# Cross-Flow Vortex Induced Vibration Fatigue Analysis of Persian South Gas Field Subsea Pipelines Due to Multi-Spanning

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## ARTICLE INFO

*Article History:*
Received: 24 May. 2016
Accepted: 15 Sep. 2016

*Keywords:*
subsea pipelines, fatigue analysis, natural frequency, multi spanning, vortex shedding

## ABSTRACT

Free-span in subsea pipelines occur at manmade supports, uneven seabed or pipeline crossing. Free spanning may induce pipeline vibration due to vortex shedding which makes pipeline susceptible to some failures such as fatigue, fracture, etc. Free spanning analysis is an important subject because fatigue is the most effective factor in reducing the pipeline design life. Free spanning analysis includes static analysis and dynamic analysis.
DNV-RP-F105 suggests a methodology of dynamic analysis for long pipeline with multi-mode responses, but the fatigue analysis method for multi-modes is not detailed. In addition, the fatigue analysis of multi-spanning pipeline is not clear. Based on the methodology of DNV-RP-F105 fatigue life relates to natural frequencies of pipeline, the method of determination of effective natural frequencies still is not clear.
In this paper, a fatigue analysis for multi-spanning pipeline in Persian south gas field is performed based on VIV analysis. ABAQUS FE model is developed to obtain the stress distribution and the natural frequency of each vibration mode for spanning pipeline on seabed with three multi-spans, then the fatigue analysis of VIV is carried out for the spanning pipeline based on DNV-RP-F105.

## 1. Introduction

Based on the high amount of subsea pipelines in transferring crude oil from wells to offshore platforms and also in exporting oil and gas from offshore facilities to onshore terminals, they play an undeniable role in offshore industries. As depth increase, the cost of repairing or replacing the linepipes is growing up, so assessment and exploration of what cause to decrease pipeline's serviceability lifetime is too much important in budget of project. Submarine pipelines can be laid on seabed in various methods (which depend on the basis of design (BOD)) either embedded in a trench (buried form) or laid on uneven seabed (unburied form). Because of the short time construction and economic consideration, unburied form is more common. In this method, however, the pipelines are subjected to some severe factors such as: free spanning, fatigue, fracture, etc. Free spanning mainly occurs as a consequence of uneven seabed and local scouring due to flow turbulence and instability (which is a resultant of artificial supports or pipeline crossing). Fatigue is the main consequence of free spanning. Resonance as main source of fatigue happens when external load frequency equal to the pipe natural frequency. Because fatigue is the most effective factor in decreasing design life time, free spanning analysis is an important item for designing subsea pipelines. DNV (2006) recommend a methodology for dynamic analysis of free spanning for long subsea pipelines, but number of Natural Frequencies for determination fatigue life is not clear.
In this study, ABAQUS software has been used to simulate structural response of subsea pipeline of 22$^{th}$ phase of South Persian Gas Field by considering three equal spans. Then the MATLAB software is used to calculate the fatigue life capacity due to Eigen frequencies and stresses based on the ABAQUS analysis results in cross-flow direction.
The following steps are performed to obtain the VIV fatigue damage of the subsea pipeline:

- Cross-flow Eigen frequencies and mode shapes are calculated at crossing.
- Fatigue life damages are calculated with Eigen frequencies and unit stress amplitudes in the

MATLAB software and then fatigue life can be calculated according to corresponding fatigue damages.
Finally, fatigue life is calculated by considering each natural frequency and effect of natural frequencies on fatigue life time is assessed.

