EVALUATION of VORTEX INDUCED VIBRATION EFFECTIVE PARAMETERS on FREE-SPAN SUBSEA PIPELINES

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ABSTRACT

Subsea pipelines due to the reduction of transfer costs and expedite the offshore operations is one of the all-purpose structures in marine industries. Subsea pipelines are exposed to a variety of hazards, including corrosion and fatigue Etc. Free span exacerbates the fatigue required parameters due to a phenomenon called the Vortex Induced Vibration (VIV). In this research, the influence of the span's length on the free span subsea pipeline has been reviewed with ABAQUS standard code. In this study the previous result has been expanded. The results of the VIV fatigue life are extensible to all of the depth. Achieved Results indicate that the fatigue life of the pipeline even in the worst condition is much higher than the required amount that it represents the upstream design of DNV-RP-F105. In this study the backrest pipeline has been investigated and result show that the pipeline under the different conditions in the backrest, by creating more vibration and displacement on one side of the pipeline reduces the fatigue life of 113 percent compared to snap. The VIV fatigue life has undergone a lot of changes due to span length changes, maximum changes occur between cable and behavioral which the amount of these changes is reduced by 75%. The free span length is another factor in VIV fatigue. VIV fatigue life will be increased by reducing the span length. As well as increasing the flow velocity that is the main factor in creating the VIV is increased fatigue. Therefore, in terms of the accuracy in the choice of the existing conditions of very high importance for the pipeline. Comparison between effect parameters in VIV fatigue life was shown that span length is the most effective parameter.

1. Introduction

In the offshore industries, marine pipelines are widely applicable to reduce the cost of transportation and speed-up in offshore operations. High economic efficiency, adaptation to the harsh conditions of the sea has made pipelines the most important structure in the maritime industry. Different forces are applied to the pipeline, due to the position of the pipeline in the seabed. The dangerous condition made by these forces during operational or hydro test time [5]. Deep waters create more critical conditions for the pipeline.

In the nineteenth century, research was carried out by August Wooler. He found that forces, which is smaller than the static strength, does not have a damaging effect on the structure. Structure's collapse made by frequentative forces during the operational time is possible. Fatigue is one of the most important factors, which reduces pipeline performance and influence on personal safety and the environment.

Free spans made by subsea topology's changes, artificial support and bed roughness [2]. According to the DNV-OS-F101 [6], free span leads to various phenomena such as bursting, fracture and fatigue. Water particles collision with the pipeline's body causes vibrations in the pipeline, which are called Vortex Induced Vibration (VIV) made by free span [7].

The effect of free span on pipeline's fatigue is due to the VIV. If the frequency of VIV is equal to the pipeline natural frequency of the pipeline, the resonance and then fatigue occurs [8].

Span length and effective parameters of VIV play an essential role in determining the fatigue life of free span subsea pipelines. Research has been conducted on the effect of the span length on multi free spans. The impact of the span length has been studied for a single free span with VIVANA and RIFLEX software [9]. Different relation is estimated in fatigue problems which are often lacking in precision [3]. In this study, based on pipeline modeling in ABAQUS standard code and recommended model DNV-RP-F105, the fatigue life of the pipeline has been determined under different conditions and compared to the required value.

2. Pipe Free-Span Fatigue Analysis Methodology

VIV occurs as the result of periodic shedding of vortex around the pipe. Free span induces the pipeline vibration due to vortex shedding which may cause fatigue damage and fracture. Calculation and analysis of fatigue in a pipeline are more necessary due to the possibility of failure in different parts of the pipeline [10].

The VIV fatigue analysis includes several factors such as water depth, current velocity, span length.

Such as multi spans, the pipeline response in a single span is divided into two parts. In the single span, fatigue life occurs in the first response. Hence use the single response to consider fatigue life.

Considering the VIV phenomenon, two directions are determined based on the response frequency. In-Line (IL) and Cross-Flow (CF) are the two directions mentioned. In the ABAQUS standard code, these results are available. Fatigue life can be calculated according to rules and frequencies.

