Assessing the Feasibility of Suspended BOP Transportation and Its Impact on VIV Fatigue Life

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Abstract. The sailing of the drilling rig along with its subsea equipment, such as the drilling riser and blowout preventer (BOP), from one well to another using traditional methods is time-consuming. This process involves lowering and retrieving the BOP after drilling, moving the rig to another well, and repeating the operation. In ultra-deep waters, where recent oil field discoveries are located, the process is even more time-consuming due to the increased water depths. Given the high costs of renting and operating drilling rigs, operators seek ways to improve efficiency. A promising alternative is navigating with the BOP suspended at a distance from the seabed, which eliminates the need to retrieve the entire drilling riser and BOP. This approach significantly optimizes the transfer of the rig and subsea equipment between wells. During BOP navigation, hydrodynamic and inertial forces act on the suspended riser column and subsea BOP. This work will analyze the fatigue effects of vortex-induced vibrations caused by current speed and navigation for different riser column lengths. The results will be presented, and the software used for these analyses includes Orcaflex and Shear7.

Keywords: sailing, drilling, VIV, riser, offshore.

1 Introduction

The growing global demand on petroleum energy is pushing the exploration of new oil and gas reserves in deeper waters. This creates the need and challenge to find more economical alternatives to reduce operational costs, which become increasingly expensive at greater depths. In well drilling, increasing depth is a critical factor affecting the time required for the installation of the BOP/LMRP. The installation is carried out using the riser column, which consists of rigid joints connected on the rig deck. These rigid joints have length limitations due to handling and storage constraints and must be connected one by one until they reach the surface casing on the seabed.

Nowadays, offshore drilling has been performed at depths going beyond 3000 meters. Consequently, the marine drilling riser must be extended, increasing the load on the riser tensioner and prolonging the time required for the deployment and retrieval of the marine riser system and BOP to the wellhead.

Installation and retrieving the BOP are usually time-consuming operations that can take many hours, or, sometimes, several days, particularly in ultra deepwater. Typically, when a Mobile Offshore Drilling Unit (MODU) completes its operations at a well site, it retrieves the marine drilling riser column, including the BOP, to the drill floor before moving to a new well site and reinstalling the same equipment to begin drilling the next well. This paper evaluates an alternative approach that involves lifting the subsea BOP above the seabed, retrieving only a few riser joints, and then transferring both the BOP and marine drilling riser column to a new well location without the need to pull all the equipment to the drill floor. Vessel transit analysis is conducted to assist in the movement between nearby wells within the same fields or in adjacent fields, aiming to reduce costs by minimizing the time-consuming.

2 Methodology

This paper considers the environmental loads from sea currents acting on the riser during the BOP sailing. Significant hydrodynamic and inertial forces are exerted on the suspended riser column and subsea BOP, directly affecting the integrity of the drilling riser.

The main objective is to evaluate the fatigue induced by vortex shedding from ocean currents flowing around the drilling riser. To achieve this, the Orcaflex software is employed to construct the riser model, conduct static analysis for the riser equilibrium position, and determine the natural frequency response. Additionally, the SHEAR7 software is utilized to estimate the fatigue damage induced by VIV (Vortex-Induced Vibration) in the frequency domain.

The analyses are performed considering a disconnected riser analysis from the wellhead, considering the drilling riser supported by the vessel. This condition is called hangoff.

In hard hangoff mode, as used in this study, the riser is effectively locked to the vessel and moves with it. In this configuration there is no motion compensation, the riser is supported by the riser spider/gimbal and the telescopic joint is locked.

The BOP sailing operation is modelled and analyzed with three different riser column suspended lengths—200 m, 500 m, and 800 m—to compare the results.

The diameters and submerged weight per unit length for each riser joints are defined in the later section, together with the weather conditions, current profiles and sailing speeds.

A VIV prediction program like SHEAR7 uses a long list of input parameters to predict VIV. The parameters can be grouped into hydrodynamic parameters, structural parameters and response interaction parameters that control how the various excited modes interact with one another. To address the uncertainties in the inputs used in the Shear7 program, sensitivity analyses are conducted to determine the influence of the parameters listed below on the response. The objective is to establish the relative impact of these factors on the resulting fatigue damage due to VIV.