## Finite Element Model

The pipeline is modeled as a 3D beam with PIPE31. Seabed and crossing supports were modeled with rigid surfaces by disregarding the pipe embedment for conservatism. Both ends of the pipe were fixed axially after the pipeline was completely laid down on the seabed with a nominal residual bottom-tension force. In the load steps, the pipe gravity force is applied to the model first, followed by the internal pressure, external pressure, and temperature to match the effective axial force [2].
After the model has been set at the appropriate loading directions, natural frequencies in the cross flow directions and corresponding mode shapes can be obtained.
The following aspects should be considered in the pipeline model:

- The pipeline coating effect is limited only to increase the pipeline submerged weight, drag forces, added mas and buoyancy, the stiffness and strength increase has been neglected.
- The pipeline element length should be in the order of the outer diameter of the pipeline.
- The boundary condition at both ends of the pipe model shall accurately represent the pipe-soil interaction and the continuity of the pipeline.
- Sufficient pipe model length at both sides of the span should be created to account the effect of adjacent spans.

## Fatigue Damage

The fatigue damage due cross-flow VIV is calculated based on DNV-RP-F105, the following fatigue criterion which is limited to stress cycles within the elastic ranges can be used for subsea free spanning pipeline fatigue assessment[[2][7]]. The fatigue criterion can be formulated as:

$$\eta . T_{life} \le T_{exposure} \quad [1] \qquad (1)$$

It is clear that the fatigue design life capacity must be longer than the exposure duration[3]. The relationship between the fatigue design life capacities, exposure time and fatigue damage is:

$$D_{fat-damage} = \frac{T_{exposure}}{T_{life}} . \eta \quad [1] \qquad (2)$$

## Cross-Flow VIV Fatigue Assessment for Multi-Mode Response

For subsea pipeline, the multi-span and multi-mode scenario, Cross-flow VIV fatigue life calculation procedures can be summarized as below based on DNV-RP-F105 [2], [6]:

- Gather the input data, including the pipeline design/operation data, soil data and environment data.
- Calculate the still water cross-flow Eigen frequencies $f_{i,cf-still}$ by ABAQUS
- Find out the dominant cross-flow mode (i="Dominant") for each span length at flow velocity $V_k$ (k=1 for the first step and the range is k=1,2,…,l$^*$),i.e. the largest cross-flow with the largest $A_{Z_i}/D$ value ($A_{ZDom}/D$ ) predicted from the response model for velocity $V_k$, then the "weak" and "negligible" cross flow mode can be determine by:

$$i = \begin{cases} "weak" & for \quad A_{Z_i}/D \ge 10\% \, A_{ZDom}/D \\ "negligible" & for \quad A_{Z_i}/D < 10\% \, A_{ZDom}/D \end{cases}$$

[1][6] (3)

- Calculate the stress induced at the cross-flow mode in the pipe location $x_j$ (j=1,2,…,n$^i$) along the span length for each cross-flow mode i (i=1,2,…,n$^*$) by the following formula:

$$S_{i,cf}(x_j) = \begin{cases} 1.2.A_{i,cf}(x_j).\left(\frac{A_{zi}}{D}\right).R_k.\gamma_s & i = "Dominant" \\ 0.5.2.A_{i,cf}(x_j).\left(\frac{A_{zi}}{D}\right).R_k.\gamma_s & i = "weak" \\ 0.0 & i = "negligible" \end{cases}$$

[1]] (4)

Where $A_{i,cf}$ is obtained by ABAQUS stress output report and $A_{Z_i}/D$ can be calculated based on the Cross-flow response model is shown in "Figure 1".

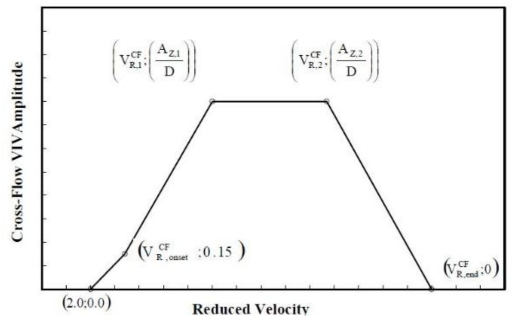


**Figure 1: Cross-flow response model generation principle [4]**

- Calculate the combined cross-flow induced stress at the location $x_j$ (j=1,2,…,m*) along the span length by the following formula:

$$S_{comb,cf}\left(x_j\right)=\sqrt{\sum_{i=1}^{n^*}\left(S_{i,cf}\left(x_j\right)\right)^2} \text{ [1][1]]} \qquad (5)$$