3. Fatigue Damage

Until 2006, in the case of VIV fatigue analysis, there was no comprehensive recipe for all of the free span state. A batch of studies conducted until 2006 only was responsible for a particular case that could not be extended to other states [8]. Other studies of fatigue capacity were obtained laboratory ally [11]. In 2006, DNV provided a general instruction that could be generalized to all modes. The calculations required by DNV-RP-F105 are possible. The fatigue life of the marine pipeline should be greater than the length of time the pipeline is exposed to the fatigue phenomenon.

$$D_{fat\_damage} = \frac{T_{exposure}}{T_{life}}.\eta \qquad (1)$$

The probability of occurrence of the vortex in the direction of IL more than CF direction. Inflexible beams at a velocity below 2.5 with not facing the direction of CF.

Cumulative failure of the free span can be achieved by using the existing equation in DNV-F-105 and the theory of linear cumulative failure.

$$D_{fat}^{cum} = \sum_{i=1}^{k} \frac{n_i}{N_i} \qquad (2)$$

In this equation, n represents the number of repetitions to subsea pipeline's force hit and N represent required repeat number for failure.

The capacity of the VIV fatigue pipeline be obtained from Eq.(3):

$$T_{fat\_life} = \frac{\eta}{D_{fat}^{cum}} \qquad (3)$$

3.1 Evaluation of fatigue for single free span in IL direction

The following steps show the route calculation of the fatigue in the IL direction:

1. Information collected includes soil properties, type of pipeline and ...
2. Calculation of the static fluid frequency.
3. Frequency calculates in IL direction for the different span length and different flow velocity.
4. Calculation of stress incurred from the VIV for each mode figure at different points with different flow velocity and in one span.

$$s_{i,il}(x_j) = 2.A_{i,il}(x_j).\left(\frac{A_{yi}}{D}\right).\psi_{il}.\gamma_s \qquad (4)$$

$\frac{A_{yi}}{D}$ can be found on the IL response model is shown in Figure 1.
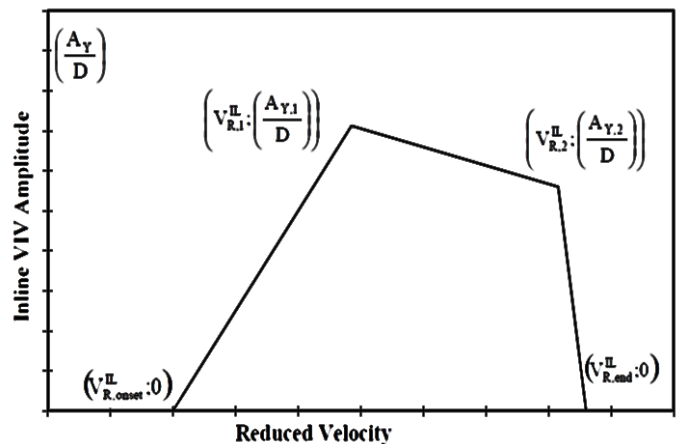

Figure 1. Response model in IL direction

5. Find the active mode at different points during the span and maximum tension exerted.

$$s_{max,il}(x_j) = \max\left(S_{i,il}(x_j)\right)$$
$$i = 1,2,\dots,n$$
(5)

6. If mode stress less than 10% of maximum tension can be regardless to simplify the model.

$$s_{n,il}(x_j) < 0.01.s_{max,il}(x_j)$$
(6)

7. The calculation of the reduction factor, for each mode.

$$\alpha_{i,i-1} = \begin{cases} 0.05 & if\ f_{i,il_{still}} < f_{i-1,il_{still}} \\ & and\ s_{i,il}(x_j) < s_{i-1,il}(x_j) \\ 1 & else \end{cases}$$
(7)

$$\alpha_{i,i+1} = \begin{cases} 0.05 & if\ f_{i+1,il_{still}} < f_{i,il_{still}} \\ & and\ s_{i+1,il}(x_j) < s_{i,il}(x_j) \\ 1 & else \end{cases}$$
(8)

$$\alpha = \alpha_{i,i-1}.\alpha_{i,i+1}(for\ i = 1,2,\dots,n)$$

8. The VIV stress in IL direction for different modes is calculated by Eq.(9):

$$s_{i,il}(x_j) = 2.\alpha_i.A_{i,il}(x_j).\left(\frac{A_\gamma}{D}\right).\psi_{il}.\gamma$$
(9)

