FATIGUE ANALYSIS OF MARINE ELECTRICAL SIGNAL CARRYING CYLINDRICAL TUBE (UMBILICAL): A CASE STUDY OF DEEP-OFFSHORE WEST AFRICA

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ABSTRACT

The Subsea umbilical is being used increasingly in turbulent harsh environments that requires its mechanical features to be subjected to the axial symmetrical loads that will be discussed. To ascertain the mechanical behavior of umbilical with multiple layers, a theoretical model is presented in this conference paper. The feature of the umbilical cross section in the model is a large-diameter central tube. The contact problem between two adjacent layers contains deformation compatibility of the contact surface. The principle of virtual work is applied in the theoretical model to formulate the governing nonlinear equations and the contact conditions are introduced into the principle of virtual work. The analysis shows greater highest maxima Force 'F' values for Ochi-Hubble as against JONSWAP. From the foregoing, this work shows that using a JONSWAP based umbilical design on an Ochi-Hubble environment like Offshore West Africa shows higher ocean current at the near surfaces which consequently leads a higher tendency for fatigue damage in the future and hence it should be properly taken into consideration in umbilical design for Deep-Offshore West Africa. In addition, the theoretical model is used for the assessment of other important parameters, such as the effects of internal pressure, lay angle and diameter-to-thickness ratio on mechanical behavior of umbilical, which are helpful for the design process of umbilical.

INTRODUCTION

The Subsea umbilical is defined as a device that provides a communication and control link between the subsea system and surface vessel in subsea oil and gas exploitation field developments. It normally consists of various functional lines for hydraulic, electrical power and signal transmission such as hydraulic tubes, electric cables, optical fibers, etc. Each field development demands a unique umbilical design. In offshore application, the umbilical is always subjected to axisymmetric loads such as tension, torsion and internal pressure, etc., no matter under the installation or operation conditions. The prediction of the mechanical behavior of the umbilical in deep water under the axisymmetric loads with an acceptable accuracy is very important for the installation and operation design. Several assumptions were made in the theoretical methods developed up to date for predicting the behavior of umbilical under axisymmetric loads. In the initial model developed by Hruska (1951, 1953, 1952), the wires in the model were assumed to be subjected to pure tensile forces (no moments). Later, a model of multi-strand wire ropes was developed for obtaining wire stress, and the interlayer pressure under tension and torsion. In a 7 x 1 single strand model (Machida and Durelli, 1973) accounted for the moments in helices and gave explicit expressions of axial force, bending and twisting moments for the helical wires. Knapp (1979, 1975) used the well-known energy method to derive a new stiffness matrix and considered the compressibility and material nonlinearity of the core element in helical armored cable under coupled tension and torsion. (Costello and Phillips (1976)) treated the cables as groups of separate curved rods based on Love's theory (Love, 1944) and gave a rigorous derivation. Fere and Bournazel (1987) gave simple formulas to calculate the stress and the contact pressure between layers due to axisymmetric load. Witz and Tan (1992) considered the umbilical or flexible pipe as two basic components: cylindrical elements and helical elements. The continuity of interface pressure and helical radius was considered to assemble all equilibrium equations. Kumar and Botsis (2001) tried to experimentally test the validity of the deformation derivation results earlier obtained for multilayered wire rope strands with metallic core. Sævik and Li (2013) investigated the validity range of formulation of theoretical models for torsion and curvature due to both axisymmetric loads and bending. Numerical method can avoid the restrictions of theoretical method such as uniform distribution of contact pressure between layers and ignoring the friction. Custódio and Vaz (2002) presented a finite element formulation and applied the principle of virtual work, as well as solving the Jacobi matrix by

Newton’s method for the umbilical model. The model considers a number of features, such as material nonlinearity, gap formation and interface contact.

