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DYNAMICS OF SUSPENDED MID-WATER FLOWLINES

Caspar N. Heyl
FMC SOFEC Floating Systems, USA
caspar_heyl@fmc.com

Charles-Alexandre Zimmermann
FMC SOFEC Floating Systems, USA
charles_zimmermann@fmc.com

Stacey L. Eddy
FMC SOFEC Floating Systems, USA
stacey_eddy@fmc.com

Arun S. Duggal
FMC SOFEC Floating Systems, USA
arun_duggal@fmc.com

ABSTRACT

The development of deepwater fields in regions with mild environmental conditions allows the use of non-weathervaning floating production units. Since these fields typically lack a connection to a pipeline system, export takes place through an offloading system located at a safe distance from the platform. The offloading system, can be a floating storage unit (in case the production platform has no storage capacity) or a conventional offloading buoy. Due to the large water depth, product is transferred from the production platform to the offloading system using mid-water suspended flowlines.

This paper provides results from a comprehensive study of a mid-water flowline system, focusing on the dynamic response of the suspended flowlines as a function of the motions imposed by the Floating Production Storage and Offloading (FPSO) system and offloading buoy. The paper presents results that illustrate the influence of the offshore loading system motions on the dynamic response of the flowlines. The results show that the surge motions of the offloading system can control the fatigue performance of the flowlines. Results are also presented from a parametric study of the flowline response to various input parameters like the drag coefficient, current velocity and swell period. The results show the strong dependence of the estimated fatigue life on these parameters.

INTRODUCTION

With the prospective development of a large number of deepwater fields in West Africa and other areas with relatively benign environments using non-weathervaning floating production units, there is a need for a reliable means of offloading processed crude to ocean going tankers. Since wind and current are largely uncorrelated and non-directional, tandem offloading from a spread moored FPSO has lower operational uptime and increased risk as compared to offloading from a weathervaning unit or from an offloading buoy. A preferred solution found in many field development plans consists of an enlarged offloading buoy located approximately one nautical mile away from the FPSO. A pair of large diameter steel flowlines, in a double wave configuration, connects the FPSO to the offloading buoy. Figure 1 gives an illustration of such a system in 1,000 meters of water.

Since this is the first application where large diameter steel flowlines are connected to a small floating object care must be taken in the design process to ensure that the dynamic behavior of the system is well understood. The main factors influencing the dynamic response of the flowlines are the motions of the offloading buoy and the FPSO (excitation), the system damping, and the definition of the wave and current environment. The dynamic response of the system is important for determining the extreme loads and the fatigue life of the flowlines. Detailed analysis of the system has shown that the flowlines are susceptible to fatigue damage caused by the high frequency, low amplitude motions of the offloading buoy in waves.

This paper provides key results from a comprehensive study of a mid-water flowline system in West Africa, focusing on the dynamic response of the flowlines and more particularly on the wave-induced fatigue caused by the local waves and swell. The paper first presents an overview of the environment at the location selected for this study and of the system being analyzed. A description is provided of the numerical model used to estimate the dynamic response of the system, and the methodology used to estimate the fatigue damage. Results from a parametric study of the system dynamic response to various input parameters are then presented. The parameters considered include the drag coefficient along the flowline, the incident current velocity, the environment direction, and the end motions of the flowline. The results are discussed to help the reader understand the dynamic behavior of these flowlines and to provide guidance for the selection of some critical parameters that are used in the analysis and design of such systems. Alternative solutions to the direct connection of steel flowlines to the surface buoy are also presented and discussed.

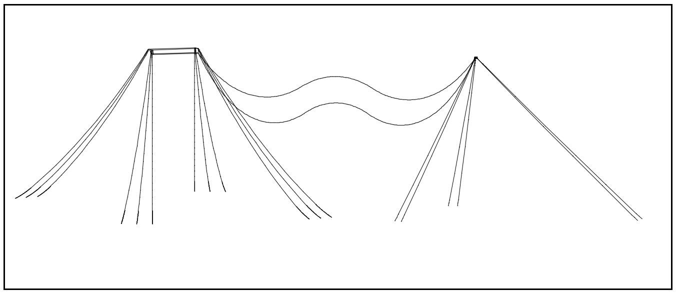

Figure 1. Typical field layout for Deepwater West Africa

ENVIRONMENT

The location chosen for the study is West Africa, which has a 100-year significant wave height of approximately 4 meters. The extreme wave climate is dominated by swells, with a period range of 7 to 17 seconds, which are a result of storms generated in the Southern Ocean and the Southeastern Atlantic. The swell direction is confined to a narrow sector from the south. Local wind-generated waves are generally small with the predominant direction from the south-southwest. The deep water currents in West Africa are mild with most of the water column driven by large-scale circulation with typical speeds less than 0.25 meters per second. For the purpose of this study, the swell and local wave environments are represented by 10 and 12 sea states respectively.

