Impact of Low Span Gap on Subsea Pipeline Vortex Induced Vibration

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Abstract

Vortex induced vibration of subsea pipelines occurs where sections of the pipeline are suspended above the seafloor, as 'free spans'. The induced vibrations can cause significant fatigue damage to pipelines, requiring costly repairs, and so there is a strong motivation to accurately characterise the phenomenon, to avoid unnecessary remediation work. This project explores vortex induced vibrations by constructing a sequence of models to describe the physical situation. 2D and initial 3D models are described and compared with experimental results.

1. Introduction

This project is intended to be the first stage of the development of a Computational Fluid Dynamics (CFD) model of a pipeline free span. The long-term goal of this model is to improve the accuracy of pipeline free span assessments by accounting for variation in the magnitude of the pipeline-seabed gap over the axial length of the span. The model should firstly indicate whether the shape of the gap affects the vortex induced vibration and accounts for the damping effect that this shape variation has on the vibration and resonance behavior of the full pipeline.

1.1 Project Background

During the installation and operational life of subsea pipelines, gaps can form between the pipeline and the seabed, creating a pipeline free span. When being installed, the pipeline may not conform exactly to a rough seabed profile, due to the combination of pipeline tension, weight and stiffness. During the operational phase of the pipeline such free spans exist, and can also arise due to the pipeline moving from its initial as-laid position (e.g. thermal expansion) or because of seabed changes due to the movement of sand and loose sediment (scour).

Currents and waves result in flow through these gaps, which can result in the shedding of vortices in the lee of the pipeline. These vortices cause periodically oscillating pressures adjacent to and on the surface of the pipeline (Palmer and King 2008). If these oscillations are close to the natural frequency for the span, they can 'lock-on' to the natural frequency, causing resonant vibration of the free spanning section of the pipeline (Bai, Bhattacharyya and McCormick 2001). This can occur in both the direction of the fluid flow (drag), and perpendicular to this direction (lift). This phenomenon is known as Vortex Induced Vibration (VIV).

Vortex induced vibrations are a significant concern in the management of subsea pipelines. These loads can result in the exceedance of the safe design conditions of the pipeline, due to fatigue damage or (rarely) by exceeding limiting stresses. Fatigue can accumulate rapidly due to the cyclic nature of VIV. Remediating free-spans identified to be beyond their design conditions can be very costly, and so accurately identifying free spans for remediation, while not 'over-identifying' stable spans, is very important.

To facilitate best-practice in assessing pipeline free spans, Det Norske Veritas – GL (DNV) maintains a Recommended Practice (RP) for Free Spanning Pipelines, outlining the methodology for conducting free span analysis (2017). This RP is intended to provide design criteria and guidance for assessing pipeline free spans, enabling identification of spans at risk of failure, and providing criteria for avoiding unnecessary rectification. It is believed that some of the assumptions used in the RP may be overly conservative, leading to unnecessary span rectification. As such, there is interest in further investigating these assumptions, to develop an improved physical understanding of VIV for free spanning pipelines.

1.2 Related Work

Experimental investigations into vortex shedding began in the 1960s (Taneda 1965). The subsequent research work combined experimental measurements, theoretical explanations, and, more recently, computational models of VIV.

Early work investigating VIV and its impact on the fatigue life of subsea pipelines has enabled development of a theoretical understanding of the formation of pipeline free spans, the initiation of VIV for pipelines far from the seabed, and design correction factors to account for seabed proximity and other factors. This work was formalised as a DNV Guideline in 1998, and later reissued as a Recommended Practise, DNV F-105 (Det Norske Veritas, 2017).

The influence of seabed proximity on VIV (both magnitude and frequency) has been investigated experimentally. (Lei, et al. 1999) reviewed previous experiments and noted that while it was generally accepted that for gap ratios (the ratio of the pipe diameter to the gap between the base of the pipeline and the seabed) less than 0.3 vortex shedding is suppressed, there was still significant uncertainty in the influence of the boundary layer, particularly in wind tunnel experiments. A more recent study using fluid flow found that reducing the gap ratio decreases the magnitude of VIV (Yang et al. 2009).

Increases in computing power enabled CFD modelling of VIV in 2 dimensions (2D) and (later) 3 dimensions (3D). A 2D model of flow around a cylinder by Zhao et al (2011) found that VIV 'lock on' occurred for a wider range of frequencies when the reduced velocity was steadily increased (the reduced velocity is the flow velocity normal to the pipe, divided by the pipeline diameter and natural eigenfrequency). This work also observed VIV for gap ratios well below the generally accepted point of suppression. Xiao (2015) used a coupled CFD/Finite Element Analysis (FEA) solver to model VIV for a range of reduced velocities and gap ratios, reproducing theoretical models from DNV RP-F105.

