The Specialist Committee on Vortex Induced Vibrations

Final Report and Recommendations to the 26th ITTC

1. REPORT FROM THE COMMITTEE

1.1 Membership and Meetings

The members of the Vortex Induced Vibrations Specialist Committee of the 26th International Towing Tank Conference are as follows:

- Halvor Lie, Dept. of Offshore Hydrodynamics, MARINTEK, Norway. (Chairman).
- Elena Ciappi, Istituto Nazionale per Studi ed Esperienze di Architettura Navale (CNR-INSEAN), Italy.
- Shan Huang, Naval Architecture and Marine Engineering, University of Strathclyde, UK.
- Sup Hong, Korea Ocean Research & Development Institute (KORDI), South Korea
- Zong Zhi, Department of Naval Architecture and Ocean Engineering, Dalian University of Technology, China

Three committee meetings were held respectively:

- CNR-INSEAN, Italy, November 2009
- Shanghai (OMAE 2010), China, June 2010
- University of Strathclyde, Glasgow, UK, February 2011

1.2 Tasks and Recommendations of the 25th ITTC

The original tasks of the 26th ITTC VIV Specialist committee recommended by the 25th ITTC were as follows.

- Task 1. Update the state-of-the-art for predicting vortex induced vibrations and motions emphasizing developments since the 2008 ITTC in various current profiles at ultra deep water. The update shall cover both small-diameter structures (e.g. risers) and large-diameter structures (e.g. SPAR platforms).
- Task 2. Organize, conduct and report the results of benchmark VIV tests. Cooperate with OMAE on the benchmark activity.
- Task 3. Prepare standard nomenclature for VIV and VIM investigations.
- Task 4. Write a procedure for VIV and VIM testing for marine applications.

1.3 Brief Description of the Execution of the Tasks

Task 1. The review is presented in the following chapters.

Task 2. The benchmark study had initially seven participating institutes. However during the 26th ITTC period two of them withdrew their participation and two others of the participants reported unforeseen delay. Therefore results from only three participants were reported to the committee in the end of spring 2011, which was considered to be too sparring for the benchmark study. The committee therefore recommends ITTC to continue and complete the Benchmark study in the next ITTC period.

Task 3. A nomenclature is included in the review.

Task 4. The committee has made a draft version of a guide line (GL) and recommends that the GL should be completed during the next ITTC period.

2. REVIEW

2.1 Numerical Models

Most of the work done in last three years concerning the VIV response of isolated rigid cylinders free to oscillate in 1 or 2 DOF and of flexible cylinders was devoted mainly to improve the prediction capabilities of wake oscillator models rather than to the development of new CFD or semi-empirical models.

In fact, a significant number of the published papers describe very sophisticated wake oscillator able to capture the nonlinear multi-mode dynamics and interactions of flexible curved or straight structures undergoing VIV and to overcome the limitation of previous models in predicting the amplitude of oscillations.

Much less CFD analyses have been done recently. All the traditional computational approaches have been adopted for the flow description including Direct Numerical Simulations (DNS), RANS methods, LES model and Detached Eddy Simulation (DES) using finite difference, finite volume and finite element scheme. In particular several authors proposed space-time finite element as a valid tool to solve fluid-structure interaction problems with moving boundaries such as VIV of an elastic cylinder and to improve the convergence rate in iterative solution of the large scale non-linear equation system.

Structural analyses are performed using finite element, finite difference and modal analysis.

Most of the numerical simulations are two-dimensional or, making use of the strip theory, quasi-three dimensional.

Notwithstanding, 3D simulations of the VIV response of flexible risers with high aspect ratio and at moderately high Reynolds number (up to $1.5x10^4$) in uniform and sheared current can be found and seem to agree satisfactorily with experimental data.

Existing CFD codes have also been applied to the study of the efficacy of VIV suppression devices. For the semi-empirical models, the work recently done is focused on the enhancement of existing codes to overcome some of the shortcomings of previous methods, on the benchmarking of different tools and on their validation with comparisons with model and full-scale experimental data.

On the other hand, considerable interest has received in last years the numerical study of the flow around multiple cylinders using principally DNS for the flow field description. However, up to date, results are available only for low Reynolds numbers (Re<300) where very limited experimental data exist for validation of simulation results.