SYSTEM DESCRIPTION

The FPSO selected for this study is a barge-shaped vessel with a displacement of approximately 300,000 Dead Weight Tons. The vessel is spread-moored with the bow heading towards the south into the dominant swell direction.

The flowline system consists of two 22-inch steel flowlines arranged in the form of a pronounced “wave” catenary configuration. The two flowlines are of different overall length to allow for vertical separation between them. Syntactic buoyancy elements are arranged over some length of each flowline near the mid-point to produce the wave shape. The “wave” configuration is used to reduce the hang-off loads at both ends of the flowline and to accommodate the low frequency motions of the FPSO, which can be substantial. Table 1 summarizes the main properties of the flowlines.

The offloading buoy used to support these flowlines has a diameter of 18 meters, a height of 7.8 meters and a displacement of 1,513 metric tons. The mooring system of the offloading buoy consists of six anchor legs arranged in three groups, each 120 degrees apart. The mooring system has an asymmetrical pattern to offset the large static horizontal load (1,918 kN) from the flowlines. Each anchor leg is made up of a section of top chain, a long section of polyester rope and a short section of end chain, in a taut leg configuration.

Table 1. Flowline physical properties

	Upper	Lower	
Horizontal span	1850	1850	m
Flowline length	2100	2300	m
Outer diameter	0.559	0.559	m
Wall thickness	25.4	25.4	mm
Buoyancy length	500	450	m
Total buoyancy	2592	2333	kN
Total end tension	1750	2010	kN
Horizontal end tension	1031	887	kN
Vertical end tension	1414	1803	kN
End angle from vertical	36	26	deg

MODELING OF THE SYSTEM

The dynamic analysis of the flowlines is performed using the time-domain finite element program OrcaFlex™ [1]. The complete analysis model consists of both flowlines attached to the offloading buoy, excited by random waves through the use of Response Amplitude Operators (RAOs). As the influence of FPSO motions on the flowline response has been shown to be insignificant compared to the motions of the surface-offloading buoy, it is not modeled in this analysis.

Hydrodynamic coefficients of the buoy are calculated with a 3D-diffraction program using a Higher Order Boundary Element Method. RAOs are then calculated for the moored buoy by solving the equations of motion including the mooring system stiffness matrix. The predicted response of the buoy was verified through large-scale model tests and found to agree well with the model test results.

The flowline is modeled using lumped mass finite elements. The element length used in the analysis was optimized by checking stress convergence for the various response modes of the flowline. Drag and inertia loading on the flowlines is modeled in OrcaFlex™ using the Morison [2] equation.

FATIGUE LIFE ESTIMATION

The fatigue damage to the flowlines consists of contributions from three main sources:

- First order wave fatigue induced by wave loading and associated FPSO and offloading buoy motions;
- Second order (or low frequency) fatigue induced by the low frequency vessel motions; and

- Vortex Induced Vibrations (VIV) fatigue induced by current or vessel/buoy motions.

Additional fatigue damage may accumulate during the installation of the flowlines. Possible installation methods for these types of systems are tow-out (surface tow or sub-surface tow) or J-lay. The paper focuses on wave induced fatigue caused by the motions of the offloading buoy to local waves and swell excitation only.

The fatigue damage induced by each sea state of the wave fatigue scatter diagram is evaluated by running a 20-minute time domain simulation to determine the stresses along the entire flowline. The standard deviation of stress is then used to calculate the fatigue damage for that particular sea state using the Rayleigh damage formulation shown below:

$$D = k \cdot N \cdot (f \cdot \sigma)^m$$

$$k = \frac{\left(2 \cdot \sqrt{2}\right)^m}{a} \cdot \Gamma(m/2 + 1)$$

where: D = damage
f = thickness modification factor
σ = RMS hot spot stress
a = constant relating to the *S-N* curve
m = negative inverse slope of the *S-N* curve
N = total number of cycles
Γ = gamma function

The fatigue S-N curve used to estimate the fatigue damage of the flowlines is the AWS C-1 curve [3]. This is a rather optimistic choice as analysis of full scale fatigue test data by Phifer et al. [4] suggest that the API X' curve [5] is an appropriate S-N curve for this type of applications.