The parameters listed below are used for both bare and the buoyance sections:

- The lift coefficient databases investigated are CL-table-1 and high Reynolds number CL;
- Structural damping evaluated are 0.3% and 1%;
- Primary Zone Amplitude Parameter Limit (PZAL), parameter responsible for modelling the interaction of the predicted VIV response frequencies and modes considered of 0.3 and 0.85.

A VIV analysis of the drilling riser includes the following:

- Generate mode shapes and modal curvatures for input to VIV analysis using Orcaflex program;
- Analyze VIV response of the riser for each current profile using Shear7;
- Evaluate the damage due to each current profile.

3 Vortex-Induced Vibrations (VIV) and Modal Analysis

One of the main concerns with deep-water drilling risers is the impact of currents on their response. Strong currents, commonly observed in many deep-water environments, induce vortex-induced vibrations (VIV), causing the riser to oscillate perpendicular to the current direction.

The VIV phenomenon depends on various parameters. For the flowing fluid, the two main parameters are the Reynolds number (Re) and the Strouhal number (St) defined by:

$$R_e = \frac{UD}{\nu} \quad \text{and} \quad S_t = \frac{f_v D}{U} \tag{1}$$

Where U is the fluid velocity, D, the diameter of the cylinder, ν the kinematic viscosity and f_v is the shedding frequency. The coupled fluid-structure is characterized by the reduced velocity U_r:

$$U_r = \frac{U}{f_m D} \tag{2}$$

Where f_m is an eigenfrequency of the structure.

The shedding of the vortices creates forces both in the cross-wise and stream-wise directions. According to Resvanis Vandiver McNeill [1] the cross-flow (CF) vibrations are always associated with higher response amplitude motions, leading to significantly larger CF response accelerations. Consequently, this paper focuses exclusively on evaluating CF vibrations. The lock-in phenomenon occurs when f_v and f_m are close to each other (i.e., $f_v \approx f_m$), corresponding to $U_r \approx \frac{1}{S_t}$. In this case, the shedding frequency becomes equal to the eigenfrequency of the structure and the vibration amplitude is maximum.

The dynamic structure of the riser is determined using eigenfrequencies and mode shapes. The goal of modal analysis is to determine the natural mode shapes and frequencies of the structure during free vibration. Natural frequencies are the frequencies at which a structure tends to vibrate when it is excited by an external force. They depend on the stiffness and mass distribution of the structure. A structure has multiple natural frequencies, each associated with a specific mode shape. Mode shapes are the characteristic patterns of deformation or displacement that occur when a structure vibrates at a natural frequency. They show how different parts of the structure move relative to each other during vibration.

4 Description of the Studied Case

4.1 Model Description

In this study, a hard hang-off is assumed, with the top of the riser directly suspended from the spider and gimbal on the drill floor. The BOP and LMRP are also suspended by the riser and disconnected from the wellhead. The effects of the upper and lower flex/ball joints and auxiliary lines are neglected, and the telescopic joint and some additional riser joints are retrieved. For this hard-hang-off method, the displacements are fixed, and the rotations are determined by the stiffness of the gimbal-spider.

Figure 1 provides a schematic representation of the suspended riser configurations scenarios evaluated in this study, accounting for variations in the riser's total length. The riser consists of both bare riser joints and riser joints with buoyancy modules attached. The riser main pipe is considered flooded by seawater.