9. The combined stress is calculated as follows:

$$f_{cyc,il(x_j)} = \sqrt{\sum_{i=1}^n f_{i,il}\frac{s_{i,il}(x_j)}{s_{comb,il}(x_j)}}$$
(10)

10. Calculation of VIV fatigue damage in IL direction with the flow velocity.

$$D_{fat_{ll_k}}(x_j) = f_{cyc,il(x_j)}.\left(\frac{s_{comb_{ll}}(x_j).SCF}{Mpa}\right)^{m(x_j)}.\frac{P_k}{\bar{a}(x_j)}$$
(11)

3.2 S-N Curve for VIV fatigue
Due to the high costs and high time required to do a lot of testing of fatigue and the number of test samples, it is necessary to take into considering statistical fatigue property. In this research has been used the standard fatigue test provided by ASME in the year of 2003 for the determination of a S-N curve with the minimum number of laboratory samples [12]. S-N Curve is one of the ways of calculating fatigue life. S-N curve, based on the input data of the fatigue test. According to the DNV-F-105, the Eq.(12) for the S-N Curve is presented.

$$\log N = \log \bar{a} - m\log \Delta\sigma$$
(12)

$\alpha\alpha$ is a constant coefficient corresponding to the S-N curve. S is also Standard Deviation compared to. To calculate the fatigue life with SN-Curve, fatigue must be a linear assumption.

$$D_{fatlife} = \sum_{i=1}^k \frac{n_i}{N_i} = \frac{1}{a}\sum_{i=1}^k n_i\,(\Delta\sigma_i)^m$$
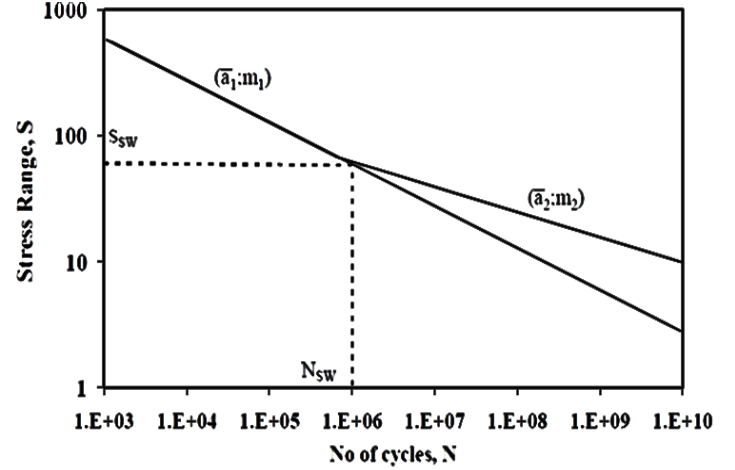(13)

Figure 2. The slope of S-N Curve [6]

4. Modeling
In this study, the pipeline modeled as a two-beam behavior and bending behavior. In order to pass up the question of the marine pipeline balance, the seabed was modeled with a rigid surface. For modeling of a free span, both ends of the pipe were fixed. To phenomenon simulation, the pipeline is located on the surface of the rigid seabed and not buried. In the load steps, the pipe gravity force is applied to the model first, followed by the internal pressure due to hydrocarbon passage, external pressure due to the water column, and temperature to match the effective axial force. Also, it is assumed that concrete coating is not effective on the weight forces and drag forces. The length of the pipeline on both was determined by following the DNV Code.

4.1. Free-Span Fatigue Analysis
VIV fatigue analysis for a single-span pipeline with a single-mode response is performed for a 30-inch gas flow line with 29.7 mm wall thickness at the water depth of 850(m). Studies have been carried out on four span lengths of 80, 100, 180, 250(m) that are exposed to flow at a range of 0.16 to 0.185(m/s) [13].

4.2. Environmental Loads
The sea pipeline is exposed to loads due to current and waves. The wave effect in deep water is neglected and only the effects of the current have been investigated. The effect of the current velocity by the Weibull distribution can be evaluated [14]:

$$F_X(x) = 1 - exp\left(-\left(\frac{x-\gamma}{\alpha}\right)^\beta\right) \quad (14)$$

In this regard, the estimated coefficients are based on the design.

