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Free Span Analysis of an Offshore Pipeline in the Gulf of Guinea

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ABSTRACT : *In an offshore oil and gas field, on-bottom(unburied) pipelines pass through varying terrains and overtime, scour, currents and wave actions do create spaces under the pipeline leading to suspended sections of pipeline termed Free Span. There arises a need therefore, to access the said free span especially, if the span is longer than the maximum allowable free span length as longer span length exposes that section of the pipeline to both current and wave induced vortex vibration (VIV) and consequently, fatigue damages leading to pipeline failure. This project focuses on developing a simple MATLAB code to investigate the responses of free spanning pipelines in an offshore field in the Gulf of Guinea under the influence of environmental forces in order to reveal its capacity against Screening and Ultimate Limit State (ULS) criteria stipulated by DNV recommended practice F105. Results show violation of all the checks conducted at the free span region hence, span intervention is advised for the selected pipe data. Further sensitivity study conducted to reveal the susceptibility of various pipe outer diameters to resonance showed that with in-line velocity, altering the pipe outer diameter may never lead to resonance however, with cross-flow velocity, there was marked possibility of resonance occurring as the difference between the cross-flow-induced natural frequency and the vortex shedding frequency closed-in tightly at pipeline design outer diameter and diameters below pipeline design diameter. Of course, this result agrees with existing literature which have noted the cross-flow velocity as most critical to pipeline free span failure. Ultimately, altering the outer diameter of pipe free span for a combined motion system which is the case in the sensitivity studies has revealed that with in-line flow velocity, there may never be any danger during the operational stage even though, the vortex shedding frequency and the in-line-flow natural frequency are seen closing-in as pipeline diameter is increasing. This of course, portends no danger during operation as pipeline diameters do not increase markedly, if at all they do. However, with Cross-flow velocity there is likely danger of the consequences of vortex-induced vibration at the design diameter and even greater danger of fatigue damage as the pipeline begins to degrade via corrosion as the pipeline facility is aging. It is therefore instructive for pipeline operators to have a robust corrosion control and monitoring mechanism particularly where there is likelihood of free span formation during operation to guarantee the integrity of the pipeline infrastructure.*

KEYWORDS *free span, offshore, pipeline, analysis, VIV.,*

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I. INTRODUCTION

Offshore pipelines are important components for the exploitation process of oil and gas located in offshore fields as they help in the transportation of oil and gas between offshore platforms and/or directly to onshore facilities.

A common construction method in offshore pipeline systems is the construction of on-bottom (unburied) pipelines, since this method results in the reduction of construction time and associated costs [1]. However, this method is vulnerable to the creation of free span (suspended section of a pipeline) due to various associated factors such as seabed unevenness, change in seabed topology, wave flow scouring, residual stress or thermal stress of pipelines, human activities, artificial support/rock beams, etc., as figure 1 below shows:

For every given pipeline and environment, there is a maximum allowable span length, below which the effects of free span can be ignored. However, once a free span longer than the allowable span length occurs, the free span may suffer vortex-induced vibration (VIV) and consequently, fatigue damages due to the actions of wave and current. To avoid such scenario therefore, it is important to analyze a free spanning offshore pipeline in order to reveal if cumulative effect of stresses developed are within accepted criteria or not, at which point intervention may be necessary.

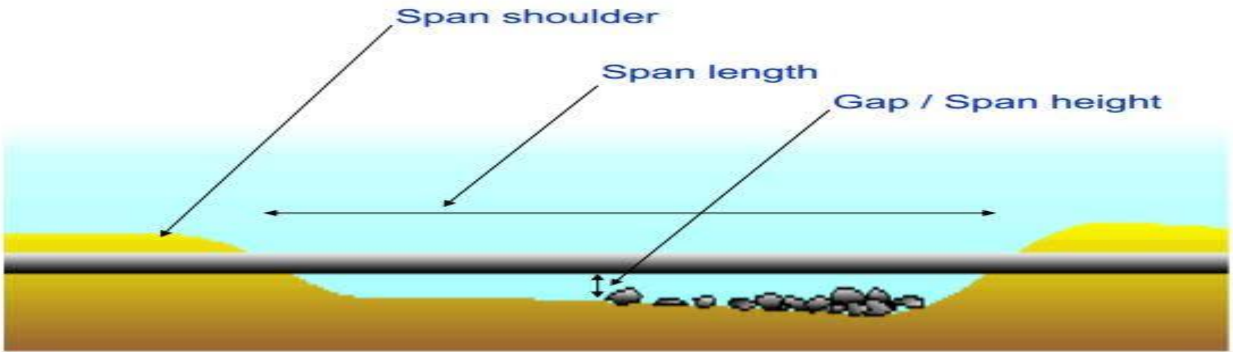

Figure 1: Free spanning section of an offshore pipeline [2]