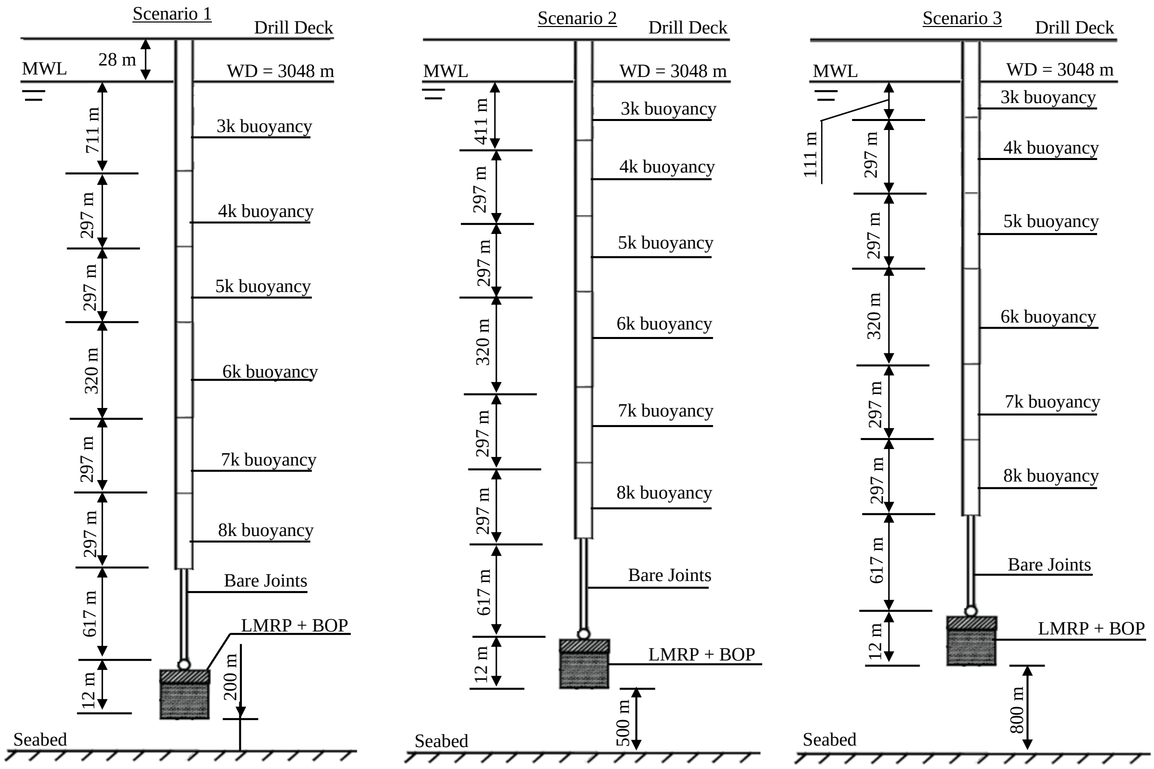

Figure 1 – Suspended Riser Scenarios Evaluated

Table 1 provides a summary of the riser joint properties data in accordance with ISO 13624-2 [2]. Table 2 presents the mechanical properties data for the riser joints, according to ISO 13624-2 [2]. The axial stiffness, bending stiffness and torsional stiffness are identical for all the different types of riser joints.

The properties and dimensions of the BOP and LMRP are detailed in Tab. 3. The gimbal rotational stiffness, added mass, drag and inertia coefficients of the riser, as well as the MODU draft are detailed in Tab. 4.

Table 1. Riser joint properties, according to ISO 13624-2 [2]

Joints Description	Weight in-air per unit length (te/m)	Weight in-water per unit length (te/m)	Equivalent external diameter (m)	Hydrodynamic diameter (m)	Internal Diameter (m)
3k buoyancy joints	0.865	0.0129	1.0289	1.2827	0.4922
4k buoyancy joints	0.905	0.0244	1.0461	1.3081	0.4922
5k buoyancy joints	0.957	0.0061	1.0869	1.3335	0.4922
6k buoyancy joints	1.009	0.0227	1.1066	1.3589	0.4922
7k buoyancy joints	1.095	0.0076	1.1620	1.4097	0.4922
8k buoyancy joints	1.080	0.1053	1.1001	1.4351	0.4922
Bare Joints	0.556	0.4836	0.3005	0.5334	0.4922

Table 2. Mechanical properties of the Riser Joints, according to ISO 13624-2 [2]

Mechanical Properties	Unit	Value
Elastic modulus (E)	kPa	2.070E+08
Shear modulus (G)	kPa	7.962E+07
Area (A)	m²	3.319E-02
Moment of inertia (I)	m^4	1.093E-03
Bending stiffness (EI)	kN.m²	2.262E+05
Axial stiffness (EA)	kN	6.870E+06
Torsional stiffness (GJ)	kN.m²	1.740E+05
Yield strength (API Spec 5L X-80)	MPa	551.6

Table 3. BOP and LMRP dimensions and properties, according to ISO 13624-2 [2]

Parameters	Unit	BOP	LMRP
Length	m	8.5	3.5
Weight in-water	kN	1642	1094
Weight in-air	kN	1714	1124
External Diameter	m	1.0351	1.0351
Internal Diameter	m	0.4763	0.4763
Bending stiffness (EI)	kN.m²	1.11E+10	1.11E+10

Table 4. Riser Parameters and MODU Draft

Parameters	Unit	Value
Gimbal Rotational Stiffness	kN.m/degree	600[(1)]
m_a (added mass)	-	1
C_D, C_M (drag and inertia coefficients)	-	1.2,2.0
MODU draft	m	13

Note 1: The gimbal rotational stiffness is in accordance with Sevillano [3].

