

The Significance of Low Velocity Near Bottom Currents on the In-Line Vortex-Induced Vibration Response of Rigid Subsea Jumpers

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Abstract

Subsea jumpers are susceptible to in-line and cross-flow vortex-induced vibration (VIV) fatigue damage due to bottom currents. From a design viewpoint, longer and less flexible jumpers are desirable in order to mitigate the effects of stresses due to high temperature and high pressure. The downside of this design is that these jumpers have low natural frequencies. A low velocity bottom current can, therefore, result in VIV excitation in the jumper. Cross-flow VIV amplitudes are typically much higher than in-line VIV amplitudes, but it is noted that the frequency of cross-flow VIV excitation is higher than the in-line VIV excitation frequency. In addition, the probability of occurrence of low velocity currents that result in low frequency vibration, is high. Therefore, the in-line VIV fatigue response of the jumper cannot be neglected, and may result in a requirement for vortex-suppression devices such as strakes.

The objective of this paper is to highlight the susceptibility of the subsea jumpers to in-line VIV due to low velocity near bottom currents. An illustrative example of a rigid jumper located in 1,300ft water depth, West Africa is presented.

Introduction

Subsea Jumpers

Welded steel pipeline and flowline jumpers are commonly employed in subsea design to accommodate the expansion and contraction associated with changes in temperature and pressure. They are often used to connect the moving end of a pipeline or flowline with a fixed point on a manifold, tree, platform spool, or even another pipeline. The same physical characteristics that make them useful for accommodating large expansions make them susceptible to vortex induced vibration. A typical jumper may have 5 or 6 bends, and have an unsupported length of over 100 feet. Such a structure will have a very low natural frequency and low structural damping. Figure 1 shows a schematic diagram of a typical rigid jumper.

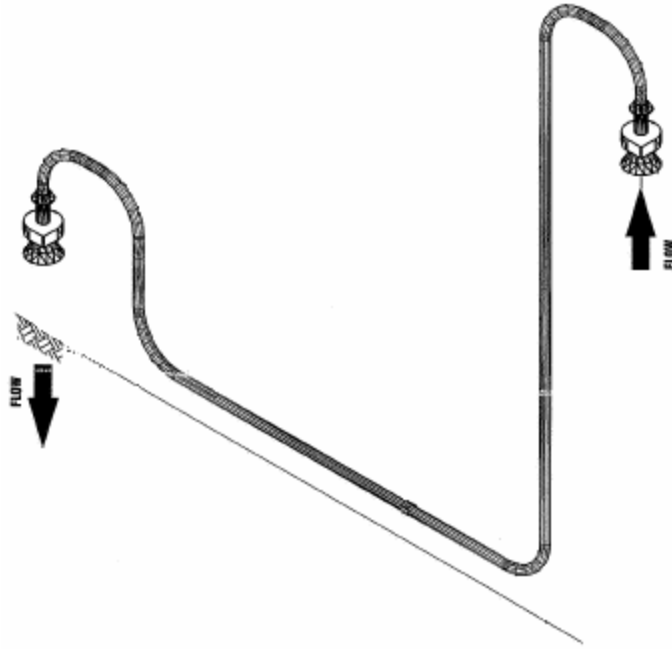


Figure 1 – Typical Jumper Configuration

Vortex-Induced Vibrations (VIV)

The presence of near bottom currents can result in vortex-induced vibrations (VIV) of the subsea jumpers. Two types of VIV are addressed. These are as follows:

- Cross-flow VIV
- In-line VIV

During cross-flow VIV the jumper motion is perpendicular to the flow of the current. During in-line VIV, the jumper motion is parallel to the direction of the current as shown in Figure 2.

The first two structural mode shapes are shown in Figure 3 and Figure 4. The predominant motion in mode 1 is out of plane to the jumper. Therefore this first mode will be susceptible to in-line VIV when the current is normal to the plane of the jumper. The displacements in mode 2 are in the plane of the riser. Flow normal to the riser plane can excite potentially excite this mode in cross flow VIV.

