Numerical Modelling of Vortex Induced Vibrations in Submarine Pipelines

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Abstract: Vortex induced vibration is a major cause of fatigue failure in submarine oil and gas pipelines and steel catenary risers. Even moderate currents can induce vortex shedding, alternately at the top and bottom of the pipeline, at a rate determined by the flow velocity. Each time a vortex sheds, a force is generated in both the in-line and cross-flow direction, causing an oscillatory multi-mode vibration. This vortex induced vibration can give rise to fatigue damage of submarine pipeline spans, especially in the vicinity of the girth welds.

In this paper, COMSOL Multiphysics is applied to study the flow pattern around submarine pipeline spans, and predict the amplitude and frequency of the vortex induced vibrations. The sensitivity of the computational fluid dynamics model to geometric parameters and flow variables is investigated. Mitigation measures - like helical strakes and fairings- are addressed, and their effectiveness is evaluated. At the end, the potential of applying multiphysics methods to solve coupled problems in pipeline design is briefly discussed.

Keywords: fluid structure interaction, pipelines, vortex induced vibrations, multiphysics

1. Introduction

Vortex induced vibration (VIV) can give rise to severe fatigue damage when the vortex shedding frequency f_s approaches the natural frequency of a submarine pipeline span.

First, an analysis of offshore pipeline spans is presented, deriving the formulas for the (lowest) natural frequency of a pipe for different boundary conditions and lengths. Then, a short review on flow patterns behind submarine pipelines is given, to study the Reynolds numbers for which a turbulent von Karman vortex street appears.

The use of COMSOL Multiphysics to model vortex induced vibration is highlighted, and several mitigation measures are evaluated and compared. At the end, the promising potential of applying multiphysics methods to solve coupled problems in pipeline design is briefly addressed.

2. Analysis of offshore pipeline spans

A span can occur when an offshore pipeline bridges across a depression in the seabed, caused by a change in topology such as scouring or sand waves [01]. For a safe operation of offshore gas and oil pipelines during and after installation, these free spans should be limited to the allowable lengths, which are determined during the design stage [02].

Indeed, when the free span is too long, the pipeline may suffer vortex induced vibration when the vortex shedding frequency is close to the natural frequency of the submarine pipeline span. For a pipe with diameter *D* and wall thickness *t*, the (lowest) natural frequency can be calculated as [03]

$$\omega_0 = \frac{C}{L^2}\sqrt{\frac{EI}{m_e}}$$

where m_e is the effective mass per unit length (including structural and added mass, and the fluid contained within the pipe), *E* is the Young's modulus, *C* the end boundary coefficient, and

$$I = \pi\left(\frac{D}{2}\right)^3 t$$

the moment of inertia. According to Palmer and King [4], a single span does not have complete fixity against rotation at the ends of the observed span length. They advice to treat the span as fixed-ended (C = 3.56), but to allow for lack of end fixity by taking L somewhat larger than the observed span length.

Figure 1 shows the natural frequency of a pipeline with diameter D = 500 m and wall thickness t = 20 mm, for different boundary conditions and span lengths.

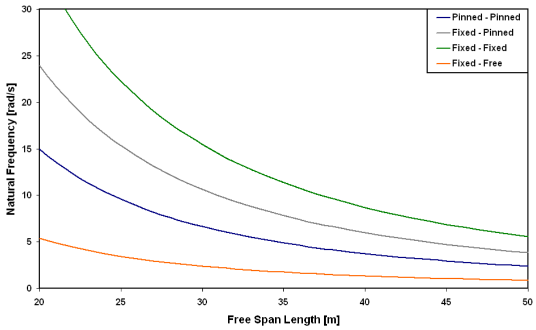

Figure 1. Influence of the span length on the natural frequency for different boundary conditions.

A pipeline will start to oscillate in-line with the flow when the vortex shedding frequency

$$f_s \approx \frac{1}{3}\frac{\omega_0}{2\pi}$$

Lock-in occurs when the vortex frequency f_0 is half the natural frequency. As the flow velocity increases further, the cross-flow oscillation begins to occur and the vortex shedding frequency may approach the natural frequency of the pipeline span, which is detrimental to its fatigue lifetime.

In the next section, numerical modeling of vortex induced vibrations with COMSOL Multiphysics is presented. First, some background on flow patterns behind submarine pipelines is briefly discussed.

3. Flow patterns behind submarine pipes

Fluid flow around a cylinder is a well known and documented [05-07] problem in computational fluid dynamics, and used in COMSOL as a benchmark for its fluid solver [08-09]. Here, this benchmark is applied to study flow patterns behind submarine pipelines.

