SUBSEA JUMPERS VIBRATION ASSESSMENT

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ABSTRACT

Subsea rigid jumpers which are used to connect flowlines and risers to other subsea structures are inherently susceptible to vibration because they must be flexible enough to accommodate translation of the flowline, installation tolerances and settlement of pipeline end terminations (PLETs.) In locations where there are bottom currents, the jumpers can be subjected to vortex induced vibrations. When internal flow rates are high, they are susceptible to flow induced vibration, and they may also be excited by slugging. In some cases, the design constraints force the designs to be 3 dimensional and employ strategies to enhance damping.

This paper describes a methodology for assessing subsea jumpers for vibration induced fatigue. The method employs a combination of transient dynamic, harmonic and modal finite element analysis with the VIV tool SHEAR7. The methodology is able to show generally improved VIV fatigue lives compared to more traditional methods based on DNV-RP-F105 because of the ability to define current loading over the jumper length and to assess the effects of strakes and coulomb damping. Further, the methodology is also capable of assessing the effect of tuned vibration dampers which are sometimes used to suppress FIV.

Keywords: Jumper, VIV, Slugging, Fatigue

INTRODUCTION

Subsea jumpers are rigid pipe sections that connect subsea architecture such as pipelines to manifolds, flowlines to trees, or pipelines to risers. The jumpers are designed with bends to allow for expansion and contraction of the flowline or pipeline due to changes in pressure and temperature. Jumpers are susceptible to vibration fatigue from a variety of sources such as external environment, internal flow turbulence and slug movement. Anecdotal reports of jumper failure are available and such failures have adverse effects on safety, environment, and production. Further, remoteness of these jumpers makes repair difficult and costly.

This paper presents practical analysis methods to determine jumper fatigue damage. The fatigue components studied here are VIV and slugging. VIV of risers is well studied in the industry and empirical tools such as SHEAR7, VIVA and VIVANA are available. In the recent years, a great deal of data has been gathered on risers because of the high consequence of riser failure. However, little or no data exists in the public domain on jumper VIV response. CFD based fully coupled analysis has been used in recent papers for jumper vibration analysis[1]. CFD is a robust tool but is computationally expensive. At the other end of the spectrum is the usage of the spanning pipeline code DNV-RP-F105[2] which is simple to use but conservative for jumper analysis. The present work uses the latest version of SHEAR7 (v4.7) [3] to evaluate jumper fatigue from a sheared current profile. SHEAR7 offers advantages over DNV-RP-F105 by allowing hydrodynamic damping of power out zones, flexibility to include strakes and external dampers. In addition to predicting the amplitude of crossflow VIV, SHEAR7 v4.7 provides lift curves to simulate first mode inline VIV.

There are two primary phenomena caused by internal fluid slugging that can be responsible for fatigue damage of a rigid jumper carrying multi-phase fluids. Firstly, changes of internal fluid weight causes a change in the deflected shape of the rigid jumper. Secondly, repetitive inertial forces are applied on the jumper bends as the slugs pass through. In this work, the gravity loads are calculated by tracking a slug’s position with time and applying the change in weight as a point load on each location that the slug passes through. Similarly, a time series of inertial forces is calculated for each location through application of Newton’s Second Law for a finite control volume. It is assumed that the fluid velocity along the pipe’s length is constant and the flow is laminar. These force timetraces are then applied to a rigid jumper model in a transient finite element analysis and fatigue damage is calculated using a rainflow counting approach. Typically slugging is described in statistical terms with the slug frequency, length, and sometimes density being treated as random variables. The presented approach is pragmatic for assessment of large number of loading conditions that typical jumper design problems often present. In this approach the
sensitivity to a range of slugging characteristics can be assessed relatively quickly. In contrast, the CFD approach requires considerably more effort to assess similar structural effects. [4][5][6].

There are other sources of jumper vibration that are not discussed in detail in this paper. These include wave induced fatigue in shallow water depths, FIV generated from turbulence and cyclic loading on jumper from pipeline expansion and contraction. Turbulent flow induced vibration has been observed in offshore fields and typically the amplitude of FIV is small. Correct simulation of turbulence is not trivial and requires a coupled fluid structure analysis. A recent paper [7] recommends safety factor of 15-20 for flow induced turbulence. The forcing function for FIV has not been well defined for application to jumper design problems and monitoring programs are required for FIV determination.

In the assessment of fatigue, the loading from adjacent structure should not be overlooked. In the case of riser base jumpers, the riser motions may result in displacements of the jumper. For flowline jumpers, under the operational variations of pressure and temperature, the adjacent pipeline will experience cycles of expansion and contraction which will generate displacement of the rigid jumper end connection. The consequent fatigue stress cycles in the jumpers can be captured using an FE model, and a histogram of stress can be constructed with knowledge of the pressure and temperature variations.