ISO 13628-5 ‘Subsea umbilicals’ /1/ is the main reference for design and load effect analysis of umbilicals. This design code states that umbilicals exposed to ocean currents shall be designed to withstand fatigue loading from Vortex Induced Vibrations (VIV). VIV response analysis shall be conducted for the following scenarios /1/:

Fatigue analyses of umbilicals in dynamic service

Fatigue analyses of umbilicals during installation operations

Assessment of need for VIV suppression devices

Assessment of effect of VIV on drag coefficients to be applied in global analyses and interference analyses

- Fatigue analyses of free spans of umbilicals in static service.
  The following requirements are given to the VIV load effect analysis methodology /1/:
- VIV analysis software for risers and pipelines may be applied
- Due regard shall be given to the structural properties of umbilicals
- Umbilical specific stiffness and structural damping shall be accounted for.

VIV PERFORMANCE OF UMBILICALS

The main structural properties governing the umbilical VIV response is given in terms of the modal damping ratio λ and the mass ratio m_r defined as:

$$m_r = \frac{m}{m_v}$$

Where m is mass per unit length $m_v = \rho \frac{\pi D^2}{4}$ is the displaced water. ρ is water density and D is the umbilical outer diameter. Due to the diversity of the cross-sectional composition of umbilical and power cables, it is obvious that the mass ratio varies significantly between different product types. Typical ranges for the mass ratio for different categories of umbilicals are indicated in the table below. The figures are based on review of typical properties from different manufactures.

Power cable/umbilical	Steel tube umbilical	Control umbilical

Figure 1 Umbilical cross-section types

Table 1. Typical mass ratios for umbilicals

Category	Mass ratio
STU - Steel tube umbilical	1.7 - 2.9
CU - Control umbilical	1.9 - 3.3
PC - Power cable	2.8 - 4.0

A significant spread in mass ratio is observed indicating a corresponding difference in VIV response characteristics.

The mass ratio and modal damping ratio can be combined into the so-called reduced damping parameter, K_S, defined as:

$$K_s = (m_r + 1)\pi^2\lambda$$

Extensive theoretical and experimental studies have been conducted to express the expected VIV response of various structures as a function of the reduced damping /3/.

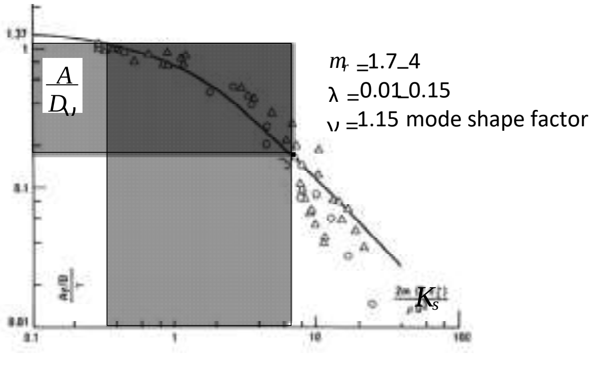


Figure 2 VIV response as function of reduced damping

Figure 2 is reproduced from /3/ with the response range of umbilicals superimposed assuming a modal damping ratio in the range of λ= 0.01-0.15 and a mass ratio range of m_r =1.7- 4. It is seen that the associated response amplitude to diameter ratio variation range is large, A/D = 0.15-1. Hence, it should be expected that the VIV response of umbilicals will vary significantly depending on the cross-sectional mechanical properties. Consistent analysis methodology accounting for the cross-sectional mechanical properties is therefore essential for prediction of the VIV response of umbilicals.

MATERIALS AND METHODS

Umbilical Material Properties

An Umbilical design data with a design life of 30years for an FPSO in Offshore West Africa was collated. The data below were entered into OrcaFlex software interface include: Outer diameter nominal – 200mm, Umbilical Minimum Bending Radius (MBR Operational) – 12m, Bending Stiffness- 2.68 x 10^4 Nm^2, Axial Stiffness- 4.62 x 10^8 N, Torsional Stiffness - 2.06 x 10^4 Nm^2.

The general design criteria considered were the following environmental data: Design water depth- 2000m, Seabed Temperature +5^{o}C, Sea surface Temperature + 40^{o}C.