The nature of the fluid flow is highly dependent on the Reynolds number

$$\mathrm{Re} = \frac{U\,D}{\upsilon}$$

expressing the ratio of inertia forces to viscous forces, where U is the fluid flow velocity and the kinematic viscosity

$$\upsilon = \frac{\mu}{\rho}$$

is the ratio of the dynamic viscosity μ with the density ρ.

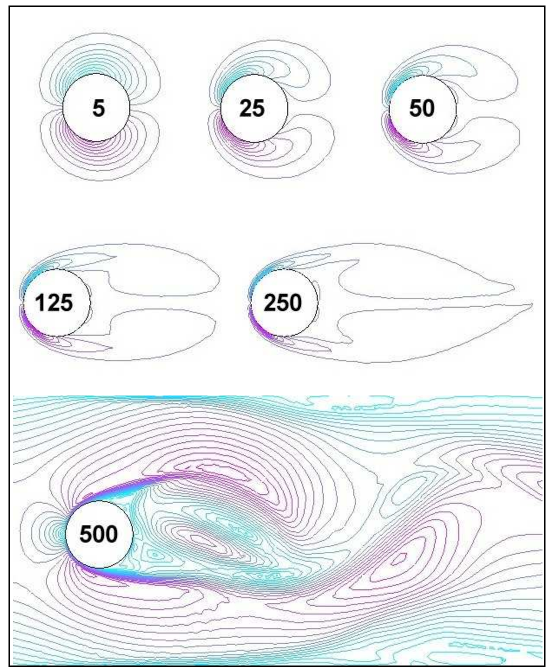

Figure 2. Regimes of fluid flow across a (smooth) submarine pipeline

The regimes of fluid flow across a (smooth) submarine pipeline can be divided in [10]

- unseparated flow for very low (Re < 5) Reynolds numbers
- the regime for 5 < Re < 40, where a fixed pair of Föppl vortices develop in the wake
- the development of a laminar vortex street, for 40 < Re < 150
- the transition range (150 < Re < 300) from laminar flow to turbulence
- the regime where the vortex street is fully turbulent ($300 < \mathrm{Re} < 3 \,.\, 10^5$)
- For even higher Reynolds numbers ($3.10^5 < \mathrm{Re} < 3.5.10^6$), the laminar boundary layer undergoes turbulent transition, and the wake will be narrower and disorganized

- At very high Reynolds numbers (Re >3.5*10^6), re-establishment of a turbulent vortex street occurs.

Figure 2 shows the isovorticity contours for the fluid flow across a submarine pipeline at different Reynolds numbers. When the fully turbulent Von Karman street appears (Re > 300), the pipeline will be subjected to alternating vortex shedding, which induces vibrations and can give rise to severe fatigue damage.

The numerical modeling of vortex induced vibration with COMSOL Multiphysics is elaborated in the next section.

4. Numerical modeling of VIV

The Navier Stokes application mode is used to model unsteady, incompressible flow past a submarine pipeline. Figure 3 shows a pipe (with diameter *D* and wall thickness *t*), placed at an offset *e* from the centre of the flow velocity field *v*. The offset e allows to destabilize what otherwise would be steady state symmetrical flow. The studied grid is 4D by 12D.

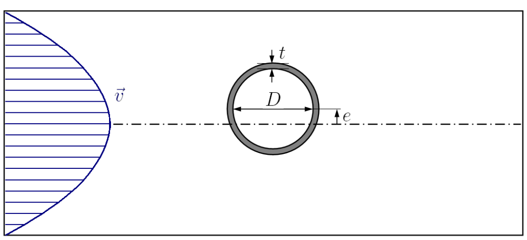

Figure 3. Submarine pipeline (diameter D, wall thickness t), placed at an offset e to the velocity field v

The Computational Fluid Dynamics solver of COMSOL Multiphysics uses a generalized version of the Navier-Stokes equations to obtain the flow pattern around the pipeline. For a Reynolds number Re > 300, a Von Karman vortex street appears with a stable frequency and amplitude. Figure 4 shows this Von Karman vortex street at the onset of turbulence.

Each time a vortex sheds, a force is generated in both the in-line and cross-flow direction, causing an oscillatory multi-mode vibration.

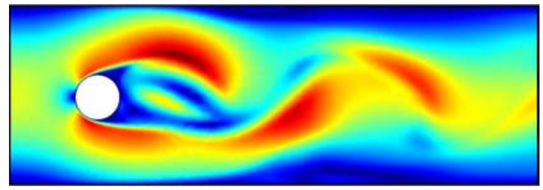

Figure 4. Flow pattern around a submarine pipeline, at the onset of turbulence.