With the possible onset of vortex-induced vibration resulting from either isolated or combined effect of current and/or wave loadings on pipeline free span, care must be taken to ensure that the vortex shedding frequency does not equal or get near the natural frequency of the free span since this can lead to resonance. Resonance amplifies loads which causes fatigue damage. A damaged pipeline may lead to pollution as hydrocarbon spills into the environment, causing contamination of the marine environment, depletion of species and a loss in biodiversity of aquatic habitat. This is undesirable justifying numerous works done on static and dynamic analysis of free span majorly in the design stage. For example, [3] established a rigorous procedure on the free span analysis of offshore pipelines. He also derived the closed-form solution of the beam-column equation, considering tension and compression force for the various possible boundary conditions. [4] carried out a study in order to improve on the understanding of undesirable effects of vibrations in a subsea pipeline which presents free span portions along its length. This understanding is fundamental for the safe design and operation of the pipeline with possible reduction of its fatigue life. [5] analyzed the dynamic behavior of a single free span offshore pipeline and also investigated the effect of various factors/parameters (different design conditions, wave and current characteristics, soil characteristics, length of the free span and boundary conditions at the ends of the pipeline) on its dynamic behavior and its structural integrity. This study also considered non-linear pipe-soil interaction of the part of the pipeline lying on the seabed and also implemented a global buckling in the assessment of the structural integrity of the pipeline. [6] carried out a research on vortex-induced vibration response of long free spanning pipelines, in which they presented hypotheses that may explain the observed behavior as the sag effect of a long free span caused different dynamic properties in vertical and horizontal directions of the span, leading to a much more complex vortex-induced vibration response pattern for long free spans than for short spans. They consequently outlined a new design format for long free spans. [7] carried out a research on causes and treatment measures of submarine pipeline free spanning, in which they introduced the various methods in the governance of pipeline free-spanning and also the current research status of wave scour, which is the most common cause of submarine pipeline free-spanning. After stating various causes of free spanning and outlining failure accidents caused by free-spanning of submarine pipelines that had occurred throughout history, they noted that the submarine pipeline free-spanning caused by wave scouring is the most important cause of failure of submarine oil and gas pipelines, hence reiterating the necessity of reviewing the mechanism and research status of pipeline scouring. [1] investigated the effects of seabed formation along with axial force on Natural Frequency for offshore pipelines, hence proposing a new simple formula based on this assessment. They evaluated the result of this study, by using Qesham Island pipelines as a case study to calculate the allowable free span length, comparing it with those of DNV (1998) and ABS (2001) guidelines and modal analysis. In this study, it was brought to notice that the influence of soil translatory parameter is a parameter that plays a significant role in the estimation of Natural frequency of free spanning sectors of offshore pipelines, hence the recommendation that the modal analysis or new approximation formula be applied for estimation of allowable length of free span even at the primary phase of offshore pipeline design. Also, it was deduced that the soil type has a significance influence on the determination of allowable length of pipe free span as clay formation reduced the intensity of Natural Frequency remarkable, whereas the rock formation (at same condition), increased the intensity of Natural Frequency Noticeably. [8] investigated the DF1-1 submarine pipeline using a dual-frequency side-scan sonar and a swath sounder system. They found more than a hundred scour pits under the pipeline, most of which had caused the span of the pipeline to increase and threatened its safety. Through the limitations regarding maximum allowable stress under static or quasi-static loads and the onset of Vortex Induced Vibrations (VIV) under different hydrodynamic actions, the maximum allowable free span length (MAFSL) of the pipeline was determined. [9] conducted a study in an attempt to investigate the natural frequency of free spanning pipelines and influence of soil characteristic in support of pipeline in free span. In this regard, various boundary conditions were considered and the results were analyzed. It was discovered that the pipeline frequency increased with shortening of pipeline length and fixity against rotation at the ends of the pipe. It was also established that with increase in soil stiffness, difference between the results reduced for different boundary conditions, such that natural frequency would not depend on the boundary conditions of the pipeline. [10] presented a new approach named the “Pipeline lowering (PL) method” for free span rectification. This unique solution ensured that the free span rectification was a long-term solution when compared to grout bags that may be affected by scour and wave loadings. The solution involved lowering the crests of the free spans such that the pipeline followed the natural seabed profile while ensuring the pipeline integrity was not compromised at any stage. The lowering operation was carried out solely by fluidizing the seabed soil by a mass flow excavator and the pipeline lowered under its self-weight. A laboratory demonstration and successful field implementation of PL method for free span rectification were presented in the study. [11] analyzed the structural response of free span under loads induced by vortex shedding, effective axial force, gravity and buoyancy with numerical simulation and theoretical analysis method, considering the real service status of submarine pipeline. He also investigated based on the ULS criterion under load-controlled condition given by DNV-OS-F101 standard, the local buckling analysis for free span with different length. [12] in their studies presented a strategy adopted to manage scour-induced free span on any offshore pipeline susceptible to scour and dynamic seabed condition. Though the case study was the BBL pipeline, this study focused on two subjects: predicting span evolution in time and quantifying the sheltering effect of the scour trenches. The study resulted in considerably longer spans being acceptable as the sheltering effect of scour trenches and the span evolution in time were taken into account. This reduced the need for offshore intervention work and, in some cases, may eliminate it altogether.

As noted earlier, most of these works were done at the design stage hence, attempt here is to carry out an investigative analysis on the sensitivity of the free spanning pipeline when it occurs in operation vis-à-vis environmental effects on the integrity of a free spanning offshore pipeline with the following objectives:

i. Development of velocity profile to determine the environmental effective force.
ii. Determination of the maximum allowable free span length to identify span lengths that exceeds this limit.
iii. Performance of preliminary screening check on a free spanning pipeline.
iv. Development of a MATLAB code for pipe free span screening and ULS criteria.
v. Performance of a sensitivity analysis to reveal the effect of varying pipe free span diameters on both vortex shedding and natural frequencies.

II. MATERIAL

Environmental Data

- The environmental data is collected from periods that are representative of the long-term variation of the wave and current climate. The environmental load conditions were established near the pipeline.
- The water depth used in this study is 1000m with water density of 1025Kg/m^3.
- A swell-dominated environment which is prevalent from the months of May to September when the highest swell waves from South Atlantic Ocean reaches Nigeria is used for this study.

Wave Data

TABLE 1: JOINT CRITERIA FOR EXTREMES DOMINATED SWELL WAVES FOR 1YR AND 100YRS RETURNS [13]

	1year return Period	100 years return period
Significant wave height (m) H_s	2.74	3.45
Peak period (sec) T_p	14.4	17

Symbols	Nomenclature	Calculated Parameters	
		1year	*100years*
λ	Wavelength (m)	323.753	451.219
κ	Wave number(/m)	0.019	0.014

ω	Wave frequency(/s)	0.436	0.370
U_w	Wave Velocity (m/s)	2.229E-09	5.715E-07

Current Data

TABLE 2: LONG-TERM CURRENT VELOCITY DISTRIBUTION (m/s) [13]

Measure depth [m]	1yr	10yr	100yr	1000yr	10,000ys
0.5	0.94	1.2	1.49	1.8	2.13
5	0.93	1.2	1.48	1.76	2.04
12	0.83	1.1	1.38	1.65	1.93
23	0.74	1.01	1.27	1.54	1.8
53	0.42	0.56	0.74	0.98	1.27
108	0.39	0.54	0.69	0.85	1
200	0.33	0.44	0.55	0.66	0.78
500	0.3	0.4	0.5	0.61	0.72
Near-bed	0.18	0.24	0.29	0.35	0.41

Pipeline Data

Table 3: Pipeline input data [14]

Parameters		**Value**	**unit**
D_o	outer diameter	0.508	m
D_i	internal diameter	0.4762	m
-	Material Grade	API 5L X60	-
t_{nom}	Nominal Pipe Thickness	0.01588	m
-	External corrosion coating	Asphalt enamel	-
t_{corr}	Corrosion Coating Thickness	0.0065	m
t_{conc}	Concrete Coating Thickness	0.1	m
h	Maximum water Depth	1000	m
g	Gravitational acceleration	9.81	m/s^2
k	Design factor	0.72	-
v	Poisson's ratio	0.3	-
μ	Coefficient of friction	0.6	-
E	Young's Modulus	2.07E+11	N/m^2
σ_y	Specified Minimum Yield Strength	4.50E+08	N/m^2
α	Linear coefficient of Expansion	1.16E-05	$/^oC$
P_i	Internal Pressure	1.2E+07	N/m^2
P_o	External Pressure = $\rho_w * g * h$	1.01E+07	N/m^2
T_{op}	Operating Temperature	25	^oC
T_{amb}	Ambient Temperature	4	^oC
ρ_{cont}	Density of Content	870	kg/m^3
ρ_s	Density of steel	7850	kg/m^3
ρ_{corr}	Density of corrosion coating	1300	kg/m^3
ρ_{conc}	Density of concrete coating	3000	kg/m^3
ρ_w	Density of water	1025	kg/m^3
v_k	Kinematic Viscosity of seawater	1.05E-06	m^2/s
U_c	current velocity	0.29	m/s
e	Span gap	0.2	m
δ	Logarithmic decrement of structural damping	0.126	-
C_e	End condition constant (pinned-pinned)	9.87	
f_{cn}		28.13	N/mm^2
L	Span Length	30	m