For a given current velocity the in-line forcing function is twice the frequency of the cross-flow forcing function. This means that, all else being equal, in-line VIV would be predicted for a current speed half of that required to excite cross flow VIV.

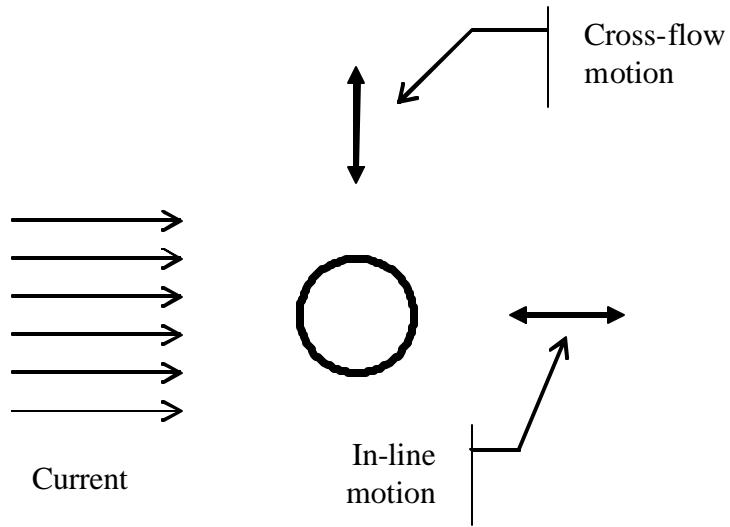


Figure 2 – In-line and Cross-flow Motions

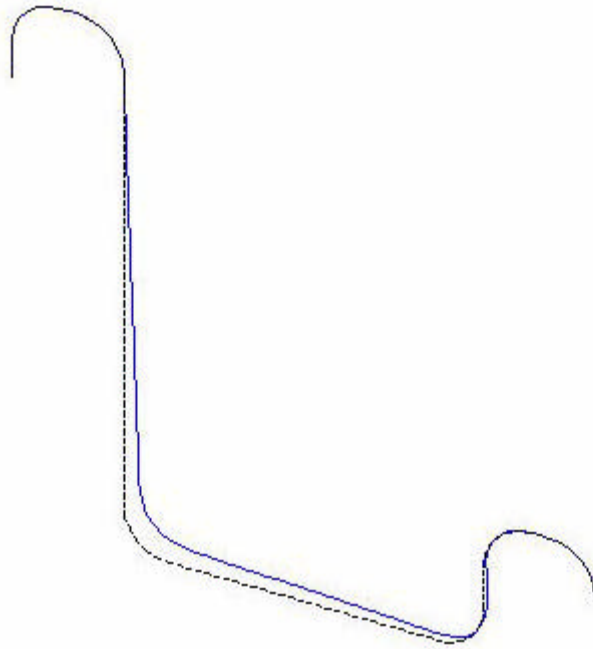


Figure 3 – In-line Excited Mode Shape of the Jumper (Mode 1)

