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IN-LINE VIV BASED ON FORCED VIBRATION TESTS

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ABSTRACT

Excitation and added mass functions determined from forced vibration tests of a rigid cylinder undergoing harmonic motion in the flow are used in the semi-empirical software VIVANA to predict the VIV response of pipelines.

An advantage of this approach, as opposed to the more-commonly-used response function approach, is that it can account for changing conditions along the length of the pipe, like changing current velocity, seabed proximity, and/or pipe diameter. This makes it useful for pipelines as well as for risers when such changes occur. Further, for pipelines, travelling wave effects play less of a role than for risers, so the VIVANA approach can be simplified by assuming the phase angle of the harmonic response is constant along the span.

The interactions between cross-flow and in-line response that complicate the prediction of cross-flow VIV by the excitation function approach, do not arise for pure in-line VIV. For the latter case, using the pure in-line forced vibration test data of Aronsen (2007), it is found that both VIVANA approach and simplified 'SIVANA' approach thereof predict VIV amplitudes consistent with experiments on flexible pipe (Ormen Lange umbilical VIV tests), and the DNVGL-RP-F105 response function for a range of structural and soil damping values.

In a companion paper, this approach is applied partially strake-covered pipeline spans, to show that a relatively small fraction of well-placed strake coverage is enough to suppress in-line VIV.

NOMENCLATURE

CF Cross-flow.
FSP Free span pipeline.
IL In-line.
RP Recommended Practice. In the present paper, it refers to DNV-RP-F105 [1].
SIVANA Simplified version of VIVANA, in which the un-

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damped mode shape for the bare pipe is used in a Rayleigh-Ritz approach, leading to one equation for the natural frequency (based on the Rayleigh Quotient) and another for the amplitude of vibration (based on energy balance).

UMB Umbilical.
VIV Vortex-induced vibrations.
VIVANA A semi-empirical VIV prediction software.
C_e Excitation coefficient.
C_a Added-mass coefficient.
F_e Excitation force.
D Diameter of the model.
D_H Hydrodynamic diameter of the model.
EA Axial stiffness.
EI Bending stiffness.
L Length.
T_{EFF} Effective tension force.
U Current speed.
U_r $U_r = U/f_nD$ Reduced velocity.
f_n Natural frequency.
$f_{osc,IL}$ IL oscillating frequency.
k Spring stiffness.
m Mass per unit length.
m^* Mass ratio.
n_{CF} CF response mode.
n_{IL} IL response mode.
w Weight in water.
ζ Damping ratio.

INTRODUCTION

Pipelines lying on the seabed usually have free spans due to uneven topography of sea bottom, stiffness and weight of the pipeline, and the residual tension force. Free spanning pipelines may experience vortex-induced vibrations (VIV) due to ocean currents. VIV can result in fast accumulation of fatigue damage and severe structure failure ultimately. Predicting VIV accurately is hence important for the design of pipelines, and structural integrity of the pipeline throughout the entire service life.

Several deepwater oil and gas fields have uneven seabed. One example is the Ormen Lange natural gas field on the Norwegian continental shelf. The water depth of the Ormen Lange field varies from 800 m to over 1100 m. Along the 120 km long pipeline from the subsea templates to the land terminals, there is a large number of free spans even with the optimized route.

Extensive model tests of Ormen Lange gas pipeline were carried out in the Ocean Basin of MARINTEK (now SINTEF Ocean) during the period between 2000 to 2003 [2]. Full-scale prototype section of the Ormen Lange umbilical was tested in a later phase [3]. The objectives of these tests

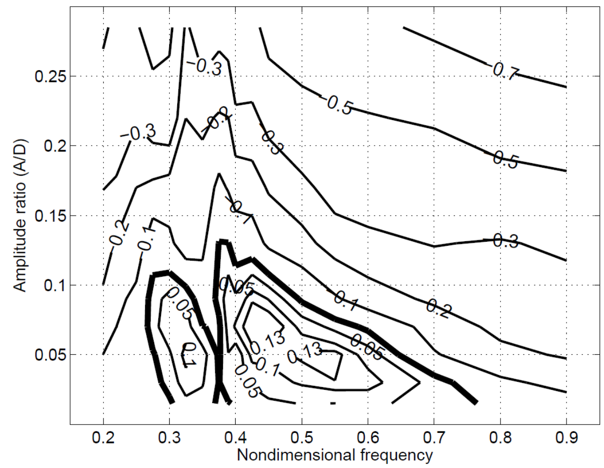

FIGURE 1. PURE IL EXCITATION COEFFICIENT CONTOUR FOR A BARE CYLINDER, OBTAINED FROM RIGID CYLINDER FORCED MOTION TESTS [8]. THE THICK LINE REPRESENTS RESPONSE AMPLITUDE WHEN EXCITATION COEFFICIENT EQUALS TO ZERO $A/D|_{C_e=0}$.

were to study the VIV response of free spans of the Ormen Lange pipelines and umbilicals, and assess the suppression effectiveness of helical strakes.