**NOMENCLATURE**

- A/D – Ratio of amplitude of motion to diameter
- CFD – Computational Fluid Dynamics
- FIV – Flow Induced Vibration
- JIP – Joint Industry Program
- PLET – Pipeline End Termination
- SCF – Stress Concentration Factor
- TRW – Topographic Rossby Waves
- VIV – Vortex Induced Vibration

**STUDIED JUMPER GEOMETRY**

A multi-planar jumper is selected for the study. The jumper is shown in Figure 1. Multi-planar jumpers provide increased flexibility compared to traditional M shapes but can be susceptible to increased fatigue loads from bending and torsion loads. The jumper is made of thick welded steel and is composed of two bends in 3D space. The pipe OD is 508mm and wall thickness is 11mm. The jumper is restrained near the top with a clamp modeled as fixity in the present study. The jumper is restrained in the lateral directions by a sliding clamp in the middle of the vertical section. Seabed support is provided in the form of grout bags in the third leg (along X axis). The middle span (aligned close to Y axis) is unsupported. The jumper touch down point is close to the grout support. The FE model of the jumper includes seabed interaction using vertical and lateral soil springs. Soil stiffness is calculated based on small displacement dynamic pipe/soil interaction model proposed by STRIDE JIP [8][9]. The internal fluid of the jumper is assumed as 815 kg/m³ crude.

**MODAL ANALYSIS**

Modal analysis is carried out using the nonlinear finite element program ANSYS [10]. Three dimensional rendering of the jumper in ANSYS is shown in Figure 2. Results of the modal analysis are used as input to the SHEAR7 program. SHEAR7 requires mode shapes, normalized in terms of A/D, the nodal angles of the modes and the curvature. However, in the procedure used, SHEAR7 is used to predict the amplitude of VIV motion, but fatigue damage is calculated independent of SHEAR7. Therefore, dummy values can be supplied for curvature. The procedure for modal analysis is as follows:

- Extract normalized mode shapes in ANSYS. These are normalized with respect to diameter and formatted for input to SHEAR7;
- Extract element bending moments in the three directions and normalized with respect to modal displacement amplitude of 1 diameter. These values are used to calculate the maximum absolute value principle stress at 8 points around the circumference of the pipe;

Modes 1 through 3 are shown in Figure 3, Figure 4 and Figure 5 respectively. All three modes correspond to bending of the vertical section below the clamps about the global Y axis (sideways movement). Modal frequency and peak curvatures of modes 1 through 4 are listed in Table 1. Modal shapes along length are illustrated in Figure 6. Modes 1 and 2 have antinodes in the middle span of the jumper. Modes 3 and 4 demonstrate double antinode characteristic. In these plots, x/L=0 corresponds to the pipeline end of the jumper on the seabed while x/L=1 is the top of the vertical section. The first (vertical to seabed) bend and second bend correspond to x/L of
approximately 0.75 and 0.5 respectively. The curvature along jumper length plot is shown in Figure 7. The highest curvatures for modes 1 and 2 are at the sliding support clamp on the vertical section of the jumper. Secondary peaks exist at the grout support location and in the middle span. The highest fatigue damage rates are expected to occur at these locations.

### Table 1 - Modal Frequencies and Peak Curvatures

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Frequency (Hz)</th>
<th>Peak Curvature (1/m²)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.35</td>
<td>9.25E-03</td>
</tr>
<tr>
<td>2</td>
<td>0.48</td>
<td>7.92E-03</td>
</tr>
<tr>
<td>3</td>
<td>0.69</td>
<td>1.46E-02</td>
</tr>
<tr>
<td>4</td>
<td>1.09</td>
<td>1.32E-02</td>
</tr>
</tbody>
</table>

¹/ Corresponds to normalized mode shape

Figure 2 - ANSYS Model of the Jumper

Figure 3 - Mode 1

Figure 4 - Mode 2

Figure 5 - Mode 3

Figure 6 - Modal Shape along Jumper Length
VIV ANALYSIS USING SHEAR7

SHEAR7 is used in this work to analyze both crossflow and inline VIV. All the modes discussed in the previous section correspond to side to side movement of the vertical jumper section. Thus a current applied along the global Y axis will cause crossflow VIV while a current in the X direction will result in inline VIV. These two analyses are conducted separately. The sheared currents applied to the jumper are shown in Figure 2. The currents applied are representative of shallow water spools or extreme TRWs and do not represent a comprehensive set of fatigue current profiles. High currents are used in order to clearly demarcate the differences between using SHEAR7 and DNV-RP-F105. Currents are applied up to the height of the top clamp on the vertical section representing a shallow water spool which is partly above water. Crossflow currents towards the positive Y axis are slightly smaller in magnitude than the inline currents owing to the slight inclination of the vertical section.