The lengths of the four (4) Umbilicals are: Umbilical-1 - 3044m, Umbilical-2 - 3215m, Umbilical-3 - 4481m and Umbilical-4 - 2873m.

From design data, buoyancy modules were applied from section length 1379.7m to 1479.7m for each umbilical. Relevant material data were imputed on the OrcaFlex software as shown in the Figure 3.

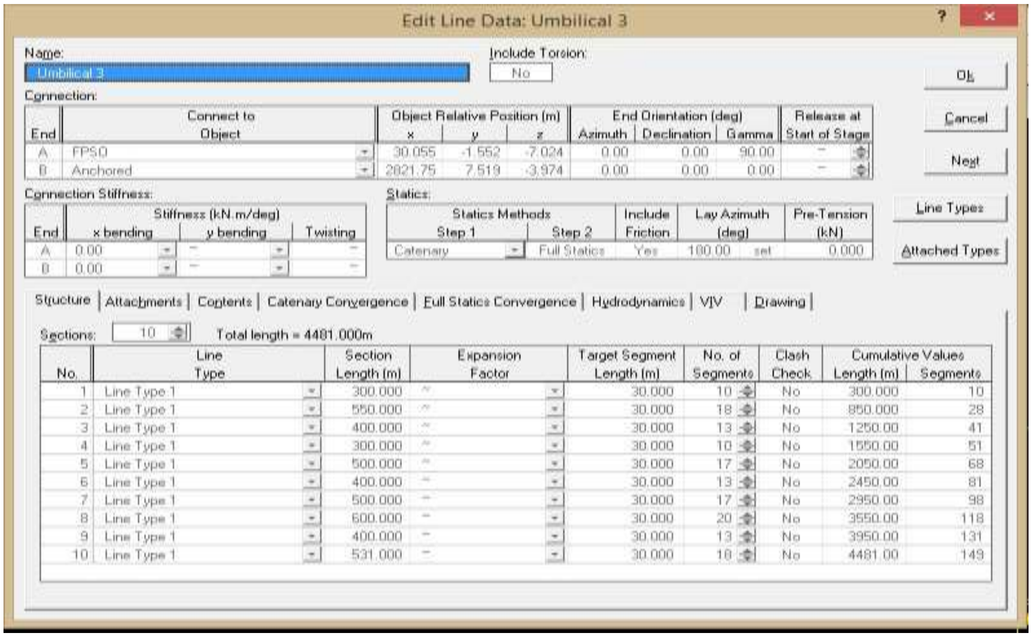
MetOcean Data

MetOcean data for Offshore West Africa including water depth, current factor, rotation, near-surfaces and near-bottom current speed and direction were imputed into the OrcaFlex platform for both JONSWAP and Ochi-Hubble wave spectra.

Another metOcean data involving the near-bottom surface current velocity versus simulation time variation showed 0, 0.103, 0.206, 0.309, 0.412, and 0.514m/s velocity for 0, 2, 4, 6, 8, and 10s simulation time, respectively

Methods

The Umbilical material characteristics and metOcean data were inputted into the OrcaFlex 8.4a7 [12] software platform and simulated using the Milan wake oscillator model for Force. Results were obtained for the Transverse Vortex Force (F) at different sections for both Ochi-Hubble and JONSWAP wave spectra.



Name: Umbilical 3

Include Torsion: No

Connection:

End	Connect to Object	Object Relative Position (m) x	y	z	End Orientation (deg) Azimuth	Declination	Gamma	Release at Start of Stage
A	FPSO	30.055	-1.552	-7.024	0.00	0.00	90.00	~
B	Anchored	2821.75	7.519	-3.974	0.00	0.00	0.00	~

Connection Stiffness:

End	Stiffness (kN.m/deg) x bending	y bending	Twisting
A	0.00	~	~
B	0.00	~	~

Statics:

Statics Methods Step 1	Step 2	Include Friction	Lay Azimuth (deg)	Pre-Tension (kN)
Catenary	Full Statics	Yes	180.00 set	0.000