2. Method

The goal of this project is to develop a computational model representing VIV that is validated against experimental results. The final model should be 3-dimensional, able to model variations in the fluid flow, movement of the pipeline and variations in the seabed geometry (including flow disturbance from additional features placed on the seabed). Such a model requires both CFD and FEA modelling. The development of the model is proceeding in several stages. The first is modelling a 2D pipeline in a uniform flow far from the seabed. This 2D model is then developed to include a flat seabed (at varying proximities) and non-uniform flow. The model is then to be extended to 3D, returning first to a pipeline far from the seabed, and then re-introducing seabed proximity. Irregularity in the seabed is then to be introduced, exploring the impact of span-shoulders and variations in span gap size. Beyond this stage, FEA of the pipeline will also be introduced, to explore the interaction between pipeline motion and the fluid flow field.

2.1 2 Dimensional Model – Uniform Upwind Velocity

The first model developed considered a 2D pipeline located in a far-field flow. Vortex shedding was observed in the lee of the pipeline. For each different model/variation, the lift and drag forces on the pipe wall were monitored, and the final pressures and vorticities were displayed as animated contour plots in order to visualise the flow field.

In the next phase either the flow velocity or the gap ratio were varied, in order to explore the impact of these parameters on vortex formation. Results have then been compared with experimental results available in the literature.

2.2 2 Dimensional Model – Non-Uniform Velocity

A non-uniform velocity profile was introduced by setting the seabed roughness to that of medium roughness sand and using a User Defined Function (UDF) to define a height-dependent velocity profile at the model inlet. The use of a UDF minimises the need for extension of the model upstream of the pipe in order to allow the flow field to develop, optimising computation.

Det Norske Veritas (2017) recommends the use of the logarithmic profile to model the seabed velocity. This was implemented as a user defined function for this model.

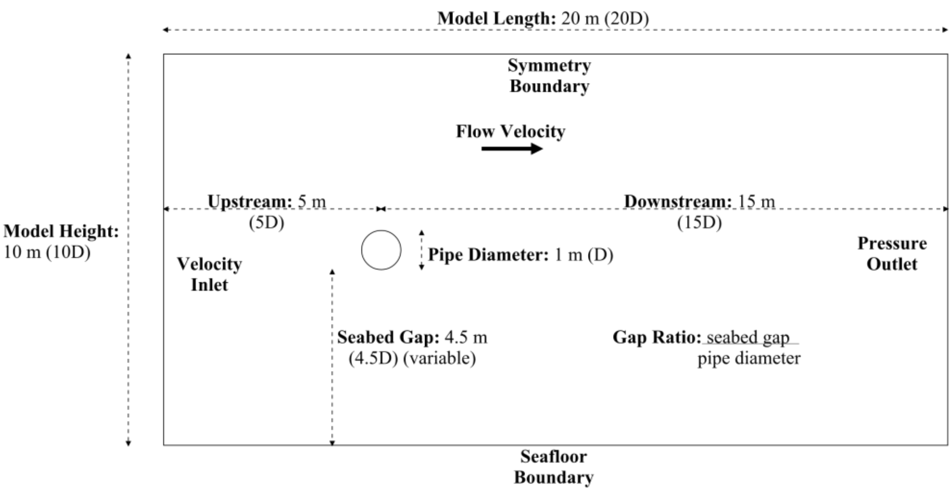

Figure 1 Model geometry and pipe positioning relative to the model extents.

3. Results and Discussion

3.1 2 Dimensional Model – Uniform Upwind Velocity

3.1.1 Varying the flow velocity magnitude.

For a pipe far from the seabed (gap ratio > 4), the uniform current flow velocity was modified in 1 m/s increments from 0.5 to 3.5 m/s. Vortex shedding was observed for velocities of 1.5 m/s and greater, and a significant oscillating force is observed in the lift force monitor (but no oscillation is noted in the drag force). The frequency of the vortex shedding, and the magnitude of the force induced by these vortices is summarised in figure 2. The data is compared to experimental results of Sumer et al. (1997). The predicted lift force amplitude corresponds closely to that measured experimentally. There is greater difference between the model and experiment for the vortex shedding frequency; this difference being most significant for a fluid velocity of 2.5 m/s. It should be noted that the lift force oscillates evenly about zero for all of the flow velocities, and so there is no positive or negative average net lift for any of these variations to the models.

