Journal of Applied Mechanics Vol.10, pp.1099-1108 (August 2007) JSCE

CFD Modeling of Fluid-Structure Interaction for Oscillating Flexible Risers

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The dynamic response of an oscillating flexible riser involves a coupled phenomenon in which the nature and magnitude of the fluid forces acting on the riser highly depend on the structural riser's response. Therefore, the development of a response prediction model for oscillating flexible risers must consider the numerical modeling of fluid-structure interaction. In this paper a response prediction model for oscillating flexible risers using CFD-derived force coefficients is presented. A 20-meter riser model, sinusoidally excited at its top end using six different values of tension forces, is employed for its experimental validation. The computed maximum amplitudes in both in-line and cross-flow directions show good agreement with the experimental data considering the range of error commonly accepted for such implementations.

Key Words: *flexible riser, vortex-induced vibration, computational fluid dynamics, beta parameter.*

1. Introduction

Deep-sea oil industry is currently demanding a riser technology capable of providing profitable oil extraction at water depths of more than 3000m. In addition, there is an ongoing interest in the use of riser systems for carbon dioxide injection in deep sea. Therefore, the research community is actively working on developing riser's response prediction models in order to comply with the aforementioned demands. However, the self regulated nature of the Vortex-Induced Vibration (VIV) process, caused by vortices shed from a riser, is highly nonlinear and therefore its accurate prediction is still not possible. Existing riser models mainly rely on large databases of experimentally derived hydrodynamic force coefficients obtained under different modeling considerations. As a result, the quality of a semi-empirical model strongly depends on the force coefficients provided by the aforementioned databases. The main limitation of this approach is associated with the high cost of the experimental facilities needed to obtain these force coefficients.

Due to the increase of the computer-simulation capabilities for CFD applications, there is an increasing interest in the development of CFD-based approaches for response prediction of risers. A riser is idealized as composed of several two-dimensional planes coupled with a Navier-Stokes solver. The calculation of the hydrodynamic forces is carried out using this solver and its results are then input to the corresponding section of the riser. It is clear that as the number of the sections, in which the riser is divided, is increased; the approach becomes extremely computationally demanding and therefore prohibited for practical implementations. Most of the existing implementations of Navier-Stokes solvers for response prediction of flexible risers have been developed for the case in which the riser is excited by steady current. However, a marine riser is also affected by oscillatory flow due to waves and oscillating forces at its top connection. Moreover, an oscillating riser exhibits a more complex response because the shedding frequency can be locked to a natural frequency of the riser several times in contrast to a riser under the action of steady current.

The quasi-steady assumption states that the dynamic response of an oscillating flexible riser can be approximated by using hydrodynamic force coefficients derived from experiments performed in fixed cylinders. Therefore, it is commonly accepted the use of force coefficients experimentally derived from oscillatory flow acting on a fixed cylinder to obtain the dynamic response of oscillating flexible risers. Nevertheless, the quasi-steady assumption neglects fluid-structure interaction and therefore introduces a source of error in the calculation of the hydrodynamic force coefficients. At low amplitudes, one may expect that the calculated force coefficients using oscillatory flow do not significantly deviate from the ones obtained from an oscillating cylinder. The main drawback in this assumption is that a clear definition of the limiting value at which the quasi-steady assumption is not valid anymore has not yet been provided by the research community.

In this paper, a response prediction model for oscillating flexible risers is presented. Increased mean drag coefficients during synchronization of the shedding and oscillating frequencies are also included. Lift coefficients are computed from an empirical formulation and the in-line force coefficients are obtained from a CFD-based approach. Therefore, a newly developed CFD-based model is also provided in this paper. Oscillatory flow acting on a fixed cylinder is simulated and its results are compared with the ones obtained from an oscillating cylinder using the same hydrodynamic considerations. Therefore, the main objective of this paper is to provide a practical model for dynamic response of oscillating flexible risers considering existing limitations related to the computer resources needed for the use of CFD-based approaches for practical applications.

2. Response Prediction Model

The Euler-Bernoulli beam equation is used herein to model a riser idealized as a beam with low flexural stiffness following the procedure proposed by Huera-Huarte[1] as shown in Eq. (1). A Cartesian reference is defined in the *x*-axis by the direction of the flow velocity in the case of a stationary body or the in-line motion in the case of an oscillating body, the *z*-axis is defined in the direction of the riser's axis and the *y*-axis is perpendicular to both.

$$EI\frac{\partial^4 u_{x,y}(z,t)}{\partial z^4}-\frac{\partial}{\partial z}\left[\left(T_t-w\left(L-z\right)\right)\frac{\partial u_{x,y}(z,t)}{\partial z}\right]+ c_0\frac{\partial u_{x,y}(z,t)}{\partial t}+m_0\frac{\partial^2 u_{x,y}(z,t)}{\partial t^2}=F_{T_{x,y}}(z,t) \tag{1}$$

where m_0 is the mass of the riser per unit length, $u_{x,y}(z,t)$ is the deflection, c_0 is the damping characteristic, *EI* is the flexural stiffness, T_t is the tension applied at the top of the riser, L is the length of the riser and *w* is the submerged weight. The external fluid force is $F_{T_{x,y}}$. The analytical representation of in-line forces acting on a riser presented by Carberry *et al.*[2] is used herein to model the external fluid force acting in the *x*-axis as shown in Eq. (2)

$$F_{T_x}(z,t)=\rho SC_m\dot{U}_1-\rho SC_i\ddot{u}_x +\frac{1}{2}\rho D(U_1-\dot{u}_x)\left|U_1-\dot{u}_x\right| \left[C_{Dmean}+C_D sin\left(2\left(2\pi tf_L+\phi_{drag}\right)\right)\right] \tag{2}$$