Empirical models to calculate VIV of free span pipelines have been developed, such as VIVANA [4–7]. Rigid pipe model forced motion VIV test was performed to find the hydrodynamic coefficients such as excitation coefficient (C_e) and added mass coefficient (C_a). Pure IL response of flexible beams will take place at the primary mode at low reduced velocities simply because the frequency of IL forces is twice the CF frequency. Hence, coefficients for pure IL response are of interest, which was the motivation of Aronsen [8]. He did pure IL VIV forced motion tests on a rigid pipe at Reynolds number of 24000 in the Marine Cybernetic Laboratory (MCLab). The key results from such experiments are the hydrodynamic coefficients - excitation coefficients and added mass coefficients. Figure 1 presents the excitation coefficients extracted from the forced motion experiments by Aronsen. It has been observed that CF motions will change the IL response significantly as compared to pure IL response. The IL amplitude will increase, and the CF and IL response frequencies will be decided by an adjustment of their added mass. Using the same rig, Aglen [9] performed forced motion tests with the measured orbits (combined IL and CF) from the Ormen Lange free span pipeline VIV model tests. Time domain approaches have been developed to tackle the non-linearities and complex flow [4, 10].

Helical strakes are usually installed on the free spans to suppress VIV. To study the fatigue damage caused by IL

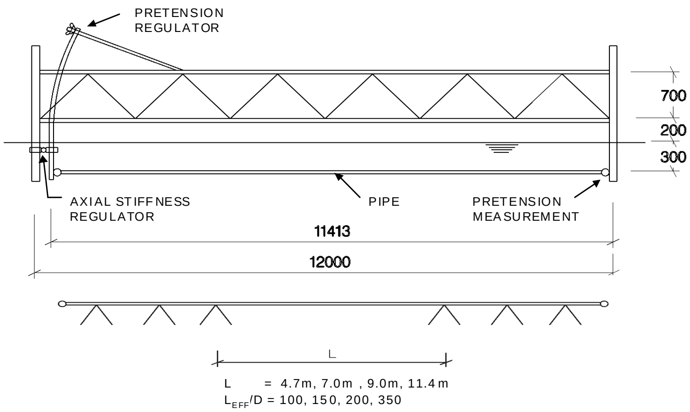

FIGURE 2. ORMEN LANGE MODEL TEST SETUP [16].

VIV on a free span pipeline partially covered with strakes, Shell carried out a series of numerical and experimental studies together with SINTEF Ocean [11–13]. A methodology to assess the VIV response for free spans partially covered with strakes - SIVANA [14] is applied. The SIVANA approach is a simplified version of VIVANA proposed by Ralf Peek whereby the undamped and not-excited modes for the bare pipe are used in a Rayleigh-Ritz approximation. This readily yields the response function for bare or straked pipe, which is then used to estimate fatigue following DNVGL-RP-F105 [1]. This SIVANA approximation greatly simplifies the calculation at little cost in accuracy when applied to pipeline spans where only the lowest modes are excited and propagating wave effects are negligible.

The overall objective of this paper and a companion paper [15] is to use the empirical VIV prediction software - VIVANA and SIVANA, to predict IL VIV of free spanning pipelines partially covered by helical strakes. The present paper validates VIVANA as an effective tool to calculate VIV of free spanning pipelines without strakes. Selected cases from Ormen Lange free span pipeline VIV tests and Ormen Lange umbilical VIV tests are analyzed and compared with VIVANA's results.

ORMEN LANGE MODEL TESTS

The Ormen Lange test setup is described in [16], see Fig. 2. A 12.0 m truss beam serves as the support structure for the pipe model. Universal joints are attached to both ends of the pipe model. At one end, the universal joint is fitted to a force transducer to measure the axial force. At the other end there is a mechanism for adjustment of axial stiffness and pretension of the pipe model.