Safety and Load Effect Factors

Table 4: Safety factors corresponding to standard safety class [15] [16]		
Description of factor	Symbol	Magnitude
Screening factor for in-line	γ_{IL}	1.4
Screening factor for cross-flow	γ_{CF}	1.4
Allowable fatigue damage ratio	η	0.5
partial safety factor for stability parameter	γ_k	1.15
partial safety factor for stress range	γ_s	1.3
partial safety factor for the in-line onset of VIV	$\gamma_{on,IL}$	1.1
partial safety factor for the cross-flow onset of VIV	$\gamma_{on,CF}$	1.2
partial safety factor for the natural frequency	γ_f	1.1
Functional load effect factor	γ_F	1.1
Environmental load effect factor	γ_E	1.3
Condition Load effect factor	γ_c	1.07
Material Resistance factor	γ_m	1.15
Material strength factor	α_u	0.96
Safety class resistance factor	γ_{sc}	1.14

III. RESEARCH METHODOLOGY

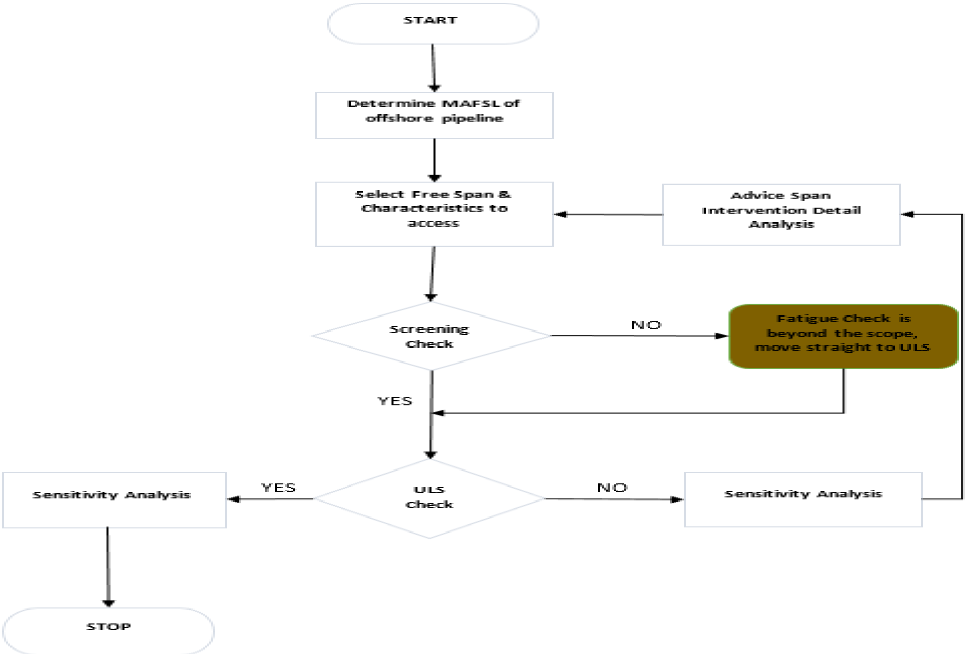

Figure 2: Workflow chart

The flow chart in Figure 2 above illustrates sequentially how this study is carried out; starting from the determination of the maximum allowable free span length that will enable identification of free span that exceeds this allowable span length, so that such could be accessed. Also identified are, the free span data and characteristics such as the main components (i.e., Environmental description, structural response, model types and the acceptance criteria) and key parameters associated with each of these main components.

Next, screening fatigue criteria in both in-line and cross-flow is checked for conformity. If these criteria are not met, a detailed fatigue analysis will be necessary however, this is not considered in this study, therefore, an Ultimate Limit State (ULS) criterion check follows.

The ULS criterion is conducted to assess if local buckling capacity anticipated at the span is satisfactory or not. If it is not satisfactory, then there will be need for intervention.

Sensitivity analysis is then conducted to ascertain the effect of various outer diameter on the vortex shedding and natural frequencies of a free spanning pipeline. This analysis is done to determine if altering the outer diameter of a free spanning pipeline could prevent the occurrence of resonance.

Determination of maximum allowable free span length (MAFSL)

A proper definition of the limit of free span length that will be used in the simulation is very vital in this work and the limit is drafted by determining the maximum allowable free span length.

Thus, necessary steps for determining the maximum allowable span length for Pipeline via dynamic analysis are:

Step 1: Determination of the design current (100 years near bottom perpendicular to the pipeline)

Step 2: Determination of the effective unit mass, $M_e$of the pipeline using eqn. 1.

$$M_e = M_{cont} + M_s + M_{corr} + M_{conc} \quad 1$$

Where; M_{cont} is unit mass of pipe content, M_s is unit mass of steel pipe, M_{corr} is unit mass of corrosion coating and M_{conc} is the unit mass of concrete coating.

Step 3: Evaluation of Reynolds Number, R_e using eqn. 2.

$$R_e = \frac{U_c D_o}{v_k} \quad 2$$

Where; U_c is design current velocity and v_k is kinematic viscosity of seawater.

Step 4: Evaluation of Stability parameter, K_s using eqn. 3.

$$K_s = \frac{2M_e\delta}{\rho_w {D_e}^2} \quad 3$$

Where; ρ_w is Density of the pipelines surrounding fluid and δ is total damping ratio taken as 0.125

Step 5: Determination of the reduced velocity for in-line motion, V_r and cross-flow motion, V_R.

Note: The reduced velocity for in-line motion is determined from figure 3 below based on stability parameter calculated while the reduced velocity for cross-flow motion is determined from figure 4 below based on Reynolds Number calculated.

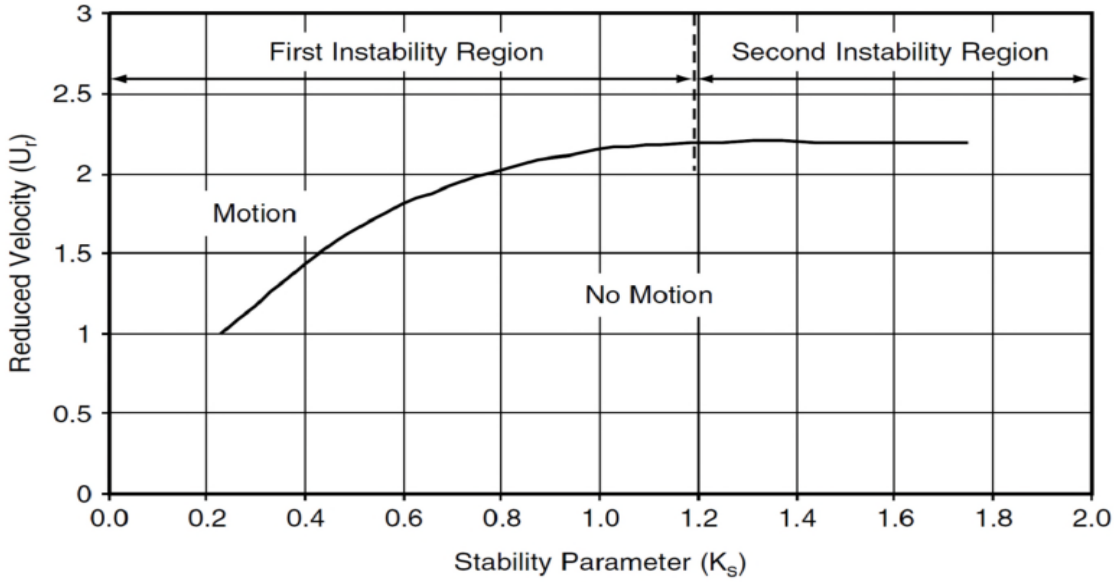

Figure 3: Relationship between Reduced Velocity and Stability parameter.