- Calculate the cycle counting frequency for this combined cross-flow induced stress at the location $x_j$ (j=1,2,…,m*) along the span length by the formula below:

$$f_{cyc,cf}\left(x_j\right)=\sqrt{\sum_{i=1}^{n} f_{i,cf}\frac{S_{i,cf}\left(x_j\right)}{S_{comb,cf}\left(x_j\right)}} \text{ [1][1]} \qquad (6)$$

Where:

$$f_{i,cf}=\begin{cases} f_{i,xf-RES} & for \quad i=\text{"Dominnant"} \\ f_{i,cf-still} & for \quad i=\text{"weak"} \\ 0 & for \quad i=\text{"negligible"} \end{cases} \text{ [1][1]]} \qquad (7)$$

$$f_{i,cf-RES}=f_{i,cf-still}\sqrt{\frac{\left(\rho_s/\rho\right)+C_a}{\left(\rho_s/\rho\right)+C_{a,CF-RES}}} \text{ [1]} \qquad (8)$$

$C_{a,CF-RES}$ value can be referred to the "Figure 2" below:

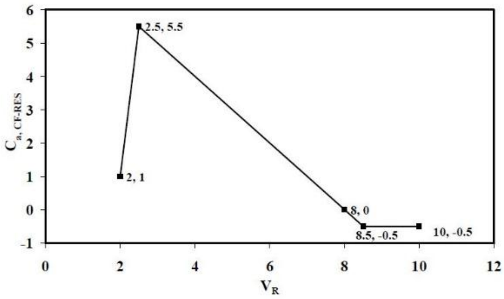


**Figure 2: $C_{a,CF-RES}$ as a function of reduced velocity [3]**

- Calculate the fatigue damage due to Cross-flow VIV at current flow velocity $V_k$ (for K=1, 2, …, l*).

$$D_{fat\_cf\_k}\left(x_j\right)=f_{cyc,cf}\left(x_j\right).\left(\frac{S_{comb\_cf}\left(x_j\right).SCF}{MPa}\right)^{m\left(x_j\right)}.\frac{P_k}{\bar{a}\left(x_j\right)} \text{ [1]} \qquad (9)$$

Where SCF is the stress concentration factor, $P_k$ is the current flow probability at $V_k$ by Weibull distribution. $m\left(x_j\right)$ is fatigue exponent by S-N curve and $\bar{a}\left(x_j\right)$ id characteristic fatigue strength constant.

- Calculate the Cross-flow VIV fatigue life:

$$D_{fat\_cf}\left(x_j\right)=\sum_{k=1}^{l^*}D_{fat\_cf\_k}\left(x_j\right) \text{ [1]} \qquad (10)$$

$$D_{fat\_cf}=max\left(D_{fat\_cf}\left(x_j\right)\right) \text{ [1]} \qquad (11)$$

for j=1,2,…,m*

$$T_{fat\_life\_cf}=\frac{\eta}{D_{fat\_cf}} \text{ [1]} \qquad (12)$$

**S-N Curve Theory for Multi-Span Fatigue Analysis**

The S-N curve is a simple and efficient method for pipeline fatigue analysis, where the S-N data are usually determined by fatigue test. According to the latest version of DNV offshore structure steel structure code DNV-RP-C203, the basic design S-N curve is given as:

$$log\,N=log\,\bar{a}-m\,log\,\Delta\sigma \text{ [1]-[3]} \qquad (13)$$

Where, N is the predicted number of cycles to failure for stress, $\Delta\sigma$ is the stress range, m is the negative inverse slope of S-N curve, $log\,\bar{a}$ is the intercept of the N-axis by S-N curve, it is given by the following formula:

$$log\,\bar{a}=log\,a-2s \qquad \text{[1]-[3]} \qquad (14)$$

Where a is the constant relating to mean S-N curve, s is the standard deviation of $log\,N$.