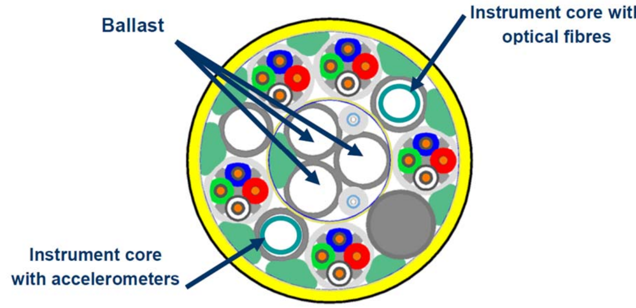

FIGURE 3. CROSS SECTION OF THE UMBILICAL WITH THE INSTRUMENTED CORES INDICATED [3].

Free span pipeline

The pipeline model was instrumented with ten sets of strain gauges that made it possible to measure bending strains for IL and CF displacements. Displacements along the pipe were found by conventional modal analysis. Hence, snapshots of dynamic displacements at given points of time can be presented and also time series of CF and IL response and modal participation factors for both directions. The procedure is described in [17].

In total three phases of free span pipeline tests were carried out. The same pipe model was used in the first two phases. It was modified for the third phase according to a change in the specifications of the real Ormen Lange pipeline.

Umbilical

The full-scale umbilical was tested in a later phase, using similar test arrangement and instrumentation as the free span pipeline tests, detail descriptions can be found from [3]. Figure 3 shows the cross section of the umbilical.

Key data for the pipe and umbilical models are shown in Tab. 1.

Table 2 shows the selected cases for the present study. Test cases from three test series are selected: series 75XX and 42XX are from Ormen Lange free span pipeline (FSP) tests, and series 28XX are from Ormen Lange umbilical (UMB) tests. Only the test cases with reduced velocity lower than 4 are studied in the present study, and pure IL VIV responses are expected.

APPROACH

VIVANA

A detailed description of VIVANA can be found in [6]. The structure is modeled using finite elements and the response found in the frequency domain by an iterative pro-

TABLE 1. KEY DATA OF ORMEN LANGE PIPE AND UMBILICAL MODELS.

Parameter	Unit	Phase 1/2	Phase 3	Umbilical
L	m	11.413	11.413	20
D	m	0.0326	0.03504	0.12
EI	kNm^2	0.203	0.203	9.3
EA	kN	5000	5000	
T_{EFF}	kN	0.05-0.07	0.05	3.4 - 15
w	N/m	3.25	3.61	
m	kg/m	1.147	1.307	21.6
k	kN/m	34.4	9.75	

TABLE 2. SELECTED TESTS FOR CASE STUDY [11].

Test No.	Test	L/D	U (m/s)	n_{IL}	n_{CF}	Ur (IL)
7502	FSP	97	0.14	1	1	1.5
7503	FSP	97	0.18	1	1	1.9
7504	FSP	97	0.23	1	1	2.4
7505	FSP	97	0.27	1	1	2.6
4210	FSP	144	0.10	1	1	2.1
4220	FSP	144	0.15	1	1	2.7
2812	UMB	167	0.30	2	1	2.4
2820	UMB	167	0.40	2	1	3.2
2830	UMB	167	0.50	2	1	4.0

cedure based on the frequency response method.

The response calculations are carried out at discrete response frequencies. Hydrodynamic force coefficients are used in VIVANA to calculate VIV responses, which includes the CF, and IL added mass, excitation and damping coefficients. The default hydrodynamic force coefficients for a bare cylinder are included in the program. The user may also specify other coefficients. User-specified coefficients are needed for helical strakes or fairings.

In VIVANA, the excitation force on an element with length ΔL is given by

$$F_{e,CF/IL} = \frac{1}{2}\rho C_{e,CF/IL} D_H U_N^2 \Delta L \tag{1}$$

Varying cross-sectional properties such as diameter, stiffness can be accounted. Effects of seafloor contact are modeled using linear springs. The current profile may be uniform, sheared and/or vary in direction.

VIVANA can be used for free spanning pipeline VIV prediction in the pure IL regime, the start-up of the CF regime up to well established CF regime. In the present prediction, a pure IL response model is used for the cases with pure IL responses at lowest current speeds. For cases with combined IL and CF responses at higher speed, a combined IL and CF prediction model is used.

SIVANA

SIVANA is a program proposed by Ralf Peek, which is used for VIV response assessment for spans that are partially covered with VIV suppression strakes [14].

