Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering
OMAE2014
June 8-13, 2014, San Francisco, California, USA

OMAE2014-24069

A COMPARATIVE STUDY OF A FREE SPAN PIPELINE THROUGH NUMERICAL SIMULATIONS

Marcus V. F. dos Santos
Graduate Program
Petroleum Science & Engineering
University of Campinas
Campinas-SP, Brazil

Celso K. Morooka
Faculty of Mechanical Engineering & Center for
Petroleum Studies, Lab*Riser*
University of Campinas
Campinas-SP, Brazil

Marcelo Caire
Marine Technology
Sintef do Brasil
Rio de Janeiro-RJ, Brazil

Ricardo Franciss
Research Center
Petrobras
Rio de Janeiro-RJ, Brazil

Cyntia G. C. Matt
Research Center
Petrobras
Rio de Janeiro-RJ, Brazil

ABSTRACT

A subsea pipeline has an important role to produce oil and gas from an offshore petroleum field, connecting a petroleum facility at the open sea and a near shore terminal at the coast. Very often, the pipeline passes over areas with uneven seafloor, and it may present free span portions. The main aim of the present work is improvements 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.

Dynamic loads can occur as a consequence of the presence of sea currents acting on portions of the pipeline with free spans. Due to this hydrodynamic current loads, the pipeline structure may oscillate in the same direction of the current (In-line) and, in its transverse direction (Cross-Line). This dynamic response at the free span is mainly caused by the Vortex Induced Vibration (VIV). It is very important for the pipeline design because it can result extreme unacceptable stresses as well as in exceeding limits for the fatigue damage of the pipeline. And, this problem of VIV is still not been completely understood.

In the present paper, different models to estimate VIV forces due to sea current are discussed. For this purpose, different computer programs were used to predict vibrations in the transverse direction of the current incidence direction, caused by the vortex shedding in a free span of the pipeline. Simulations of the dynamic behavior of a free span portion of the pipeline were carried out by two approaches, respectively: an empirical hydrodynamic VIV force model, in frequency domain and, a semi-empirical VIV force model based on the lift coefficient and Strouhal number, in time domain. Simulations results are analyzed through comparisons with experimental data and also limitations of the each model are discussed.

Keywords: Subsea pipeline, Sea current, Vortex-induced vibration, Free-span, offshore systems

NOMENCLATURE

A_{CF}	Cross-flow amplitude of vibration
D_o	Outer hydrodynamic diameter of pipeline
L	Pipeline element length
f_{osc}	Vibration frequency
f_n	Natural frequency
f_s	Strouhal frequency
U	Current velocity
V_R	Reduced velocity, $V_R = U/(f_n D)$
$[M]$	Mass Matrix
$[C]$	Damping Matrix
$[K]$	Stiffness Matrix
C_D	Drag coefficient
C_a	Added mass coefficient
C_L	Lift coefficient
F_{VIV}	Vortex induced vibration force
F_y	Cross-flow external force
A_O	External area of the pipeline section
A_I	Internal area of the pipeline section

EI	Bending stiffness
m	Mass per unit length of the pipe and contents
S_t	Strouhal number
φ	VIV force phase
t	Time
ρ_w	Fluid density

INTRODUCTION

Subsea pipelines in a deepwater offshore petroleum field are an important component of the production system for the transport or transfer of oil and gas over long distances. Frequently, they pass over areas with uneven seafloor and, free span portions appear. Over the free spans the sea current can cause Vortex Induced Vibrations (VIV) as a result of the hydrodynamic sea current loads. VIV forces have an oscillatory nature and they can cause vertical and horizontal oscillations of free span portions of the pipeline. And, depending on the vortex shedding characteristics, this part of the pipeline can experience great structural stresses and, sometimes, fatigue damage. Furthermore, the dynamic behavior of a pipeline with free span is still not completely understood.

In recent years, a strong effort has been observed to improve models for calculating VIV in general, particularly, for free span pipelines (Larsen, 2004). And, due to major problems caused by the VIV have led to a large number of fundamental studies. Experimental results have been presented by Sarpkaya (1978), who carried out experiments with forced oscillations of cylinders and, reported large amplitude oscillations (A/D=0.9). Vikestad (1998) and Govardhan & Williamson (2000) reported results from experiments for elastically-mounted rigid cylinders that the maximum VIV response amplitude reached 1.13 and 1.19 times the diameter, respectively.

Empirical models for uniform flow have been developed, in which equations have been put forward from several studies. Blevins (1994) proposed a linear harmonic model and a wake oscillator to calculate the maximum amplitude response. Griffin & Ramberg (1975) developed a curve fit data and, Sarpkaya (1979) an analytical method to calculate de maximum amplitude ratio A_{CF}/D_0. Those empirical functions are listed in Franciss (1999).

The cylinder proximity to the wall was investigated by Bearman and Zdravkovich (1978). The non-linearities caused by interaction between pipe-seafloor and the influence from tension variation on pipe stiffness that influence on span natural frequency and damping were discussed by Larsen (2002). And also, pipe sagging, dynamic coupling between adjacent free spans. All those parameters influence the Vortex shedding induced response of the pipe.