The density of the surrounding fluid is denoted by *ρ*, the cross-sectional area of the displaced fluid by *S*, the steady velocity of the fluid in the in-line direction acting on the surface of the structure is defined by U_1, and *D* is the diameter of the riser. The mean drag coefficient is denoted by C_{Dmean}, the fluctuating drag coefficient by C_D, the inertia coefficient by C_m and the added-mass coefficient is defined by C_i. f_L is the dominant frequency defined as the most dominant frequency in the *y*-axis or cross-flow direction based on the fact that transverse response in flexible risers is a multi-frequency phenomena. ϕ_{drag} is the phase of the drag with respect to the cylinder's displacement in the cross-flow direction. It is widely recognized that the dominant frequency of the drag force is two times the dominant frequency in the cross-flow direction ($2f_L$). Therefore, ϕ_{drag} is used to relate the phase of the drag to the displacement of the riser in the cross-flow direction and it is experimentally derived from drag traces whose correlation coefficient with a sinusoidal signal is greater than 0.6 as proposed by Carberry *et al.*[2]. The dominant frequency is related to the cross-flow motion and is presented in Eq. (3).

$$F_{T_y}(z,t)=\frac{1}{2}\rho DU_0{}^2C_L sin\left(2\pi tf_L+\phi_{lift}\right) \tag{3}$$

U_0 is the relative in-line maximum velocity. C_L is the lift coefficient and ϕ_{lift} is the phase with respect to the cross-flow displacement. f_L mainly depends on the Keulegan-Carpenter number (KC) and the Strouhal number S_t. C_L varies with the amplitude of the cross-flow motion (A_y) according to the empirical formulation presented by Blevins[3], which is shown in Eq. (4).

$$C_L = 0.35 + 0.6\left(\frac{A_y}{D}\right) - 0.93\left(\frac{A_y}{D}\right)^2 \qquad (4)$$

Finally, the increased mean drag coefficient (C_{Dinc}) model, used in the proposed response prediction model, was empirically validated by Khalak and Williamson[4)] as shown in Eq. (5).

$$\frac{C_{Dinc}}{C_{Dmean}} = 1.0 + 2.0\left(\frac{A_y}{D}\right) \qquad (5)$$

Khalak and Williamson[4)] using experimental data proved the existence of three modes of response defined by them as initial, upper and lower branches. The three branches identified by Khalak and Williamson[4)] are associated to a mass ratio (calculated as the mass of the riser divided by the mass of the fluid displaced) value lower than 3.3 and low damping. For a high mass ratio, larger than 10, there exist only two branches, namely the initial and lower. Therefore, the mass-damping parameter plays a crucial role in the type of response achieved by a flexible riser and is strongly related to the peak amplitude in the cross-flow direction. Khalak and Williamson[4)] collected experimental and simulation data in order to establish a confident range for the maximum displacement in the cross-flow direction. Some differences were found when the flow acting on a cylinder corresponds to low Reynolds numbers (Re). A peak value of 0.6D was found by Khalak and Williamson[4)] for low Reynolds numbers and a peak value of 1.2D for high Reynolds numbers. A more recent study presented by Willden and Graham[5)] at Reynolds numbers between 50 and 400 stated that for the low-Re region, the peak amplitude in the cross-flow direction is independent of the mass-ratio parameter showing a peak value of 0.5D.

The experimental riser model presented in this paper has a mass-ratio value of 1.7 and it is excited at low Reynolds numbers. Therefore, the predicted response of the experimental model corresponds to the low mass-damping case and therefore cross-flow amplitudes are not expected to be larger than 0.6D. Khalak and Williamson[4)] also highlighted the importance of appropriately define the oscillation frequency and based on their experimental study found that the "classical" definition of synchronization as the match of the oscillating frequency to a natural frequency of an oscillating body is not completely correct for the low mass-damping case. They concluded that a more appropriate definition of lock-in can be stated as the matching of the frequency of the periodic wake vortex mode with the body oscillation frequency.

3. Experimental Model

The forced oscillation experiments are carried out in the deep-sea basin of the Integrated Laboratory for Marine Environmental Protection located in the National Maritime Research Institute (NMRI). This deep-sea basin is depicted in **Fig.1** and consists of a circular basin (depth: 5m, effective diameter: 14m) and a deep pit (depth: 30m, effective diameter: 6m). The underwater 3-dimensional measurement equipment is composed of 20 high-resolution digital cameras (2 units/set x 10 sets).

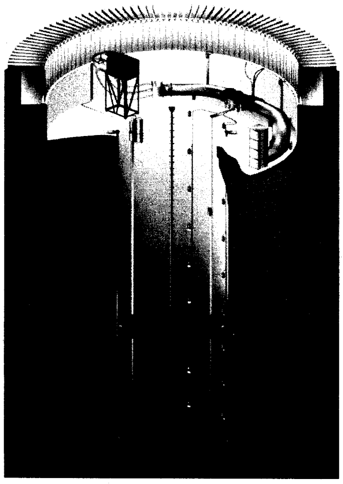

Fig.1 Deep-Sea Basin (NMRI).