Sections: 10 Total length = 4481.000m

No.	Line Type	Section Length (m)	Expansion Factor	Target Segment Length (m)	No. of Segments	Clash Check	Cumulative Values Length (m)	Segments
1	Line Type 1	300.000	~	30.000	10	No	300.000	10
2	Line Type 1	550.000	~	30.000	18	No	850.000	28
3	Line Type 1	400.000	~	30.000	13	No	1250.00	41
4	Line Type 1	300.000	~	30.000	10	No	1550.00	51
5	Line Type 1	500.000	~	30.000	17	No	2050.00	68
6	Line Type 1	400.000	~	30.000	13	No	2450.00	81
7	Line Type 1	500.000	~	30.000	17	No	2950.00	98
8	Line Type 1	600.000	~	30.000	20	No	3550.00	118
9	Line Type 1	400.000	~	30.000	13	No	3950.00	131
10	Line Type 1	531.000	~	30.000	18	No	4481.00	149

Figure 3. Typical Umbilical Material Description on OrcaFlex Interface

Discussion

Jonswap Wave Spectra

Data extracted from Figure 4, Figure 5 and the other metOcean data involving the near-bottom surface current velocity versus simulation time variation were inputted into the environment and variable data section of the OrcaFlex platform.

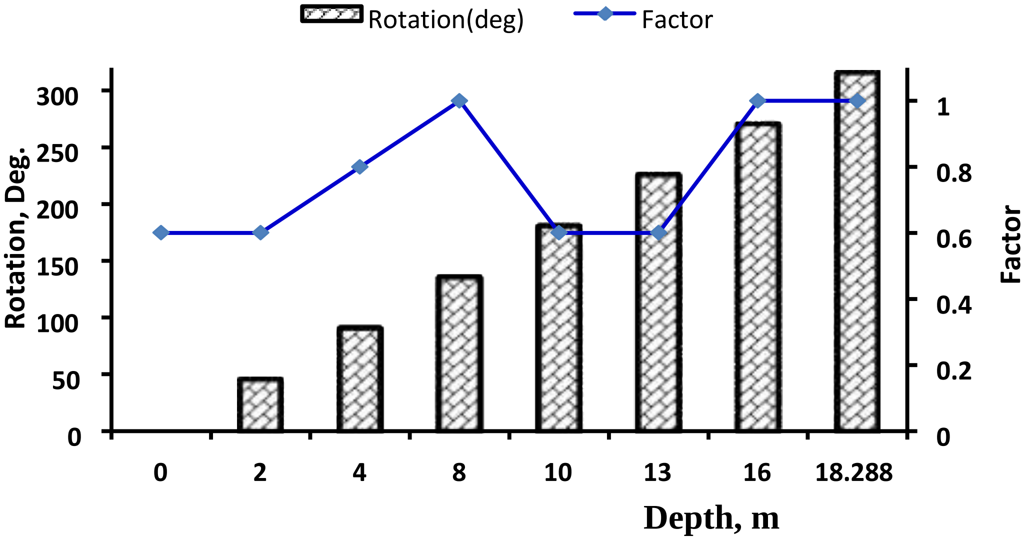


Figure 4. Current Factor and Angle of rotation for various water depths as simulated on OrcaFlex