Throughout West Africa local waves and swell are statistically independent and co-exist throughout the year. To correctly account for their combined effect, analyses must be performed for all possible combinations of local waves and swell. For example, for 12 local wave bins and 10 swell bins a total of 120 sea states have to be evaluated. To speed up the analysis the fatigue damage due to local waves and swell are treated as completely independent. The damage due to local waves and the damage due to swell are calculated separately and then added to obtain a minimum fatigue life for the flowline.

RESULTS

Results from the sensitivity analysis performed on the suspended flowline response are presented here. Since results for both flowlines are very similar, all results presented in this paper are for the lower flowline. The figures show the annual fatigue damage from one representative sea state of local waves (Hs = 1.125 meters, Tp = 5.8 seconds) plotted over the length of the flowline. All figures present a comparison of a base case with a variation for the parameter of interest. The base case wave direction is 23 degrees with respect to the flowlines.

Buoy Motions

The effect of the buoy motions on the dynamic response of the flowlines was investigated by varying one degree of freedom (DOF) of the buoy while keeping all the other DOFs constant. For this study this was achieved by multiplying the surge, heave and pitch RAO amplitudes by 0.5 to give a reduction of 50 percent of the DOF of interest.

Figure 2 shows the effect of reduced surge motions on the annual fatigue damage. The figure illustrates that a 50 percent reduction of the surge amplitude results in a reduction of the fatigue damage by a factor of four.

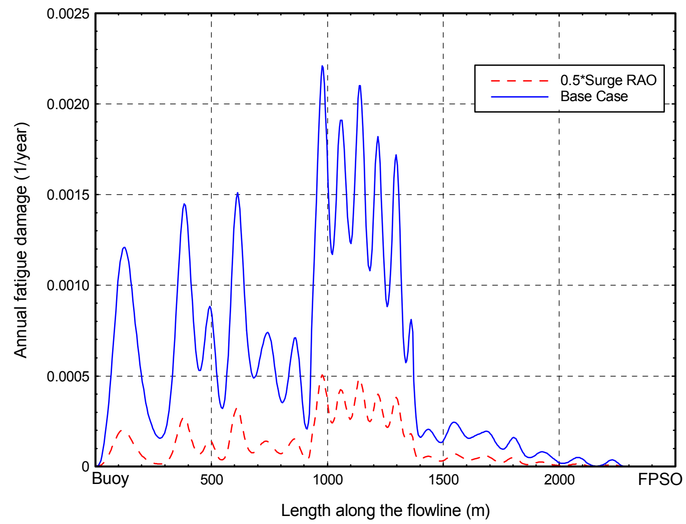

Figure 2. Effect of surge amplitude on fatigue damage

Figure 3 shows the effect of a reduction in heave motions on the annual fatigue damage. As seen from the figure, the fatigue damage is actually larger for the case with reduced heave motions. This can be understood when considering the shape of the motion envelope of the end of the flowline that is attached to the offloading buoy. The behavior of a small floating structure such as the offloading buoy is similar to that of a "wave follower" which means that the motion envelopes are close to circular. When the surge motion of the offloading buoy is reduced by 50 percent, the motion envelope becomes more like an ellipsoid with a vertical main axis. This reduces the fatigue damage in the flowline. When the heave amplitude is reduced by 50 percent, the motion envelope becomes more like an ellipsoid with a horizontal main axis. This leads to a small increase in fatigue damage of the flowline. It is not only the amplitude of the horizontal motion that affects the fatigue damage, but also the ratio of horizontal and vertical motions.