The proposed methodology follows the VIVANA approach, but it is simplified by neglecting the variation in flow velocity along the span length. Further phase winding phenomena that are accounted for in VIVANA essentially by calculating the complex modes of the system are neglected in the simplified method. Instead, the simplified method relies on the modeshapes calculated without any damping, neglecting the change in mode shape due to damping, and added mass changes, if any. The amplitude of the modal response is then determined from energy balance between the zones of the pipe where excitation occurs and zones (including straked ones) where dissipation occurs, as in a Rayleigh-Ritz approximation for the response based on the still-water, undamped mode shape.

With these approximations the applicable response function is readily calculated for any strake coverage, and can replace those in DNVGL-RP-F105 [1] for spans with partial strake coverage. SIVANA employs the same excitation and added mass functions as VIVANA [6].

In Fig. 4 the bare pipe response function from SIVANA is compared with that from DNVGL-RP-F105 [1]. In this case the mode shape is taken from an analytical solution, and the mass ratio is 1.23, but the SIVANA response function is not sensitive to these parameters. The agreement is as good as might be expected, considering that the RP response function is an envelope, based on a range of experimental results, while the SIVANA approach uses only the IL experimental data from Aronsen [8]. For this reason, the gap in the excitation between the first and second instability zones is seen in the SIVANA but not in the RP response function.

DNVGL-RP-F105

The DNVGL-RP-F105 is a recommended practice (RP) for predicting fatigue damage due to VIV and direct wave loads on free spanning pipelines [1]. It describes amplitude response models of VIV (both IL and CF response) and

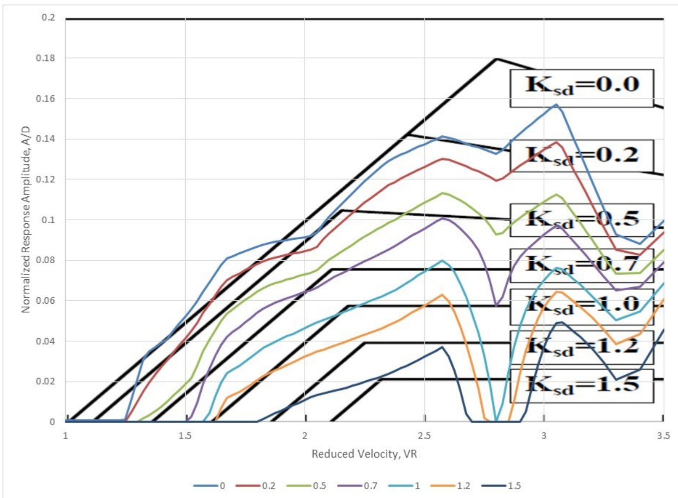

FIGURE 4. COMPARISON OF THE RESPONSE FUNCTION IL VIV OF BARE PIPE FROM THE SIVANA APPROACH WITH THAT FROM DNVGL-RP-F105 [1]: COLORED LINES ARE FROM THE SIVANA APPROACH WITH K_{sd} DAMPING VALUES (AS DEFINED IN [1]) SHOWN IN THE LEGEND.

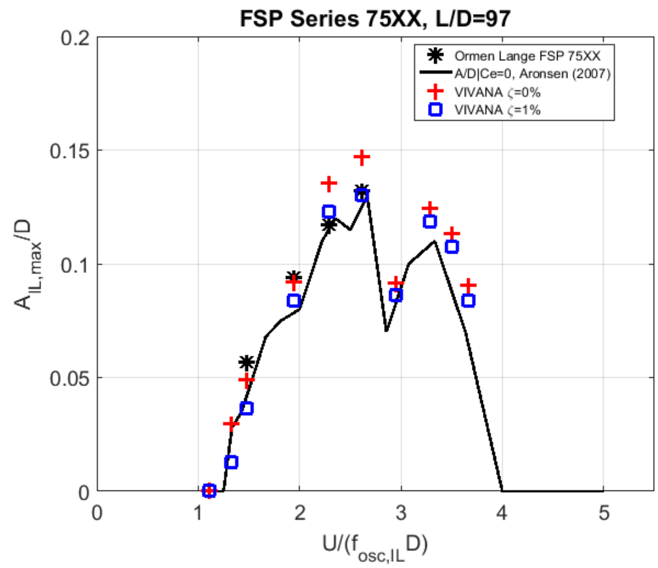

FIGURE 5. MAXIMUM IL RESPONSE AMPLITUDE RATIO COMPARISON BETWEEN EXPERIMENT, VIVANA ANALYSIS AND DNVGL-RP-F105 ON SERIES 75XX.

a force model for prediction of direct wave load response. Guidance on how to perform the structural analysis and how to model pipe-soil interaction is also given.