Reduced current velocity ($V_R V_R$) and stiffness (K) are VIV fatigue parameters.

$$V_R = \frac{U_c + U_W}{D_c f_n} \quad (15)$$

$$K_S = \frac{4\pi m_e \xi_T}{\rho_w D_c^2} \quad (16)$$

The approximate amount of raw natural frequencies of structures can be gained from the DNV-F-105 that is:

$$f_1 \approx c_1 \cdot \sqrt{1 + CSF} \sqrt{\frac{EI}{m_e L_{eff}^4} \cdot \left(1 + \frac{S_{eff}}{P_{cr}} + C_3 \left(\frac{\delta}{D}\right)^2\right)} \quad (17)$$

$$P_{cr} = \frac{(1 + CSF)C_2 \pi^2 EI}{L_{eff}^2} \quad (18)$$

$$m_e = \left(\frac{\int m(s)\emptyset^2(s)ds}{\int \emptyset^2(s)ds}\right) \quad (19)$$

5. Case Study

Case studies in this paper are the actual numbers of the Ormen Lange gas field in western Norway in the Norwegian Sea. Free span specification in the case study to be considered according to table 2.

Table 1. Properties of case study

Characteristic	Value
Depth	850 [m]
Outer Diameter	762 [mm]
Wall Thickness	29.7 [mm]
Concrete thickness	8 [mm]
Water density	1025[kg/m^3 kg/m^3]
Steel density	7850 [kg/m^3 kg/m^3]
Significant Mean Yield Stress(SMYS)	450 [MPa]
Significant Mean Tensile Stress(SMTS)	540 [MPa]
Young's modulus (E)	207 [GPa]
Soil	Firm clay
Fluid density	150 [kg/m^3 kg/m^3]
Span Length	100 [m]
Span gap	1 [m]
Current velocity	0.16-0.165 [m/s m/s]
Current coefficient	α=0.12, β=1.55

6. Results & Discussion

The free-span subsea pipelines with different span lengths were modeled by the ABAQUS standard code. In this paper, the effect of VIV in the direction of CF is not considered due to the dominance of the IL direction. Table 2 shows the fatigue life in the IL direction for four different span lengths.

Table 2. Fatigue life for multi-span length sensitivity analysis

Case No.	L/D	In-line VIV fatigue life (year)	Fatigue life based on DNV (year)
1	80	1614.215	50
2	100	1352.79	50
3	180	209.314	50
4	250	112.752	50

According to DNV, VIV fatigue life is considered to be 50 years in the design of subsea pipelines. Table1 shows that the results of numerical simulations are very different from the DNV, which indicates that rule is over design.

The subsea pipeline has different dynamic behaviors based on the free span length. According to DNV-F-101 for each L/D ratio the pipeline as a modeled beam, cable or combination of beam and cable. In this research, investigated all possible pipeline behaviors across different span lengths. The result of a pipeline with different behaviors is present in figure3. According to figure1 Variations of VIV fatigue life in the pipeline with beam, behavior tends to be steeper than other pipeline behaviors, and as far as full cable behavior proceeds, changes occur with less slope, and VIV fatigue life changes slowly with length increases.
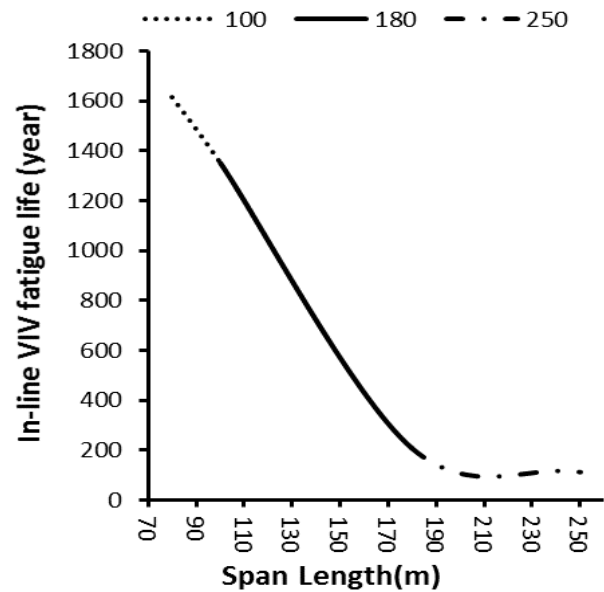