The response prediction model presented in this paper is experimentally validated using a 20-meter model sinusoidally excited at its top end along the x-axis with amplitude of 0.01m and period of 2 seconds. Its coordinate system is therefore defined in the x-axis by the in-line motion, the y-axis corresponds to the transverse motion and the z-axis is defined in the direction of the riser's axis. The model is excited in still water and steel bars are added to the riser model in order to increase its self-weight. The total weight of the riser, including the steel bars, is 68.14N. Pinned connections are used at its both ends and the tension forces, applied at its top end, range from 4.31Kgf to 6.47Kgf. The properties of the experimental model are presented in Table 1.

Table 1 Properties of the Riser Model.

Material	Polyoxymethylene
Model length (m)	20
Outer diameter D (m)	0.0160
Inner diameter (m)	0.0108
Density (kg/m^3)	1410
Young's modulus (MPa)	2.937

3.1 Numerical Implementation

The Finite Element Method (FEM) is used herein to numerically solve the differential equation governing the static and dynamic response of a flexible riser presented in Eq. (1). The commercial software ABAQUS6) is selected for this purpose. The riser is therefore idealized as an assembly of 40 cubic pipe elements. Geometric nonlinearity is considered by using a nonlinear time-domain method during the application of the riser's self-weight. The dynamic response of the riser is then computed employing the direct-integration method. An in-house FORTRAN subroutine (developed by the authors) computes displacements, velocities and accelerations at each time step in order to generate the data needed for the numerical implementation of the amplitude-dependent lift and increased mean drag coefficient models. The developed subroutine compares current and previous results. Therefore, representative peak values can be found at each stage of the simulation.

Blevins3) stated that in-line VIV usually occurs with twice of the shedding frequency in the range $2.7<U_r<3.8$. Where $U_r=U_l/(f_{osc}D)$ and f_{osc} is the oscillating frequency of the body. The occurrence of both in-line and cross-flow synchronization events is carried out by computing the reduced velocity U_r at each time step and if its value is between 2.7 and 3.8, the fluctuating drag force part of Eq. (2) is included in the calculation. On the other hand, if U_r is located in between 4 and 8, the increased mean drag coefficient model is used to compute the magnitude of the drag force. According to Carberry *et al.*1), $\phi_{lift}=0$, $\phi_{drag}=0$ and $C_D=0.2$. A structural damping ratio of 0.3% was incorporated during the numerical implementation using as a reference the value presented by Huera-Huarte *et al.*1).

In the numerical implementation of the proposed model, drag forces are first applied during 25 cycles. Then, at the end of the first stage, in-line amplitudes are computed in order to calculate the KC values for each section of the riser and update drag coefficients. In the second stage, cross-flow forces are applied during 10 additional cycles. Synchronization events are considered in the third stage after updating hydrodynamic force coefficients. In the calculation of f_L, which is a function of KC and S_t, the empirical formulation derived by Norberg7) for Strouhal number calculation is used in the proposed model. Although the riser model is sinusoidally excited at its top end, its dynamic response is transient due to a time-varying load. It takes approximately 4 seconds for the wave to completely excite the bottom end of the riser; then, the steady response is achieved and all sections of the model are sinusoidally excited at different oscillating frequencies, amplitudes and phase angles. As a result, each section of the riser is excited at a particular dominant frequency in the cross-flow direction, which indeed is related to its corresponding in-line amplitude. Therefore, a phase angle must be calculated for the numerical implementation of Eq. (3) only when the steady response is achieved. Otherwise, wrong in-line amplitudes obtained during the transient response may under-estimate the phase angle and lead to out-of-phase response between the in-line and the cross-flow motions of the riser. A numerical procedure is implemented in the proposed prediction model using the top end of the model as a reference. The initial phase angle is then calculated using the time difference between the time required for each section of the model to achieve its maximum cross-flow displacement and the required time at the top end to achieve the same condition.

4. Hydrodynamic In-line Force Coefficients

As previously mentioned, existing semi-empirical models for response prediction of risers highly depend on the experimentally derived values of hydrodynamic force coefficients. Therefore, most of those models rely on large databases of force coefficients. On the other hand, the quasi-steady approach assumes that hydrodynamic force coefficients can be used for oscillating flexible risers. As a result, static fluid forces due to oscillatory flow can be used to predict hydrodynamic forces acting on an oscillating body.

A more straightforward approach is the modeling of the sinusoidal movement of the cylinder in the in-line direction while computing the cross-flow forces due to shed of vortices. The cylinder is therefore allowed to freely move in the cross-flow direction. At low amplitudes it is expected similar simulation results for the cases of oscillatory flow acting on a fixed cylinder and an oscillating cylinder in otherwise calm water. In this paper, a CFD-based model for prediction of in-line hydrodynamic force coefficients is developed using the commercial finite volume CFD code, named FLUENT8). Its validation is carried out using experimental and simulation results from previous studies for fixed cylinders. **Fig.2** depicts the computational domain assembled in GAMBIT9). A blockage ratio (D/B) of 10% is selected in this paper based on the simulation results presented by Anagnostopoulos and Minear10), who performed a parametric study using blockage ratios ranging from 10% to 50% and found that the blockage effect is almost negligible for blockage ratios lower than 20%.