Figure 4 shows the effect that reduced pitch motions have on the annual fatigue damage. The figure shows that a 50 percent reduction in pitch leads to a much smaller reduction in fatigue

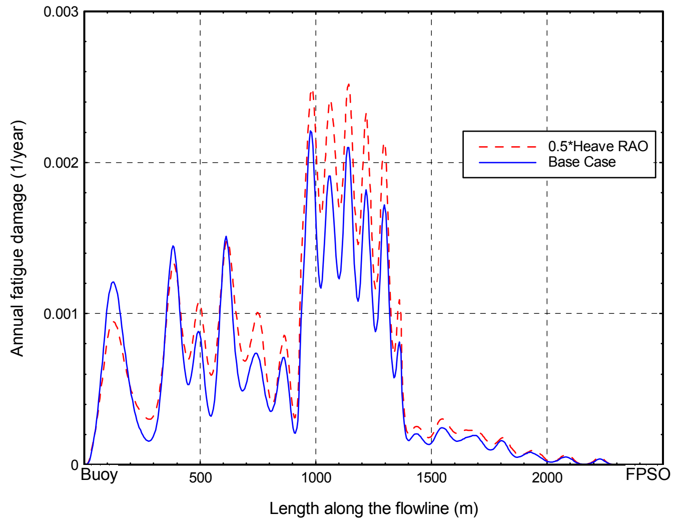

Figure 3. Effect of Heave amplitude on fatigue damage

damage. The reason is that the distance from the center of rotation of the buoy to the attachment point of the flowline is small (approximately 5 meters). With pitch motions on the order of a few degrees, the resulting pitch-induced surge and heave motions are very small, so that the overall horizontal and vertical motions of the flowline attachment point are hardly affected by changes in the pitch response.

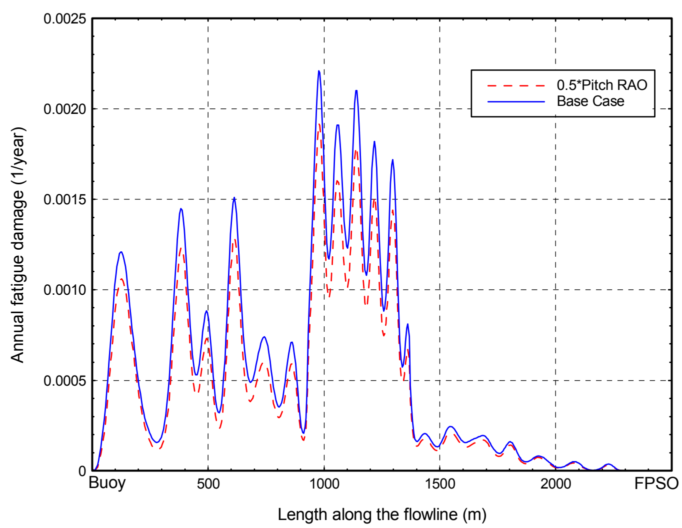

Figure 4. Effect of pitch amplitude on fatigue damage

The sensitivity analysis on the buoy motions reveals that the high frequency surge motion is the most damaging for the suspended flowline in the configuration assumed in this study. This is expected, as horizontal excitation will produce waves that travel along the entire flowline and reflect at the other end. Standing waves in the mid-section of the flowlines are a result of this excitation. A vertical excitation at one end of the flowline will not result in such wave propagation. The results presented demonstrate that the design of a “minimum heave” buoy will not result in a large reduction in the flowline dynamic response.

Drag Coefficient

In the past, much research has been performed on the drag characteristics of oscillating cylinders. It is generally found that the drag coefficient (C_d) is a function of the Reynolds number (Re), the Keulegan Carpenter number (KC) and the roughness ratio. Characteristic values for these parameters for this specific study are Re = $2X10^5$ and KC = 3. From Sarpkaya and Isaacson [6] it is found that the appropriate C_d for these values lies between 0.8 and 0.5.

Figure 5 shows the sensitivity of the annual fatigue damage to the drag coefficient used in the analysis. Two C_d values are used to study the sensitivity, 0.6 and 1.2. The figure shows a strong dependency of the fatigue damage on the value of the drag coefficient used in the analysis. It can also be seen that the location of highest damage along the flowline shifts from the region close to the attachment point on the buoy (for a high C_d) to the buoyancy section (for a low C_d).

