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Investigation of Vortex Induced Vibration of Offshore Pipelines near Seabed

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Abstract: Recently, dynamic interaction between pipelines, seabed and the ocean currents has received wide concern from marine pipeline designers and researchers. The analysis of dynamic responses of subsea pipeline, in vicinity of the seabed in severe ocean environments, is very important. In this regard, this study reviews and sums up recent researches and investigations performed on vortex induced vibration of pipelines near seabed for analysis and design. In addition, the preliminary results of a developed model around a pipe subjected to steady current have been presented. Future trends and challenges in this research are also identified.

Introduction

In oil and gas industry, owing to the highly increasing activity, submarine pipelines become basic arteries of fluid and energy transportation. These pipelines are laid on different soils and are exposed to different hydrodynamic conditions. In this regard, considerable research effort has been devoted in the recent years for the installation and operation of pipelines in deep water [1, 2].

When a submarine pipeline laid on an erodible seabed is subjected to ocean currents, complex interactions between pipeline, soil and current are developed. Pipeline may become free spanning in some locations as a result of the scour around the pipeline and/or unevenness of the seabed. As discussed by [3], the hydrodynamic forces caused by the flow action, acting on marine pipeline spans are represented by two components; one the drag force (in-line with the flow) and the other is the lift force (perpendicular to the flow). In vibrating pipes with two degrees of freedom, experimental results demonstrate that the amplitudes of in-line vibration are typically much less than those in cross-stream vibration. Hence, many researchers focus their attentions on the cross stream vibrations of cylinders [4]. At the downstream part of the marine pipe, due to the incidence of vortex shedding, oscillation and unsteady nature in pipe vibration are inevitable. According to [5], vortex shedding leads to Vortex-Induced-Vibration (VIV), which has been extensively known as one of the main reasons of the fatigue damage in pipelines. Therefore, forecasting behavior of vortex-induced-vibration in the proximity of seafloor is a major factor for pipeline design.

Vortex Induced Vibration

Generally, when a pipeline is placed in a flow path, the flow structures are changed by this obstacle close to the seabed. In the disturbed flow field around a cylinder, four typical regions are distinguished. As depicted in Fig.1, (a) the upstream postponed flow region; (b) the boundary layers that develop at upstream side of the cylinder; (c) the accelerated, curvilinear sidewise flow region; and (d) the downstream flow region named ‘‘the wake’’, are these four regions. This downstream flow region is the most complex part of the flow around a cylinder exposed to current. The interaction between the body and the fluid flow can cause vortices behind the body [6]. According to [7], vortex shedding is caused as a result of instability existing between two shear layers released from the separation points at top and bottom of cylinder toward the downstream flow (Fig. 2).

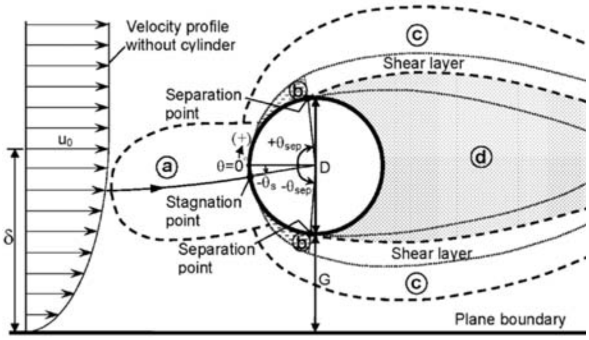

Figure.1 Four typical regions around a circular cylinder in steady flow

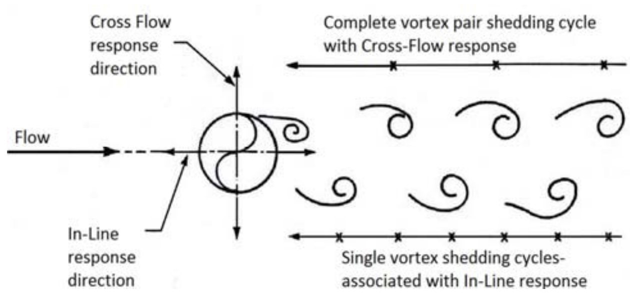

Figure. 2 Staggered alternate vortex shedding cross-flow and in-line response

Experimental Studies on Vortex Induced Vibration

As a result of vortices produced by the flow passing through a bluff body, vibration may occur due to several factors. The hydrodynamic force, material damping, Reynolds number, shedding frequency, added mass effects, and the structural stiffness of the bluff body are just a few of these factors.