The amplitude response models are empirical models providing the maximum steady state VIV response amplitudes as a function of some basic hydrodynamic and structural parameters. The models for estimation of response due to VIV are based on several research and development programs, including the Ormen Lange free span pipeline VIV model tests.

RESULTS AND DISCUSSION

FSP test series 75XX

The maximum IL response amplitude ratios of a free span from Ormen Lange model tests are compared with VIVANA prediction and RP response curves. Figure 5 shows the comparison of maximum IL response amplitude ratios between measurement from Ormen Lange FSP test series 75XX and VIVANA prediction. In general, VIVANA prediction agrees well with measurements. The response amplitude when $C_e = 0$ from rigid cylinder forced motion experiments are plotted in black line (see Fig. 1). It is also seen that the maximum IL response amplitude ratios from both Ormen Lange FSP tests and VIVANA prediction follow the rigid cylinder forced motion zero excitation line, which is expected.

For a free span pipeline in uniform flow, there is a balance between the positive energy by the excitation force and dissipation by the damping forces, and the damping level determines the response amplitude. The damping forces consist of structural damping and hydrodynamic damping. In Fig. 5 and Fig. 6, VIVANA calculations are carried out at two structural damping levels, 0%, and 1%. The predicted amplitude ratio with 0% structural damping is higher than the response curve with zero excitation in the forced motion test (see Fig. 5), such amplitude may correspond to a negative excitation coefficient.

The predicted maximum IL response amplitude ratios are compared with RP response curve in Fig. 6. The RP-F105 response curve is seen to be conservative for reduced velocity up to 4.5. For higher reduced velocities ($U_r > 4.5$), CF response starts to build up, and the response will be combined IL and CF VIV response, pure IL responses will no longer exist.

It is important to note that the x-axis in Fig. 5 is the inverse of non-dimensional frequency, $1/\hat{f} = U/(f_{osc,IL}D)$. In Fig. 6, x-axis is reduced velocity. The relationship between the two axes is explained in Eq. 2, and it is seen that for small mass ratios, a small change in $\hat{f}$ results in a large change in U_r [8].

$$U_r = \frac{1}{\hat{f}}\sqrt{\frac{m^*+1}{m^*+C_a}} \tag{2}$$

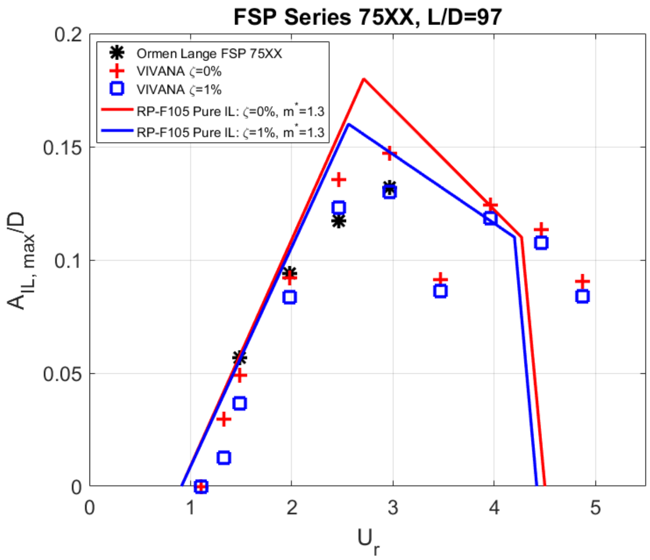

FIGURE 6. MAXIMUM IL RESPONSE AMPLITUDE RATIO COMPARISON BETWEEN EXPERIMENT, VIVANA ANALYSIS AND DNVGL-RP-F105 ON SERIES 75XX.