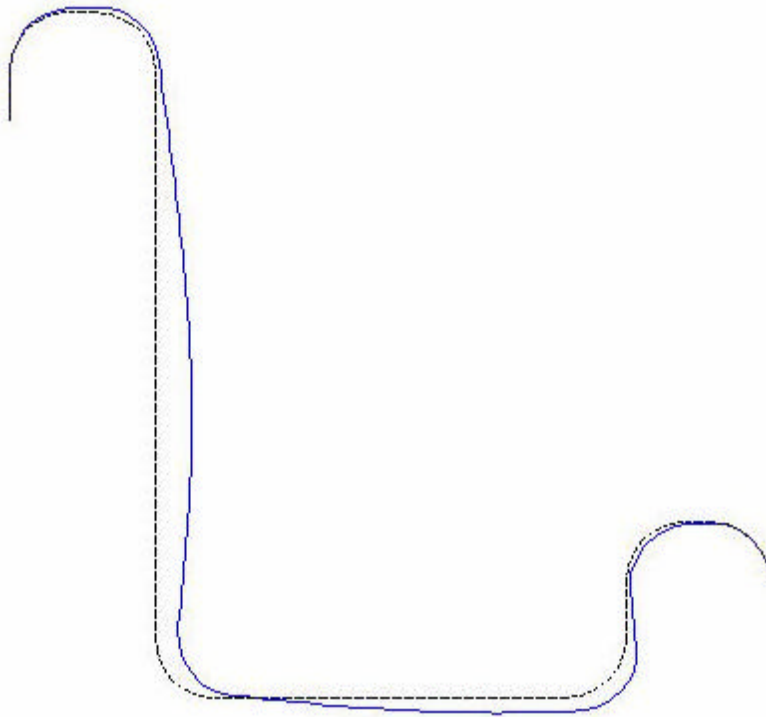


Figure 4 – Cross-flow Excited Mode Shape of the Jumpers (Mode 2)

Analysis Methodology

Software Tool

Static analysis of the jumper considered in the test study is conducted using the finite element analysis tool, ANSYS [Ref. 4]. Modal analysis is then conducted on the static models in ANSYS to extract the natural frequencies of the jumper.

Modeling

The jumper is modeled in ANSYS using pipe elements. The bends for each of the jumpers are modeled with the appropriate bend radius taken into account. The jumper model includes the internal fluid and added mass effect. The jumper fatigue is studied at the critical “hotspots” as shown in Figure 5.

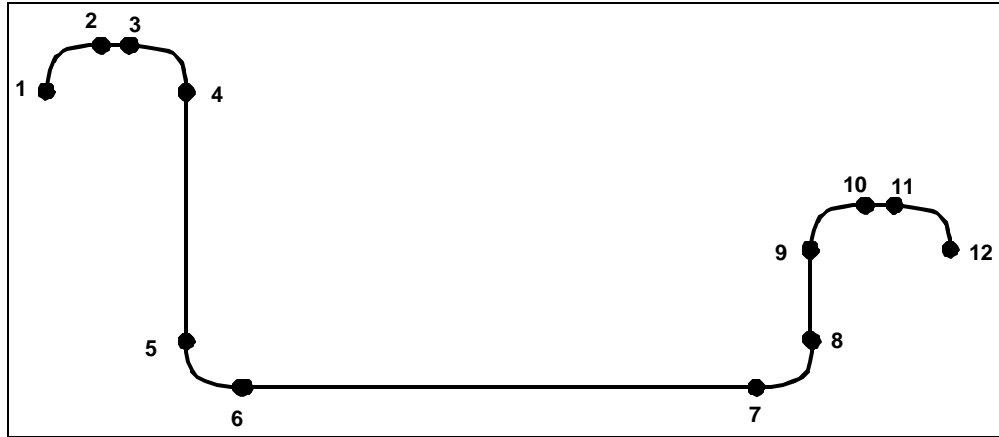


Figure 5 – Critical Fatigue “Hotspots” in the Jumper

Theory

The in-line and cross-flow response models are constructed using DNV-RP-F105 guidelines. To determine whether or not a structure experiences in-line and cross-flow VIV, the natural frequency is compared with the vortex shedding frequency, both of which have partial factors of safety applied on them. In-line or cross-flow VIV occurs when the condition in Equation 1 is satisfied.

Equation 1 :
$$\frac{f}{g_f} > \frac{U}{V_R \cdot D} \cdot g$$

Where,

- f Natural frequency (in-line or cross-flow) of the jumper
- U Maximum flow velocity
- V_R In-line or cross-flow onset value for reduced velocity
- D Hydrodynamic diameter of the jumper
- γ_f Factor of safety on the natural frequency for in-line or cross-flow VIV
- γ Screening factor for in-line or cross-flow VIV (Note: In-line screening factor takes into account the length of the jumper)

Typical response models are shown in Figure 6 and Figure 7. The response amplitude from the diagrams corresponding to each frequency is used to calculate stress range and hence, damage.