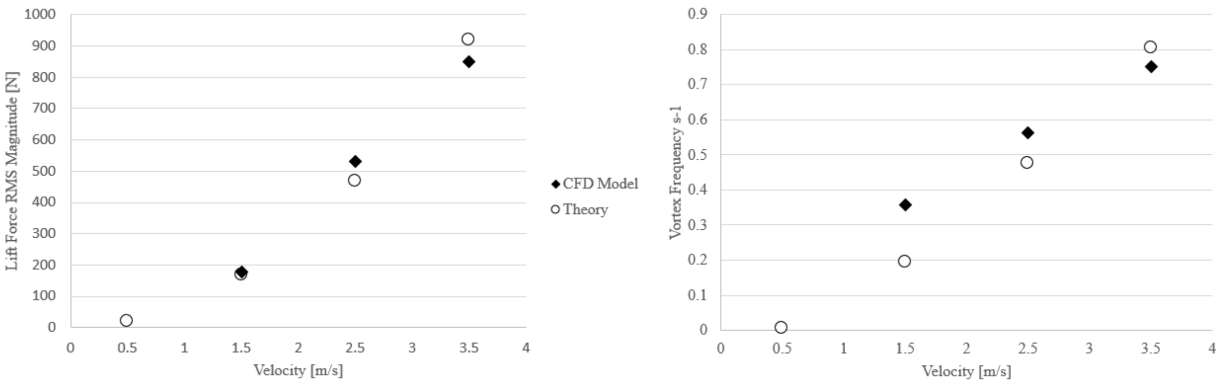

Figure 2 Plots of (i) the lift force oscillation amplitude and (ii) the vortex shedding frequency, for a 2D model with varying flow velocities.

3.1.2 Varying the pipeline-seabed gap/diameter ratio

For a fixed flow velocity of 2.5 m/s, the model geometry was adapted to gap ratios of 0.1, 0.2, 0.5, 1 and 4.5. Adapting the meshing approach for the tests very close to the seabed (gap ratio of < 1) required some revision of the initial approach. As the pipe approaches the seabed, asymmetry develops in the net lift force, and so an averaged net lift force is also recorded. A force is registered in the in-line direction for models between gap ratios of 0.25 and 1. These results are shown in Figure 2. Experimental data indicates that vortex shedding frequency will increase slightly for lower gap diameters (Sumer et al. 1997), and that the net lift force is expected to follow an inverse relationship, increasing rapidly as the gap ratio decreases. These experimentally observed trends agreed well with those observed in the model, although the model did not replicate the experiment exactly, the magnitudes of the results varying.

3.2 2 Dimensional Model – Non - Uniform Velocity

Results for the 2D non-uniform velocity model are shown together with those of 3.1.2 in the figure overleaf.

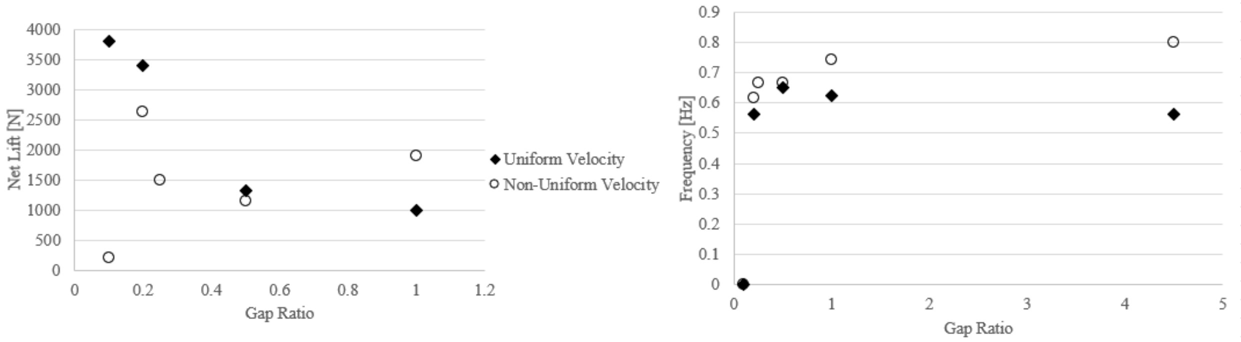

Figure 3 Vortex shedding frequency and lift force magnitude, for a uniform flow field (diamonds) and a non-uniform flow field (circles).

For the non-uniform velocity the averaged net lift force is expected to remain lower in magnitude than for the corresponding uniform-velocity case at all gap ratios, and will decrease in magnitude below a gap ratio of 0.1 (Sumer et al. 1997). Compared to these expectations, the model results are largely as expected, with the net lift force remaining generally lower than that of the uniform flow velocity (except for a gap ratio of 1, which appears to be an outlier). The decrease in the magnitude of the let lift for low gap ratios is also observed as expected. The frequencies for the non-uniform case also slightly larger, particularly for large gap ratios. The unexpected results are currently under investigation.