2.1.1 CFD

Single cylinder

Atluri et al. (2009) examined the differences in the wake structures of a periodically forced oscillation and a self-excited oscillation both at constant amplitude and the influence of the Reynolds number on the vortex-shedding modes. The study is performed by using a 2D LES with a Smagorinsky model to simulate uniform flows past a circular cylinder oscillating at modulated frequency for a Reynolds number range between 500 and 8000. With regards to long riser simulations, He et al. (2010) simulate the VIV of a flexible riser with aspect ratio equal to 250 for Reynolds numbers up to $1.28x10^4$ using Finite Element for the structure and Finite Volume for the fluid domain. The model is based on strip theory which assumes that the flow is locally 2D due to the correlation of lock-in effects. They found that the in-line and cross-flow motion are strongly coupled and exhibited similar behaviour for particular values of the reduced velocity. Moreover, Huang et al. (2009a, 2009b) presented 3D numerical simulations of the motion of a flexible riser (L/D=482) in uniform and sheared current, respectively. The time domain simulations are performed using the Finite Analytic Navier-Stokes (FANS) code. The flow field around the riser is calculated solving the unsteady, incompressible 3D Reynolds-Averaged Navier-Stokes (RANS) in conjunction with a large eddy simulation (LES) model for Reynolds numbers between $7.5x10^3$ and $1.5x10^4$. The motion of the riser is predicted through a tensioned beam equation with structural damping. The numerical results agree satisfactorily with experimental data both for the in-line and cross-flow motion and for the sheared current case a fatigue life analysis is performed.

Wanderley et al. (2008) used the Roe-Swebe scheme to solve the slightly compressible 2D RANS equations and the k-ε turbulence model to simulate the turbulent flow in the wake of a circular cylinder. The aim of the paper was to duplicate numerically the experiments of Khalak and Williamson (1996). The results achieved agreed very well with experimental data and demonstrated the ability of this methodology in predicting correct amplitudes in the entire range of reduced velocity for the low mass ratio case.

Prasanth and Mittal (2008) presented numerical simulation of VIV of a circular cylinder of low non-dimensional mass in the laminar flow regime (60<Re<200). A stabilized space-time finite element formulation is utilized to solve the incompressible flow equations in two dimensions. They have shown that for low Reynolds number regime the cylinder response is characterized only by two branches: initial and lower. They also examined the effect of blockage and the results obtained were satisfactory compared with experiments. Li et al. 2010 performed numerical simulations of VIV of a two dimensional elastic circular cylinder in uniform flow at Re=200. Two dimensional Navier-Stokes equations are solved with the space-time finite element method, low mass-damping situation was analyzed and the nonlinear phenomena such as the limit cycle and bifurcation of lift coefficient and displacement are analyzed for both the 1 and 2 DOF and the results of the two cases discussed and compared.

Multiple cylinder configuration

A comprehensive review of the literature on the flow around two circular cylinders of equal diameter in cross flow can be found in Sumner (2010). The attention is focused on the three main configurations, namely the tandem, side by side and staggered configurations, with a particular emphasis on the near-wake flow patterns, Reynolds number effects, intermediate wake structure and behaviour. Borazjani and Sotiropoulos (2009) investigated numerically VIV of two identical two-dimensional elastically mounted cylinders in tandem in the proximity-wake interference regime at Reynolds number *Re*=200 for systems having both 1 and 2 DOFs. By analyzing the simulated flow patterns obtained directly integrating in time the governing equations they are able to identify the VIV excitation mechanisms and elucidate the near wake vorticity dynamics and vortex shedding modes excited in different conditions. Although most of the experimental observations are at significantly higher Reynolds number the results indicated that important aspects of the VIV dynamics can be observed numerically at lower Reynolds. Three-dimensional simulations are also carried out to examine the adequacy of 2D simulations showing that 3D modes are too weak to affect the dynamic response of the system. Prasanth and Mittal (2009) presented numerical results for the free vibrations of a pair of equal-sized circular cylinders of low nondimensional mass ratio in tandem arrangement. The computations are carried out for various values of reduced speed in the laminar flow regime (Re=100). A stabilized finite element method is utilized to carry out the 2D computations. The differences in the response of the two cylinder system with respect to that of the single cylinder are analyzed in detail. Springer et al. 2009 investigated the VIV response of two flexible risers in cross-flow using the CFD Finite Element Navier Stokes solver AcuSolve. Bare and straked geometries are simulated and the results are successfully compared against experimental results. To this aim a three dimensional CFD solver was coupled with a linear structural model at $Re=10^5$. Carmo et al. (2011) performed two- and three-dimensional direct numerical simulations of the flow around two circular cylinders in tandem arrangements with the upstream one fixed and the downstream cylinder free to oscillate in the transverse direction. Reynolds number is kept constant at 150 for the 2D simulations and at 300 for the 3D simulations, the reduced velocity is varied by changing the structural stiffness and the centre to centre distance is varied from 1.5 to 8 diameters. The comparison of the obtained results with those for the isolated cylinder show that, for the tandem arrangements, the lock-in boundaries are wider, the maximum displacement amplitudes are greater and that the amplitudes of vibration for high reduced velocities, outside the lock-in, are very significant.