Due to the alternating vortex wake, the oscillations in lift force L(t) occur at the vortex shedding frequency f_s, and oscillations in drag force D(t) occur at twice this frequency. The in-flow oscillation is governed by the dimensionless drag coefficient

$$C_x = \frac{D(t)}{\frac{1}{2}\rho\langle U\rangle^2 D}$$

with <U > =2 * U_{max}/3 the mean velocity, while the cross-flow oscillation can be described by the corresponding lift coefficient

$$C_y = \frac{L(t)}{\frac{1}{2}\rho\langle U\rangle^2 D}$$

Figure 5 shows the evolution of the fluctuating lift and drag coefficients when the von Karman vortex street is fully developed. Note that the average lift force is zero, while the average drag force is a measure for the resistance against fluid flow.

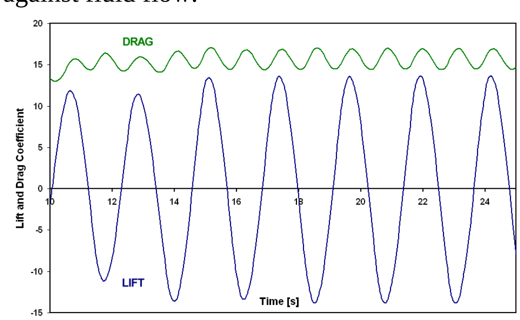

Figure 5. Fluctuating lift and drag forces acting on the pipeline

For a long, flexible pipeline span than can move in both directions, the trajectory is found as the solution of an equivalent spring-mass system with a harmonic forcing term [11]. Submarine pipelines, subjected to vortex induced vibrations, tend to trace an ‘8’ shaped motion, like shown on Figure 6. These motions can induce fatigue damage in the pipe itself, the girth welds or the coating.

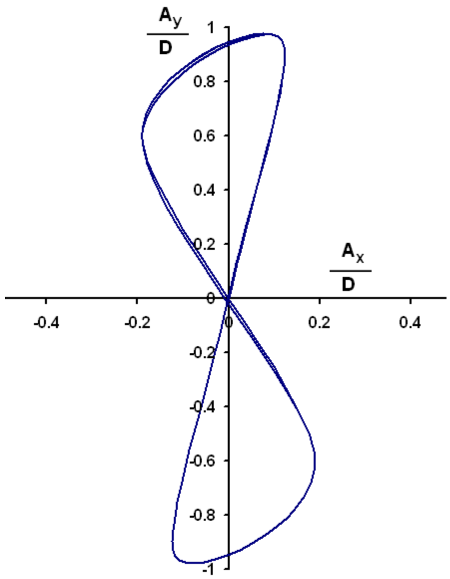

Figure 6. Trajectory of a pipe subjected to vortex induced vibration

In the next section, the most commonly used mitigation measures to avoid (or at least reduce) vortex induced vibrations are briefly addressed.

5. Mitigation measures to suppress VIV

Several mitigation measures have been developed to avoid or reduce the effects of vortex induced vibrations. The COMSOL CFD model to simulate flow patterns across a submarine pipeline (cfr. Figure 4) provides an elegant tool to compare these measures, and evaluate their effectiveness. In this section, the use of control cylinders, fairings, helical strakes, spoilers and splitters is addressed.

5.1 Control cylinders

The use of very small control cylinders can give rise to almost complete wake suppression behind the pipeline [12]. Figure 7, for instance, shows the flow pattern for the same conditions as Figure 4, with addition of two control cylinders with diameter d = D/8 at a position x = D and y = ± D. The presence of the control cylinders stabilizes the near wake and causes the wake to be essentially time-independent. The result is a decrease in drag, and a virtual elimination of the fluctuating lift.

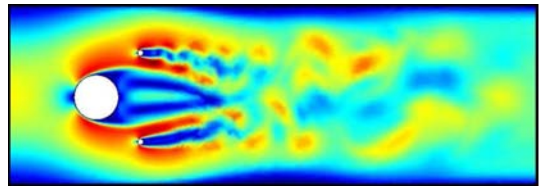

Figure 7. Inclusion of control cylinders decreases the drag and eliminates fluctuating lift

However, the use of control cylinders is only an interesting solution when the flow is unidirectional. Moreover, the location of the control cylinder depends on the Reynolds number, which limits the versatility of this mitigation measure.

5.2 Fairings versus helical strakes

For a long time, helical strakes have been used to suppress vortex induced vibrations, e.g. on the upper part of high smokestacks [13]. Their primary functional mechanism is to disrupt the correlation of vortex shedding along the pipeline span, hence reducing the vortex strength and the magnitude of the oscillatory lift forces.

