze the riser dynamic response. The example results indicate that at a certain current speed, the amplitude of the lifting force is about more one grade than that the resistance, and the cycle of the lateral vibration caused by the lifting force is 2 times as large as the cycle of the vertical vibration induced by resistance following the flow direction. When considering the Interaction of the riser vibration and the current movement, that is, considering the Solid-fluid interaction, the cycles of lift force and resistance force become small and the amplitude become large. Thus it can be seen that the release speed of the vortex is aggravated and structure destroy is accelerated.

3 Conclusion and preview

The vibration of marine platform riser is a hot-topic for the vast number of marine engineering workers. Although some achievements have been obtained, several major problems are to be improved.

(1) The forces imposed on the riser are complicated. the presented literatures all focus on certain loads, but, the influence of all forces together on the riser should be considered comprehensive and systematically.

(2) Different simplified model were adopted for boundary conditions of the riser, most literatures adopt the riser model as a simply supported beam hinged at both ends of the riser. Although, a few considered the horizontal offset of drilling platform, all are dealt with as static displacement. Actually, the horizontal offset of the platform is a random variable of time.

(3) The difference between the model of wave force and the reality wave is larger. Most literatures regarded the wave force as a certainty force model. Although, a few regarded the wave force as random model, some simplified were made in the calculation process. In fact, more attention should be paid to the effect of the ocean wind on the vibration, fatigue life and strength of risers.

(4) The existing literatures did not discuss the effect of ocean earthquake on riser mechanical. Actually, a riser is easily to be damaged when the earthquake occur in the marine, which should be paid more attention.

(5) The existing literatures failed to discuss the problem of collision between the drill string and the riser. In fact, it is an important subject worth considering.

(6) Because of different assumptions of the riser mechanical model, there is a large difference between the present results of research on marine risers. Therefore, it is difficult to provide effective assistance for riser design and use. A variety of models of a riser and analysis methods should be further carried out to compared and analyzed, so that the results are more in line with the actual engineering.

(7) Only as soon as possible to carry out real-time monitoring on-site for dynamic response of marine platform riser, the basis for improving and revising a variety of models and algorithm is supplied.

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