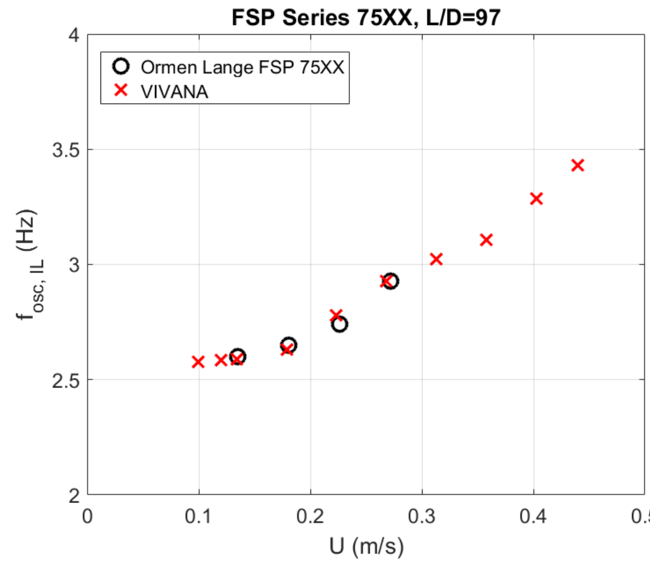

FIGURE 7. RESPONSE FREQUENCIES COMPARISON BETWEEN EXPERIMENT AND VIVANA ANALYSIS ON SERIES 75XX.

Figure 7 shows the response frequencies of 75XX series from Ormen Lange model test and VIVANA calculation, a good estimation of the response frequency is observed from the plot.

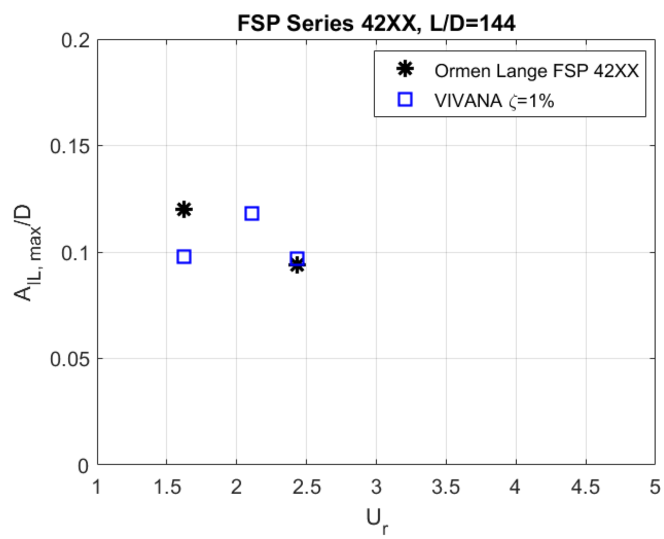

FIGURE 8. MAXIMUM IL RESPONSE AMPLITUDE RATIO COMPARISON BETWEEN EXPERIMENT AND VIVANA ANALYSIS ON SERIES 42XX.

FSP test series 42XX

Test series 42XX have a length-to-diameter ratio of 144, which is significantly higher than the test series of 75XX. The response will be dominated by a combined beam and cable behavior, while for a shorter span ($30 < L/D < 100$), the response is dominated by beam behavior [1]. Two pure IL model test cases are selected, and the maximum IL response amplitudes are compared with VIVANA calculation. The comparison is shown in Fig. 8, it shows that VIVANA pure IL prediction agrees with measurement well. The predicted mode and frequency are also in agreement with measured mode [7].

UMB test series 28XX

The sketch of the umbilical model cross-section is shown in Fig. 3, in which the instrumentations are also indicated.

From decay tests in air, it is found that the material damping of bare umbilical was less than 1.0 % of the critical damping [18]. However, the actual structural damping level during VIV is difficult to calibrate, the actual structural damping ratio can be much higher than 1%. A complex cross-section such as an umbilical or a flexible pipe mainly have two sources of structural damping: 1) damping due to the strain variation in the individual materials that make up the cross-sections, 2) damping due to the different layers slipping against each other. The first may be denoted material damping and is present at all response levels, and