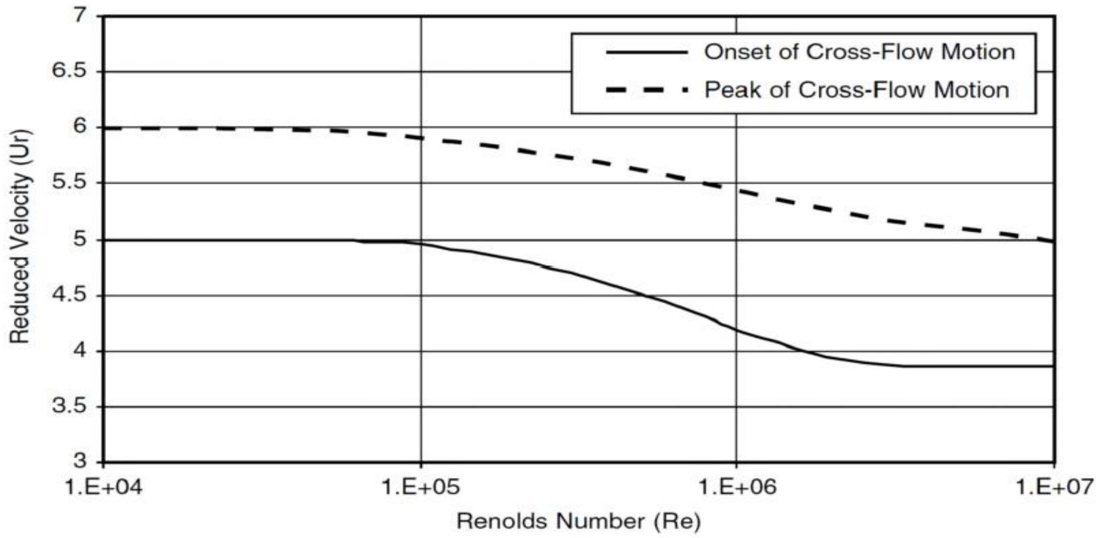

Figure 4: Relationship between Reduced Velocity and Reynolds Number

Step 6: Determination of the type of free span end condition and end condition constant, C_e based on the terrain and conditions involved.
Note: The free span end condition for this study is pinned-pinned and its constant is calculated based on the DNV guideline as follows
$C_e = (1.50\pi)^2$
Step 7: Determination of the critical span length for in-line motion, L_c and cross-flow motion, L_C using eqns. 4 and 5 respectively.

$$L_c = \sqrt{\frac{C_e}{2\pi f_n}\sqrt{\frac{EI}{M_e}}} = \sqrt{\frac{C_e V_r D_e}{2\pi U_c}\sqrt{\frac{EI}{M_e}}} \quad 4$$

$$L_C = \sqrt{\frac{C_e V_R D_e}{2\pi U_c}\sqrt{\frac{EI}{M_e}}} \quad 5$$

Where; f_n is Pipe span natural frequency, E is Pipe's young modulus and I is Pipe moment of inertia given as

$$I = \frac{\pi}{64}(D_o^4 - D_i^4) \quad 6$$

The necessary steps for determining the maximum allowable span length for Pipeline via static analysis are:
Step I: Determination of the submerged weight of the pipeline, W_{sub} using eqn. 7.

$$W_{sub} = W_p - \frac{\pi}{4}{D_e}^2\rho_w g \quad 7$$

Where; W_p is weight of pipe, W_s is Weight of steel, W_{cont} is Content Weight, W_{corr} is Weight of corrosion coating, W_{conc} is Weight of Concrete Coating and g is Gravitational acceleration
Step II: Determination of the Maximum allowable bending stress on the pipeline via the following sub-steps

a. Hoop stress, σ_h is evaluated using eqn. 8.

$$\sigma_h = \frac{(P_i - P_o)D_o}{2t_{nom}} \quad 8$$

Where; P_i is Internal Pressure, P_o is Outer Pressure, t_{nom} is Nominal Pipe Thickness

b. Longitudinal Stress, σ_L is evaluated using eqn. 9.

$$\sigma_L = \sigma_{LP} + \sigma_{Lt} \quad 9$$

Where; σ_{LP} is Longitudinal Stress due to Poisson's effect given as $v\sigma_h$, v is Poisson's ratio, σ_{Lt} is Longitudinal Compressive stress due to Thermal effect given as $-E\alpha\Delta T$, ΔT is the difference between operating and ambient temperature.

c. Von misses equivalent stress, σ_{eqv} is evaluated using eqn. 10.

$$\sigma_{eqv} = \sqrt{\sigma_h^2 + \sigma_L^2 - \sigma_h\sigma_L} \quad 10$$

d. Maximum allowable bending stress, σ_b is evaluated using eqn. 11.

$$\sigma_b = min\left[|\sigma_{L1} - \sigma_{Lp}|, |\sigma_{L2} - \sigma_{Lp}|\right] \quad 11$$

Where; σ_{L1} and σ_{L2} are the Maximum and minimum Longitudinal stress by Von Misses criterion respectively, given as

$$\sigma_{L1,2} = \frac{\sigma_h \pm \sqrt{(-\sigma_h^2) - 4(\sigma_h^2 - \sigma_{eqv}^2)}}{2} \quad 12$$

Step III: Determination of the static critical free span length, L using eqn. 13.

$$L = \sqrt{\frac{20\sigma_b I}{D_o W_{sub}}} \quad 13$$

Mathematical model

The following algorithms were followed to develop the user-friendly MATLAB codes that will aid the free span analysis of pipelines

Screening fatigue Criteria

The screening criteria as proposed by DNV-RP-F105 is applicable to fatigue caused by vortex induced vibrations (VIV) and direct wave loading in combined current and wave loading conditions. If this criterion is violated, a more detailed fatigue analysis would be performed. The Ultimate limit states (ULS) criterion would always be checked.

In-line natural frequency $f_{n,IL}$

The In-line motion natural frequency must fulfil the following condition:

$$\frac{f_{n,IL}}{\gamma_{IL}} > \frac{U_{c,100year}}{V_{R,onset}^{IL} \cdot D} \cdot \left(1 - \frac{L/D}{250}\right) \cdot \frac{1}{\bar{\alpha}} \quad 14$$

Where; γ_{IL} is Screening factor for in-line, $U_{c,100year}$ is 100-year return period value for the current velocity at the pipe level (m/s), $V_{R,onset}^{IL}$ is In-line onset value for the reduced velocity (m/s),D is outer pipe diameter incl. coating (m), L is Free span length (m) and $\bar{\alpha}$ is the Current flow ratio.

If this criterion is violated, then a full in-line VIV fatigue analysis will be conducted.