Moreover, guidelines exist for estimation of response due to VIV as presented by Tura et al. (1994), based on the research performed in the GUDESP project. And, the guideline issued by Det Norske Veritas-DNV (1998) also referred DNV-G14, after improved and released as DNV-RP-F105 based on MARINTEK experiment results (Fyrileiv et al., 2004; Mørk et al., 1998).

It is observed that different alternatives have been proposed to predict the VIV, in the literature. In this way, empirical and semi empirical models based on experiments with riser and pipelines are more common in the practical engineering point of view.

The present work aims to discuss the dynamic behavior of free span pipelines under hydrodynamic current forces. Calculations are performed through semi-empirical method in time domain, and empirical linear one in frequency domain. The main purpose is to compare results from different models for the prediction of VIV dynamic responses in a free span pipeline, in the transverse direction. Computer simulation results are compared with experiments ones.

In this work, only cross-flow vibrations have been considered beside the great importance of in-line vibrations which also induce a reduction of the pipeline lifetime due to fatigue damage.

AN OVERVIEW OF MODELS

In the present section, a brief description is summarized for the each model applied in the simulations and analysis.

All programs here used are mainly applied for designing and analysis of vertical slender riser, in which L/D is higher than that for a pipeline with typical free spans, in a presence of the shear current and the multi-modal response. Also important non-linearity issue caused by seabed-pipeline and tension variation can make those programs not able to answer all demands related to an actual free span pipeline.

VIVANA

In this paper, the standard version of VIVANA (Larsen et al. 2000) which applies an empirical VIV force model based on three dimensional Finite Element Method (FEM) of the pipeline structure is used. The Riflex (Fylling et al. 1998) is used to solve equation of motion of the pipeline dynamic behavior in the cross-flow direction.

Solution is obtained for a set of empirical hydrodynamic coefficients, such as added mass, external forces and damping of the pipeline, for different discrete frequencies of the pipeline response (Larsen, 2001).

The discrete frequency response method is used to calculate the dynamic response at the dominating frequency identified in which this value is previously found by using the lift coefficient curve, defined by three points, as in this code (Larsen et al. 2002). Parameters to define the lift coefficient curve are based on data from Gopalkrishnan (1993) and Vikestad (1998).

SHEAR 7

SHEAR7 is based on superposition and modal excitation regions combined with response-dependent lift coefficient curves. By finding out the location on the riser in which coincidence occurs between a given natural frequency and the frequency obtained from the Strouhal number, it's defined the center of power-in region for each responding nodal point. For each center point a power-in region is defined where the reduced velocity is within a settled range of the lock-in condition. All other parts of the riser for each mode are considered sources of hydrodynamics damping. For the free span pipeline this situation is different. Since current is uniform constant along the pipe and the excitation zone will cover the entire length of free span, hence the response amplitude is determined by the balance between excitation in zones of low and moderate osculation amplitudes and the damping in zones with high oscillation amplitudes.

The basic solution used is modal analysis and power-balance iteration. From iterations, the Shear7 program calculates the correct combination between lift and damping coefficients and the response at each point and frequency. (Vandiver 1999; Lyons et al., 2003; Chaplin et al.; 2005)

RiserProd & ANAPIPE-VIV

In the RiserProd, the riser is represented by beam elements solved by the planar Euler-Bernoulli equation in a quasi-3D fashion. Small displacement assumption is considered. The quasi-3D approach consists to solve the beam equation in the plane of the current coupled with the solution obtained in cross-flow plane, as described in Morooka et al. (2003). A time-domain solution is used to consider nonlinearities related for the riser structure and the current, in order to calculate the behavior of pipeline due the VIV.

The ANAPIPE-VIV is a time-domain program for VIV prediction that combines the Anflex (Mourelle, 1995) as solver for the pipeline structural model, and the hydrodynamic model as presented by Tsukada and Morooka (2013). The Anflex presents a co-rotated beam element solved by Lagrangian method. This element is solved in three dimensions considering large displacements. Non-linear Finite-Element Method is applied for the pipeline structure.

A semi-empirical method is applied on both programs to estimate hydrodynamic current forces and to simulate in time domain the behavior of pipeline. Hydrodynamic coefficients from the literature are used. The Morison formulation was adopted to represent the fluid reaction forces opposing to the transverse motion of the pipeline. And, the influence of the in-line relative flow is taken attenuating on transverse response in a more realistic manner.

Then, the transverse force is given by the following equation:

$$F_y = F_{VIV} - C_D A_D |V_{rel}| \dot{y} - C_A A_I \ddot{y} \tag{1}$$

where, $\dot{y}$ and $\ddot{y}$ are, respectively, velocity and acceleration of the pipeline in the transverse direction. V_{rel} is the relative velocity between pipeline that provides the coupling of the system behavior between the in-line and transverse directions. $A_D = 1/2\rho D$ and $A_I = \pi D^2 \rho/4$. Distributed weight per unit of length (P) is considered as an external load in the transverse direction.