3.3 3 Dimensional Model

A 3D model 6 metres in depth (6 times the pipeline diameter) is now being explored. This length is sufficient to resolve axial variation in the vortex formation along the pipeline. There remains the possibility that the imposition of symmetry conditions on the sides of this 3D section leads to non-physical patterns in the modelled vortex formation. This will be investigated by considering different pipe lengths in future work.

Contours of vorticity as 2 planar slices are shown in Figure 4. There is evidence of vortex shedding along the length of the pipeline (with vortex shedding out of phase at different sections of the pipe, but with a similar frequency and magnitude). Further analysis of the transition to a 3D model will consider the lift and drag forces at slices along the pipe.

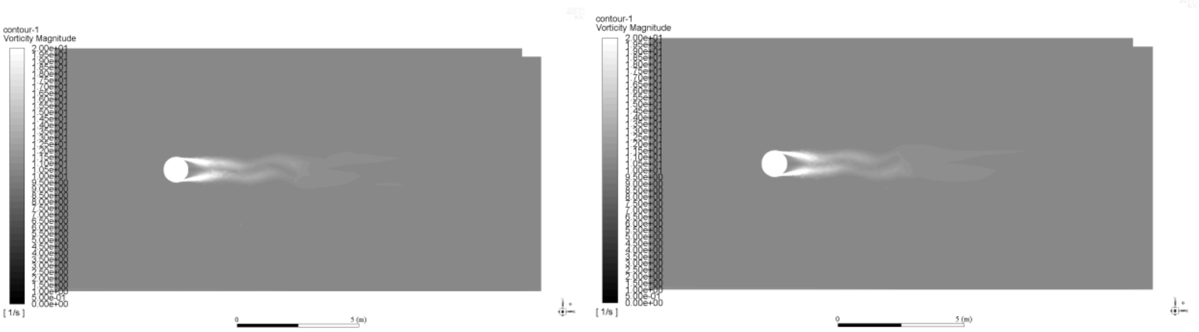

Figure 4 2 planes (with 4D separation) plotting vorticity contours, taken from a 3D model of a pipe far from the seabed, with a flow velocity of 2.5 m/s.

4. Conclusions and Future Work

This project has developed 2 and 3 dimensional models of vortex shedding in the lee of a model cylindrical pipeline of 1m in diameter. The flow velocity and seabed gap ratio have been varied in 2D models to consider the impacts of these changes on the frequency of vortex shedding and lift forces experienced by the pipe. The results for uniform approach velocities correspond well to results from theory, while the results from a non-uniform velocity profile also generally correspond, but contain some unexpected results, which are undergoing further investigation.

4.1 Future Work

The next phase of this project will investigate the impacts of non-uniform seabeds on vortex formation. Following this, variations in the pipe shape (to include sagging and pipeline movement) will be incorporated. The final stage of the project will consider coupled CFD/FEA analysis to capture the interaction between pipe vibration and vortex formation.

Beyond the current project, other areas of interest include modelling the effectiveness of vortex suppression pipeline modifications and considering the impact of wave motion. Consideration of more complex current flows (varying axially in magnitude, or flowing at an angle to the pipeline axis rather than approaching perpendicularly) is also possible.

5. Acknowledgements

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6. References

Bai, Y., Bhattacharyya, R. and McCormick, M. E. (2001) 'Vortex-induced Vibrations (VIV) and Fatigue', in *Pipelines and Risers*. Elsiver, pp. 117–135.

Det Norske Veritas (2017) *DNV-RP-F105 Free spanning pipelines*.

Lei, C., Cheng, L. and Kavanagh, K. (1999) 'Re-examination of the effect of a plane boundary on force and vortex shedding of a circular cylinder', *Journal of Wind Engineering and Industrial Aerodynamics*, 80(3), pp. 263–286.

Palmer, A. C. and King, R. A. (2008) 'Upheaval Buckling, Lateral Buckling, and Spans', in PennWell (ed.) *Subsea Pipeline Engineering*. 2nd edn.

Sumer, B. M. and Fredsoe, J. (1997) "Hydrodynamics around cylindrical structures", *World Scientific*

Taneda, S. (1965) 'Experimental Investigation of Vortex Streets', *Journal of the Physical Society of Japan*, 20, pp. 1714–1721.

Xiao, F. (2015) *CFD Simulation of Vortex–Induced Vibrations of Free Span Pipelines Including Pipe-Soil Interactions*. Texas A&M University.

Yang, B. *et al.* (2009) 'Experimental study of vortex-induced vibrations of a cylinder near a rigid plane boundary in steady flow', *Acta Mechanica Sinica*, 25(1), pp. 51–63.

Zhao, M. and Cheng, L. (2011) 'Numerical simulation of two-degree-of-freedom vortex-induced vibration of a circular cylinder close to a plane boundary', *Journal of Fluids and Structures*. Elsevier, 27(7), pp. 1097–1110.