The cross-flow natural frequency $f_{n,CF}$

The cross-flow natural frequency must fulfil the following condition:

$$\frac{f_{n,CF}}{\gamma_{CF}} > \frac{U_{c,100year} + U_{w,1year}}{V_{R,onset}^{CF} \cdot D} \quad 15$$

Where; γ_{CF} is Screening factor for cross flow and $V_{R,onset}^{CF}$ is the Cross-flow onset value for the reduced velocity (m/s)

If this criterion is violated, then a full in-line and cross-flow VIV fatigue analysis would be carried out.

Fatigue analysis due to direct wave action is not required provided the following condition is fulfilled:

$$\frac{U_{c,100year}}{U_{w,1year} + U_{c,100year}} > \frac{2}{3} \quad 16$$

and the screening criteria for in-line VIV is fulfilled. *If this criterion is violated, then a full fatigue analyses due to in-line VIV and direct wave action would be conducted.*

ULS Criterion

The ultimate limit state (ULS) is checked according to the criteria as stipulated in DNV-OS-F101 for load-controlled condition (LC condition) combined loading criteria for local buckling. Load-Controlled condition (LC condition) is one in which the structural response is primarily governed by the imposed loads.

Pipe members subjected to bending moment, effective axial force and internal overpressure should satisfy the following criterion at all cross sections:

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left\{\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{Sd}(p_i)}{\alpha_c \cdot S_p(t_2)}\right\}^2\right\}^2 + \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b(t_2)}\right)^2 \le 1 \quad 17$$

Applied for

$15 \le D/t_2 \le 45, P_i > P_e, |S_{Sd}|/S_p < 0.4$

Where; γ_m is Material resistance factor, γ_{SC} is Safety class resistance factor, M_{Sd} is Design moment (Nm), S_{Sd} is Design effective axial force (N) p_i is Internal pressure (Pa), p_e is External pressure (Pa), p_b is Burst pressure (Pa), S_p and M_p are Plastic capacities for a pipe, α_c is Flow stress parameter, α_p is Effect of D/t_2 ratio and t_2 is pipe wall thickness.

Pipe members subjected to bending moment, effective axial force and external overpressure should satisfy the following criterion at all cross sections:

$$\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left\{\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{Sd}}{\alpha_c \cdot S_p(t_2)}\right\}^2\right\}^2 + \left(\gamma_m \cdot \gamma_{SC} \cdot \frac{p_e - p_{min}}{p_c(t_2)}\right)^2 \le 1 \quad 18$$

$15 \le D/t_2 \le 45, P_i < P_e, |S_{Sd}|/S_p < 0.4$

Where; p_{min} is minimum internal pressure that can be sustained (Pa) (Zero for this study) and p_c is characteristic collapse pressure based on thickness t_2 (Pa).

IV. RESULT AND DISCUSSION

Current Velocity Profile

The figure 5 below represents the current velocity profile in the region of the free spanning pipeline

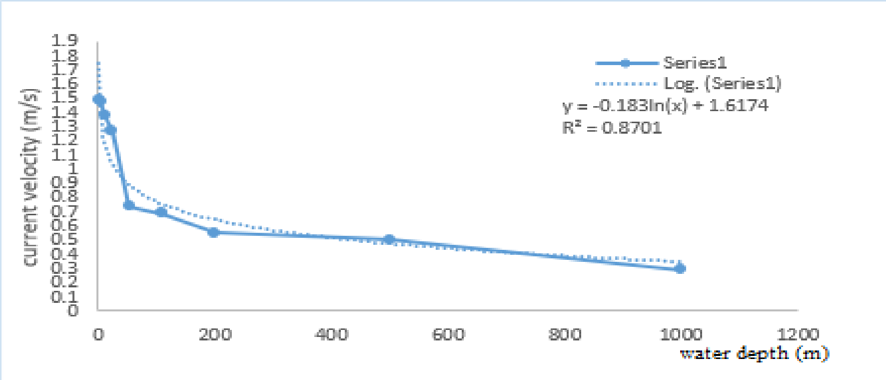

Figure 5: Current Velocity Profile

From the logarithm curve fitting in figure 5, an equation of velocity with respect to depth is derived with 87% accuracy which is:

$\boldsymbol{V_c(d) = -0.183 \ln d + 1.6174}$

The average velocity will be

$$V_{cavg} = \frac{\int_{d_2}^{d_1}(-0.183 \ln d + 1.6174)\delta d}{d_2 - d_1}$$

$$V_{cavg} = \frac{-0.183 \ln d + 1.8004d]_{d_2}^{d_1}}{d_2 - d_1}$$

$$V_{cavg} = \frac{-0.183 \ln d_2 + 1.8004d_2 - (-0.183 \ln d_1 + 1.8004d_1)}{d_2 - d_1}$$

$$V_{cavg} = \frac{0.183\,(\ln d_1 - \ln d_2) + 1.8004(d_2 - d_1)}{d_2 - d_1}$$

Where; $d_2 - d_1$ is the pipe outer diameter (including all coating), d_2 is the distance from the sea surface to the part of the pipeline resting on the seabed given as 1000m and d_1 is the distance from the sea surface to the upper part of the pipeline which is 999.279m in this study

$$V_{cavg} = \frac{0.183(\ln(999.279) - \ln(1000)) + 1.8004(1000 - 999.279)}{1000 - 999.279}$$

$\boldsymbol{V_{cavg} = 1.8002 m/s}$

Environmental effective force, S_E becomes

$$S_E = 1025\frac{kg}{m^3} * 1.8002^2\frac{m^2}{s^2} * 50 * 1.229m^2$$

$$S_E = 2.041E05\ {kg.m}/{s^2}$$

$$S_E = 2.041E05N$$

Maximum Allowable free span length

Table 5 below shows the critical span lengths as determined by static and Dynamic (in-line and cross-flow motions) analyses of the free spanning pipeline.

Table 5: Critical Span lengths from Static and Dynamic analyses	
	Critical span Lengths (m)
Outer Diameter	0.508
Static Critical span	18.925
In-Line-Critical Span	48.219
Cross-flow Critical Span	92.23

The maximum allowable free span length is the minimum of the static in-line and cross- flow critical span lengths.
Hence, $MAFSL = min(L, L_c, L_C)$, as seen from Table 5 above is the static critical span length with the value 18.925m.
This maximum allowable free span influences the decision to further assess/analyze the measured/recorded free span length of 30m as it is longer than the maximum allowable free span length. Table 6 below shows categories of span characteristics and associated response that will inform further analysis as documented by DnV.

Table 6: Free Span response behavior [15]		
Category	Span Length / Pipe Outer Diameter (L/D)	Response Description
1	L/D < 30	Very little dynamic amplification • Normally not required for fatigue check • Unlikely to experience VIV
2	30 < L/D < 100	Response dominated by beam behavior • Typical span length for operating condition
3	100 < L/D < 200	Response dominated by combined beam and cable behavior
4	L/D >200	Response dominated by cable behavior • Vigorous pipeline movement

It is observed from Table 6 above that critical span length for the investigated pipeline is in category 2 as the condition, 30<L/D<100 is fulfilled. Accordingly, span length in this category is typical for operating condition with response dominated by beam behavior. It could thus be concluded that the free span does not require any further checks. However, since the pipeline is operated in deep water, it is important to carry out further checks to reveal the behavior of the free span as it interacts with the hydrodynamic characteristics of deep water in order not to be conservative.