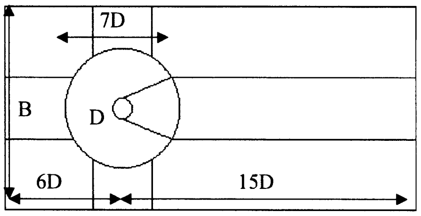

Fig.2 Computational Domain.

The final grid is composed of 17494 nodes. The cylinder is placed in the center of a circular domain composed of triangular cells. The remaining regions of the computational domain are composed of quadrilateral cells. The solution is time-dependent (time step of 0.01 seconds). Therefore, an unsteady solver is used herein allowing the modeling of the oscillatory flow condition. The experimental model presented in this paper is sinusoidally excited at Re numbers up to 600 and KC numbers up to 5, which correspond to a beta parameter (β=Re/KC) of 120.

Based on the Re numbers achieved by the riser, a laminar viscous model is selected. The proposed model is first validated for steady flow at Re=100. Zhou and Graham[11], using a vortex-based method to simulate flow around a circular cylinder, found a mean drag coefficient value of 1.37. They compared this value with 15 experimental and numerical results and found good agreement in their comparisons. The model proposed in this paper is therefore implemented for the same simulation conditions presented by Zhou and Graham[11]. The C_{Dmean} value computed from the proposed model is remarkably similar to the one presented by Zhou and Graham[11] having a value of 1.38.

Oscillatory flow with amplitudes ranging from 0.0025m to 0.0125m and period of 2 seconds is simulated using a user defined function (UDF) developed by the authors. C_{Dmean} and C_m are then calculated through least squares fit of the force time series. Obasaju *et al.*[12] experimentally found that there is a range of β in which C_{Dmean} is not sensitive to changing β. It was identified that the upper boundary of the range lies between β=964 and 1204. Therefore, the simulation results obtained from the proposed model are compared with the ones found by Anagnostopoulos and Minear[10] at β=50, Obasaju *et al.*[12] at β=196, Lin *et al.*[13] at β=70 and Bearman *et al.*[14] at β=200 as shown in **Figs.3 and 4.** Finally, the proposed CFD-based model is numerically implemented for the oscillating body case. The moving/deforming mesh capability provided by FLUENT[8] is used herein to sinusoidally move the cylinder in the in-line direction while applying pressure forces in the cross-flow direction based on the explicit Euler formulation presented in Eq. (6). The main idea of this procedure is to use the computed velocities at which the cylinder is excited in both in-line and cross-flow directions and then allows the cylinder to move in accordance with these velocities. In order to improve the simulation results, a time step ($\triangle t$) of 0.001 seconds is selected for the numerical implementation of Eq. (6).

$$v_t = v_{t-\Delta t} + (F/m_0)\Delta t \tag{6}$$

where v_t is the velocity of the cylinder in the cross-flow direction and F is the pressure force in the same direction at a given value of time t. The cylinder is then allowed to sinusoidally move in the in-line direction with amplitudes ranging from 0.0025m to 0.0125m and period of 2 seconds. In the cross-flow direction, the computed pressure forces are used to move the cylinder based on the cross-flow velocity computed from Eq. (6). The aforementioned procedure is repeated at each time step. The simulation results for the oscillating body case are also presented in **Figs.3 and 4.** The oscillatory flow and oscillating body results are related to a fixed cylinder excited by oscillatory flow and an oscillating body in otherwise calm water, respectively.

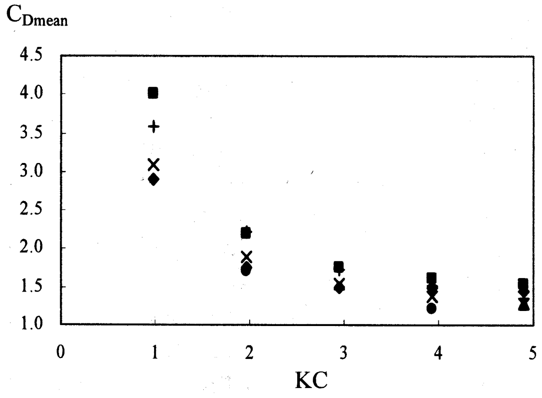

Fig.3 C_{Dmean}:▪Anagnostopoulos and Minear[10]; ◆Lin *et al.*[13]; ▲Obasaju *et al.*[12]; •Bearman *et al.*[14]; Present Results (×Oscillatory Flow; +Oscillating Body).

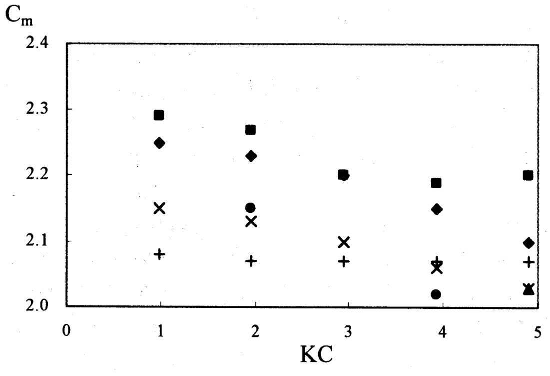

Fig.4 C_m:▪Anagnostopoulos and Minear[10]; ◆Lin *et al.*[13]; ▲Obasaju *et al.*[12]; •Bearman *et al.*[14]; Present Results (×Oscillatory Flow; +Oscillating Body).