The vortex induced vibration is a phenomenon that occurs due to the fluid separation when the fluid contours around the external pipeline surface (Larsen, 2001) throughout its length. Usually, this effect is taken as two dimensional at a pipeline cross section and it causes pressure differences between the opposite two sides. It generates an alternated hydrodynamic forces leading to the pipeline transverse vibration. In the present study, estimation of the VIV force is given by:

$$F_{VIV(t)} = \frac{1}{2} \rho_w U^2 D_0 C_L L \cos(2\pi f_s t + \phi) \tag{2}$$

and,

$$f_s = \frac{U S_t}{D} \tag{3}$$

Fluid forces are calculated for a section of the pipeline at the each pipeline element node. For the section, hydrodynamic coefficients (C_L, C_D, C_a, S_t) and phase angle ϕ between VIV force and pipeline motion are defined.

OrcaFlex

In the OrcaFlex (Orcina, 2008), there are four time domain models. Two of them are wake oscillator based models, and other two are vortex tracking based models. Vortex tracking models are much more computationally demanding than wake oscillator models. Following Chaplin (2005) results for VIV simulations of a tensioned riser, in the present simulations, it was decided to apply the Milan wake oscillator model.

Simulations with wake oscillator model in the OrcaFlex in time-domain are made. The wake equations of motions only predict vortex excitation in Cross-Flow direction.

Wake Oscillator uses differential equations adjusted to reproduce effects of the VIV. According to Chang and Ishewood (2003), a typical wake oscillator model uses a single degree of freedom, time-dependent, to represent the wake behind a rigid cylinder, in which obeys a differential equation.

The system is composed by a cylinder of mass m_s and oscillator of mass m_o, and they are connected by non-linear springs and dash pots. The cylinder and oscillator are supported by linear springs and damping and non-linear springs and dash pots respectively.

By the action of oscillator to the cylinder this model predicts the vortex shedding on a cylinder oscillating in the cross-flow direction.

The equation of motion for the cylinder can be written, as in follow:

$$M_s \ddot{y} + C\dot{y} + Ky = F_i + F_m \quad (4)$$

$$M_0 \ddot{x} = F_0 + F_i \quad (5)$$

where, F_m is the transverse component of a Morison type force, in which cylinder hydrodynamic inertial and damping coefficients are taken into account. F_i is the total of forces on the cylinder, and F_O is the force on the oscillator.

The stiffness and damping coefficients k_{ol}, k_{on}, k_{il}, k_{in}, c_{ol}, c_{on}, c_{il}, c_{in} were determined experimentally (Falco et al, 1999). These coefficients are non-dimensionalized and, they are used for calculations by following the present model. The non-dimensionalized values are shown in Table1. Subscripts "o" refers to the oscillator and, "i" to the interface. The linear or non-linear contributions are, respectively, denoted by "l" and "n".

Table 1 – Coefficients of the Milan wake oscillator

C_{kol}	3.100	C_{kon}	0.050
C_{col}	2.150	C_{con}	0.450
C_{kil}	1.364	C_{cin}	0.200
C_{cil}	5.400	C_{cin}	0.000

COMPARATIVE STUDY

A laboratory data set of a pipe with aspect ratio L/D approximate 230 were used in the comparative study. The experiment was conducted at the Technological Research Institute of Sao Paulo-IPT (Cunha et al, 2009). An aluminum pipe horizontally positioned in a towing water tank with 6 meters of width and 220 meters of length was used.

The pipe was attached to the moving carriage with universal joints at the ends, free to vibrate in both directions In-line and Cross-Flow, being pinned-pinned supported. End plates were installed at the ends to avoid three dimensional effects of the flow. Uniform current has been reproduced and the velocity as varied reduced velocity (V_R) from ~4 to ~9. The Table 2 shows main characteristics of the model.

The pipe mass ratio (without the added mass) is nearby 1.0. Natural frequency in air is 2.358Hz, with a structural damping ratio of 0.9%. The natural frequency in still water is 1.025Hz, and the damping ratio increases to 6.35%.

Calculations for the pipeline response were carried out for conditions, as shown in Table 3. Measured data and calculation results presented in below refer to transverse displacements. Comparisons are also made between calculated and measured cross-flow frequencies f_{osc}, and the Strouhal number ($S_t = f_{osc} D_O / U$) was used to do comparisons.

Table 2 – Main characteristics of the pipeline model

Parameter	**Value (unit)**
Length	4.57 (m)
External diameter	0.02 (m)
Internal diameter	0.0184(m)
Pipe mass per unit length	0.400(Kg/m)
Add mass coefficient (from the decaying test)	1.001
Bending Stiffness	132.75(Nm²)
Total mass (pipe mass, internal fluid and added mass)	0.715(N/m²)
First mode natural frequency (decaying test – in air)	2.358(Hz)
First mode natural frequency (decaying test – in water)	1.025 (Hz)

Initially, the set of VIV modeling parameters and the computer program to predict VIV is determined. Simulations are performed and, calculated results are compared with the experimental ones. Comparisons are observed in terms of the maximum cross-flow non-dimensional response amplitude A_{CF}/D_0, and the frequency of oscillation of the pipe.

A set of ten (10) comparative cases were chosen for the study to realize the best possible modeling program for the most general application. The cases involve eighteen (18) different values of V_R (reduced velocity).