The SHEAR7 parameters are shown in Table 3. The crossflow parameters are relatively well known. The inline parameters (lift curve#7) are described as “very conservative” in the SHEAR7 manual [3] and are based on rigid cylinder forced testing published in [11]. The inline lift curve is listed in Table 4 indicating a maximum A/D of 0.20. This compares to the maximum inline VIV A/D of ~0.16 in DNV-RP-F105.

The SHEAR7 model of the multi-planar jumper does not include information on the 3-D geometry. The external modal solution and correct application of currents is necessary. The application of currents to the SHEAR7 model is illustrated in Figure 8. The currents in the Y-direction are nearly parallel to the mid span (x/L = 0.5 to x/L = 0.75). Currents in the X-direction are similarly parallel to the third leg (x/L=0 to x/L=0.5).

SHEAR7 predicts mode 1 excitation for both the inline and crossflow currents. The A/D output along the jumper length is shown in Figure 9. Response is lower than 0.12A/D due to hydrodynamic damping from most sections on the jumper. Power-in for the cross flow current is observed on the vertical section. For the inline current, the mid span and the vertical section are both power-in regions. Comparable inline and crossflow A/Ds are attributed to greater extent of the power-in regions for the inline currents.

Fatigue damage rates along jumper length are shown in Figure 10. The DNV F2 fatigue curve [12] and an SCF of 1.3 are used. Maximum fatigue damage rates are observed at the sliding support on the vertical section and are equal to 16.1 and 10.4 per year respectively. This does not include a factor of safety and represents fatigue lives of 23 days and 35 days respectively. These fatigue lives are low because of the relatively high speed current profile and lack of supports in the mid span. It should be noted again that this is a hypothetical problem.

<table>
<thead>
<tr>
<th>Location</th>
<th>x/L</th>
<th>Crossflow Current (m/s)</th>
<th>Inline Current (m/s)</th>
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</thead>
<tbody>
<tr>
<td>Top clamp on vertical section</td>
<td>0.87</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td>Vertical section</td>
<td>0.85</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>0.84</td>
<td>0.97</td>
<td>0.97</td>
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<tr>
<td></td>
<td>0.83</td>
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<td>0.96</td>
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<td></td>
<td>0.81</td>
<td>0.93</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>0.91</td>
<td>0.92</td>
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<tr>
<td></td>
<td>0.79</td>
<td>0.89</td>
<td>0.89</td>
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<tr>
<td></td>
<td>0.77</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>Middle span</td>
<td>0.51 to 0.74</td>
<td>No current</td>
<td>0.66</td>
</tr>
<tr>
<td>Third leg</td>
<td>0.00 to 0.51</td>
<td>0.58</td>
<td>No current</td>
</tr>
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<table>
<thead>
<tr>
<th>Parameter</th>
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<td>Added Mass (Ca)</td>
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</tr>
<tr>
<td>Strouhal No.</td>
<td>0.18</td>
</tr>
<tr>
<td>Cl Table</td>
<td>1</td>
</tr>
<tr>
<td>Damping Coefficients</td>
<td>0.2,0.18,0.2</td>
</tr>
<tr>
<td>Vr Bandwidth</td>
<td>0.4</td>
</tr>
<tr>
<td>Primary Zone-Amplitude Limit</td>
<td>0.3</td>
</tr>
<tr>
<td>Power Cut Off</td>
<td>0.05</td>
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</table>

<table>
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<th>Value</th>
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<td>ndfreq</td>
<td></td>
</tr>
<tr>
<td>aCL0</td>
<td>0.15</td>
</tr>
<tr>
<td>aCLmax</td>
<td>0.1</td>
</tr>
<tr>
<td>CLmax</td>
<td>0.07</td>
</tr>
<tr>
<td>CLa0</td>
<td>0.05</td>
</tr>
<tr>
<td>0.64</td>
<td>0.15</td>
</tr>
<tr>
<td>0.91</td>
<td>0.20</td>
</tr>
<tr>
<td>1.52</td>
<td>0.20</td>
</tr>
<tr>
<td>2.36</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Figure 8 - Application of Currents to the SHEAR7 Model, Left - Currents towards Y-Axis, Right - Currents towards X-Axis