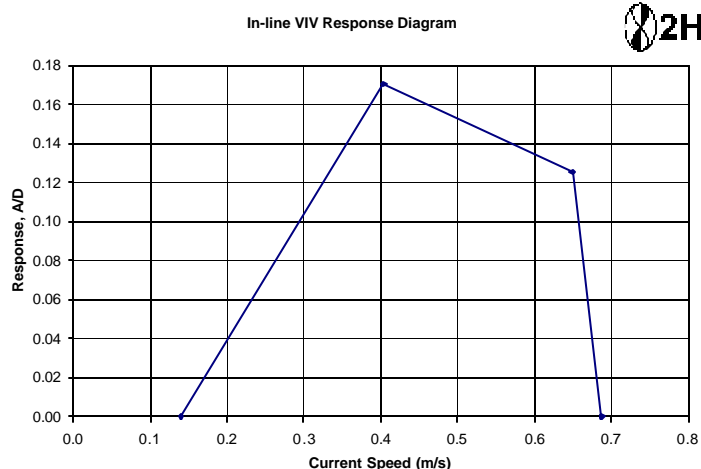


Figure 6 – Typical In-line VIV Response Diagram

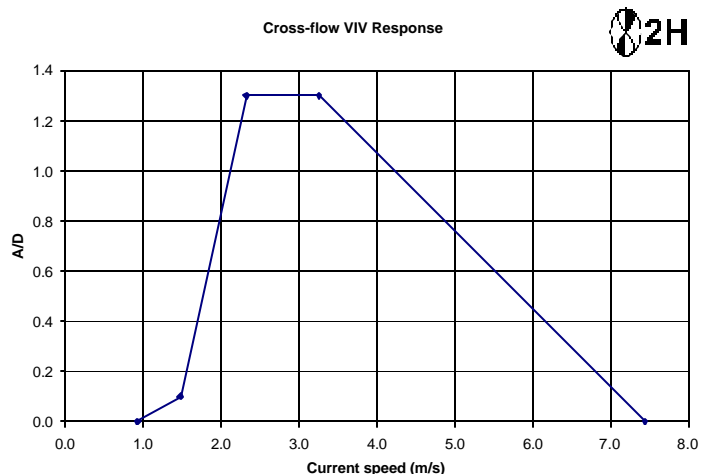


Figure 7 – Typical Cross-flow VIV Response Diagram

Case Study

Analysis

To illustrate the susceptibility of the subsea jumper to in-line VIV due to near bottom currents, results of VIV analysis of a 16inch subsea rigid gas export jumper is presented. This jumper is to be located at 1280ft water depth at the base of a compliant tower in offshore West Africa. The steel jumper connects the bottom of the export riser, located at 80ft above the mudline to the pipeline end termination (PLET) located on the seabed. The service life is 25 years. The jumper is expected to encounter sour service in its service life.

The export jumper properties are given in Table 1 below. The environmental data considered for the analysis is given below in Table 2. The table gives current speeds with

corresponding probability of occurrences. The extreme events have a 3 hour duration. The current is assumed to be uniform over the jumper length and perpendicular to the plane of the jumper. An inertial coefficient of 2.0 is assumed for the jumper.

	16 inch
Outer Diameter (mm, inch)	406.4, 16.0
Wall Thickness (mm, inch)	22.2, 0.875
API 5L Grade	X60
Coating	FBE
Anti-Corrosion Coating (mm, inch)	0.4064, 0.016
Coating Density (kg/m ³ , pcf)	1442, 90
Corrosion Allowance (mm, inch)	0
Internal Fluid	Gas
Internal Fluid Density (kg/m ³ , pcf)	181, 11.3
Design Pressure (MPa, psig)	20.68, 3000
Design Temperature (degC, degF)	85, 185
Horizontal Distance between Jumper ends (m, ft)	30.626, 100.48
Vertical Dimension (highest pt to lowest pt along jumper) (m, ft)	26.304, 86.3
Sour Service Expected?	Yes