Motion suppression devices

Baek and Karniadakis (2009) investigated numerically the hydrodynamic effect of a slit in circular cylinders with the aim of finding a geometric modification that minimizes VIV without energy consumption. From the results of a series of 2D and 3D simulations over a wide range of reduced velocity, performed using the code NEKTAR, which implements the spectral/hp element method, the optimal size of the slit to suppress VIV is found at Reynolds number 500 and 1000.

2.1.2 Wake oscillator and semi-empirical models

Srinil (2010) presented a general low-order fluid–solid interaction model capable of evaluating the nonlinear multi-mode dynamics and interactions of flexible curved/straight structures undergoing VIV. Srinil et al. (2009) presented a new reduced-order model capable of analyzing the vortex-induced vibration of catenary riser in the ocean current allowing a significant reduction in computational effort for the analysis of fluid–riser interactions. The equations of riser 3-D motion are based on a pinned–pinned, tensioned-beam or flexural cable, modeling which accounts for overall effects of riser bending, extensibility, sag, inclination and structural nonlinearities. The unsteady hydrodynamic forces associated with cross-flow and in-line vibrations are modeled as distributed Van der Pol wake oscillators. This hydrodynamic model has been modified in order to capture the effect of varying initial curvatures of the inclined flexible cylinder and to describe the space-time fluctuation of lift and drag forces. Depending on the vortex-excited in-plane/out-of-plane modes and system fluid–structure parameters, the parametric studies are carried out to determine the maximum response amplitudes of catenary risers, along with the occurrence of uni-modal lock-in phenomenon. The obtained results highlight the effect of initial curvatures and geometric nonlinearities on the nonlinear dynamics of riser undergoing vortex-induced vibration.

Xu et al. (2008) analysed a long riser undergoing VIV in uniform and sheared flow using the Van der Pol wake oscillator for the near wake. A two DOF nonlinear structural model which ignored the inline deflection and considered the nonlinear coupling between axial and cross-flow direction is employed, the coupling term between structure and wake oscillator is acceleration. They compared the predicted results with experimental data and CFD results observing a good agreement. Xu et al. (2010) proposed a novel wake oscillator model able to overcome the limitations of previous models in predicting the cylinder oscillation amplitude by introducing a set of relations between empirical parameters and the mass ratio and damping parameters that govern the oscillatory response. These relations are used to calculate empirical parameters which were assumed constant by other researchers. The model was used to predict qualitatively the resonant response amplitude and frequency for elastically supported cylinder and the results were successfully compared to experimental data.