Table 3 – Conditions adjusted for the each Program

Case	**Program**	C_L	S_t
1	VIVANA	Gopalkrishnan	Built-in
2	VIVANA	Gopalkrishnan	Adjusted
3	ANAPIPE-VIV	1	Experiment
4	ANAPIPE-VIV	1	0.2
5	RiserProd	1	Experiment
6	RiserProd	1	0.2
7	ORCAFLEX	Default	0.2
8	ORCAFLEX	Default	Experiment
9	SHEAR7	Gopalkrishnan	0.18
10	SHEAR7	Gopalkrishnan	Experiment

Table 4 – Current velocity conditions

Condition	Velocity (m/s)
1	0.085
2	0.092
3	0.096
4	0.101
5	0.108
6	0.112
7	0.117
8	0.123
9	0.129
10	0.137
11	0.147
12	0.152
13	0.159
14	0.169
15	0.170
16	0.176
17	0.180
18	0.185

RESULTS AND DISCUSSIONS

Numerical simulations in time and in frequency domain, respectively, were performed by applying the procedure as previously presented in above. Then, VIVANA, SHEAR7, OrcaFlex, ANAPIPE–VIV and RiserProd were used as the VIV computer programs for comparisons between numerical simulations and experiment.

For modeling the pipeline for simulations, its characteristics and properties, as in the Table 2, were applied. Boundary conditions for the pipe are pinned-pinned ones, to represent universal joints at the pipe ends in the experiment. One of extremities of the pipe is free to move in the axial direction to represent the small gap of the experimental set-up.

Peak response amplitude

In Figures below, measured results from experiment and calculated ones of the maximum displacement for each velocity condition are presented, as a function of reduced velocity (V_R). Note that all results discussed here are related to cross-flow response, the in-line response is not taken into account. The focus of the analysis is V_R > 4.0 condition, which is suited for a Reynolds number ranging from 1,700 up to 3,500.

However, it must be emphasized that Reynolds number is an important parameter for the VIV, and free spans in actual pipelines often experience Reynolds numbers much higher than those in the experiment here analyzed. Dependence of the Vortex-induced Vibration with the Reynolds number has been studied by Govardhan & Williamson (2006) showing that it influences the peak response with the increase of this parameter, and those analysis results is taken in the present study.

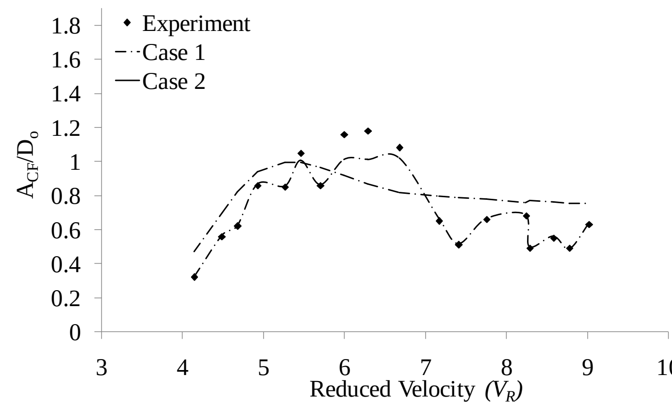

Figure 1 – Comparison between experiment and VIVANA results for the maximum cross-flow amplitude.

Comparisons between VIVANA and experiment results are shown in Figure 1. In general, experiment results present a little bit smaller response in comparison with the VIVANA results, with the exception for the region of V_R located between 6 and 7 in which, vibration amplitude achieve the maximum. It may happen due to the response is strongly dominated by the first mode in the VIVANA calculations. According to the current condition, the pipe can vibrate in a different mode shapes and with strong interaction between in-line and cross-flow vibrations. Nielsen et al. (2002) have shown that the interaction between the in-line and cross-flow responses for free spans may reduce responses in the cross-flow direction.

The original Strouhal number in VIVANA is close to 0.2 for all cases and, it is in agreement with the relationship between the Strouhal number and the Reynolds number from experiment, as reported in the literature (Lienhard, 1966).

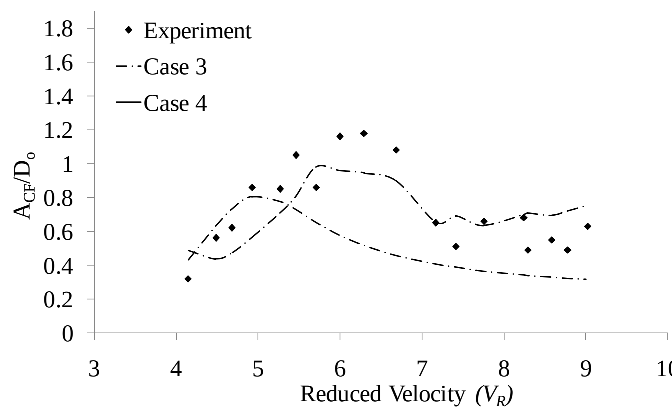

Figure 2 – Comparison between experiment and ANAPIPE-VIV for the maximum cross-flow amplitude.

In order to improve understanding of the comparison between VIVANA and experiment results, the St number as the key parameter in VIVANA was tuned to give the same response amplitude as the model in the experiment. In this case, the response frequency is different from the experiment and the previous analysis; however, amplitudes of response are in better agreement. It was observed that if the Strouhal number is adjusted, the lift coefficient curve used by VIVANA is affected and the calculated response matches with the experiment.

Simulation results from ANAPIPE-VIV are shown in Figure 2. The case 3 underestimated experiment results for low values of the $V_{R.}$ However, it has shown more conservative result for larger values of V_R.