By considering the mechanism of vortex shedding phenomenon behind a fixed bluff body, Bearman [8] concluded that the primarily reason for creation of vortex shedding is existence of two shear layers. Existence of bluff body, instead of directly causing the vortex shedding, improve the vortex shedding by giving feedback between the shedding of circulation and the wakes at two separation points of the body surface. Also the span-wise which is coupled between two shear layers, leads to generation of vortex shedding but it is usually weak. This shows that unsteady quantities which lead to vortex shedding (e.g., pressure of body surface) in the span of the body are not constant. Moreover Bearman manifest the frequency of the vortex shedding by the natural frequency of the body in the range of reduced velocity is inevitable. The length of vortex shedding is considerably increased when the vortex shedding frequency is near to the body fluctuations frequency. Drag and lift forces on a surface of cylinder have a beating motions because of following reasons: (1) decrease in the mean drag coefficient; (2) raising up in the root mean square of fluctuating drag coefficient; (3) increase in the primary excitation zones. Similarly the time-averaged of drag coefficient value is consistently higher when the cylinder is held fixed and this result is basically self-dependent on Reynolds number [8]. As investigated by Sumer and Fredsoe [9], for a tubular body exposed to a current flow, vortex shedding will happen if the Reynolds number is larger than about 40. As mentioned before, the vortex shedding results in periodical changes in the quantity of hydrodynamic force on the surface of cylinder. The lift force fluctuates at the frequency of vortex shedding, whereas the drag force fluctuates at twice the frequency of vortex shedding. If the pipeline is flexibly built, these forces may cause the pipe to vibrate. When the reduced velocity reach in the range of $5 < V_r < 7$ ($V_r = U/f_n D$), the frequency of vortex shedding locks into natural frequency of pipe. This means that the Strouhal law is not valid to control the vortex shedding, but the pipe vibration has significant influence on vortex shedding. The separation vortices enforced to cooperate with the body vibration, caused to vortex shedding at a same frequency of body vibration. Then the body fluctuation and the vortex shedding frequency overtake to a single frequency near to the natural frequency of the oscillated body which is identified as lock-in phenomenon [3, 9].

VIV can be categorized into three main types; (i) wake–body, wherein the wake fluctuations and the body are coupled over common phase; (ii) single degree-of-freedom, a single dynamic equation with interaction of inertial, elastic and aerodynamic forcing terms; (iii) force–decomposition, based on measurement of particular factors of the forces on the surface of body [8]. Physics behind pipelines near a boundary are quite different from free cylinder. For a free cylinder placed in steady flow, the vibrations are caused by regular vortex shedding, and frequency is determined by the Strouhal number. In the case of presence of a boundary near pipe, this vortex shedding takes place even if the distance between the wall and cylinder is larger than about 0.3d (d being the pipe diameter). Closer to the wall, regular vortex shedding does not take place. However, vibrations still take place [9]. The comparison of cross-stream vibration and in-line vibration shows that the amplitudes of in-line vibration are usually much less than cross-stream vibration [10].

Numerical Studies on Vortex Induced Vibration

The calculation of hydrodynamic forces on pipe, vortex induced vibration and local scour often need proper simulation of the flow near and around the pipe. Some recent studies on numerical modeling proved that, using different models to calculate flow equations, affects on result. Most of the previous researches like Li and Cheng [11], Liang and Cheng [12, 13], Smith and Foster [14] used numerical modeling to simulate fluid flow around pipe. They observed the k-ω and k-ε turbulence models that under-predicted the fluctuation vortices as well as the mean drag coefficient. Besides, 2D Smagorinsky's model (SGS) at all times calculates stronger vortex shedding than that observed in experiments. The model is also affected by the computational mesh, the change in grid size affecting the frequency and magnitude of the shedding [12, 14]. It has been understood that the mild slope of the scour hole is mainly due to the vortex shedding. Likewise, simulation of the scour dose not much depend on the mass of computational mesh [13]. Liang and Cheng asserted that in the 2D scour modeling, the standard k-ε turbulence modeling is much preferred than the SGS [13]. And also it is capable to model the velocity profile near an offshore pipeline [14]. Smith mentioned that as the grid size decreased, LES model accurately estimated the mean velocity profiles, but overestimated the size of eddies and it was unable to reproduce the length of the wake [14].

In the work by Zhao, sediment transport and pipeline response were coupled in the numerical model, the vibrating forces to be shed from the bottom side of pipeline which is closer to the seabed. According to the results, three vortex shedding modes were identified: (i) When the reduced velocity is very small, the vortex shedding is in the single-vortex mode only, and shed from the top of the cylinder; (ii) vortex shedding after bounce-back mode, occurs when the VIV amplitude increases with increasing reduced velocity; (iii) vortex shedding before bounce-back mode, occurs in the resonance range of reduced velocity [15].