Figure 3. VIV fatigue life of subsea pipelines with different behaviors

The free span first mode frequency of the subsea pipeline depends on the axial force on the pipeline. Different parameters and phenomena are effective to determine the mentioned forces. The free span first mode frequency of the pipeline for different axial forces is shown in figure 4. The change of free span first mode frequency relative to the axial load is linear. In another word free span first mode frequency Independent on VIV parameters.
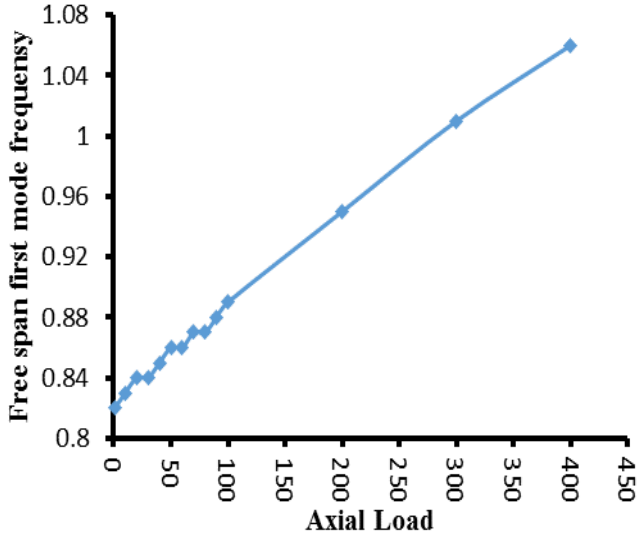

Figure 4. Free span first mode frequency of the pipeline relative to the axial load

Information on the trend of changes in VIV fatigue life with different span lengths exposed to currents with variable values is presented as a curve in figure 5. According to the curves in figure 5, increasing the current velocity increases VIV fatigue life. The rate of fatigue life in different lengths of the span is not the same. The pipeline has been faced with a significant increase in fatigue life by moving away from its beam behavior and moving toward cable behavior.
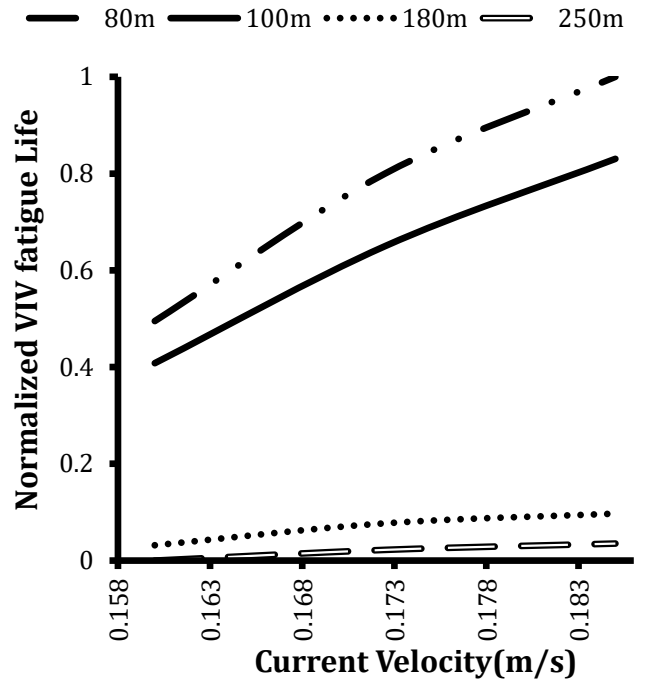

Figure 5. VIV fatigue life for different span lengths in variable current velocity

In this research, fixed supports one of the assumptions to determine VIV fatigue. For pipeline with L/D ratio, less than 80 behaves exactly like the beam.

For the pipeline like a beam, if snap support change to cantilever support, the VIV fatigue life increased 18% and support changes are independent to the current velocity.