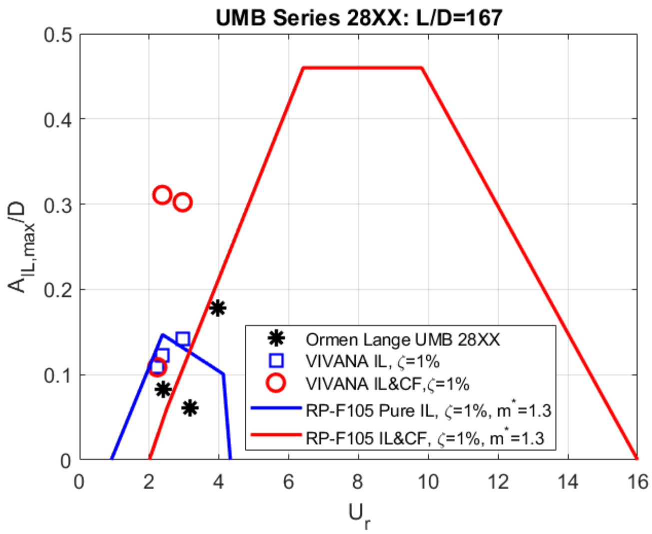

FIGURE 9. MAXIMUM IL RESPONSE AMPLITUDE RATIO COMPARISON BETWEEN EXPERIMENT AND VIVANA ANALYSIS ON SERIES 28XX.

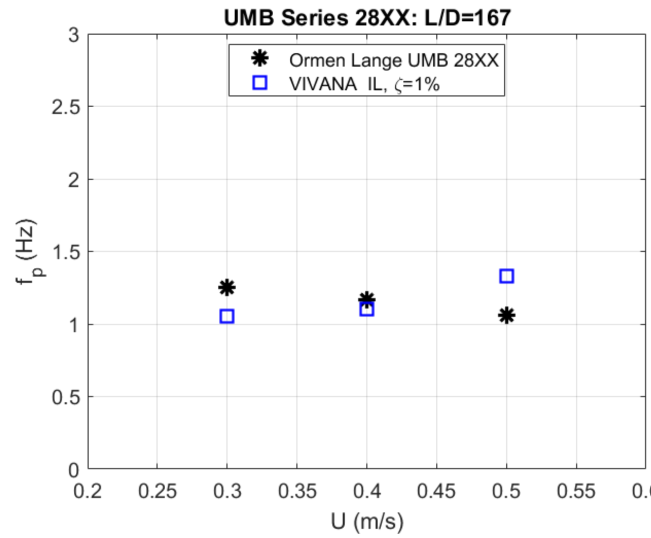

FIGURE 10. PEAK FREQUENCY COMPARISON BETWEEN EXPERIMENT AND VIVANA ANALYSIS ON SERIES 28XX.

will be particularly important at low response levels. The second may be denoted slip damping and will contribute when the curvature exceeds the initial slip curvature [19].

The comparison of the maximum IL response amplitude ratio between the model test results and the RP-F105 curve (1% structural damping) is presented in Fig. 9. Significant over-prediction is seen in the U_r ranges from 2 to 3.5. This suggests that the actual damping level in the experiment is much higher than 1%.

The maximum IL response amplitude ratio predicted by VIVANA is also presented in Fig. 9. Significant over-prediction by VIVANA is seen. Simulation using higher structural damping (5% of the critical damping) shows better agreement with measurements.

Figure 10 and Fig. 11 present the peak response frequency and dominating mode number comparison. The VIVANA prediction is in agreement with measurement for two of the cases. The response mode is over-predicted by VIVANA for the highest speed case.

Coupled IL and CF VIV analysis has been performed using VIVANA, and significant over-prediction of IL response amplitude ratio compared to the model test is observed in Fig. 9. For the coupled IL and CF analysis, VIVANA assumes that the dominating IL response frequency is always two times the dominating CF frequency. It is important to note that the IL hydrodynamic coefficients for combined IL and CF responses are preliminary for the present version of VIVANA, the prediction results are expected to be improved by using more robust hydrodynamic

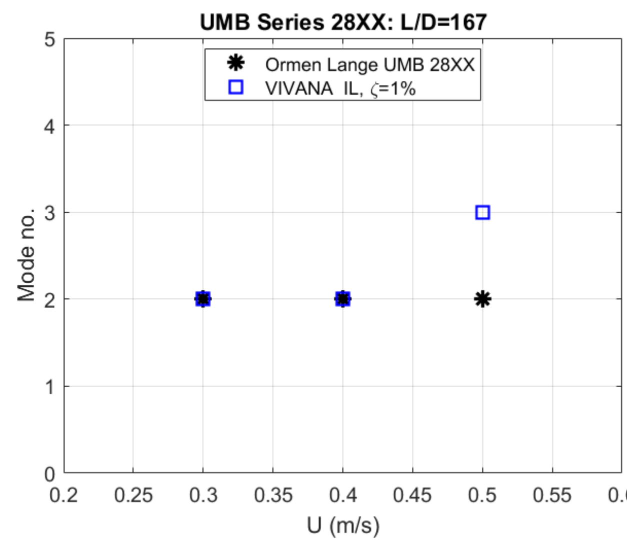

FIGURE 11. DOMINATING IL RESPONSE MODE COMPARISON BETWEEN EXPERIMENT AND VIVANA ANALYSIS ON SERIES 28XX.

coefficient data. Secondly, the selected cases have reduced velocities between 2 and 4, where CF responses start to develop. Compared to fully developed CF responses (reduced velocity from 5 to 8), the motion orbits in reduced velocity range with the 'onset' of CF responses are quite different, see Fig. 12.