It can be seen from **Fig.3** that the values of the C_{Dmean} computed from the oscillatory flow and oscillating body cases are in good agreement with the experimental and simulation data provided by previous studies. The simulation results presented in this paper also support the statement given by Obasaju *et.al.*[12)] as previously mentioned. The simulation results presented in **Fig.4** show that it is important to consider the value of β in the calculation of C_m. It is also important to highlight that for the oscillating body case C_i is obtained through least squares fit of the force time series and it is assumed that C_m=C_i+1.0. Finally, it is observed that there is no significant variation of C_m for the KC numbers presented in this paper. The computed values of C_m show lower values than the ones obtained from the oscillatory flow case showing the importance of fluid-structure interaction, which is expected to be significant at large amplitudes.

5. Simulation Results

Six different values of tension forces applied at the top end of the riser are used to carry out the experimental validation of the proposed response prediction model. **Fig.5** shows the maximum displacements in the in-line direction and **Fig.7** in the transverse direction. **Figs.6 and 8** show the simulation results for the same conditions used in the experimental model. Maximum displacements are computed when the riser has achieved its steady response. As previously mentioned, Khalak and Williamson[4)] stated that a cylinder with a low mass-damping parameter exited at low Reynolds numbers has a limiting displacement value in the cross-flow direction of 0.6D. Willden and Graham[5)] found a limiting value for maximum cross-flow displacements of 0.5D when the riser is excited at Reynolds numbers between 50 and 400. The simulation results obtained from the proposed prediction model show a maximum cross-flow displacement of 0.4D, which agrees well with the aforementioned findings.

Chaplin *et al.*[15)] compared experimental data obtained from a riser model in stepped flow with blind predictions using nine different numerical models. The models used by Chaplin *et al.*[15)] correspond to the state of art in dynamic response prediction of risers. The experimental model developed by Chaplin *et al.*[15)] is pinned at its bottom end and has a length of 13.12m, a diameter of 0.028m and a mass ratio of 3.0. The stepped current effect was achieved by mounting the riser model on a towing carriage with the upper 55% of the model in still water condition while the lower 45% was exposed to current[15)].

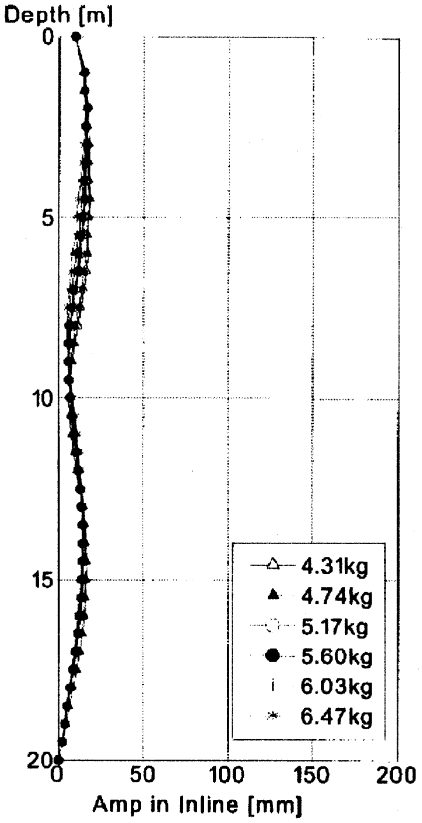

Fig.5 Maximum in-line Displacements (Experiment).

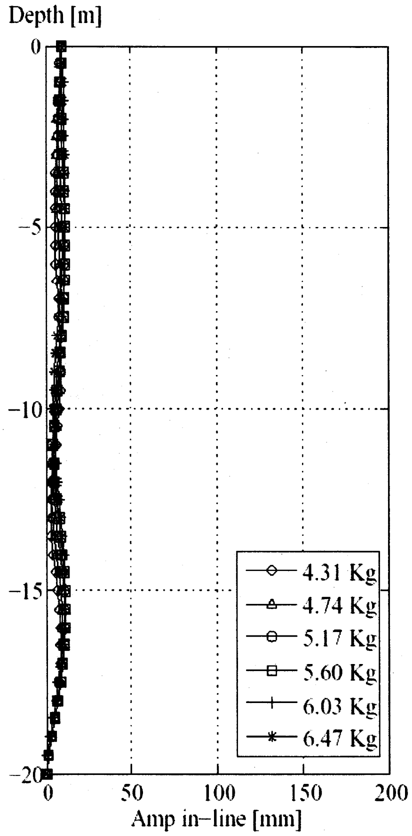

Fig.6 Maximum in-line Displacements (Simulation).

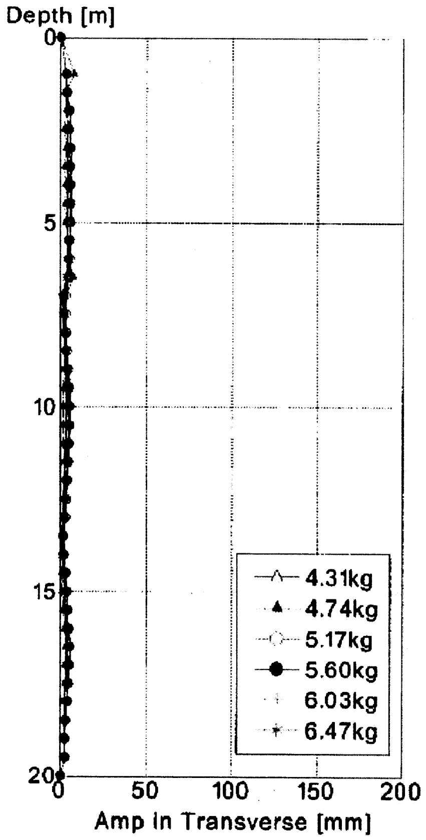

Fig.7 Maximum Transverse Displacements (Experiment).