This model does not consider the synchronization between pipeline vibration and vortex shedding. It means that the pipeline motion does not control the shedding process, and the shedding frequency depends on the incident flow perpendicular to the cylinder longitudinal axis, pipeline diameter and Strouhal number. There are differences between experiment and numerical simulation results, for the region of V_R located around 6 and, in which, vibration amplitudes in cross-flow direction achieve the maximum.

For the case 4, when the St is constant and equal to 0.2, initially a good agreement can be observed with measured results. However, for higher V_R values, numerical simulation amplitudes are underestimated. It may be concluded that to obtain a good agreement from this model, it is necessary to consider an accurate hydrodynamic coefficient.

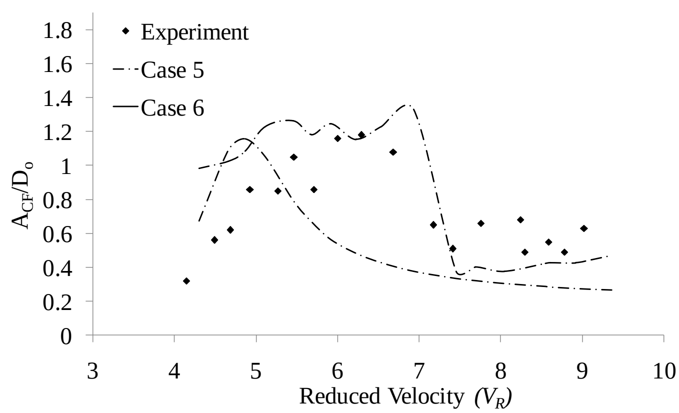

Figure 3 – Comparison of experiment and RiserProd for the maximum cross-flow amplitude.

Figure 3 shows result from simulations with the RiserProd. Case 5 numerical simulations underestimated experiment for larger values of the $V_{R.}$ However, more conservative result is observed for low values of $V_{R.}$

For the case 6, with constant St and equal to 0.2, the lock-in in the region of V_R located between 4.5 and 5.5, occurred beforehand the experiment, as can be observed in Figure 3.

The VIV model in the RiserProd also does not represent the synchronization between pipeline vibration and vortex shedding. It means that simulations in the region of V_R between 5.5 and 7.0 do not reproduce exactly the experiment.

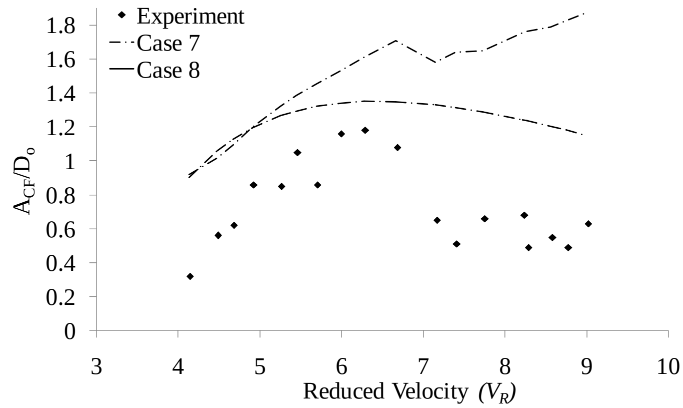

Figure 4 – Comparison of experiment and OrcaFlex results for the maximum cross-flow amplitude.

Figure 4 shows the OrcaFlex result through the Orcina wake oscillator model, the Milan model (Falco, et al 1999). Results were very conservative and, when the St was tuned, results were not good compared with the experiment. The Milan model looks not suitable for predicting the vortex induced forces on the pipe with free span and, perhaps, it cannot reproduce the transverse cylinder amplitudes for all V_R range. Moreover, the OrcaFlex was very conservative, overestimating dynamic cross-flow response for about 114% or more.

The difference observed between cases 7 and 8 can be explained because the OrcaFlex model has various parameters that determine their property and, the Strouhal number interacts with those parameters. Therefore, it is not recommended adjusting the Strouhal number since parameters are intended to be used with the default Strouhal number.

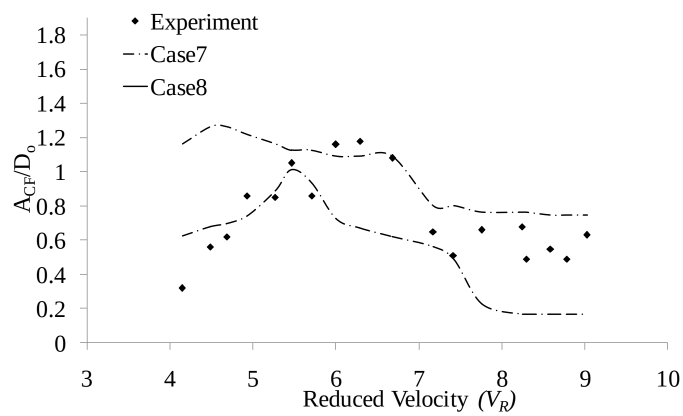

Figure 5 – Comparison of experiment and Shear7 for the maximum cross-flow amplitude.