The fatigue life can be calculated based on the S-N curve under the assumption of linear cumulative damage by Palmgren-Miner and can be found from the following equation:

$$D_{fatLife}=\sum_{i=1}^{k}\frac{n_i}{N_i}=\frac{1}{a}\sum_{i=1}^{k}n_i\left(\Delta\sigma_i\right)^m \qquad \text{[1]-[3]} \qquad (15)$$

Where $D_{fat}$ is the accumulated fatigue damage, $\bar{a}$ is the intercept of the design S-N curve with the log N axis, m is the negative inverse slope of the S-N curve, k is the number of stress blocks, $n_i$ is the number of stress cycles in stress block i, $N_i$ is the number of the cycles to failure at constant stress range $\Delta\sigma_i$.

**Multi-Span Fatigue Analysis Case Study**

**Design Data**

VIV fatigue analysis for multi-span pipeline with multi-mode response is performed for 32$^{inch}$ gas flow with 28/8$^{mm}$ wall thickness at water depth of 64$^{m}$ in Persian Gulf. Span design procedure is determined by allowable static and dynamic loads on free span. Then

on-bottom roughness analysis is performed to determine actual spanning condition. Free span length in this case study is considered about $20^m$ and L/D=24.6. This case study is a line pipe of $22^{th}$ phase of south pars gas field complex.
The design data in VIV fatigue analysis are present in "Table 1".

**Table 1: Design Data for Multi-span fatigue analysis**

| Design Parameter | Unite | Value |
|---|---|---|
| Outer diameter of steel pipe | mm | 812.8 |
| Outer diameter of the pipe with coating | mm | 862.8 |
| Nominal wall thickness | mm | 28.8 |
| Pipeline model length | m | 200 |
| Pipe free span length L(m) | m | 20 |
| Water depth | m | 64 |
| Submerged weight at operation condition | N/m | 1110.56 |
| Current | | Short term bottom current probability |
| Soil Type | | Very soft Clay |
| Pipe Material | | API-5L-X65 |
| Steel Density | $Kg/m^3$ | 7850 |
| Young's modulus | GPa | 207 |
| Specified Minimum Yield Strength(SMYS) | MPa | 448 |
| Specified Minimum Tensile Strength(SMTS) | MPa | 535 |

## The Environment Loads

The environment data must be collected for the long-term variation of the wave and current climate. For deep water pipeline fatigue analysis, the wave induced oscillatory flow can be negligible and only the steady flow due to current is considered in the analysis. In this regards, DNV-RP-F105 define a parameter named α which is ratio of velocity of current ($U_c$) to summation of velocity of current and velocity of current induced by significant wave amplitude ($U_w$).

$$\alpha = \frac{U_c}{U_c + U_w} \quad [5],[6] \qquad (16)$$

So in deep water effect of wave are negligible and only effect of current should be considered.
Current velocity is described by Weibull distribution which α, β and ϒ will be determine by Design Basis.

$$F_X(x) = 1 - exp\left(-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right) \quad [5],[6] \qquad (17)$$

The current flow velocities varying from $0.5^{(m/sec)}$ to $0.7^{(m/sec)}$ have been considered for the pipeline fatigue life assessment. The probabilities of the current flow by Weibull distribution are present in "Figure 4".
Current reduced velocity and stability parameter are two parameters to control the vortex vibration resonance.