4.2 Loads considered on Riser and BOP Stack

The MODU, marine drilling riser, and subsea BOP stack are subjected to various environmental forces during a BOP sailing activity as already mentioned previously. The environmental load considered in this paper is due to the current (the vertical component of the current is neglected). This paper simulates the MODU moving forward with a suspended drilling riser column and subsea BOP. To simulate this, the MODU sailing speed is added to the current speed.

Table 5 illustrates how the MODU speed is added to the original current speed. For current #1 listed in Tab. 5, where the MODU is moving at 0.5 knot against the current, the speeds are summed. For current #2, where the MODU is moving in the same current direction, the speeds are subtracted.

Table 5. Current Velocities Considered (Current #1 and Current #2)

Current Velocities (m/s)															
Depth (m)		50	100	200	300	800	1200	1600	1800	2000	2200	2400	2600	2800	3000
Orig.	Prof. 1	0.63	0.61	0.48	0.39	0.34	0.29	0.27	0.21	0.17	0.13	0.10	0.08	0.05	0
Cur. #1	Prof.1+0.5 knot	0.89	0.87	0.74	0.65	0.60	0.55	0.53	0.47	0.43	0.39	0.36	0.34	0.31	0.26
Cur. #2	Prof.1-0.5 knot	0.37	0.35	0.22	0.13	0.08	0.03	0.01	0.05	0.09	0.13	0.16	0.18	0.21	0.26

4.3 Input Data for VIV Fatigue Analysis

The S-N curve B1 in seawater, with cathodic protection and a Stress Concentration Factor (SCF) of 2.0, is applied to the entire length of the riser according to Bai [4]. A design fatigue factor (DFF) of 10 is utilized according to DNVGL-RP-F204 [5]. Table 5 provides a summary of the SHEAR7 parameters used to obtain the results. The model is developed, and fatigue damage results are obtained using the Rain-flow method, S-N curve, and Miner-Palmgren rule.

Table 6. SHEAR7 Parameters

Sections	Parameter	Default values	Values for Sensitivity #1	Values for Sensitivity #2	Values for Sensitivity #3
Bare & buoyant sections	Lift Table	CL-table-1	High Reynolds	High Reynolds	High Reynolds
	Bandwidth	0.4	0.4	0.4	0.4
	Strouhal Number	0.18	0.18	0.18	0.18
	Hydro damp. coef.	0.2,0.18,0.2	0.2,0.18,0.2	0.2,0.18,0.2	0.2,0.18,0.2
Global paramet.	Struct. damp. ratio	0.003	0.003	0.01	0.003
	Power cut-off	0.05	0.05	0.05	0.05
	PZAL	0.3	0.3	0.3	0.85

In deepwater drilling risers, severe currents are expected, resulting in turbulent flow. For current #1 evaluated in this paper presented in Tab. 5, the Reynolds number varies from approximately 4.0E+05 to 8.5E+05. For current #2 also presented in Tab. 5, the Reynolds number varies between 1.0E+04 and 3.5E+05. It can be concluded that the flow regime is not laminar and falls within the subcritical and critical ranges according to DNVGL-RP-C205 [6].

To reduce conservatism and evaluate the impact of changing from the CL-table-1 curve to the high Reynolds CL-table curve on VIV damage, the sensitivities 'default values' and 'sensitivity 1' presented in Tab. 6 are being assessed.

The precise level of structural damping in a drilling riser equipped with kill and choke lines, and buoyancy modules is not well understood and has never been measured underwater. Significant efforts have been made to assess the structural damping of various joints in air Padelopoulos [7], and these tests have demonstrated that the inclusion of kill and choke lines along with buoyancy modules can considerably elevate the structural damping. Therefore, sensitivity analysis considering a damping of 0.1 is conducted to understand its effect on the damage result, 'sensitivity 2' presented in Tab. 6.