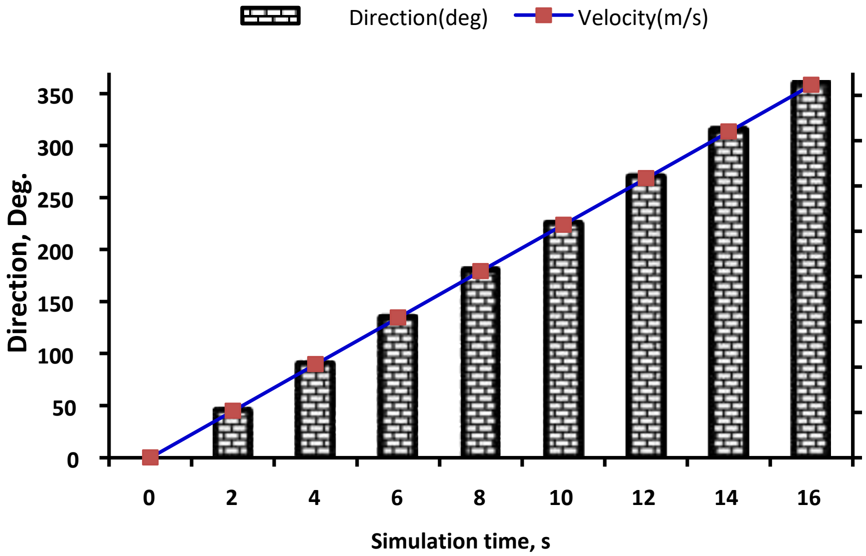


Figure 5. Near Surface Current velocity and Direction versus simulation time

For JONSWAP wave spectra the following result was obtained for F;

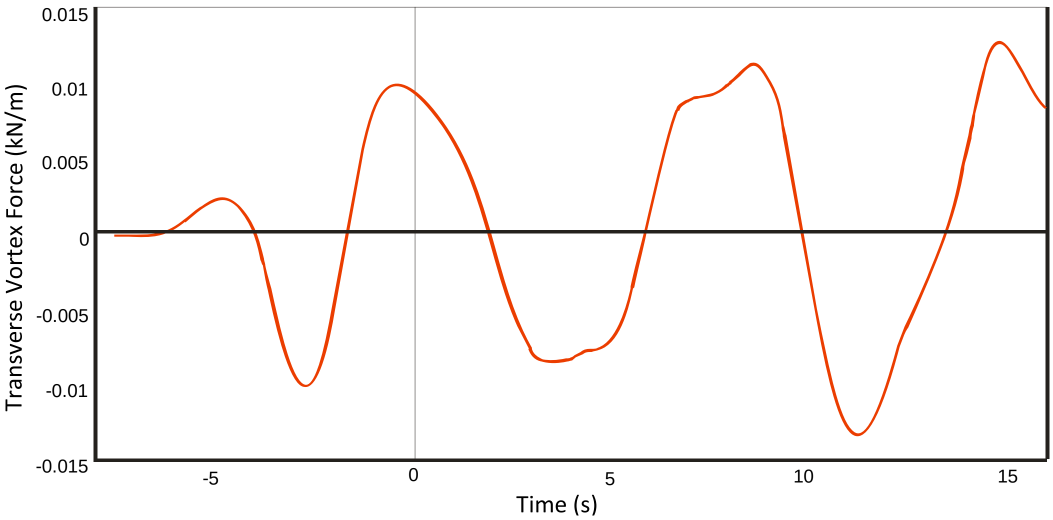


Figure 6. TVF- time graph of Umbilical at 300m (Near Surface Current)

At Umbilical length 300m, 600m, the Force - time plot showed maxima at (t, F) = (8.0, 0.0115); (14.1; 0.013) and (8.0, 0.018); (14.6, 0.0175). The highest maximum is 0.013kN/m and 0.018kN/m. No values exist for the minimum since it is negative. Fluctuations occur at this segment due to instability in current flow and wave spectral properties hence the reason for the graph showing mesokurtic peaks of both double and single nature as well as flat sags and gullies.

For the JONSWAP spectra analysis, the results of Figure 6, at 300m showed double-peak while at 600m and 850m, showed single peak. But significantly as we go down in depth for the four umbilicals at 600m and 850m, there is shown a return to single peak which is the normal JONSWAP model. This shows that as we go deeper the adjustment of the peakedness parameter to suit Offshore West Africa Ochi-Hubble environment loses its applicability and tends to revert back to the natural wave spectra of this region.