Simulation of steady flow over a pipeline by using Reynolds-Averaged-Navier-Stokes equation with k-ε turbulence closure model was also done by Kazeminezhad and Yeganeh-Bakhtiary [16]. They proved that by analyzing the power spectrum of the momentary lift force the Strouhal number can be calculated. Main finding shows that the Strouhal number is slightly affected by the gap to diameter ratio while the root mean square of lift coefficient and the mean force coefficients are involved by the gap ratio. Yeganeh-Bakhtiary [17], evolved a numerical model using an Euler–Lagrange coupling two-phase flow model to explore the current-induced live-bed scour. Finally they agreed on a general trend of scour depth formation at the whole scour processing.

Mathematical Model

In this area for modeling the flow field around a subsea pipeline, the incompressible two-dimensional Reynolds averaged Navier Stokes (RANS) equations are used:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \vartheta \frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{\partial \overline{\acute{u}_i \acute{u}_j}}{\partial x_j} \qquad (2)$$

While x_i $(i = 1, 2)$ indicates the Cartesian coordinate system, the x_1 is referred to the horizontal *(x)* and x_2 is referred to the vertical *(z)* direction, respectively. In the cited equations u_j and p implies the x_j components of pressure and velocities in x and z direction, t implies time marching, $\overline{\acute{u}_i \acute{u}_j}$ implies Reynolds stress tensor and υ implies kinematics viscosity. Boussinesq assumption is used to model the Reynolds stress tensor. By introducing ϑ_t as a eddy viscosity, following formulation is reached:

$$-\overline{\acute{u}_i\acute{u}_j} = \vartheta_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \quad (3)$$

In which k is dimensionless turbulent kinetic energy and δ_{ij} is the Kronecker delta. The variables of mentioned equations need to be converted to non-dimensional form by dividing *x* and *y* by L, a reference length u and v by *U0*, upstream wind velocity, and $p$by ρU_0^2.

Liang and Cheng [13] Smith and Foster [14] and Kazeminezhad and Yeganeh-Bakhtiary [16] illustrated that the $k-\varepsilon$ turbulence model is more adequate to simulate the streamlines of flow around a circular cylinder. Therefore, the $k-\varepsilon$ model is employed to compute turbulent schemes.

$$\frac{\partial k}{\partial t} + u_j\frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\vartheta + \frac{\vartheta_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + p_k - \varepsilon \quad (4)$$

$$\frac{\partial \varepsilon}{\partial t} + u_j\frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\vartheta + \frac{\vartheta_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + [c_{\varepsilon1}p_k - c_{\varepsilon2}\varepsilon]\frac{\varepsilon}{k} \quad (5)$$

$$p_k = \vartheta_t\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (6)$$

Where ε and p_k are show dissipation rate of turbulences and produce k. The eddy viscosity is distinguished by using k and ε value as well:

$$\vartheta_t = c_\mu\frac{k^2}{\varepsilon} \quad (7)$$

The standard $k-\varepsilon$ model coefficients are consider as bellow value [16]:

$$c_{\varepsilon1} = 1.44, \quad c_{\varepsilon2} = 1.92, \quad c_\mu = 0.09, \quad \sigma_k = 1.00, \quad \sigma_\varepsilon = 1.30 \quad (8)$$

The scour profile under the pipe due to crossing flow will forcefully rely on shear stress which acts on the sandy soil of seabed. To find out the scour profile, calculation of the shear stress acting on sandy soil under the pipe is very important. So in this research, shear stress has been derived by the flow field acquired through the Navier-Stokes equations.

Numerical Method and Preliminary Result

In this research, the discretization process is based on “Galerkin Finite Volume Method” to derive the discrete formulas of the governing equations on triangular meshes. The main problem is increasing numerical errors, which usually disturbs the explicit solution of the formulations. This was overcome by adding artificial dissipation terms, suitable for the triangular meshes. These extra terms are used to reduce the unwanted errors and stabilize the procedure of numerical solution while conserving the accuracy of the results. In order to develop the computational efficiency, various numerical techniques such like Runge-Kutta multi-stage time stepping, edge-base algorithm and the residual smoothing have been applied. Free stream velocity imposed at inflow unit as boundary conditions and pressure is imposed at outflow boundaries unit as well. At every computational node, the free stream flow factors such as inflow velocity and outflow pressure, are set as initial conditions.

The test case consider as cylindrical body facing an incompressible viscid flow. The flow field around this object is modeled in a discrete form using 2529 grid points and 7191 unstructured triangular elements (Fig.3). The effect of artificial compressibility coefficient on converge behavior was examined by [18], and the in this test case convergence behavior was satisfied (Fig.4.). As well, Fig.5 indicates the computed results on the cylinder wall at supercritical Reynolds number ($\mathrm{Re} = 4.5 \times 10^5$) plotted in terms of colored stream line with velocity value.