Generally, pipeline parameters and environmental conditions that are associated with uncertainty are criteria for the design. Figure 6 illustrates probable failure per different span length and different current velocity. To appear probability results, the negative logarithm of the probability based on different flow rate is plotted in figure 7. 4 curves in the chart represent the increase in the probability of VIV fatigue. Fatigue probability changes greatly due to the pipeline behavior interface from beam to the cable.
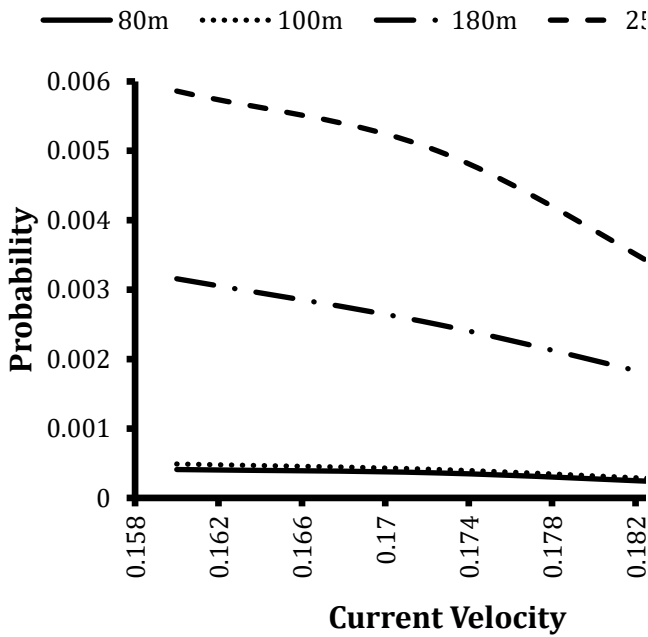
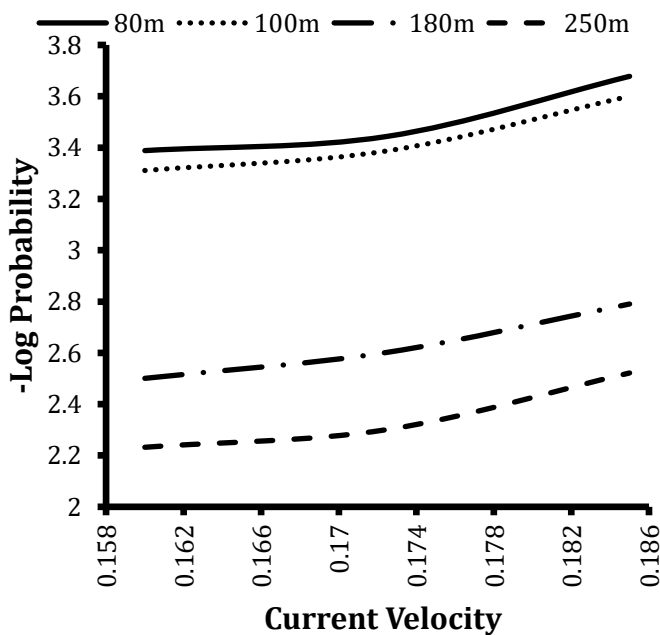**Figure 6. Fracture probability under the effect of VIV fatigue**

- The VIV fatigue damage of the pipeline with vertical displacement at one end is much greater than the pipeline with snap support. In other word by creating more vibration and displacement on one side of the pipeline reduces the fatigue life of 113 percent compared to snap.
- By reducing the span length from 250(m) to 80(m), VIV fatigue life increases by seven times. Maximum changes occur between cable and behavioral which the amount of these changes is reduced by 75%.
- Among the VIV effective parameters that affect pipeline fatigue, free span lengths are more effective and free span first mode frequency is independent of VIV parameters.
- Fatigue probability changes greatly due to the pipeline behavior interface from beam to the cable.

List of Symbols

E	Modulus of elasticity
k	Stiffness
V_R	current velocity
$C_1 - C_3$	boundary conditions coefficient
I	Inertia
CSF	Increase the stiffness factor of concrete
L_{eff}	Effective span length
m_e	Effective mass
D	Outside diameter
P_{cr}	Critical buckle load
Δ	Static displacement
S_{eff}	Effective axial force
Φ	Mode shape of boundary condition
α	Current coefficient
β	Current coefficient

Figure 7. -Logarithm fracture probability under the effect of VIV fatigue

7. Conclusions

In this study, based on pipeline modeling in the ABAQUS standard code and recommended model DNV-RP-F105, the fatigue life of the pipeline has been determined under different conditions and compared to the required value. The obtained results are presented:

8. References

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