Ochi-Hubble Wave Spectra

Raw data from Figure 4, Figure 5 and the other metOcean data involving the near-bottom surface current velocity versus simulation time variation were imputed into the environment and variable data section of the OrcaFlex platform. For Ochi-Hubble wave spectra the following results were obtained for Force;

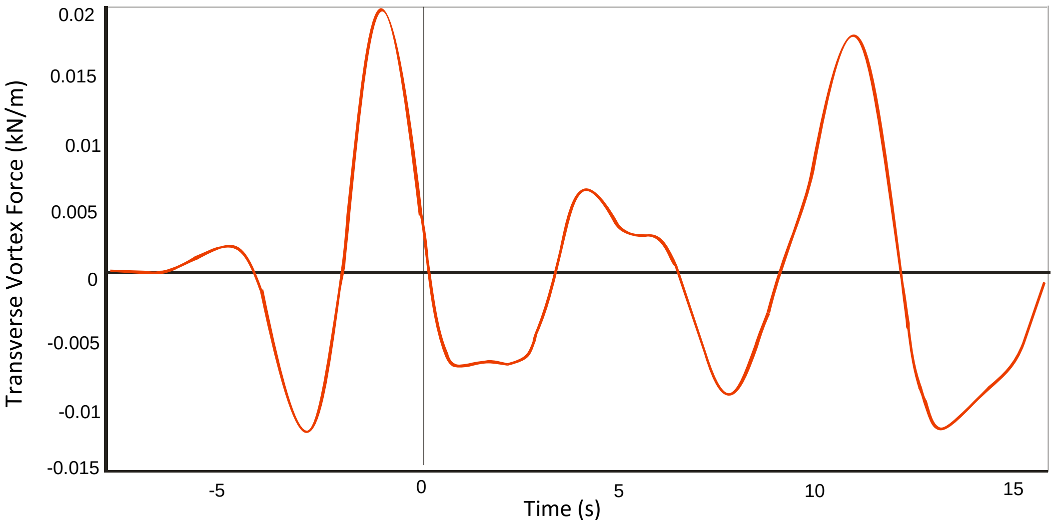


Figure 7. Force time graph of Umbilical-1 at 300m (Near Surface Current)

Umbilical at length 300m and 600m showed maxima at (t, F) = (4.0, 0.006); (11.1, 0.018) and (3.8, 0.004); (5.6, 0.0075); (11.2, 0.0305). The highest maximum is 0.018kN and 0.0305kN/m. No minimum value exists. Fluctuations occur at this segment due to instability in current flow and wave spectral properties hence the reason for the graph showing mesokurtic peaks of both double and single nature as well as flat sags and gullies.

Also, Umbilical at 850m showed maxima at (t, F) = (3.0, 0.003); (5.9, 0.0074); (11.3, 0.027). The highest maxima is 0.027kN/m. Fluctuations occur at this segment due to instability in current flow and wave spectral properties hence the reason for the graph showing mesokurtic peaks of both double and single nature as well as gullies.

The overall representation of the four Umbilicals can be well demonstrated or better still be represented in an excel graphical tools. Using a bar chart to analyze the result clearly, it can be seen that from Figure 9, that there is descending order for the heights from Umbilical-1 to 4 at 300m for JONSWAP but for Ochi-Hubble it showed descending heights from Umbilical-1 to Umbilical-3 with Umbilical-4 being the exception because it shows an ascending height.