Figure 9 - SHEAR7 Results (A/D)

Figure 10 - Fatigue Damage Rates from SHEAR7

VIV ANALYSIS USING DNV-RP-F105

DNV-RP-F105 [2] was developed to address fatigue of free spanning pipelines subjected to combined wave and current loading. However, since being released in 2002 it has provided the basis for most jumper VIV assessments in the industry [13][14]. In order to apply this code to the jumper problem, the jumper is modeled in ANSYS using pipe elements. Similar to the SHEAR7 analysis, current applied along the global Y axis causes cross-flow VIV while a current in the X direction results in inline VIV. A uniform current speed of 1.0 m/s is considered. There is no way to account for sheared current profiles in this method and hence the maximum current speed is used.

The in-line and cross-flow amplitude response models are then constructed in accordance with the DNV-RP-F105 guidelines. For cross-flow VIV excitation, a maximum A/D of 0.78 is predicted for Mode 1, as shown in Figure 11. The response is significantly conservative when compared to 0.11 A/D obtained from the SHEAR7 analysis. This results in a fatigue damage rate significantly higher than that predicted by SHEAR7 for cross-flow response. A factor of 7 on the displacement implies a factor of 343 in fatigue damage using k=3. For inline VIV, a maximum A/D of 0.06 is observed for Mode 4, as shown in Figure 12. For the same problem, SHEAR7 predicts mode 1. The difference in mode prediction is due to the difference in methodologies. Under the DNV-RP-F105 guidelines, in the event that more than one mode is excited, the mode which results in the highest fatigue damage is selected for fatigue calculation. This is contrary to the SHEAR7 methodology which utilizes the power balance law as a basis for determining the dominant excited mode. In general, the DNV-RP-F105 guideline results in significantly higher response in the prediction of fatigue life due to VIV.
SLUGGING INDUCED FATIGUE

Slugging can be a potential source of significant fatigue damage in a rigid jumper. In order to assess its effects, slugging profiles must first be determined based on the expected fluid contents and production rate. Predictive models do exist to generate these profiles but they are usually subject to significant levels of uncertainty when predicting the fluid contents and production rate over the entire field life. Early in field life when pressure and flow rates are high, slugging can be particularly damaging. In many cases slugging only appears later in field life when water production increases and lower flow rates lead to segregation. As Figure 13 indicates, slugs are not generally pure liquid and the bubble zone separating them is not purely gas. Additionally, the flow rate may also be modified during different stages of the field life in order to optimize production. These factors can lead to a different rigid jumper response to that initially predicted. Considering the slug randomness and flow rate variations, a computationally intensive and time consuming CFD analysis is unlikely to provide a workable solution to the fluid-structure interaction problem. In this paper, a more practical transient finite element analysis is used to evaluate and analyze the fatigue response due to slugging. This method allows the analyst to quickly explore the potential damage from a range of possible slugging regimes.

There are two primary phenomena caused by internal fluid slugging that can be responsible for fatigue damage of a rigid jumper carrying multi-phase fluids. Firstly the changes of internal fluid weight cause a gross change in the deflected shape of the jumper through gravity effects. Secondly, there is a change of the inertial force on each jumper bend as each slug enters and exits. These forces are proportional to the velocity squared. They are applied abruptly as the slug passes and will excite the natural frequencies of the jumper much like a hammer blow would. This effect is illustrated in Figure 14.

The rigid jumper fatigue response is determined for three typical slugging regimes whose parameters are listed in Table 5. These slug profiles are selected as they represent the most onerous response in terms of fatigue damage due to slugging. It should be noted that all these slugging regimes have low occurrence probabilities. This aspect needs to be taken into account when assessing the combined fatigue response on the jumper due to both VIV and slugging.

Figure 11 – Cross-flow VIV Response Diagram Using DNV-RP-F105

Figure 12 – Inline VIV Response Diagram Using DNV-RP-F105

Figure 13 – Slug Composition

Figure 14 – Impulsive Effects of Higher Velocity Slugs Cause Response at Jumper Natural Period.
The change of internal fluid weight and inertial force due to the passage of each slug are developed and time-traces of the resulting vertical and lateral forces at each node generated. It should be noted that the forces calculated are the change in force between when the slug is present and when it is not, as opposed to the absolute force of the slug. When a slug is not present, there are no additional inertial forces applied to the model due to the velocity of the gas bubble (the weight is included in the static step of the analysis by setting the internal fluid density equal to that of the gas bubble). This methodology is correct for fatigue analysis because only the change in stresses is considered. However, the stresses calculated with this methodology should not be used to evaluate the strength performance of the structure.