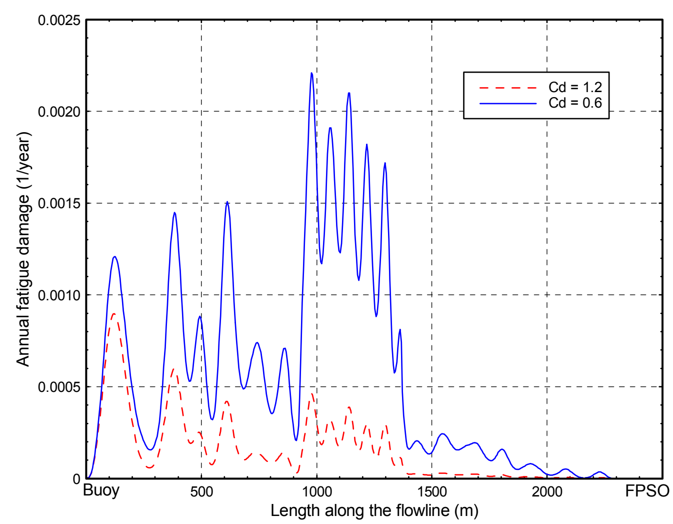

Figure 5. Effect of drag coefficient on fatigue damage

The results presented in the figure can be explained as follows. The wave frequency motions of the buoy excite several natural modes of the flowline, resulting in the resonant response of the flowline. The magnitude and attenuation of resonant response along the length of the flowline is primarily controlled by the damping present in the system. The majority of this damping comes from the viscous drag forces on the flowlines as the structural damping of the steel flowlines is very small.

Selecting a low drag coefficient for the analysis should lead to conservative estimates of the fatigue damage of the system. This is also the recommendation in the DNV Offshore Standard for Metallic Risers [7]. The DNV guidelines state that in areas where drag is acting as a forcing mechanism a high value of the drag coefficient should be selected, and in areas where drag is acting as a damping mechanism a low value of the drag coefficient should be selected.

Environmental Direction

As a result of the large dependency of the fatigue damage to the surge motions of the buoy, the orientation of the flowlines relative to the wave direction is very important. The swell that is present in most deepwater developments in West Africa is typically confined to a narrow band of directionality of approximately 30 – 45 degrees. When the position of the buoy with respect to the FPSO is such that the dominant swell direction is parallel to the flowlines, the resulting buoy motions in line with the flowlines will be a maximum. This is illustrated in Figure 6, which shows the fatigue damage for two different wave directions. The angle between the waves and the flowlines for the base case is 23 degrees while the angle for the alternative case is 68 degrees. The component of the horizontal buoy motion inline with the flowline for the base case is 0.80 meter per meter while for the alternative case it is 0.34 meter per meter. This is a surge motion reduction of approximately 60 percent, with a dramatic reduction in the fatigue damage of the flowline.

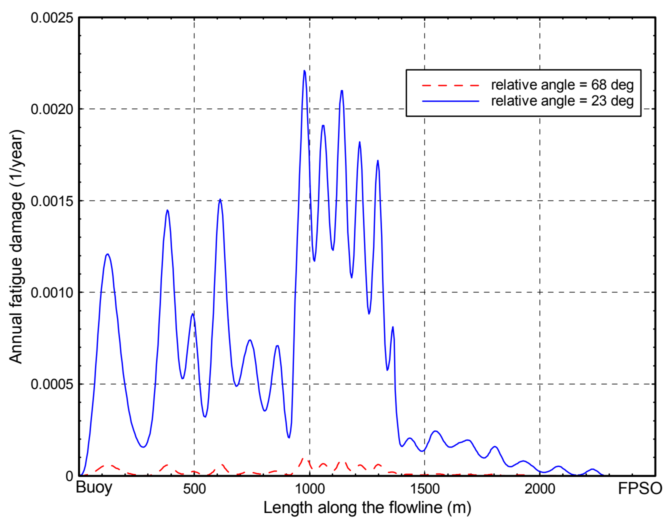

Figure 6. Effect of wave direction

Bin Width

Environmental data used for fatigue analyses is typically comprised of wave scatter diagrams that distribute the long term environment over a number of sea states characterized by significant wave height and spectral peak period. For each sea state in the scatter diagram the probability of occurrence is given so that the annual fatigue damage can be calculated as a weighted average over all sea states. The spectral peak period typically has an increment of 2 – 4 seconds between different sea states. The problem arises with swell sea states, which have a very small spectral width. While in reality the range of peak periods that occur is continuous, the representation in bins separated by two or more seconds causes certain periods (the mid point between two consecutive peak periods) to be under represented. This can lead to an under or over estimation of the fatigue damage as illustrated in Figure 7.