Results for Shear7 are shown in Figure 5. For numerical simulations with the Strouhal number set to be the same frequency (case 9) in the experiment, we observe that the calculation results generally show higher responses in comparison with the experiment ones, with exception in the region of V_R located between 6 and 7, in which, vibration amplitude achieves the maximum. For the case 9, the Strouhal number is kept constant an equal to 0.18. And, results of A_{CF}/D_0 for the V_R greater than 5.2 have shown lower than those of the experiment.

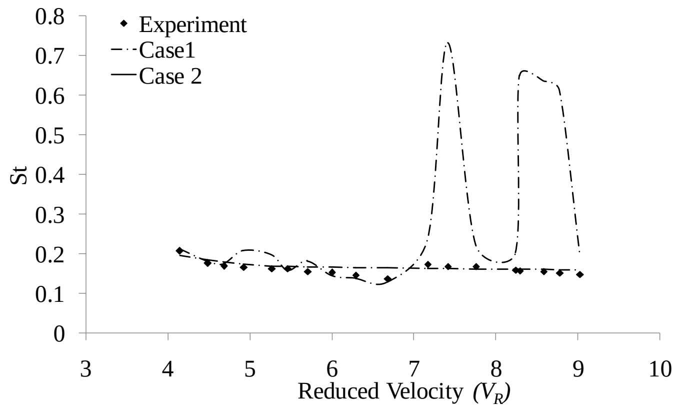

Figure 6 – Response frequency (through the Strouhal number) from experiment and VIVANA.

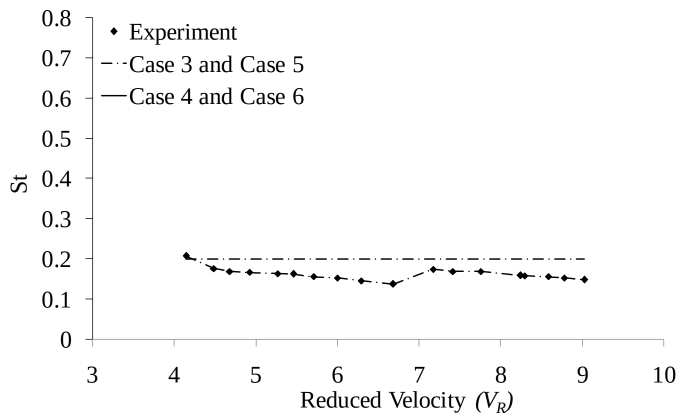

Figure 7 – Response frequency (through the Strouhal number) from experiment, ANAPIPE-VIV and RiserProd.

Vibrations Frequencies

Results in Figures 6, 7, 8 and 9 show the single dominant temporal frequency (through the Strouhal number), for experiment and of each the numerical model, respectively, as function of the V_R.

For the ANAPIPE-VIV (Fig. 7), RiserProd (Fig. 7) and Shear7 (Fig 9), the Strouhal number were obtained, firstly, from the Re number in the literature, and secondly, estimated from experiment by using the measured frequency of response. In Figure 6, the case 1 of VIVANA in which Strouhal number is obtained by the program, results are close to the experiment. In the case 2, where Strouhal number was tuned to give the same response amplitude as the model in the experiment, the result for Strouhaul number was not good. In Figure 8, the results for the OrcaFlex (case 7 and 8) presented good agreement with the experiment.

Observing Figures 1 and 6, for the case 2, when Strouhal number in the VIVANA is adjusted to achieve same response amplitude of the experiment, differences can be noticed in the response frequency. It occurs because adjusting the Strouhal number, the non-dimensional frequency will change, and consequently, the parameters in VIVANA such as the lift and the added mass coefficients also changes.

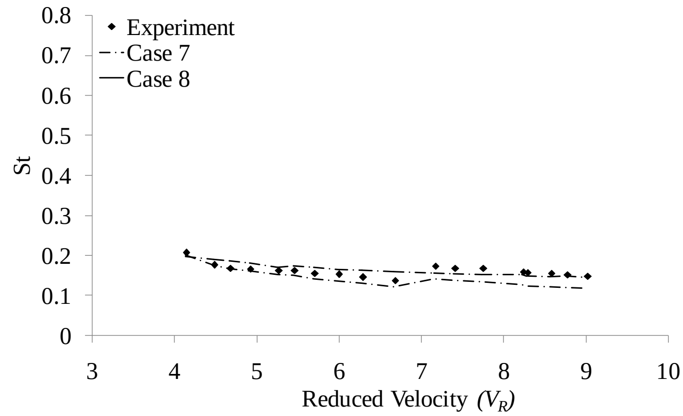

Figure 8 – Response frequency (through the Strouhal number) from experiment and OrcaFlex.

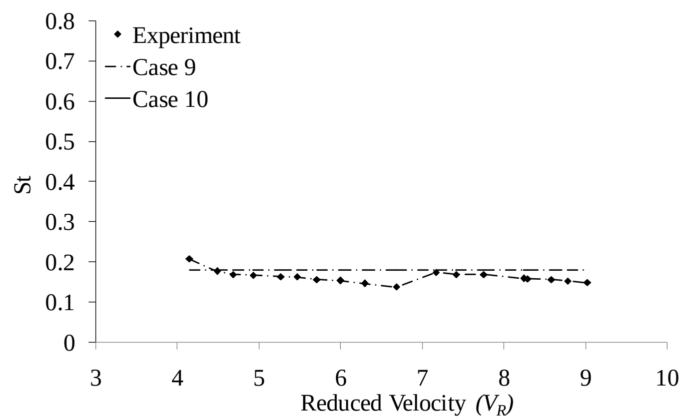

Figure 9 – Response frequency (through the Strouhal number) from experiment and Shear 7.