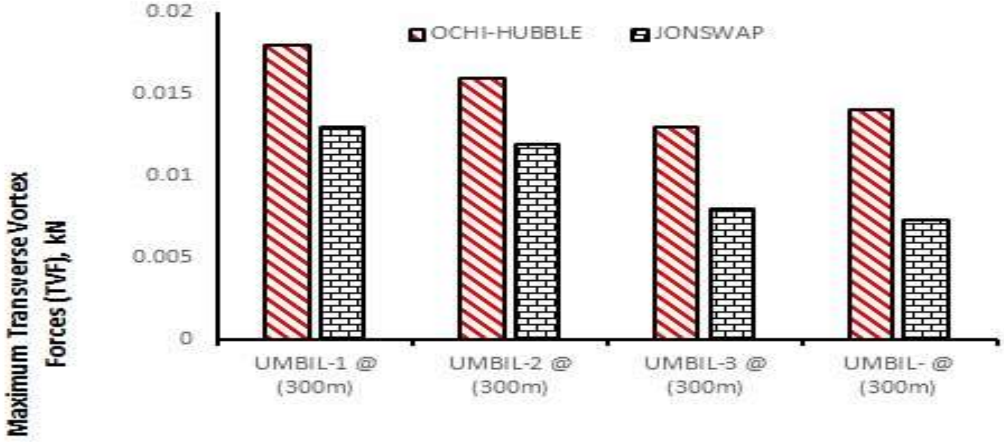


Figure 9. Force Maxima for Ochi - Hubble and JONSWAP at 300m

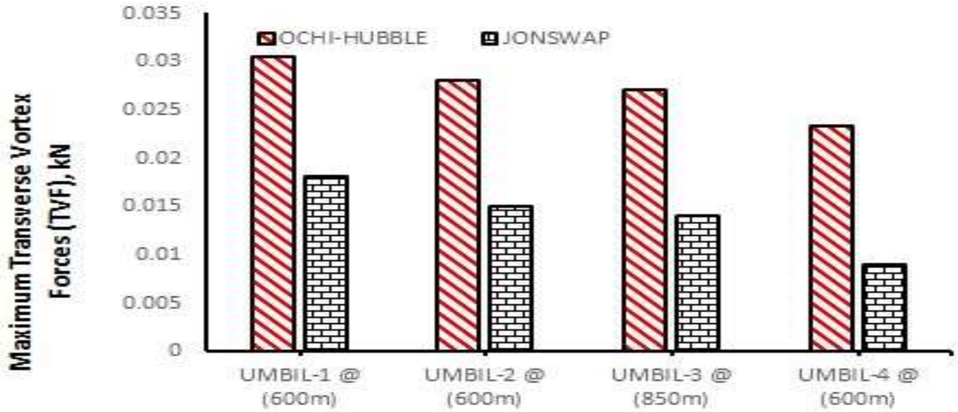


Figure 10. Force Highest Maxima for Ochi- Hubble and JONSWAP

Also, Figure 10 equally shows the highest maxima Force values for Umbilical-1 (600m), Umbilical-2 (600m), Umbilical- 3 (850m), and Umbilical-4 (600m) for both wave spectra. It can be clearly seen that the bar chart shows heights in descending order for Ochi Hubble and JONSWAP. Hence, the Force values decrease steadily from Umbilical-1 through Umbilical-4. From this Figure 10 Umbilical-1 showed the maximum Force while Umbilical-4 showed the minimum.