Table 1 – Export Jumper Properties

	Percentage Exceedence	Percentage Occurrence	Current Velocity	
			m/s	kts
Persistence Current Data	100.00	0.00	0.00	0.0000
	100.00	0.00	0.05	0.0972
	97.77	2.23	0.10	0.1944
	78.46	19.31	0.15	0.2916
	46.19	32.27	0.20	0.3888
	23.61	22.58	0.25	0.4860
	12.51	11.10	0.30	0.5832
	6.72	5.79	0.35	0.6804
	3.70	3.02	0.40	0.7776
	1.34	2.36	0.45	0.8748
	0.34	1.00	0.50	0.9720
	0.00	0.34	0.55	1.0692
Extreme Current Data	100 yr **	3.42E-04	0.8230	1.6
	10 yr **	3.42E-03	0.7202	1.4
	5 yr **	6.85E-03	0.6687	1.3
	1 yr **	3.42E-02	0.5658	1.1

** Assuming 3 hr event

Table 2 – Bottom Current Speeds

An F2 class fatigue curve [Ref. 2] is assumed for the outer surface of the critical welds. For the internal surface of the jumper, this curve is modified with a reduction factor of 4

to account for sour service. Research is still underway to determine whether this factor is appropriate. A stress concentration factor (SCF) of 1.25 is assumed as an “achievable” figure. The DNV-RP-F105 methodology uses partial factors of safety in the calculation of damage, as summarized in Table 3.

DNV-RP-F105 Partial Safety Factors			
Factor	Description	Value	Comment
γ_s	factor on stress	1.0	Value is applied to stress range in damage calculation.
γ_f	factor on frequency	1.15	Value affects the bounds of the response diagram
γ_k	factor on stability	1.30	Value is used in calculating response amplitude. Higher number lowers stability and increases response.
γ_{on}	factor on onset of VIV	1.10	Effectively lowers the current speed required to excite jumper.
η	usage factor for high safety class	0.25	Locations of operations within a minimum distance of 500m around the platform are classified as high safety class locations [Ref. 3]

Table 3 – Summary of Partial Safety Factors in Methodology [Ref. 1]

Results

The modal analysis is conducted in ANSYS using 3-dimensional coordinates. The consecutive modes are distinctly different in that they tend to be either predominantly in-plane or out of plane. The natural frequencies are categorized as in-plane or out of plane modes. The lowest natural frequency is always out of plane and, in this case, approximately one third the natural frequency of the cross-flow mode as shown in Table 4.

Mode	T(s)	Frequency (Hz)	Type of Mode
1	2.66	0.38	In-line
2	0.76	1.31	Cross-flow
3	0.72	1.39	In-line
4	0.48	2.09	In-line
5	0.47	2.13	Cross-flow
6	0.30	3.34	Cross-flow
7	0.25	4.05	In-line
8	0.22	4.51	Cross-flow
9	0.19	5.30	In-line

Table 4 - Natural Frequencies from Modal Analysis of 16inch Jumper

The analysis predicts that the 16inch jumper will experience in-line VIV but not cross-flow VIV. The plots shown in Figure 8 and Figure 9 show the near bottom current velocities with their respective percentage exceedence along with the in-line and cross flow response diagram. Figure 9 shows that it takes approximately a current of 0.9m/s to experience cross-flow VIV excitation.