## Analysis Results

Calculation of accumulated fatigue life of subsea pipelines is a complicated and long-time process. For the sake of the clarity, the procedure of calculation cumulative fatigue life is drawn in "Figure 5". The pipeline natural frequencies are summarized in "Table 2". The natural frequencies which shown in "Table 2" are the same output of ABAQUS software.
These data are based on the pipeline configuration for the operation load condition. For these natural frequencies, no significant VIV damage will occur in the present bottom current velocity range.
Refer to "Table 2", it is evident that the accumulated fatigue life is fairly significant for 25 years of design life.
It is well known that fatigue assessment due to multi-spanning in subsea pipelines are dependent to many factors such as soil-pipe interaction, pipeline residual laying tension, seabed properties, wall thickness of linepipes, environmental condition, etc. For determining the effect of any parameter in accumulated fatigue life time, it is essential to perform a sensitivity.
In this paper, accumulated fatigue life is calculated by consideration of the natural frequencies in constant span length-diameter ratio, and it is concluded that the effect of the first three natural frequencies in calculation of accumulated fatigue life are undeniable. As the natural frequency increases, its effect in calculation fatigue life is decreased and vice versa.

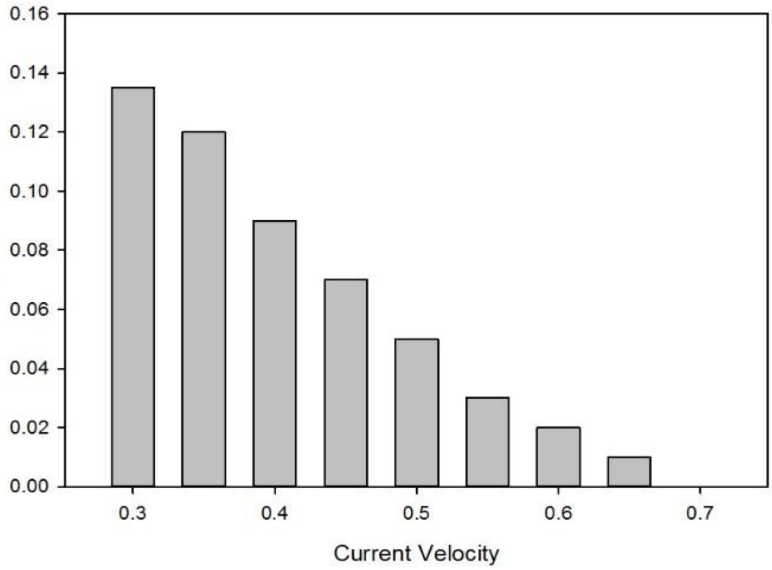


**Figure 4: The current velocity probability by Weibull**

**Table 2: fatigue damage results for the design condition**

| Mode Number | Natural Frequencies(Hz) | VIV Fatigue Life | Design Fatigue Life |
|---|---|---|---|
| 1 | 0.35 | 1768 | 25 |
| 2 | 0.93 | 1960 | 25 |
| 3 | 1.6 | 1972 | 25 |
| 4 | 2.1 | 1973 | 25 |