Figure 7 shows the fatigue damage due to three sea states with the same significant wave height of 1.75 meters, and spectral peak periods of 10, 11 and 12 seconds respectively. These sea states are considered representative of the swell bin between 10 and 12 seconds. As seen from the figure, the fatigue damage from the sea states is very different. The strong dependence of the response on the spectral peak period is due to the spacing between the flowline's natural periods and the potential resonant excitation for the peak period considered. The discretization of the scatter diagram is therefore critical to the evaluation of the fatigue damage for these suspended flowlines and attention should be paid to the level of refinement required when specifying the wave scatter diagram.

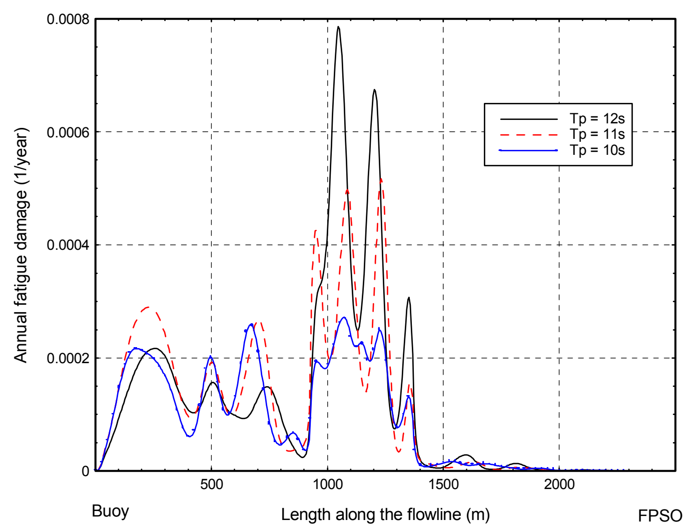

Figure 7. Effect of spectral peak period

Current

As described earlier, the day-to-day current velocities at the depth most affecting the flowlines are very small. However it was found that even small current velocities could have a beneficial effect on the fatigue damage. Figure 8 shows the effect of current on the annual fatigue damage. The current has a direction perpendicular to the main orientation of the flowlines. A current profile representative of West Africa with a surface velocity of 0.5 meters per second was used. It can be seen that a fairly small current leads to a reduction of 30% in the maximum fatigue damage estimated. Therefore assuming no current along the entire length of the flowline will result in a more conservative estimate of the fatigue damage.

The examples listed above illustrate the importance of properly understanding and specifying the environmental conditions at the location where these systems are being installed.

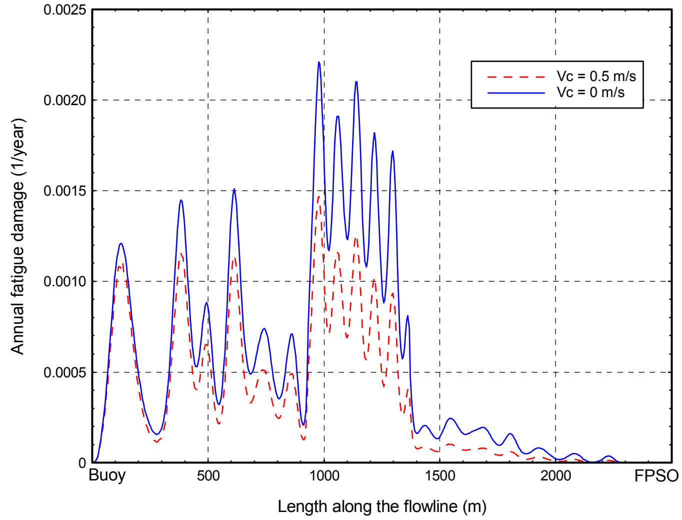

Figure 8. Effect of current

Buoyancy

One of the means to control the configuration of the flowlines is the amount of distributed buoyancy placed in the mid-section of the flowlines. By varying either the diameter of the buoyancy modules or the length over which they are applied, any desired configuration can be achieved. A reason for varying the configuration would be to find a configuration that results both in low extreme stresses and in a long fatigue life. Figure 9 illustrates the effect that a variation in the amount of distributed buoyancy has on the annual fatigue damage. As seen from the figure, increasing the amount of buoyancy can reduce the fatigue damage, but the effect is relatively limited compared to the sensitivity of the flowline response to other parameters.