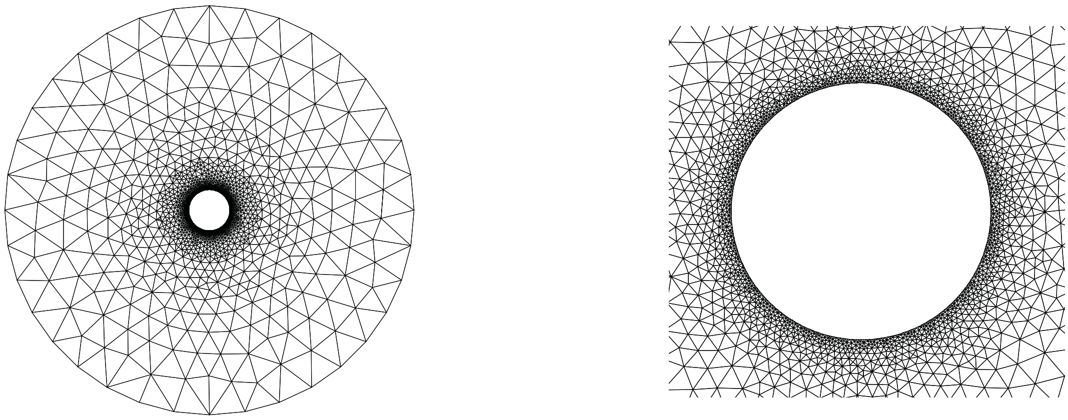

Figure. 3 Unstructured triangular mesh for a circular cylinder general view and closed view

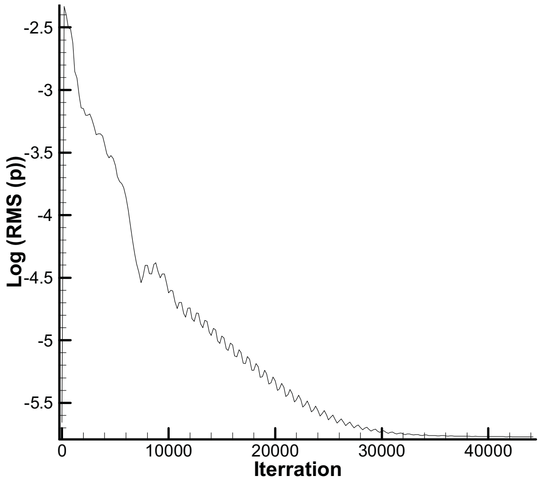

Figure. 4 Converge Error behavior

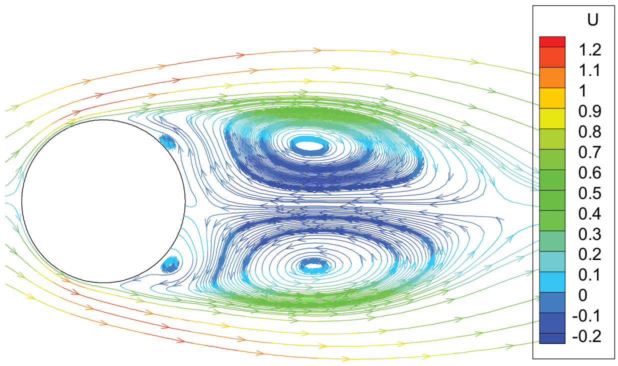

Figure. 5 Stream line colored with velocity at supercritical Reynolds number

Concluding Remarks

Significant research has been conducted to study vortex induced vibrations of a pipelines close to a solid boundary, and extensive findings have been reached during the last three decades. Recent evidences have proven that physical modeling is a useful method to understand the mechanisms of the phenomenon. However, numerical models can enable engineers to understand and appraise the process and developing phases of local scour under marine pipelines. Consequently it is essential to develop suitable numerical modeling to investigate the coupling effects between seabed, ocean currents and the pipelines. Finding from literature shows (1) VIV is naturally self-regulated, nonlinear and multi-degree of freedom fact; (2) Vortex shedding is caused by complex forces; (3) For pipes which are laid on seabed, three vortex shedding modes may take place; (4) Till the scour depth under the pipe becomes large enough, the VIV does not happen.

A preliminary mathematical model has been developed to numerically simulate a fluid flow around circular cylinder to model submarine pipelines. The results show that in computational modeling to solve the equations, the artificial dissipation method is well adapted to limit unwanted errors.

Outlook on Future Challenge

The overview of the references and preliminary results show clearly that Galerkin finite volume method has the potential to play an effective role in the analysis and design of pipelines for the calculation of dynamic interaction between pipe, current and seabed. Although there are proofs for the existence of rapid development in recent years, some of the main challenges may stimulate thinking for the next research in this area, mainly including:

- Improve the model to calculate hydrodynamic forces that result from the flow action.
- Effective method to determine frequency of pipeline motions due to vorticity around pipe.
- Numerical approach which considers interaction of vortex induced vibration and scour beneath pipe lying on seabed.

Acknowledgements

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