Normalization between calculation and measurement

An index of the proximity was calculated for each simulation result and measured one. In the Figure 10, sum of A_{CF}/D_0 ratios is shown for the middle length of the pipeline, calculated as follows:

$$< \bullet >= \frac{1}{N} \sum \frac{[\bullet]_{n,calculated}}{[\bullet]_{n,measured}} \qquad (6)$$

where N is the number of cases calculated for the each case.

Number in the parenthesis denotes the case calculated with the each computer program.

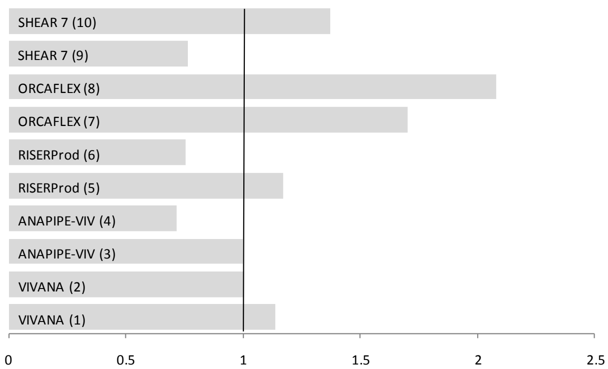

Figure 10 – Normalization between calculated and measured cross-flow displacement in the middle of pipeline.

CONCLUSIONS

A comparative study has been conducted in the present work, by comparisons of experiment and numerical simulation results for displacements of a pipe with free span. Cross-flow vibrations were focused, and simulations were carried out through different computer programs and, respective VIV models. Numerical simulations were done for different current velocity conditions and calculations by varying model parameters were conducted. The understanding of experiment data set was examined, and performance of the each program has been studied. As the main result, improvements in the comprehension of the VIV problem and, limitations of the each program and VIV model could be achieved.

On the average, overall condition computed by all programs, calculated cross-flow displacements were between 69% and 200 % of the corresponding experiment data.

In the time domain, the OrcaFlex has shown very conservative results, overestimating the dynamic cross-flow amplitude of vibrations by 200%. Perhaps, additional investigation is desired regarding appropriate adjustment of stiffness and damping reduced coefficients, in order to obtain better results compared with experimental ones.

The ANAPIPE-VIV presented good result when the Strouhal number was set being equal to the experiment response frequency, on average by 97% of the corresponding measured data in the experiment. However, both ANAPIPE-VIV and RiserProd were not satisfactory for the lock-in range. In order to improve calculations, it is concluded that reliable empirical coefficients are needed.

VIVANA in the frequency domain, by using default parameters, has shown good agreement with the experiment with average of 111% of the corresponding experiment data set.

Shear7 by using constant Strouhal number and equal to 0.18 has shown on average, by 73% of the corresponding experiment data set and, when the Strouhal number was set to be the same as experiment, on average by 134%.

In conclusion, all the programs do not represented with good agreement the lock-in region located for V_R between 6 and 7. Simulations underestimated the cross-flow amplitude of vibration, in general, and further investigation is still needed for this region of V_R.

Finally, the most of programs uses empirical and semi empirical approaches to estimate VIV forces uses, based on measured coefficients in laboratory or field tests, such as the lift coefficient and Strouhal number. Then, further laboratory experiment as well as field test data measurements are still needed to clarify and to support better estimation of VIV hydrodynamic forces.

For practical purposes, it is fundamental further investigations regarding the interaction between pipeline and seabed soil.

ACKNOWLEDGMENTS

The authors would like to thank Marintek/Sintef and Petrobras for making possible the present work, and PRH/ANP and CNPq for the support for the present academic research.

REFERENCES

[1] Larsen, C. M., Baarholm, G. S., Passano, E., Koushan, K., 2004, "Non-Linear Time Domain Analysis of Vortex Induced Vibrations for Free Spanning Pipelines", 23rd International Conference on Offshore Mechanics And Arctic Engineering (OMAE), Vancouver, Canada.

[2] Sarpkaya, T., 1978, “Fluid Forces on Oscillating Cylinders”, J. Water, Port, Coast, And Oc. Div., 104, Pp. 270-290.

[3] Vikestad, K (1998). “Multi-frequency Response of a Cylinder Subjected to Vortex Shedding and Support Motions,” PhD Thesis, Norwegian University of Science and Technology, Trondheim.

[4] Govardhan, R., Williamson, C. H. K., 2000, "Response And Vortex Formation Modes of an Elastically-Mounted Cylinder at High and Low Mass-Damping", IUTAM Conference on Bluff Body Wakes And Vortex-Induced Vibration (BBVIV-2), Marseille, France.

[5] Blevins, R. D., 1994, “Flow Induced Vibration”, New York Nostrand Reinhold.

[6] Griffin, O. M., Skop, R. A., Ramberg, S.E., 1975, “The Resonant Vortex-Excited Vibrations of Structures and Cable Systems”, Offshore Technology Conference (OTC), Houston, Texas, USA.