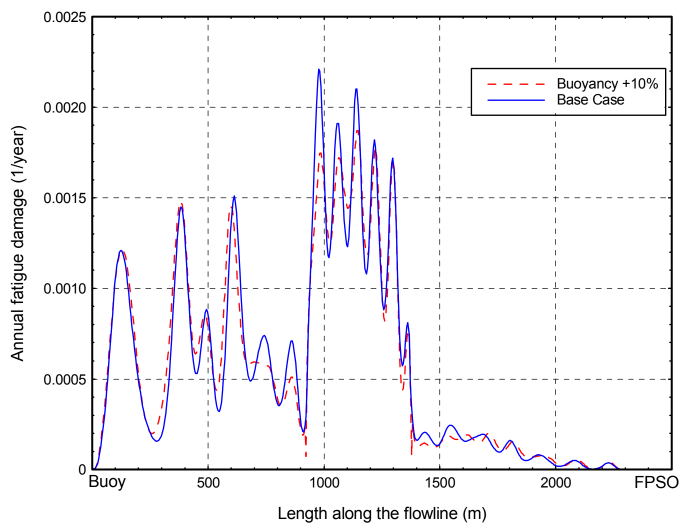

Figure 9. Effect of buoyancy

DISCUSSION

In the previous section the sensitivity of the flowline fatigue damage to a range of parameters have been demonstrated. The required fatigue life for the flowlines is usually ten times the design life. For most deepwater developments with a design life of 20 years, the required minimum fatigue life is 200 – 300 years. When the total fatigue damage of the flowline is calculated for all local wave and swell bins using the methodology described earlier with a C_d of 0.6 and no current, the minimum fatigue life obtained is approximately 50 years. This estimate is based on the AWS C1 S-N curve; using an S-N curve like the API X' would result in a further reduction of fatigue life. This results in an unacceptable flowline design. The fatigue life estimation methodology used is a simplistic one, but expected to give reasonably accurate results.

VIV induced fatigue damage of the mid-water flowline is not discussed in this paper. Most analysis tools used for the evaluation of VIV induced fatigue on slender structures are not designed to analyze a suspended "wave" configuration. Instead an approximate model can be utilized to obtain a first estimate of VIV fatigue damage on the flowline. Alternatively, a conservative approach would be to systematically use Vortex Suppression Devices such as strakes, which disrupt or prevent vortex street formation, regardless of the evaluation performed. The use of strakes over the regions of the suspended flowline most affected by the VIV (near both end points and in the buoyancy section) greatly reduces risk associated with unknown environmental parameters or limitations of the software used.

Several possibilities exist to improve the design of the offloading flowlines. One is to use flexible non-bonded pipe instead of steel tubular pipe. Due to its construction flexible pipe has a high level of internal damping compared to steel pipe. This results in a reduction of dynamic response due to buoy motions. However, the maximum size of flexible pipe currently available has an internal diameter of 19-inch, but due to limitations in supply it is more likely that 16-inch pipe would be used for this application. This means that depending on the flow rate requirements, three flowlines instead of two will be required, and can impact the cost of pumping the crude to the offloading system.

The use of flexible pipe for this application can also introduce other design problems. Experience with the use of flexible pipe attached to surface buoys has indicated that the connection of the flexible to the buoy is a critical point and that a detailed fatigue analysis is needed to ensure proper performance (Levi et al. [8]). Other solutions include the use of long strings of marine hose in a similar configuration as the steel flowlines. The drawback to this solution is that no long-term (20-years) performance data is available.

A promising solution that allows the use of large diameter steel flowlines is to use a de-coupled offloading system. These are systems where the flowlines are not directly connected to the offloading buoy on the surface, but instead to a buoy submerged at a depth of about 75 meters. The product is then transferred to the offloading buoy on the surface through standard submarine hoses or flexible jumpers. An illustration of such a system with a flowline termination buoy (FTB) is presented in Figure 10. Duggal et al. [9] provides a detailed description of this offloading system and its advantages over a large surface offloading buoy.