These force timetraces are applied to the ANSYS rigid jumper model in a transient finite element analysis. This is the same FE model that is used for the modal analysis described in the previous section. Fatigue damage due to slugging is then calculated using a rainflow counting approach. It can be seen from the results that high fatigue response is observed due to slugging along the spanned sections of the jumper. Fatigue damage rate is significantly less for the jumper portion on the seabed, as shown in Figure 15. This indicates that a jumper with long unsupported sections and high flexibility will be subject to high damage when subjected to gross internal fluid weight variations.

### Table 5 - Slug Profile Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Slug Profile 1</th>
<th>Slug Profile 2</th>
<th>Slug Profile 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble Density (Kg/m³)</td>
<td>86.3</td>
<td>89.3</td>
<td>100.4</td>
</tr>
<tr>
<td>Slug Density (kg/m³)</td>
<td>545.7</td>
<td>874.1</td>
<td>727.1</td>
</tr>
<tr>
<td>Slug Velocity (m/s)</td>
<td>7.5</td>
<td>11.8</td>
<td>6.3</td>
</tr>
<tr>
<td>Mixture Velocity (m/s)</td>
<td>5.7</td>
<td>9.1</td>
<td>4.9</td>
</tr>
<tr>
<td>Slug Length (m)</td>
<td>131.6</td>
<td>83.9</td>
<td>69.2</td>
</tr>
<tr>
<td>Time Between Start of Consecutive Slugs (s)</td>
<td>19.7</td>
<td>26.1</td>
<td>14.38</td>
</tr>
</tbody>
</table>

**Figure 15 – Slugging Fatigue Loading**

**HARMONIC ANALYSIS**

Normal modal analysis is linear and cannot easily account for damping, hysteresis, or non-linear boundary conditions. However, such effects can be accounted for in the time domain or through harmonic analysis such as is available in ANSYS. In the current problem, the effect of adding a vibration damper to the jumper is studied. The external dampers are assessed in harmonic analysis (frequency sweep) to determine amplitude and curvature reduction and effectively factor the fatigue damage from SHEAR7.

For the studied jumper geometry shown in Figure 1, a tuned damper is considered to study the change in natural response of the jumper. The damper shown in Figure 16 is attached to the structure and tuned for mode 1 of the unmodified structure. The damper is modeled as a beam mass system and the natural frequency of the damper is tuned to be close to the natural frequency of the structure. The comparison of natural frequency response of the unmodified and with tuned damper is shown in Figure 17.

Harmonic analysis is conducted using an external excitation moment at one end of the structure. Same magnitude of external excitation moment is used at jumper end for the unmodified structure and structure with tuned damper. The maximum excitation amplitude for both unmodified and with tuned damper is shown in Figure 18.

The maximum excitation amplitude for the tuned damper structure is 50% smaller than that of excitation amplitude of the unmodified structure. Assuming a fatigue curve exponent of 3 for a typical weld, the fatigue life is improved by a factor of 8.
CONCLUSIONS
A comprehensive and efficient approach to determine rigid jumper vibration is presented in this paper. Subsea jumpers are integral to any modern offshore architecture and are subjected to vibration from a number of sources including VIV (currents), slug flow, waves, internal flow turbulence and adjacent structure (pipeline or risers) motions. Of these, VIV and slug induced vibrations are especially critical considering the uncertainty in predictive tools and the common prevalence of the phenomena.

For VIV, a SHEAR7 based approach is presented that provides an alternative to CFD and the spanning pipeline code DNV-RP-F105. SHEAR7 is demonstrated to be significantly less conservative (factor of ~300 on fatigue for the case studied) than DNV-RP-F105 as it allows for the existence power out zones (hydrodynamic damping) and application of a sheared current profile. Further, inclusion of strakes and external dampers in a SHEAR7 model is not difficult. At the same time, it is noted that many more rigid jumper tests will be required before crossflow and inline vibration of jumpers is understood in the same manner as riser VIV. This paper also demonstrates the usage of harmonic analysis to study the effect of external dampers, hysteresis and nonlinear boundary conditions. Harmonic analysis in conjunction with linear modal analysis and SHEAR7 can be used to predict jumper fatigue life to a sufficient level of accuracy.

A transient finite element analysis based slugging fatigue calculation method is also presented in this paper. Slug flow regimes can be difficult to predict resulting in multiple load conditions to be considered in jumper design. The FE based approach provides a powerful tool to analyze multiple load cases without requiring significant computational resources. Vibration from inertial load as the slug travels through a bend and from density variations due to slug movement are both taken into account.

REFERENCES