Modes with well-separated power-in regions may respond simultaneously because waves from one region attenuate as they travel. If two power-in regions are far enough apart, the dynamic response from one will not affect the other. Thus, both regions can operate at the same time. When the dynamic response from the dominant mode's power-in region drops below a value inputted in Shear7, it is assumed that it no longer disrupts the formation of a new power-in region at a different frequency. The primary zone amplitude limit (PZAL) determines how much the response must decay before allowing simultaneous secondary regions. Higher PZAL allow for larger secondary regions and more concurrent power-in regions. Therefore, when the response drops to 30% or 85% (the two cases evaluated as presented in Tab. 6) of its initial amplitude, a secondary zone at a different frequency can coexist simultaneously.

5 Results

The Fig. 2 to Fig. 4 present the factored fatigue damage per hour from VIV for top section (0 to 20 m), buoyant section and bare section, considering the parameter variations in Shear7 listed in Tab. 6 and the riser length variations presented in Fig. 1.

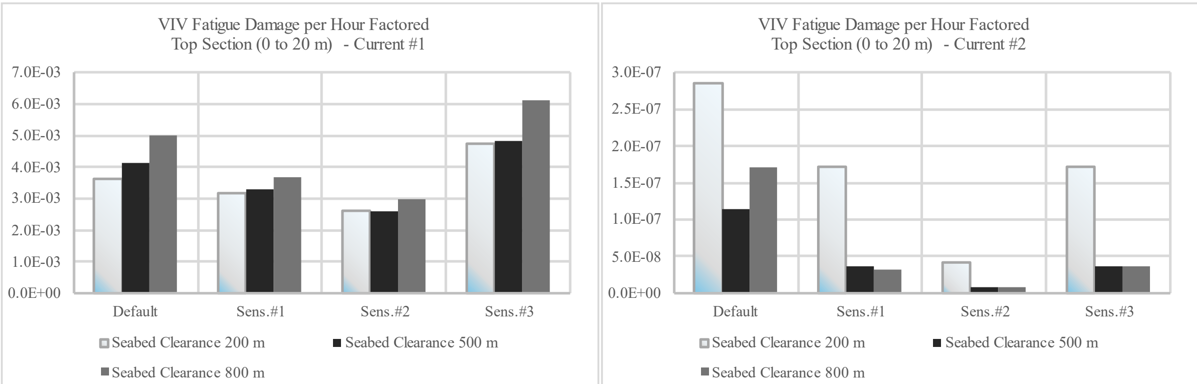

Figure 2. VIV Fatigue Damage per Hour Factored – Top Section (0 to 20m) – Current #1 & Current #2

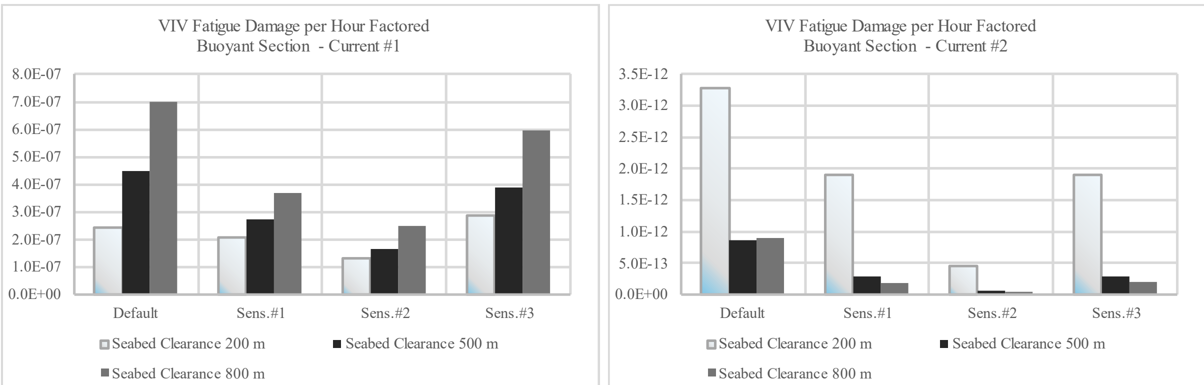

Figure 3. VIV Fatigue Damage per Hour Factored – Buoyant Section – Current #1 & Current #2