Screening and ULS Criteria check

Figures 6 and 7 below are plots gotten from the MATLAB code generated through the mathematical model presented in equations 3.13-3.20 and the table created thus.
Figure 6 depicts the right and left-hand sides of equation 3.13 at various steel pipe diameter. Curve n1 (green colour) represents $\frac{f_{n,IL}}{\gamma_{IL}}$ values while Curve m1(blue colour) represents $\frac{U_{c,100year}}{V_{R,onset}^{IL} \cdot D} \cdot \left(1 - \frac{L/D_e}{250}\right) \cdot \frac{1}{\bar{\alpha}}$ values at different steel pipe diameters with line Do (red colour) being the reference diameter for this study.

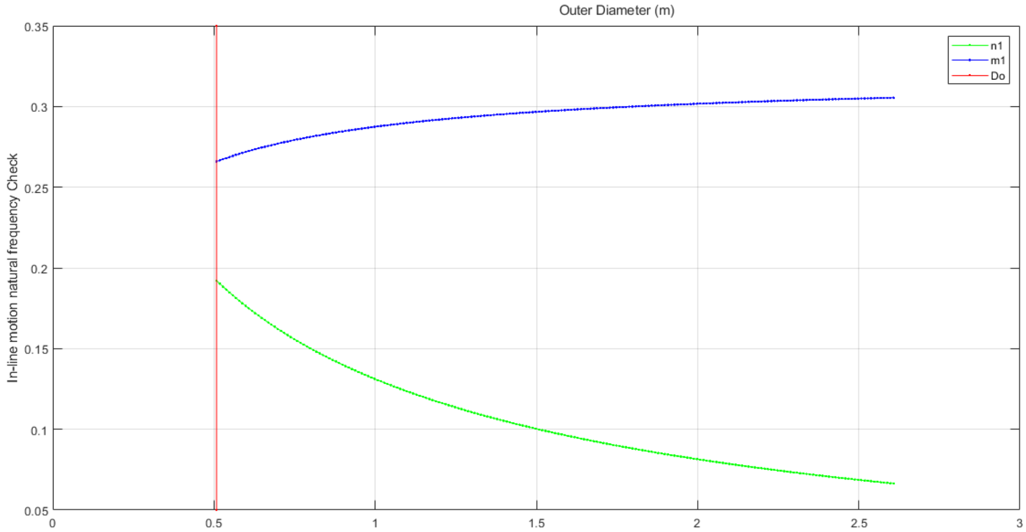

Figure 6: Outer diameter vs Left and Right-hand sides of in-Line motion natural frequency check

Figure 7 is a graphical representation of the left and right-hand sides of equation 3.14 at various steel pipe diameter. Curve n2 (green colour) represents $\frac{f_{n,CF}}{\gamma_{CF}}$ values while Curve m2 (blue colour) represents $\frac{U_{c,100year}+U_{w,1year}}{V_{R,onset}^{CF} \cdot D_e}$ values at various steel pipe diameters with line Do (red colour) being the reference diameter for this study.

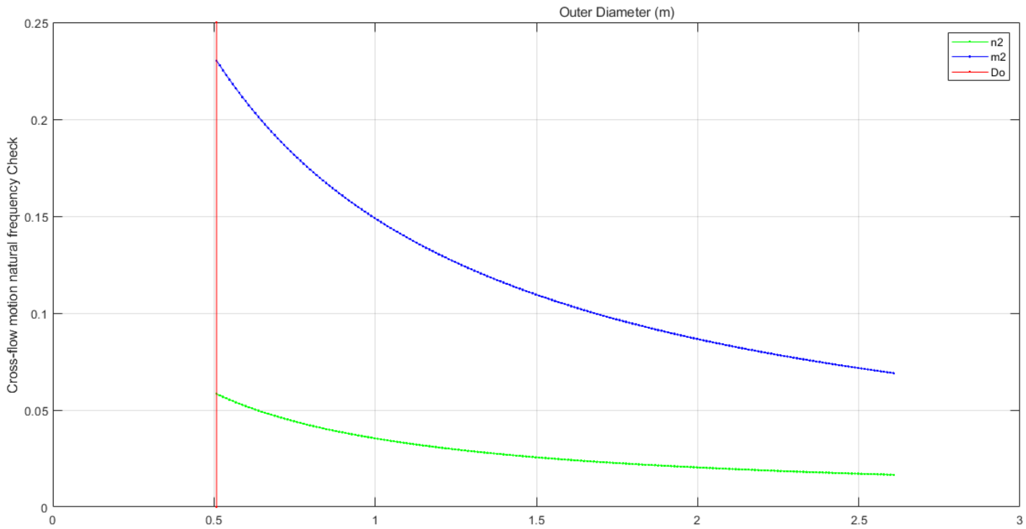

Figure 7: Outer diameter vs Left and Right-hand side of Cross-Line motion natural frequency check

From figures 6 and 7 at the pipe steel diameter of 0.508m
$n1$ is 0.1921,
$m1$ is 0.2959,
$n2$ is 0.0583 and
$m2$ is 0.2302

From the above, it is seen that 0.1921 is not greater than 0.2959 and 0.0583 is not greater than 0.2302 and so, it is evident that the criteria for the screening check for both in-line flow natural frequency and cross-flow motion natural frequency are violated and as such full fatigue analysis is required. However, a ULS check was carried out assuming that the fatigue analysis was ok.

Considering that the pipe section is subjected to internal overpressure as $P_i > P_e$, the criterion in Equation 3.21 is employed in conducting the ULS check. Figure 8, a MATLAB plot of mathematical model presented in equations 3.21 – 3.33 expresses the left-hand side of equation 3.21 at different outer diameters, where Curve l (green colour) represents $\left\{\gamma_m \cdot \gamma_{SC} \cdot \frac{|M_{Sd}|}{\alpha_c \cdot M_p(t_2)} + \left\{\frac{\gamma_m \cdot \gamma_{SC} \cdot S_{Sd}(p_i)}{\alpha_c \cdot S_p(t_2)}\right\}^2\right\}^2 + \left(\alpha_p \cdot \frac{p_i - p_e}{\alpha_c \cdot p_b(t_2)}\right)^2$ and line Do (red colour) marks the reference point for this research work .

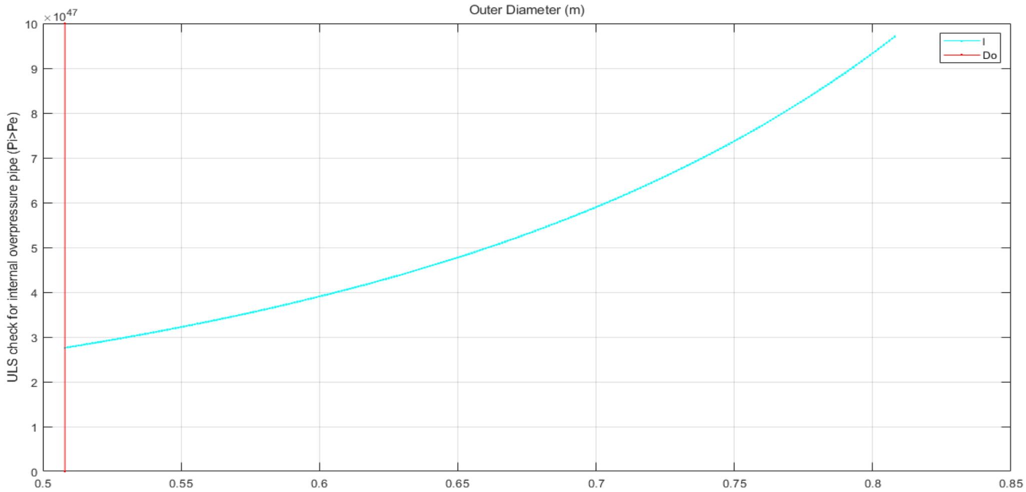

Figure 8: Outer diameter vs ULS check for internal overpressure pipe (Pi>Pe)

From figure 8, at the pipe steel diameter of 0.508m
l is $2.7589 * 10^{47}$
Hence, since $2.7589 * 10^{47}$ *is not less than* 1, the criterion for the Ultimate limit state check is violated and as such this free spanning segment is not fit to continue operation without span interventions or supports. So span intervention is advised.