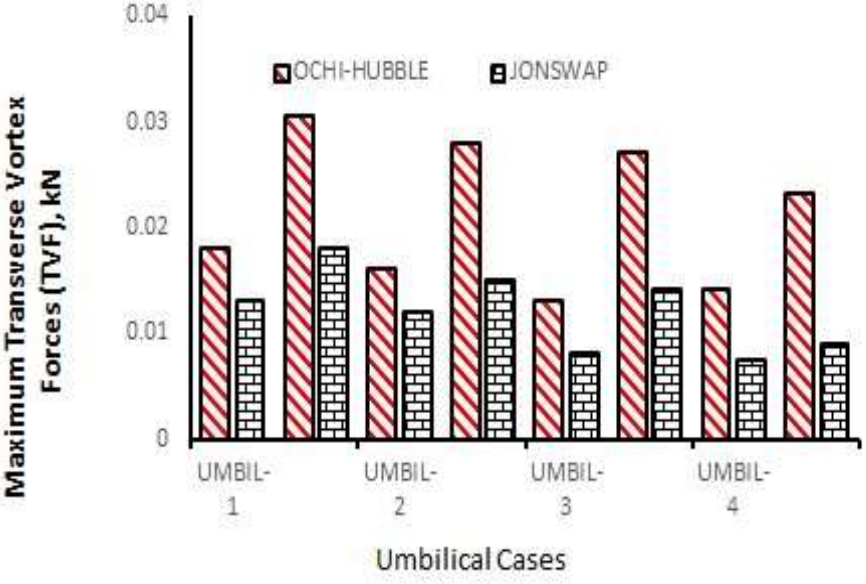


Figure 11. Force Maxima for Ochi- Hubble and JONSWAP

From the Orcaflex result conducted, from the wave spectra analysis of Umbilicals 1 to 4, the results for JONSWAP and Ochi-Hubble were shown. Umbilical-1, Umbilical-2 and Umbilical-4 at arc length 300m and 600m gave highest maxima F values for 0.013kN and 0.018kN; 0.012kN and 0.0149kN; 0.0074kN and 0.0086kN, respectively. Umbilical-3 at 300m and 850m gave 0.008kN and 0.014kN. It can be seen that the F values at 600m and 850m were higher than that of 300m. Hence, at near- surfaces the deeper the Umbilicals are from the FPSO the higher the F. Similarly, for the Ochi-Hubble spectra results, Umbilical-1, Umbilical-2 and Umbilical-4 at arc length 300m and 600m gave highest maxima F values for 0.018kN and 0.0305kN; 0.016kN and 0.028kN; 0.0141kN and 0.0232kN, respectively. Umbilical-3 at 300m and 850m gave 0.013kN and 0.027kN. Also, as the case of JONSWAP, it can be seen that the

F values at 600m and 850m were higher than that of 300m. Hence, at near-surfaces the deeper the Umbilicals the higher the F.

Looking at of Figures 9, 10 and Figure 11 tells us that during the positioning of the Umbilicals at subsea with regards to the current flow and speed at different wave frequencies is the mainly cause of the disparity in F values and not the order in which the Umbilicals are numbered in this work. It should be noted here that the JONSWAP model though it was designed for the North Sea, but because the bandwidth can be adjusted by changing its peakedness parameter, it is used almost anywhere to design the Umbilical. Do to the adjustment in the peakednesss, this has change the charlatanistic design of the system and hence leads to low life spam of the system. Hence, there is little evidence to support its use when the climate is somewhat different from that of North Sea. Ewans et al. [13] and Forristall et al. [14] suggested the use of Gaussian or log-normal distributions. Normally double-peak is associated with Ochi-Hubble spectra while single peak is associated with JONSWAP. For the Ochi-Hubble spectra analysis, the results showed double-peak which was not consistent.

This results clearly shows that the adjustment of the peakedness parameter of the JONSWAP based design to suit Ochi-Hubble environment of Offshore West Africa is in proper alignment. From the results, its precision is not guaranteed since this phenomenon is not applicable to every gradient on the graph.

CONCLUSIONS

The dynamic analysis due to Force on the four Umbilicals gave highest maxima F values at the near surfaces (water depths of 300m, 600m and 850m) for the Ochi-Hubble wave spectra against the JONSWAP. This clearly shows that using a JONSWAP based design marine electrical signal carrying cylindrical tube (umbilical) on an Ochi-Hubble environment like Offshore West Africa causes higher ocean current and a high tendency to develop fracture at the near surfaces and consequently a higher fatigue damage in the future. Based on the findings in this study, design of marine electrical signal carrying cylindrical tube (umbilical) for installation in Deep-Offshore West Africa should be based on proper research on the wave spectra of this region (Ochi-Hubble) as adjusting the peakedness of the JONSWAP spectra does not give the desired accuracy and hence has significant consequences on the high current fracture Force values.

Nomenclature

F - Force
PM -Pierson and Moskowitz
G_o -Normalization factor
D -Double
W -Wallops
f - Frequency [Hz]
f_n - Normalized frequency
f_p -Peak frequency [Hz]
g - Acceleration due to gravity [m/s^2]
H_s -Significant wave height [m]
j - Integer counter
S_f - Wave spectral density [m^2/Hz]
T_p -Peak period [s]
T_s -Average zero up-crossing period [s]
t -Time [s]

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