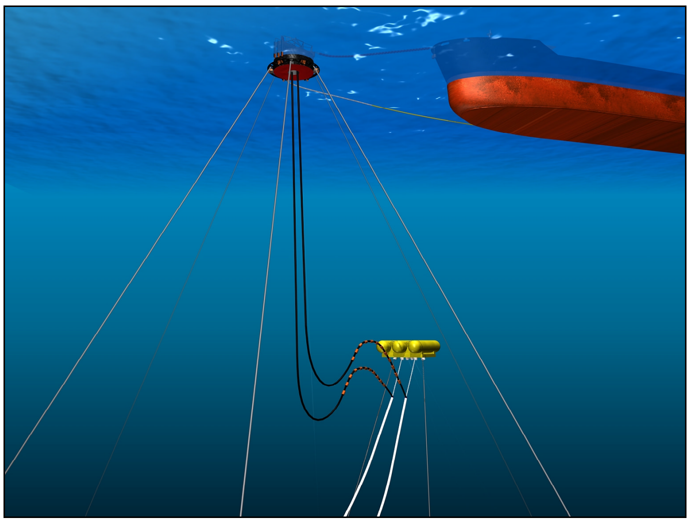

Figure 10. De-coupled deepwater offloading system

To investigate the effect of a de-coupled system on the fatigue performance of the flowlines, an analysis was performed on the system illustrated in Figure 10. At a water depth of 75 meters, the wave kinematics of the local waves approach zero, while those for the swell waves are reduced by 90 percent. This results in very small motions of the submerged buoy and a resulting reduction in the dynamic response of the flowlines. The results of the fatigue analysis for the submerged buoy are shown in Figure 11 with the results for the large surface buoy discussed earlier in this paper. One can see that the annual fatigue damage is reduced by several orders of magnitude. The resulting minimum fatigue life of the flowlines due to wave fatigue is at least 1,000 years. This reduction in fatigue damage of the flowlines also allows the use of larger diameter pipe with a smaller wall thickness, resulting in higher flowrates and associated lower costs for offloading the crude, compared to a large surface buoy solution.

CONCLUSIONS

The paper presents key results from a comprehensive study on the dynamic response of mid-water flowlines, as used in offloading systems for fields in deepwater West Africa. The results illustrate the sensitivity of the dynamic response of the steel flowlines to the motion characteristics of the offloading buoy, and to other parameters like the drag coefficient along the flowline, the incident current velocity, the relative flowline – wave direction, and the discretization of the incident wave environment. The sensitivity of the flowline response to these parameters illustrates the importance of a comprehensive and accurate analysis of the flowline system, in order to ensure an accurate estimate of the reliability of such a system.

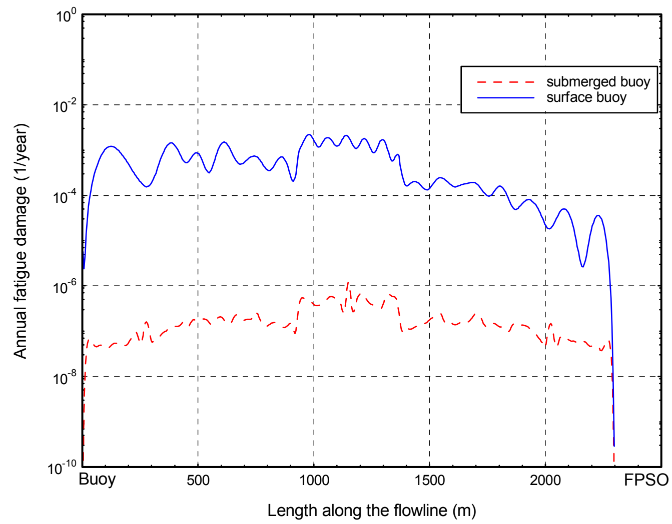

Figure 11. Comparison of suface and submerged buoy

The paper also presents some guidelines for the accurate analysis and design of deepwater offloading systems. The results from the sensitivity study clearly illustrate the importance of properly understanding and specifying the environmental conditions at the location where these systems are being installed. The motion characteristics of the buoy supporting the flowlines, and the drag coefficient used to model the viscous drag forces on the flowline, are shown to have a large impact on the dynamic response of the flowlines. Optimization of the relative wave – flowline orientation, and the flowline configuration are shown to result in a reduction of fatigue damage.

The paper also presents an alternative solution that results in a reduction of the dynamic response, and thus the fatigue damage of the flowlines. The solution is to de-couple the flowlines from the surface offloading buoy and support them on a buoy submerged 75 – 100 meters below the surface. This almost eliminates the wave loading on the support buoy and results in a decrease in the fatigue damage of the flowlines by up to three orders of magnitude. This results in a more robust solution than a large surface-offloading buoy.

ACKNOWLEDGMENTS

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