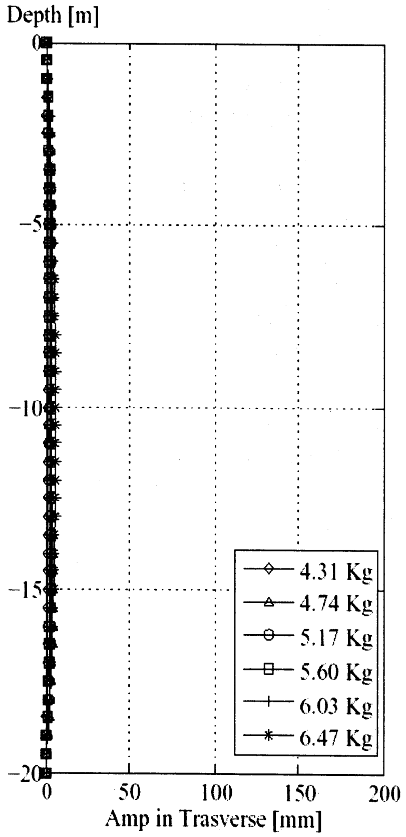

Fig.8 Maximum Transverse Displacements (Simulation).

Although, the experimental model presented in this paper is excited at Reynolds numbers up to 600, Chaplin *et al.*[15] proved in their comparative study that the prediction of the maximum response of a flexible riser under synchronization events is complex due to the unpredictable nature of the riser response. The Reynolds numbers achieved by experimental model developed by Chaplin *et al.*[15] ranged from 4480 to 26600. It was found that the in-line and cross-flow displacements were under predicted by 20% to 40% and by 10% to 30%, respectively. The simulation results presented in this paper are located within the aforementioned ranges and the proposed prediction model also under predicted in-line and cross-flow displacements. The maximum differences found for the in-line and cross-flow displacements were 25% and 18%, respectively. It is important to highlight that Chaplin *et al.*[15] used in their study the most widely recognized models for response prediction of risers.

Finally, the experimental model having a tension force at its top end of 6.47 Kgf is selected in order to compare its time series response during 20 seconds with the one obtained from the proposed prediction model as shown in **Figs.9, 10 and 11.** In-line and transverse responses were computed at depths of 5m, 7m, 9m, 10m, 12m and 15m. The experimental data were passed through a 6th order high-pass Butterworth filter with a 0.1 Hz cutoff.