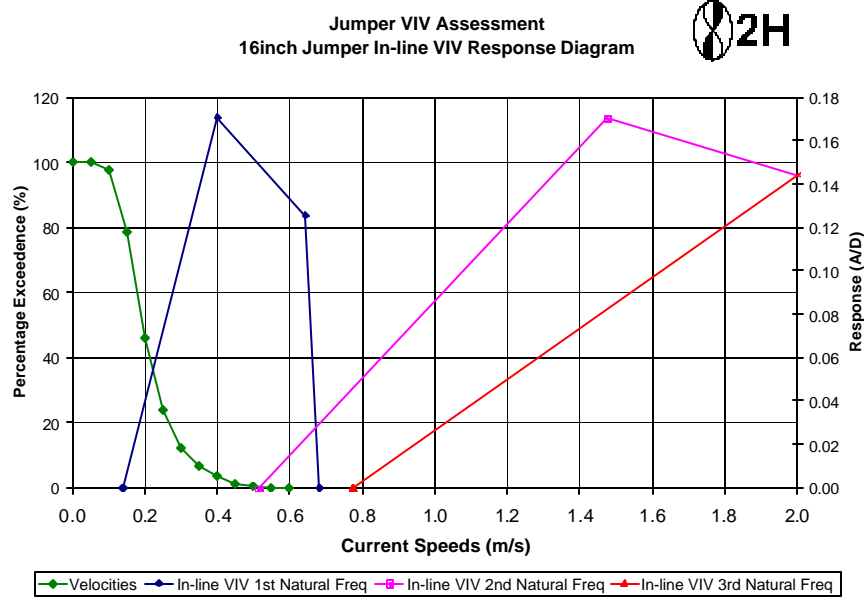


Figure 8 – In-line VIV Response Diagram

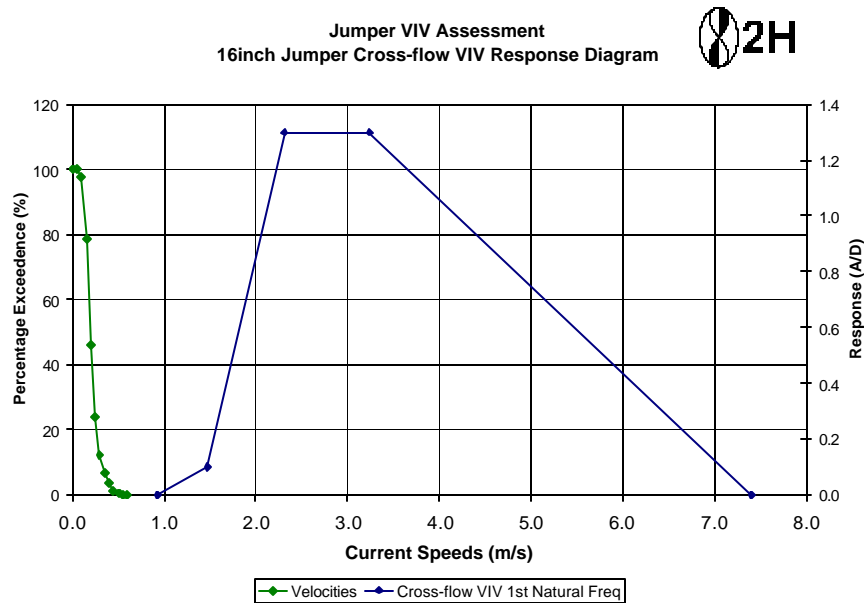


Figure 9 – Cross-flow VIV Response Diagram

The fatigue damage in the jumper from each bottom current is calculated. Where more than one mode is potentially excited by a current, the most damaging mode is assumed to prevail. Fatigue lives are calculated at the weld locations shown in Figure 5. The cumulative damage is calculated at each location factoring the damage with the probability of occurrence of the corresponding current. The damage is then summed as per Miner’s rule. The location of the maximum in-line and cross-flow VIV fatigue damage around the circumference of the jumper is shown in Figure 10.