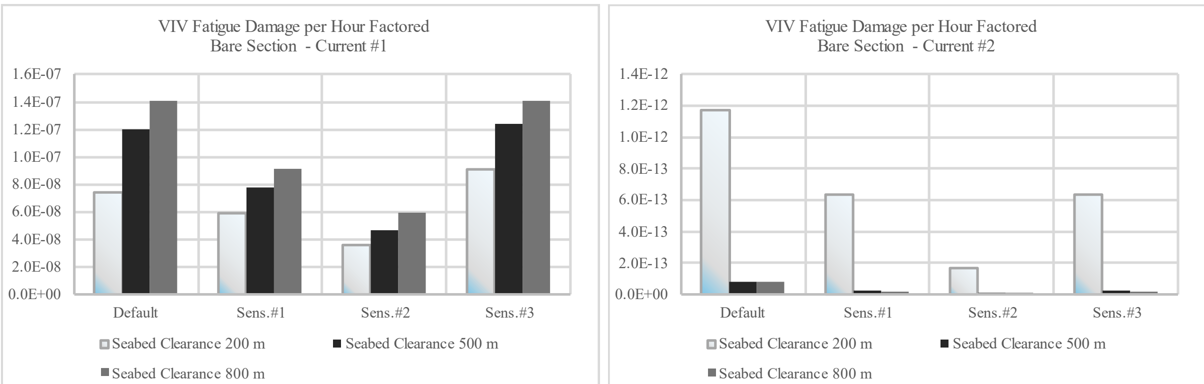

Figure 4. VIV Fatigue Damage per Hour Factored – Bare Section – Current #1 & Current #2

6 Conclusions

Based on the results presented in item 5, the main conclusions are:

1) The top section is the most affected, where the highest VIV fatigue damage is found, followed by the buoyant section, and lastly the bare section, which have significantly less damage compared to the top.

2) The results using the High Reynolds lift table (sensitivity #1) show a reduction in VIV damage compared to the default parameters. The improvements, assuming a riser length with a seabed clearance of 200 meters and current #1, are as follows: top section 14%, buoyant section 17%, and bare section 26%.

3) Among all the sensitivities presented in Tab. 6, the sensitivity #2 showed the best VIV damage results, where the High Reynolds lift table along with a damping factor of 0.01 is being evaluated. The improvements compared to the default parameters, assuming a riser length with a seabed clearance of 200 meters and current #1, are as follows: top section 38%, buoyant section 82%, and bare section 108%.

4) Sensitivity #3, which considers a primary zone amplitude limit (PZAL) of 0.85 in conjunction with the High Reynolds lift table, shows worse results compared to all other sensitivities and also compared to the default parameters, specifically for current #1. For current #2, which has lower velocities, the PZAL had no effect on the results; they were identical to those of sensitivity #1, except for the riser length with a seabed clearance of 800 meters. However, the default parameters for current #2 are still more critical than the results from sensitivity #3.

5) For current #1, which has higher velocities, the riser with the greatest length and a seabed clearance of 200 meters showed the best result, followed by the riser with a length of 500 meters, and lastly the one with 800 meters. In contrast, for the lower velocity profile, current #2, the riser with the longest length exhibited the worst damage result.

6) The damage results obtained for current #2 are significantly lower compared to those for current #1. Therefore, if the MODU is moving in the same direction as the current, at a controlled speed, and depending on the current velocity during the MODU's movement, there is a possibility of making the move without the entire riser retrieval and subsequent installation process for short distances between wells in the same field.

7) According to a study by Holland [8], which calculates the time required to perform the retrieval and subsequent installation of the BOP using the traditional method at depths ranging from 61 to 2134 meters, the time needed for a depth of 2134 meters is 105 hours. Therefore, if two wells are to be drilled sequentially and are 1000 meters between them, the time required to cover this distance at a navigation speed of 0.5 knots (~0.25 m/s) is only ~1.1 hours. This is significantly less than the 105 hours needed exclusively for retrieval and subsequent installation of the riser, not including the navigation time. Consequently, this represents a substantial cost savings, given the high day rate of a MODU.

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