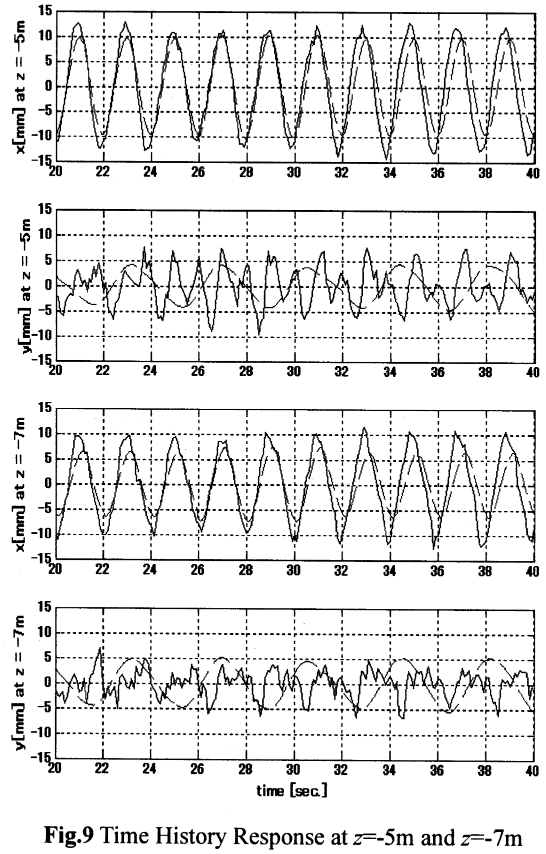

Fig.9 Time History Response at z=-5m and z=-7m
---- Simulation —— Experiment

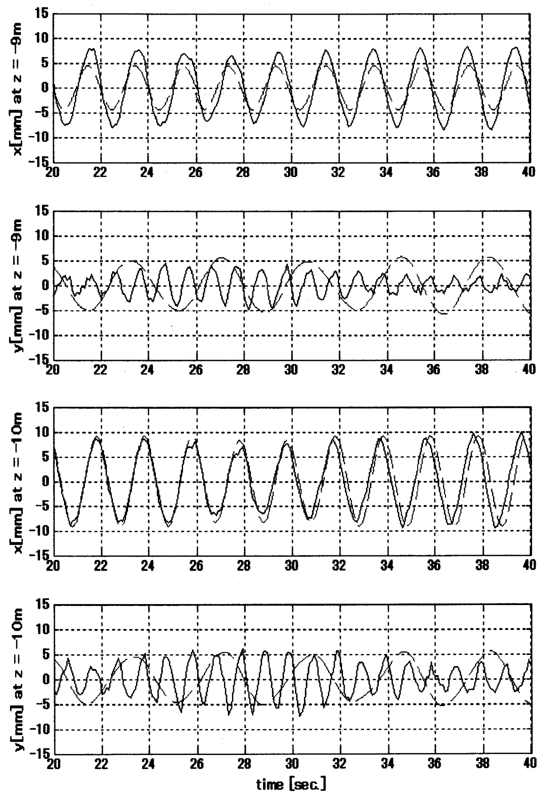

Fig.10 Time History Response at z=-9m and z=-10m
---- Simulation —— Experiment

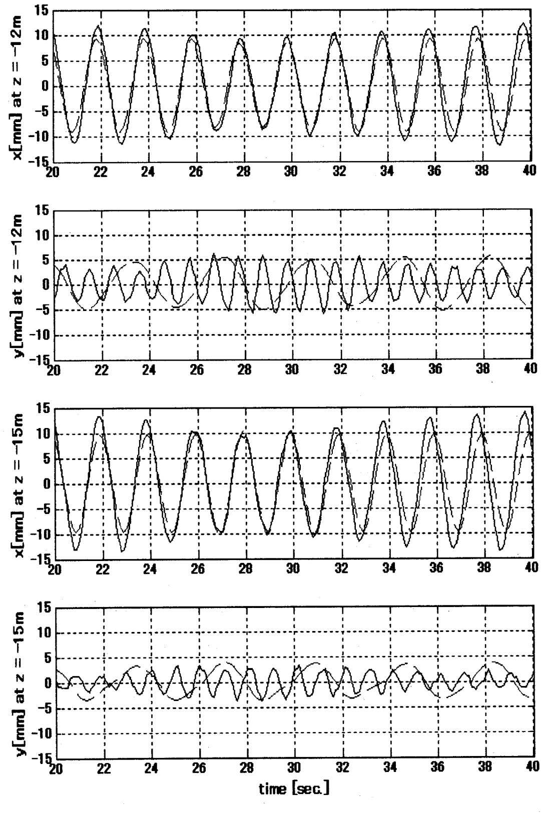

Fig.11 Time History Response at z=-12m and z=-15m
---- Simulation ____ Experiment

The in-line phase angles were corrected in order to improve the quality of the graphical results. Variations in the phase angles were found when the experimental results were compared with simulation results. These variations may be caused in part by the initial unsteady response of the riser.

The in-line response is relatively well predicted in both amplitude and frequency content. It can be observed that although the experimental model is sinusoidallly excited at its top end, the experimental data show that there is a variation in the amplitude involving a nonlinear phenomenon almost impossible to model using numerical simulation. It is also observed a variation in the frequency content. As previously mentioned, the "classical" lock-in condition is not considered in this paper and although it is widely recognized that the Strouhal law is not followed and the frequency of the motion in the cross-flow direction does not coincide with the shedding frequency during synchronization events, it can be seen from the experimental data that the cross-flow frequencies significantly deviate from the cross-flow frequencies of the simulated time series responses. Nevertheless, the shedding frequency is proportional to the in-line velocity at a given section and therefore is expected that at low KC numbers the cross-flow frequency decreases. According to the Strouhal law, the experimental model presented in this paper achieves a maximum value of the shedding frequency of approximately 0.4Hz. It is clear that there are significant deviations in the cross-flow frequencies. However, these deviations can be partially explained by the unpredicted nature of the phase angle in the cross-flow direction. It seems that a more powerful scheme using an appropriate model for the calculation of the phase angle can somehow account for this deviation. The main difficulty is that the development of such model involves challenges such as the exact location of a jump in the phase angle for a specific reduced velocity.

The accurate prediction of the cross-flow response in flexible risers is still challenging due to its highly nonlinear nature. In addition, the assumption that only one frequency dominates the cross-flow response may introduce considerable deviations in its numerical calculation. Using the experimental data at z=-5m and z=-15m, it is possible to observe that the KC numbers achieved by the sections of the riser in these regions have similar values, as shown in **Figs.9 and 11**. The values of the KC numbers obtained from the numerical simulation at z=-5m and z=-15m are 4.55 and 4.39, respectively. However, the transverse response at z=-5m is considerable different to the one achieved at z=-15m, as shown in **Figs.9 and 11**.

When Fourier analysis of the experimental data in the cross-flow direction at *z*=-5m and *z*=-15m is carried out, the differences become more evident in both amplitude and frequency content as shown in **Figs.12 and 13**. Furthermore, there is no clear distinction of the dominant frequency that must be used at *z*=-5m.