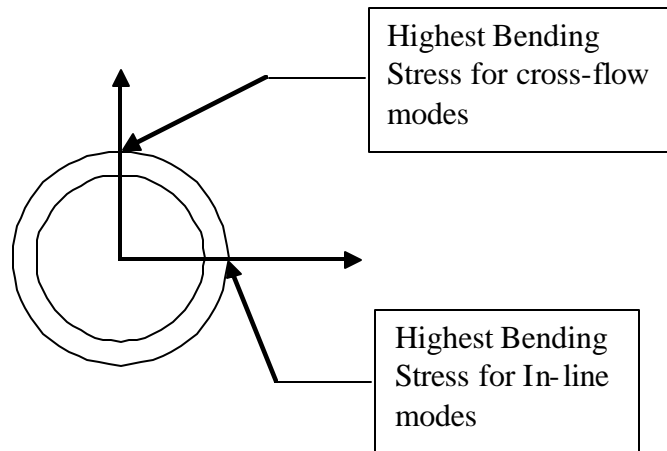


Figure 10 – Location of Peak Stresses for In-line and Cross-flow Modes

The minimum fatigue lives along the 16inch gas export jumper without VIV suppression devices such as strakes are given in Table 5. The results show that the minimum fatigue lives are far below the required minimum of 25years and hence the jumper requires strakes to suppress VIV. The strakes are assumed to result in an 80% reduction in vibration amplitudes. Therefore the resulting fatigue damage is reduced by a factor of $(1/(1-0.8)^3)$, i.e. 125. The minimum fatigue lives of the 16inch straked jumper are given in Table 6. The results show that strakes are required for the jumper to have adequate fatigue life.

Jumpers		In-line VIV Fatigue Lives (years)	Cross-flow VIV Fatigue Lives (years)
		SCF = 1.25	SCF = 1.25
16inch	OD	3.1	VIV not Expected
	ID (Sour Service)	1.1	

Table 5 – Minimum Factored VIV Fatigue (years) for Unstraked Jumper

Jumpers		In-line VIV Fatigue Lives (years)	Cross-flow VIV Fatigue Lives (years)
		SCF = 1.25	SCF = 1.25
16inch	OD	389	VIV not Expected
	ID (Sour Service)	138	

Table 6 – Minimum Factored VIV Fatigue Lives (years) for Straked Jumper

Discussion of Analysis

The issues addressed in this case study are typical of those encountered in any jumper VIV assessment. As with any analysis, the choice of input parameters will drive the analytical outcome. There is always some degree uncertainty in the input parameters. Some of these are discussed as follows:

- Environment:
 - Sparse environmental data: The subsea jumper is located offshore at a water depth of almost 1300ft. There is a paucity of long term current data at this ocean depth.
 - Directionality: Apart from the uncertainties in the actual bottom current speeds and their occurrence probabilities, the data on the direction of the current loading is also quite sparse. The current is, conservatively, assumed to be perpendicular to the jumper plane.
- Fatigue parameters:
 - Fatigue Curve: Jumpers are not traditionally designed as fatigue critical components and the welds are not qualified for fatigue by test. Therefore a conservative choice of a fatigue curve is appropriate.
 - Stress concentration factors (SCFs): One of the uncertainties has to do with the level of quality control of welds on joints. A change in SCF seriously impacts the fatigue prediction therefore fabrication tolerances which govern the selection of SCF must be verified.
 - Sour Service: Presence of sourness in the hydrocarbon has a detrimental effect on the fatigue performance of the jumper. Quantifying this effect is currently the subject of much research in the industry.

In addition to the input parameters the analytical model also drives the VIV response prediction. Although the theory predicts the response, there are no test data or observations that close the loop and confirm that in-line VIV actually occurs at very low velocities like 0.2m/s in subsea jumpers.

Conclusions

- Unlike risers and spanning pipelines, which have orthogonal modes at similar frequencies, jumpers have out of plane modes at much lower frequencies than in-plane modes. This predisposes them towards in-line VIV.

- Despite the low amplitude of response, in-line VIV cannot be dismissed out of hand. The high probability of occurrence of the currents results in a high damage prediction.
- Although DNV-RP-F105 is directed towards spanning pipelines, the response functions are applicable to jumpers also. However, modal analysis with FEA is required.

References

1. DNV-RP-F105 “Free Spanning Pipelines” March 2002.
2. DnV – “Fatigue Analysis for Mobile Offshore Units”. DnV Classification Note no. 30.2, Aug 1984
3. DNV-OS-F101 “Submarine Pipeline Systems”, 2000.
4. Swanson Analysis Systems Inc – “ANSYS/Structural Finite Element Analysis Software.” Version 6.0, April 2002.