Violette et al. (2010) analyzed the motion induced by vortex shedding on slender structures subjected to cross-flow by considering the linear stability of a coupled system that includes the structure and the wake dynamics. The wake dynamics is modeled by a continuum of wake oscillators distributed along the span of the structures. They found, as already observed in some experiments and numerical simulations, that in the case of a straight tensioned cables in uniform flows VIV arise as an instability related to the merging of two waves while in the case of a non-uniform flows several unstable wave systems are identified. Mukundan et al. (2009) starting from the wake oscillator model proposed by Facchinetti et al. (2004) allow model parameters to vary randomly along the length so as to capture the variability in the experimental data. In this way they were able to obtain a rough estimate of the riser fatigue life in a stochastic sense. Gabbay and Benaroya (2008) presented a generalized variational equation based on the extended Hamilton's principle as a starting point for a procedure from which wake-body models for the two-dimensional vortex induced vibration of a cylinder can be derived. The procedure is illustrated considering as a model problem the case of an elastically mounted cylinder with a transverse degree of freedom in a uniform current. A number of wake-body models from the literature are shown to be recoverable from the more general model derived. Ogink and Metrikine (2010) developed a wake oscillator model that conforms to both the free and forced vibration experiments. To comply with the forced vibration experiments, starting from the model by Facchinetti et al. (2004), a frequency dependent coupling is introduced that allows to reproduce the measured frequency dependence of the fluid force on the cylinder. By using an appropriate transform the frequency dependent coupling can be written as a convolution integral in the time domain. However, the authors concluded that it is impossible to find a unique set of frequency dependent coefficients that would satisfy the forced experiments at different amplitudes of vibration. Furthermore, they do not succeeded in extending the coefficients from the measured frequency interval to the infinite frequency domain in a non-contradictory manner that it is necessary to have a true time domain model. The main result of the work is that: to prove the validity of a wake oscillator model one has to require that it describes both the free and forced vibration experiments and then show that the frequency dependent coefficients are not contradictory. These findings can help to identify the correct nonlinearities of the wake oscillator model in the future.

For the use of semi-empirical models, Cheng et al. (2009) investigated the VIV fatigue prediction for a top tensioned riser (TTR) used with a Spar in deep water. The predictions are based on the frequency domain program SHEAR7 whereas the nonlinear finite element program ABAQUS is used to model the riser for the generation of modal parameters. They investigated the sensitivity of the results to the type of lift coefficients, mode bandwidth, mode cut-off and the Strouhal number using different version of the program. In addition they compared the results obtained by SHEAR7 with those by ABAVIV obtaining good agreement both in terms of fatigue damage variation along the riser and most damaging location. In the paper of Tognarelli et al. (2009) BP's benchmarking of different version of SHEAR7 is described. In particular comparisons are made between predicted and measured VIV fatigue damage for several full-scale drilling risers to demonstrate the efficacy of a calibration for the latest version. They found that while the prediction, on average, are similar, the scatter in predictions which leads designers to large factor of safety is not reduced from version to version. Thus, they recommended to obtain more measured, full-scale VIV fatigue and current data for better calibration and development of VIV fatigue analysis methods and to consider improved/new analysis models that will reduce prediction scatter.

A new stochastic model for prediction of fatigue damage from VIV in risers is developed and implemented in VIVANA (Lie et al., 2008). As in the original model the structural model applies a non-linear 3-D FE which makes it able to work with an arbitrary distribution of tension, mass, stiffness, buoyancy and diameter. Response frequencies are identified while considering a frequency dependent hydrodynamic mass along the structure. Response amplitudes are calculated at the discrete frequencies by the frequency response method. The excitation force model includes a lift coefficient that is a function of the response amplitude and the response frequency.

The new method overcomes some of the shortcomings of previous methods. A fully 3D model is implemented, 3D (non-uniform) current conditions can be analyzed, "cross-flow" (CF) and "in-line" (IL) response are predicted and the stochastic nature of the response is accounted for. This is done by introducing a time varying envelope function of the response combined with "time sharing" between dominating response frequencies.

DNV has issued a new recommended practice on riser interference (DNV-RP—F203). The RP recommends methodology for engineering analysis, design criteria and guidance for assessment of riser interface (Rustad et al., 2009). Wu et al. (2008) present a method for calculating 3D riser wake interference. The numerical model take into account the drag reduction on a downstream riser due to being in the wake of and upstream riser, and the lift force on the down stream riser towards the centre of the wake of upstream riser.

2.2 Experiments

A survey of the papers presented in OMAE, ISOPE, international journals of Offshore Mechanics and Arctic engineering, Applied Ocean research, Ocean engineering in recent two years shows that the majority of the reported work are concerned with model tests. The typical scaling factors are within the range of 1:40-1:75.