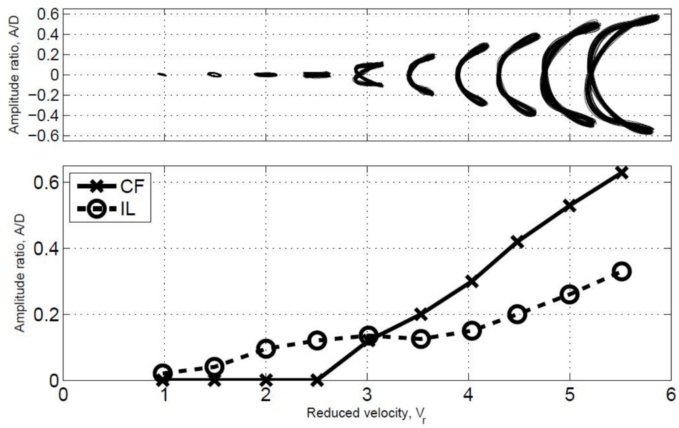

FIGURE 12. RESULTS FROM A FLEXIBLE BEAM EXPERIMENT PERFORMED FOR THE ORMEN LANGE FREE SPAN PIPELINE PROJECT. THE UPPER FIGURE SHOWS THE RESPONSE ORBITS AT MID-SPAN. THE LOWER FIGURE SHOWS CORRESPONDING RESPONSE AMPLITUDE RATIO. THE INCREASING REDUCED VELOCITY WAS GENERATED BY INCREASING THE FLOW SPEED [8].

Consequently, the hydrodynamic coefficients used to predict pure IL VIV response, IL response of coupled IL and CF VIV responses with an onset of CF response and IL response of coupled IL and CF VIV responses with fully developed CF response should be different. However, due to insufficient experimental data, in the present version of VIVANA, for coupled IL and CF analysis, the hydrodynamic coefficients are mainly based on experimental results from coupled IL and CF responses with fully developed CF responses. Finally, the over-prediction also indicates that the actual structural damping level might be much higher than 1%, however, there is no accurate calibration of this damping parameter, which leads to large uncertainty in the prediction.

SUMMARY AND CONCLUSION

Summary

Very few experimental works have been done on the free span pipeline VIV responses at low reduced velocities. Existing Ormen Lange free span pipe and umbilical model test data have been reviewed. Selected cases from Ormen Lange model tests are analyzed and the results are used to validate the semi-empirical VIV prediction programs VIVANA and SIVANA, focusing on the pure IL VIV response prediction.

VIVANA pure IL prediction is in good agreement with model test data. VIVANA prediction also compares well with DNVGL-RP-F105 and differences are explained. The VIVANA results leading to this good agreement are only on the forced vibration tests and the VIVANA methodology, without any calibration against flexible pipe tests like the ones it was predicting.

Combined IL and CF responses are observed in Ormen Lange umbilical test. Bare pipe cases with the lowest response mode (IL mode 2) are first analyzed, and results show large uncertainty in material damping due to the complex cross section.

Conclusion

Based on the results of the present work, the following conclusion and recommendations could be made:

1) VIVANA can predict pure IL response accurately. The predicted responses compare well with flexible cylinder model test and DNVGL-RP-F105.

2) It is especially remarkable to that in the reduced velocity range 0 to 2.1, the agreement between VIVANA and the DNVGL-RP-F105 response function is excellent.

3) At higher reduced velocities the picture becomes more complicated due to combinations of pure IL VIV and an IL component of coupled IL and CF VIV, which can have similar of even greater amplitudes. From a practical point of view, at these higher reduced velocities, the fatigue damage would likely be dominated by larger CF vibration amplitudes. However, the IL contribution could be equally important due to higher mode (resulting in higher stress) or higher response frequency.

ACKNOWLEDGMENT

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