Sensitivity Analysis
Figures 9 and 10 were generated from the MATLAB code presented in Appendix A.
Figure 9 depicts how various pipe diameter affects the Vortex shedding frequency f_s and the inline natural frequency f_{nIL} of a free spanning pipeline.

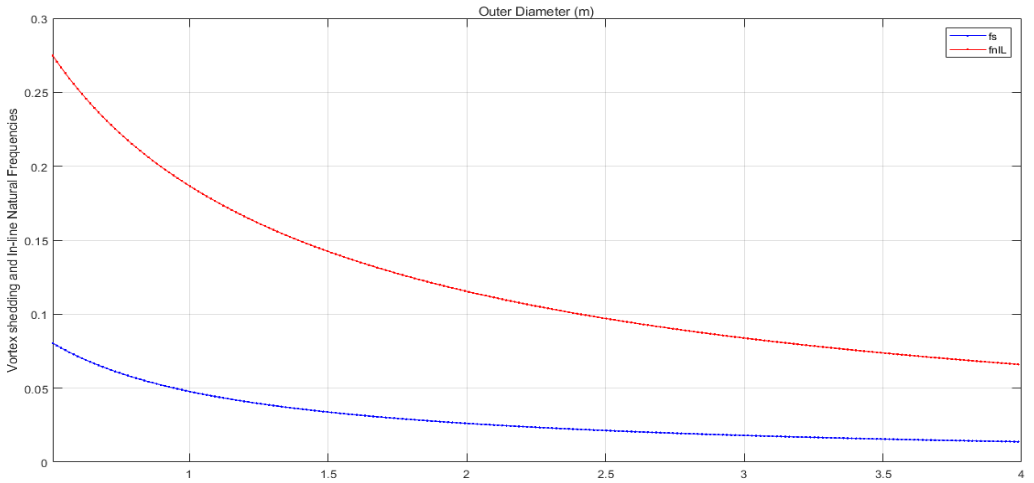

Figure 9: Outer diameter vs Vortex shedding frequency and In-line Natural frequency

Figure 10 depicts how various pipe diameter affects the Vortex shedding frequency f_s and the cross-flow natural frequency f_{nCF} of a free spanning pipeline.

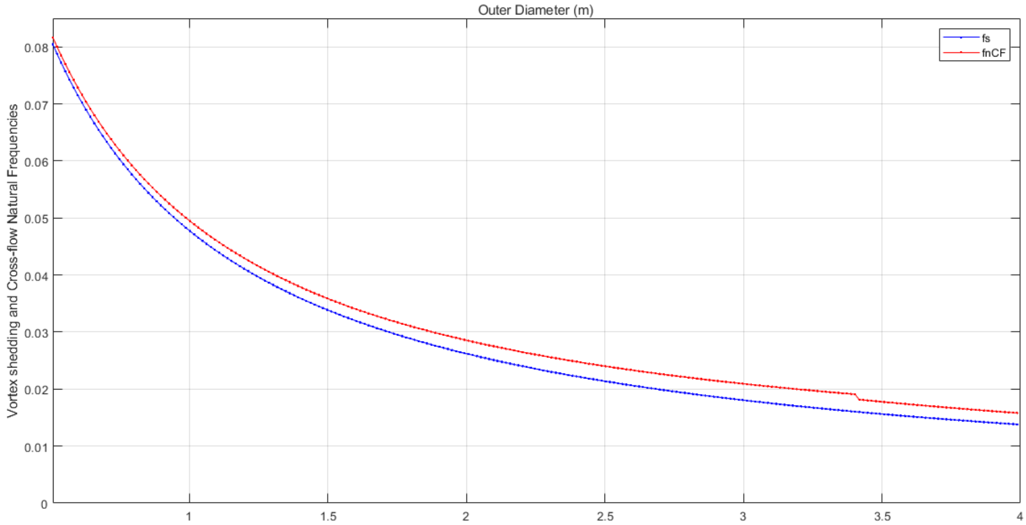

Figure 10: Outer diameter vs Vortex shedding frequency and Cross-flow Natural frequency

From figures 9 and 10 at the pipe steel diameter of 0.508m,
Vortex shedding frequency is 0.080444,
In-line Natural frequency is 0.27478 and
Cross-flow Natural frequency is 0.081658.
Considering figure 10, it is observed that at the design diameter, the vortex shedding frequency is almost same as the cross flow natural frequency which means that resonance can occur at this point and this is a phenomenon that needs to be avoided if fatigue damage is to be prevented. The trend also shows the likelihood of resonance thinning out as the diameter is increased beyond the design diameter. However, at diameters lower than the design as the trend reveals, resonance might be more likely corroborating the fact that slender bodies are more prone to vibration. Hence it is advised to monitor pipeline corrosion coatings during operation as any wastages below critical at the free span region could agitate cross-flow vortex induced vibration detrimental to safety.
With In-line-flow however as seen in figure 9, there is a very clear gap between the vortex shedding frequency and the in-line natural frequency which depicts that in a pure in-line motion system, though the pipeline has a segment of spanning, resonance will never occur and fatigue failure due to vibration may likely not occur. However, this possibility is observed to narrow down with gradual increase in outer diameter even though, it is not detrimental to safety as operational pipe diameters are not subject to marked increases that would warrant such adverse effect.

Generally, altering the outer diameter of pipe free span for a combined motion system which is the case in the sensitivity studies has revealed that with in-line flow velocity, there may never be any danger during the operational stage as pipeline diameters do not increase markedly, if at all they do, however, with Cross-flow velocity, there is likely danger of the consequences of vortex-induced vibration at the design diameter and even greater danger of fatigue damage at reduced diameter as the pipeline begins to degrade via corrosion as the pipeline facility is aging. It is therefore instructive for pipeline operators to have a robust corrosion control and monitoring mechanism particularly where there is likelihood of free span formation during operation to guarantee the integrity of the pipeline infrastructure.

V. CONCLUSION

In this study, the maximum allowable free span length of an offshore pipeline was determined as the basis for investigation so as to streamline for further checks. Though it was revealed that the critical span length of the investigated pipeline fell under category 2 according to DnV standard [15], which is the typical span length for operating condition requiring no further checks, further checks were done considering the depth of operation of the pipeline in order not to be conservative. Hence, mathematical models for screening and ULS criteria checks were transcribed into MATLAB codes and used to investigate the free span of the pipeline and it was established that span interventions were imperative since the span region violated all the checks conducted.