It is known that Reynolds number and Froude number scaling are the two relevant scaling parameters for model testing. However, simultaneously satisfying Reynolds and Froude scaling for the model and prototype conditions is practically impossible in the ocean engineering. Therefore, full scale testing is necessary.

2.2.1 2D test

Forced oscillation tests of rigid cylinder have been extended from pure cross-flow (CF) oscillation tests and pure in-line (IL) oscillation tests to combined forced oscillations.

Soni (2008) performed extensive model tests to investigate the realistic interaction between IL and CF responses. Long flexible pipe model tests were conducted in uniform current conditions, and the couple VIV displacements at each cross-section were analyzed. The cross-section trajectories resulted from the 3D tests were used as input conditions for motion-controlled tests of rigid cylinder. Based upon the test measurements, the hydrodynamic coefficients for empirical VIV prediction models have been renewed (Soni et al., 2009). Soni and Larsen (2009) showed the higher order harmonic components of the forces were correlated with vortex shedding patterns observed by PIV method.
Yin and Larsen (2010) performed motion-controlled tests of rigid cylinder in order to determine VIV coefficients under shear flows (NDP riser). The IL excitation force coefficients have much higher values than found from pure in-line test.

However, Reynolds number is still in the subcritical regime even for experiments on the Reynolds number effects on hydrodynamic coefficients (Szwalek and Larsen, 2009). Practical concern on reduction of VIV response were continued by experimental investigations using strakes (e.g. Hao et al., 2010, Korkischko and Meneghini,2010) and rotating splitter plates (Assi et al., 2009).

2.2.2 3D test

Various conditions have been undertaken in 3D VIV tests such as hybrid risers, free spanning pipeline, locally strong shear flow condition, tension riser with internal flow, CF VIV in current and waves, VIV in linearly sheared flows, etc. Fibre optic strain sensors have been widely used for 3D VIV tests of long flexible pipes (e.g. Vandiver et al., 2009; Hagatun et al., 2010; Tang et al., 2010; Wu et al., 2010a; Hong et al., 2011).

Liu et al. (2009) experimentally studied the VIV of free standing hybrid riser. Measurements show that buoyancy and riser can both contributes to the system VIV response. VIV response of buoyancy can dominates at all current speeds. However, the contribution of riser VIV response to the system increases with current speed.

Hagatun et al. (2010) conducted VIV tests of a neutrally buoyant hybrid riser model to investigate VIV during towing operations. Fatigue calculations were performed with respect to current speeds and angles, and back tension. It was shown that the reduced back tension gives increased fatigue damage.

Vandiver et al. (2009) investigated field test data (Miami II). They have shown that, in tension dominated condition, travelling waves at high mode numbers occur. It was suggested to investigate if bending stiffness effects causing wave dispersion, will reduce VIV at the fundamental CF frequency and/or at the higher harmonics.

Cunha et al. (2009) suggested a closed-form analytic solution of pin-pin conditioned beam for symmetrical response mode (1^{st}, 3^{rd}, 5^{th} …), and carried out model tests to evaluate literature data.

Experiments of long free-span pipeline with sag were carried out by Soni and Larsen (2010). Moreau and Huang (2010) performed model tests on CF VIV in combined IL current and oscillatory flows. The VIV amplitude response is dependent upon velocity ratio and much reduced compared to the steady flow only. Wu et al. (2010a) experimentally investigated the suppression of VIV of long flexible riser by four control rods, running parallel along quadrant of the riser. Internal flow effects on riser VIV was experimentally investigated by Zhang et al. (2009).

Wavelet transform has been applied to investigate time-frequency response of long flexible riser in uniform and sheared flows (Larsen et al., 2010 and Wu et al., 2010b). Wu et al. (2010b) estimated the hydrodynamic coefficients using inverse force analysis based on VIV response data of deepwater riser in sheared current (Hanøytangen test program, MARINTEK). Shi et al. (2010) employed wavelet transforms and weighted waveform analysis (WWA) to estimate fatigue damage. They show that, using WWA, it is possible to estimate reasonably accurate fatigue damage, if properly placed, with limited number of sensors.