[7] Sarpkaya, T., 1979, “Vortex-Induced Oscillations – A Selective Review”, Journal of Applied Mechanics, vol. 46, pp. 241-258.

[8] Franciss, R., 1999, “Vortex induced Vibration of Slender Members of Floating Offshore structures”, Ph.D. Thesis, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil (In Portuguese).

[9] Bearman, P.W.; Zdravkovich, M.M., 1978, “Flow Around a Circular Cylinder near a Plane Boundary”, Journal of Fluid Mechanics, Vol. 89, pp. 33-47.

[10] Tura, F., Dumitrescu, A., Bryndum, M. B. & Smed, P.F., 1994, “Guidelines for Free Spanning Pipelines: The GUDESP Project”, 13th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Houston, Texas, USA.

[11] Fyrileiv, O., Chezhian, M. and Mørk, K., 2005, "Experiences Using DNV-RP-F105 in Assessment of Free Spanning Pipelines", 24th International Conference on Offshore Mechanical and Arctic Engineering (OMAE), Halkidiki, Greece.

[12] Mørk K.J., Fyrileiv, O., Verley, R., Bryndum, M. & Bruschi, R., “Introduction to the DNV Guideline for Free Spanning Pipelines”, 17th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Lisbon, Portugal.

[13] Larsen, C.M., et Al., 2000, “VIVANA Theory Manual”, MARINTEK, 513102.01, Trondheim, Norway.

[14] Fylling, I., Larsen, C.M., Sødahl, N., Passano, E., Bech, A., Engseth, A.G., Lie, E., Ormberg, H., 1998, “RIFLEX User’s Manual”, MARINTEK, Trondheim.

[15] Larsen, C. M., Larsen V. K., Yttervik, R., Passano, E., 2001, “Empirical Model for Analysis of Vortex Induced Vibrations –Theoretical Background and Case Studies”, 20th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Rio de Janeiro, Brazil.

[16] Gopalkrishnan, R., 1993, "Vortex-Induced Forces on Oscillating Bluff Cylinders", D.Sc. Thesis, Department of Ocean Engineering, MIT, Boston, U.S.A.

[17] Vandiver, J. K., Li, L., 1999, “SHEAR7 Program Theory Manual”, Department of Ocean Engineering, MIT, Boston, USA.

[18] Lyons, G.J., Vandiver, J.K., Larsen, C.M., Ashcombe, G.T., 2003, “Vortex Induced Vibrations Measured in Service in the Foinaven Dynamic Umbilical, and Lessons from Prediction”, Journal of Fluids and Structures 17, 1079–1094.

[19] Chaplin, J.R., Bearman, P.W., Cheng, Y., Fontaine, E., Graham, J.M.R., Herfjord, K., Huera Huarte, F.J., Isherwood, M., Lambrakos, K., Larsen, C.M., Meneghini, J.R., Moe, G., Pattenden, R.J., Triantafyllou, M.S., Willden, R.H.J, 2005, “Blind Calculated of Laboratory Measurements of Vortex-Induced Vibrations of a Tension Riser”, Journal of Fluid Structures, V.21, pp. 25-40.

[20] Morooka, C.K., Kubota, H.Y., Nishimoto, K., Ferrari Jr., J.A., Ribeiro, E.J.B., 2003, “Dynamic Behavior of a Vertical Production Riser by Quasi-3D Calculations”, 22nd International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Cancun, Mexico.

[21] Mourelle, M.M., Gonzalez, E.C., Jacob, B.P., 1995, “ANFLEX – Computational System for Flexible and Rigid Analysis”, International Offshore Engineering, John Wiley & Sons, Chichester/NewYork, USA.

[22] Tsukada, R.I., Morooka, C.K., 2013, “Numerical Simulation Procedure for Vortex-induced Vibration of Pipelines with Free Span”, 32nd International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Nantes, France.

[23] Chang, S., H.M., Isherwood, M., 2003, “Vortex Induced Vibrations of Steel Catenary Risers and Steel Offloading Lines due to Platform Heave Motions”, Offshore Technology Conference (OTC), Houston, Texas, U.S.A.

[24] Falco, M., Fossati, F., Resta, F., 1999, “On the vortex Induced Vibration on Submarine Cables: Design Optimization of Wrapped Cables for Controlling Vibrations”, 3rd International Symposium Cable Dynamics, Trondheim, Norway.

[25] Cunha, S.B., Matt, C.G.C, Morooka, C.K., Franciss, R., Tsukada, R.I., 2009, “Pipeline VIV: Analytical Solution, Experiments and Parameter Identification”, 28th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Honolulu, Hawaii, U.S.A.

[26] Nielsen, F.G., Soreide, H.T., and Kvarme, S.O., 2002, “VIV Response f Long Free Spanning Pipelines”, 21st International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Oslo, Norway.

[27] Orcina, 2008, “OrcaFlex User Manual”, www.orcina.com, UK.

[28] Vandiver, K and Li, L, 2003 “SHEAR7 - Program Theoretical Manual”, MIT, January 2003

[29] Larsen, C.M., Vikestad, K., Yttervik, R. and Passano, E., 2001, “VIVANA - Theory Manual”, MARINTEK, Trondheim.