The study also investigated the effect of various pipe outer diameters on the vortex shedding and natural frequencies of a free spanning pipeline. Generally, altering the outer diameter of pipe free span for a combined motion system revealed that with in-line flow velocity, there may never be any danger during the operational stage even though, the vortex shedding frequency and the in-line-flow natural frequency are closing in as pipeline diameter is increasing. This of course portends no danger during operation as pipeline diameters do not increase markedly, if at all they do, however, with Cross-flow velocity, there is likely danger of the consequences of vortex-induced vibration at the design diameter and even greater danger of fatigue damage at reduced diameter as the pipeline begins to degrade via corrosion as the pipeline facility is aging. It is therefore instructive for pipeline operators to have a robust corrosion control and monitoring mechanism particularly where there is likelihood of free span formation during operation to guarantee the integrity of the pipeline infrastructure.

An important aspect of this work is fatigue analysis and this is recommended for further studies in order to give fully convincing judgement for pipeline intervention. Fatigue analysis will reveal not just the free span fatigue capacity but also, possible associated pipeline cracks both of which will provide the best-informed decision for intervention. Semi-empirical tools such as VIVANA as well as established commercial software, ABAQUS should also be used for validation.

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APPENDIX

Code for Conducting Sensitivity Analysis

```
clear; clc; clear All
```

A. Sensitivity analysis INPUT

```
% Constants and Pipe Parameters
a = 0.508; % Minimum Value of outer diameter
b = 4; % Maximum Value of outer diameter
s = 0.015; % Step size of outer diameter
D_o = a:s:b; % Outer diameter
t_corr = 0.0065; % Corrosion thickness
t_conc = 0.1; % Concrete thickness

g = 9.81; % gravitational acceleration in m/s^2
v = 0.3; % poisson's ratio
mu = 0.6; % coefficient of friction
v_k = 1.05E-06; % Kinematic viscosity of seawater
del = 0.126; % total modal damping
E = 2.07E+11; % Young's modulus
h = 1000; % Water Depth

alpha = 1.17E-05; %Linear coefficient of Expansion
rho_cont = 870; % Density of content
rho_s = 7850; % Density of steel
rho_corr = 1300; % Density of corrosion coating
rho_conc = 3000; % Density of concrete coating
rho_w = 1025; % sea water density
U_c = 0.29; % Current velocity
```

```
C_e = 9.87; % pinned-pinned end condition constant
e = 0.2; % span gap
S = 0.2;
P_i = 1.2e7; % Internal pressure
P_o = rho_w*g*h; % external pressure
T_op = 25; % Operating Temperature
T_amb = 4; % Ambient Temperature
delta_T = T_op-T_amb; % Temperature difference
```

B. Calcutations

```
for i=1:((abs(b-a)/s)+1)
    t_nom = 0.0127;
    D_i = D_o(i) - 2*t_nom;
    D_corr = D_o(i)+(2*t_corr);
    D_e = D_corr+(2*t_conc);

    C_a = 0.68 + 1.6*(1+5*(e/D_e));
    M_a = C_a*rho_w*pi()*(D_e^2)/4;
    M_cont = (pi()/4)*(D_i^2)*rho_cont;
    M_s = (pi()/4)*(D_o(i)^2-D_i^2)*rho_s;
    M_corr = (pi()/4)*(D_corr^2-D_o(i)^2)*rho_corr;
    M_conc = (pi()/4)*(D_e^2-D_corr^2)*rho_conc;
    M_e = M_cont+M_s+M_corr+M_conc;

    K_s = 2*M_e*del/(rho_w*(D_e^2));


    % Determine In-line Reduced Velocity
    if K_s>=0.2 && K_s<=0.4
       V_rIL = 1.4+(2*(K_s-0.4));
    elseif K_s>0.4 && K_s<=0.6
        V_rIL = 1.8+(2*(K_s-0.6));
    elseif K_s>0.6 && K_s<=0.8
        V_rIL = 2.05+(1.25*(K_s-0.8));
    elseif K_s>0.8 && K_s<=1
        V_rIL = 2.2+(0.75*(K_s-1));
    elseif K_s>1 && K_s<=1.2
        V_rIL = 2.225+(0.125*(K_s-1.2));
    elseif K_s>1.2 && K_s<=1.8
        V_rIL = 2.225;
    end

    R_e = U_c*D_e/v_k;

    % Determine Cross-Flow Reduced Velocity
    if R_e>=1E05 && R_e<=5E05
       V_RCF =4.7-(7.5E-07*(R_e-5E05));
    elseif R_e>5E05 && R_e<=7E05
        V_RCF = 4.5-(1E-06*(R_e-7E05));
    elseif R_e>7E05 && R_e<=1E06
        V_RCF = 4.2-(1E-06*(R_e-1E06));
    elseif R_e>1E06 && R_e<=2E06
        V_RCF = 4.2-(2E-07*(R_e-2E06));
    elseif R_e>2E06  && R_e<=3E06
        V_RCF = 4-(1.5E-07*(R_e-3E06));
    elseif R_e>3E06 && R_e<=1E07
        V_RCF = 3.85;
    end


    f_s = S*U_c/D_e; % vortex shedding frequency
    f_nIL = U_c /(D_e*V_rIL); % in-line Natural frequency
    f_nCF = U_c / (D_e*V_RCF); % Cross-flow natural frequency



    count(i,:) = i;

    VSf(i,:) = f_s; % vortex shedding frequency at different diameter
    NfIL(i,:) = f_nIL;  % in-line Natural frequency at different diameter
    NfCF(i,:) = f_nCF;  % Cross-flow natural frequency at different diameter

end
outerDiameter = D_o';
```

C. Create a Table of Values

```
tableOfSensitivityAnalysis = table(count,outerDiameter,VSf,NfIL,NfCF);
```

D. Plot graphs

```
figure(1)
plot(D_o,VSf,'b.-')
axis([0.508 4 0 0.3])
grid on
xlabel('Outer Diameter (m)','Position', [2.25, 0.31])
ylabel('Vortex shedding and In-line Natural Frequencies')
title({'figure 4.5: Outer diameter vs Vortex Shedding Frequency', 'and In-line Natural
frequency'}, ...
    'Position', [2.25, -0.035], ...
    'VerticalAlignment', 'bottom', ...
    'HorizontalAlignment', 'center')
hold on
plot (D_o,NfIL,'r.-')
hold off
legend('fs','fnIL')

figure(2)
plot(D_o,VSf,'b.-')
axis([0.508 4 0 0.085])
xlabel('Outer Diameter (m)','Position', [2.25, 0.088])
ylabel('Vortex shedding and Cross-flow Natural Frequencies')
grid on
title({'figure 4.6: Outer diameter vs Vortex Shedding Frequency', 'and Cross-flow Natural
frequency'}, ...
    'Position', [2.25, -0.01], ...
    'VerticalAlignment', 'bottom', ...
    'HorizontalAlignment', 'center')
hold on
plot(D_o,NfCF,'r.-')
hold off
legend('fs','fnCF')
```

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