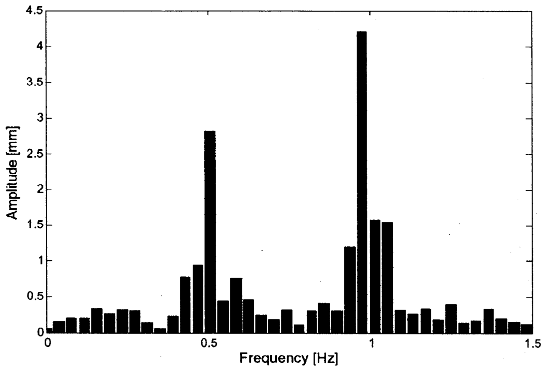

Fig.12 Fourier Spectrum Transverse Response Experimental Data (*z*=-5m)

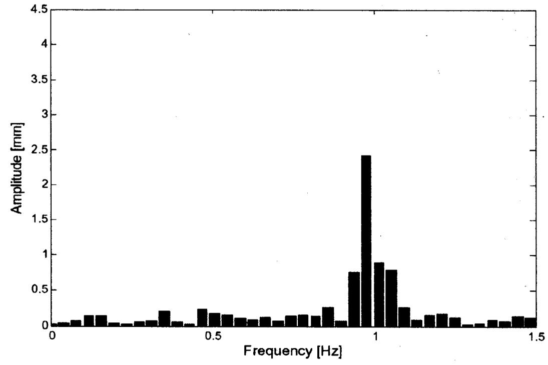

Fig.13 Fourier Spectrum Transverse Response Experimental Data (*z*=-15m)

Riveros *et al.*$^{16)}$ experimentally validated a numerical scheme for dynamic response of oscillating flexible risers using a 35-meter riser model. They found good agreement between experimental data and the simulation results in the in-line direction. On the other hand, the cross-flow response was under predicted. One of the most significant differences between the response prediction model proposed in this paper and the one proposed by Riveros *et al.*$^{16)}$ is related to the definition of the "lock-in" condition. Therefore, a more convenient approach was presented in this paper based on previous research work that shows that synchronization events can be alternatively defined as the matching of the frequency of the periodic wake vortex mode with the oscillating frequency of the cylinder at low values of mass-damping parameter. Therefore, the newly proposed model eliminates a possible source of error related to the calculation of the natural frequencies of the riser. It is important to stress that the response prediction model presented by Riveros *et al.*$^{16)}$ used an increased mean drag coefficient model based on the reduced velocity U_r and therefore its accuracy is strongly related to the correct calculation of the natural frequencies of the riser, which is not easy considering the huge number of variables involved in the analysis. Based on the simulation results obtained from the CFD-based model presented in this paper, it is possible to observe that the inertia coefficient depends on the beta parameter for the range of the KC numbers presented in this paper. On the other hand, the mean drag coefficient for oscillating cylinders can be indistinctly obtained from the oscillatory flow case without much incidence on the final simulation results.

6. Conclusions

A CFD-based approach for response prediction of oscillating flexible risers at low values of beta parameter was presented. Experimental data obtained from a 20-meter riser model, sinusoidally excited at its top end with amplitude of 0.01m and period of 2 seconds, were used to validate the proposed response prediction model. The selection of the amplitude of the force oscillation was based on the fact that the quasi-steady assumption is still valid at low amplitudes. The clear definition of the range in which quasi-steady models can be used to predict the dynamic response of oscillating flexible risers is still a topic of active research. Therefore, a CFD-based model was developed in this paper in order to compute hydrodynamic force coefficients using oscillatory flow. The simulation results were then compared with experimental data and simulation results collected from previous studies performed for steady and oscillatory flows. Good agreement was observed in these comparisons.

The CFD-based model was then used to model the case of an oscillating cylinder. The main idea of this procedure is to develop a model completely independent of the quasi-steady assumption allowing fluid-structure interaction to be considered in the CFD-derived hydrodynamic force coefficients. At low amplitudes it is expected good agreement between the simulation results obtained from the oscillatory flow case and the oscillating body case. Therefore, the validation of the proposed CFD-based model for oscillating cylinders is carried out using the simulation results obtained from the oscillatory flow case. Good agreement was observed in the computed mean drag coefficients and a tendency of the oscillatory flow case to over-predict inertia coefficients when those coefficients are used to predict hydrodynamic forces on an oscillating cylinder highlighting the importance of considering fluid-structure interaction. Finally, the response prediction model for oscillating flexible risers was experimentally validated as previously mentioned. It was observed a tendency of the proposed response prediction model to under predict maximum in-line displacements. However, considering existing limitations for response prediction of risers, the simulation results presented in this paper are within the range of error found by Chaplin *et al.*[15].

The response prediction of an oscillating flexible riser involves several challenges due to the nonlinear and self-regulated nature of the VIV process. It has been sufficiently proved that synchronization events lead to an increase of the cross-flow response which indeed causes a rapid rise in the drag force and therefore affect the whole in-line response of the riser. Moreover, the dynamic response of a flexible riser having a value of mass ratio lower than 3.3 is more complex due to the existence of three modes of response in contrast with the two modes of response found in risers with values of mass-ratio larger than 10.

Further studies are needed in order to develop a coupled model for dynamic response of oscillating flexible risers. Nevertheless, the main limitation for the development of this coupled model is related to the computational resources needed for such implementations. The CFD-based model presented in this paper can be easily coupled with the FE model of the riser by assigning to each of the sections of the FE model a CFD-based model similar to the one proposed in this paper. The main idea is that the coupled model uses instant cross-flow velocities obtained from the FE analysis to compute the hydrodynamic forces employing the CFD-based model.

Considering the nonlinear and self-regulated nature of the VIV process, especially during synchronization events that leads to large displacements and sudden changes in the phase angles, this paper presents a practical methodology for response prediction of oscillating flexible risers.

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(Received April 12, 2007)