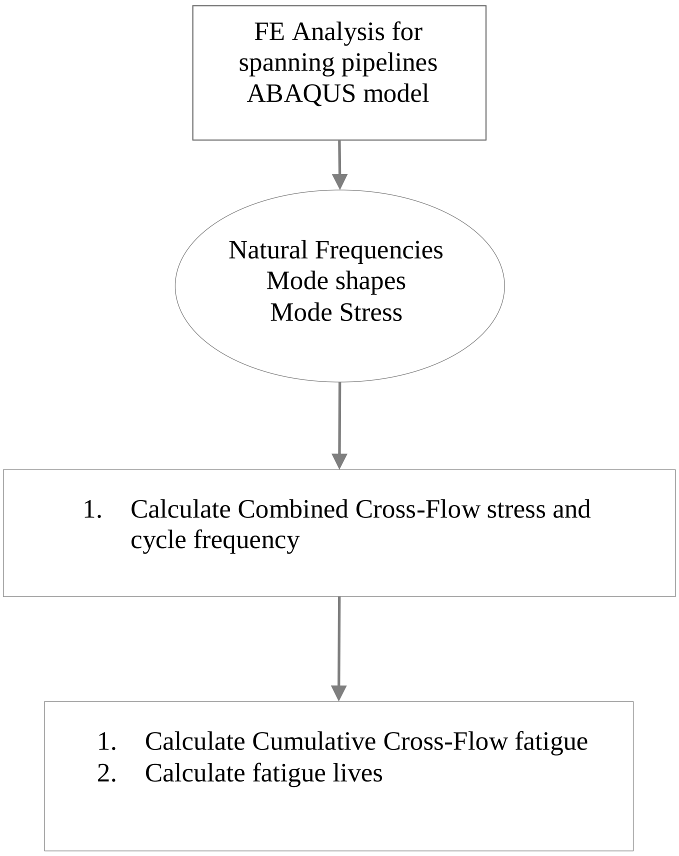


**Figure 5. Flowchart to calculate fatigue life**

## Conclusion

The current paper refers to the effect of natural frequencies in fatigue assessment of Iranian south pars gas field due to multi-spanning. It is concluded that (table 2) that the first-three natural frequencies make 99.5% of cumulative fatigue life of pipe and others make only 0.5% of that. Also it is concluded that the mode shapes with lower frequencies have more cooperation in fatigue life of a pipeline. Consideration of the first-three mode shapes of the pipeline is suitable and fairly good for calculation of cumulative fatigue life time due to multi-spanning in cross-flow direction. Also it can be observed that the rule (DNV-RP-F105) gives a pipe with an over design fatigue life.

**List of Symbols**

| | |
|---|---|
| $A_i$ | $i^{th}$ mode cross-flow unit amplitude stress |
| $\left(A_Z/D\right)$ | Normalized cross-flow VIV response |
| a | constant relating to mean S-N curve |
| $C_{a,CF-RES}$ | added mass coefficient |
| D | Pipe outer diameter (include any coating layer) |
| $D_{fat}$ | Deterministic fatigue damage |
| F(x) | cumulative fatigue damage |
| $f_v$ | dominating vibration frequency |
| $f_i$ | $i^{th}$ eigen frequency of span cross-flow( $f_{n,CF}$ ) natural frequency |
| $f_{cyc}$ | Frequency used for fatigue stress cycle counting in case of multimode response |
| k | number of stress blocks for fatigue damage or number or flow velocity ranks |
| $l^*$ | number of flow velocity rank |
| m | fatigue exponent or negative inverse slope of S-N curve |
| $m^*$ | Number of ABAQUS pipeline mode node |
| $m_e$ | effective mass per unit length |
| M | negative inverse slope of S-N curve |
| $n^*$ | number of VIV modes |
| N | number of independent events in the return period |
| $N_i$ | number of cycles to failure at constant stress range $\Delta\sigma_1$ |
| $n_i$ | number of stress cycles for i'th stress cycle |
| Pi | Probability of occurrence at flow velocity $V_k$ by Weibull |
| $P_{Hs,T_p,\theta}$ | Probability of occurrence of each individual sea-state |
| $T_{life}$ | fatigue design life capacity |
| s | the standard deviation of LogN |
| Si | i’th stress range |
| t | pipe wall thickness or time |
| $U_s$ | significant wave-induced flow velocity normal to the pipe, corrected for wave direction and spreading |
| $U_c$ | current for wave direction and spreading |
| $V_k$ | flow velocity at rank k |
| $x_c$ | return period value |
| $x_j$ | the axial location coordinate for the pipeline model at node j |

**Greek symbols**

| | |
|---|---|
| $\alpha$ | Weibull scale parameter |
| $\beta$ | Weibull shape parameter and relative soil stiffness parameter |
| $\gamma$ | Weibull location parameter |
| $\gamma_s$ | safety factor on stress amplitude |
| $\gamma_{on,CF}$ | safety factor on onset value for cross-flow |
| $\gamma_f$ | safety factor on natural frequency |
| $\sigma$ | stress, or standard deviation |

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