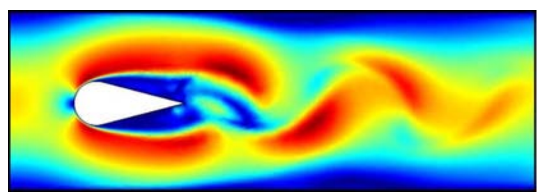

Figure 8. Fairings attempt to streamline the flow, in order to reduce the size of the vortices

Fairings attempt to streamline the flow, in order to reduce the size of the vortices while they are adjacent to the cylinder. Figure 8 indicates that a vortex street still can be formed downstream of the fairings, since they still shed a significant amount of vorticity.

The best performance is achieved when the fairing is aligned with the flow direction. To ensure a stable flow pattern, 'fish tail' fins are placed on the pipeline fairing. The optimum fairing geometry to suppress vortex induced vibration for a given Reynolds number is discussed in [14].

The ability of both helical strakes and fairings to effectively suppress vortex induced vibration is compared in [15]. The general conclusion reads that fairings suppress vortex induced vibration somewhat more reliably than helical strakes, due to their slightly better performance with marine growth present, and their substantially better performance for downstream cylinders. However, installation, maintenance and economic issues must also be considered during the selection [16].

5.3 Splitters and spoilers

Vortex shedding can be reduced by either spoiling or splitting the turbulent flow in the pipeline wake. Figure 9 compares the effect of a spoiler and a splitter on the flow pattern. Note that spoiler plates can still be successfully applied when the flow is no longer unidirectional.

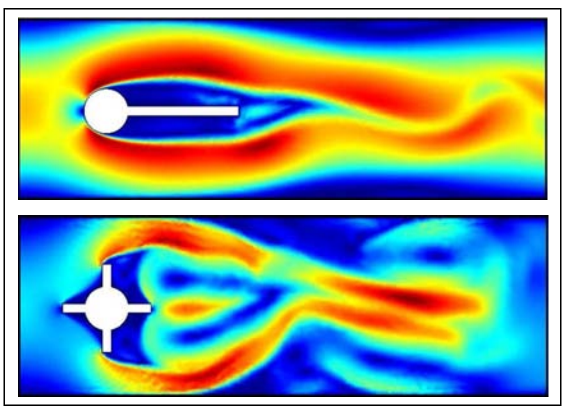

Figure 9. Splitters and spoiler plates and splitters to reduce vortex shedding

5.4 Other mitigation measures

The effectiveness of the different techniques to reduce vortex induced vibration is presented in Figure 10, by comparing the root mean square values of the different drag coefficients. This diagram clearly favours the inclusion of control cylinders to stabilize the flow, but the limits of this method were already expressed in §5.1.

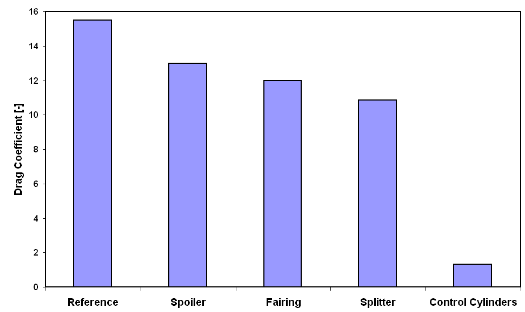

Figure 10. Effectiveness of mitigation measures

Several other add-on devices for suppression of vortex induced vibration exist, like axial slats (a), shrouds (b), ribboned cables (c) and pivoted guiding vanes (d). These commonly used mitigation measures are shown on Figure 11. More details on these methods can be found in [17].

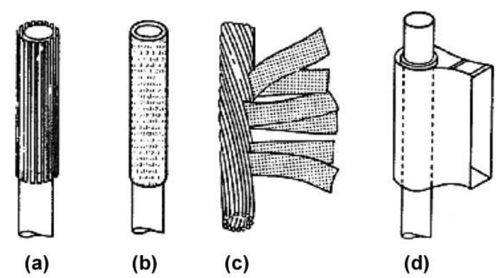

Figure 11. Other mitigation measures to suppress VIV

6. Multiphysics in pipeline design

COMSOL provides an elegant tool to study flow patterns across submarine pipelines. Their multiphysics module allows performing simulations of fluid-structure interaction, to calculate the motion of the pipe in response to the flow.

Moreover, COMSOL Multiphysics could prove to be an added value in other areas of pipeline design as well, like

- Prediction of fluid flow in the pipeline
- Structural mechanics modeling, to predict the natural frequencies and the fatigue damage
- Seabed scour simulation [18] with the Earth Science module

7. Conclusions

In this paper, COMSOL Multiphysics was applied to study flow patterns across submarine pipelines. For a Reynolds number Re > 300, a turbulent von Karman vortex streets appears in the pipeline wake, giving rise to multi-mode oscillations. These vortex induced vibrations can give rise to severe fatigue damage of submarine pipelines. Hence, different mitigation measures were evaluated and compared to suppress vortex induced vibrations.

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