Kim et al. (2009) studied the effects of locally strong sheared flow on VIV response. Hong et al. (2011) performed VIV model tests of long flexible pipe in linearly sheared flows. It was shown that the peak VIV frequency equals to the Strouhal frequency corresponding to approximately 70% of the maximum flow speed, and it was confirmed that the VIV response is multi-mode. Drag amplification of long flexible riser models undergoing multi-mode VIV in uniform flow were studies by Huang, et al. (2011). They used measurement data to estimate the drag amplification due to VIV and compare the results with existing empirical expression.

Vortex and wake-induced vibrations of a tandem arrangement of two flexible cylinders has been investigated in a model test program by Huere-Huarte and Bearman (2011). The dynamic response for small centre-to-centre distance was studied. Planar digital particle image velocimetry (DPIV) was used to visualise the wake. One main observation was that both cylinders response showed classical VIV resonance whenever the reduced velocities are near to those typical at lock-in, independently of the gap distance between the cylinders. When the reduced velocity is higher, their behaviour is different depending on the gap separation and hence on the existence or not of vortex shedding between the cylinders.

2.2.3 Field measurements

Irani et al. (2008) considered Vortex Induced Motion (VIM) of a Spar platform. Field measured data for VIM of BP's Horn Mountain Truss Spar, presented in this paper, shows that the Horn Mountain Truss Spar VIM response is within original design assumptions. The maximum VIM measured in the field A/D ≈ 0.26) is well below the acceptable design value of A/D = 0.5. The field data is analyzed and results presented in the form of Spar VIM response time traces, Spar VIM response versus the reduced velocity and variation of period of VIM oscillation with Spar offsets. The field data shows VIM response characteristics consistent with model test observations.

BP has conducted several full-scale VIV measurement program on drilling risers, confer Tognarelli et al. (2008), Beynet (2008) and Srivilairit (2009). The first paper presents results from some of the measurements, with particular emphasis on fatigue results which is compared to predicted fatigue results. For full scale drilling risers without suppression, the data show that state-of-the-art analysis methods are, on average, inherently 30% conservative on a maximum fatigue damage basis. The data also reveal that VIV does not occur nearly as often as it is predicted. Further the results showed that both in-line and higher harmonic response were often observed during the monitoring of risers. However, their contribution to the total VIV fatigue damage to the riser was found to be relative small. The second paper presents results from full scale VIV response measurements of a drilling pipe in GoM loop currents. The test set-up is a free hanging system that represents non-connected risers hanging from the platform during temporary operation. The paper presents observations of cross-flow VIV, in-line VIV and additional response at higher frequencies. The response was found to be predominantly standing wave behaviour up to 17th mode. The last paper presents results of current and riser VIV response analysis applying the proper orthogonal analysis technique, which is found to be an efficient numerical technique for characterizing the spatial coherence in a random field.

3. TECHNICAL CONCLUSIONS

The ITTC VIV Specialist Committee has produced report describing the four tasks.

3.1 Review

3.1.1 General

- The offshore oil and gas industries still have a strong interest in VIV of marine risers, free spanning pipelines, tethers and floating vessels. Recent accidents of the offshore platforms demonstrated the need of an accurate design of all the platform components. Moreover, offshore oil and gas industries are the proponents of benchmarking between different prediction tools and of full scale VIV measurement campaigns.
- The huge number of technical papers on VIV, published in last three years in international journals and presented at conference indicated the great attention of the research community on this subject.
- Despite the tangible improvements made in last years in the understanding and description of VIV of an isolated cylinder, this complex fluid-structure interaction problem has not yet been fully understood and there is not a consolidated procedure for its analysis.
- Less well studied and understood are the changes to the flow around two or more circular cylinders placed in close proximity to one another.

3.1.2 Prediction methods

The prediction methods comprise a large variation in methods where the three main groups are CFD, semi-empirical methods and wake oscillator models. The status of these groups is:

- CFD codes are nowadays able to simulate the 3D VIV response of long flexible risers at Reynolds number up to the high sub-critical regime ($Re=1.5x10^4$). Several questions remain open issues *e.g.* the use of 2D or 3D models for flow description, the accuracy of less time consuming simulation methodologies (LES, RANS, DES etc) with respect to DNS. CFD remains a research tool for multiple cylinder configurations.
- Semi-empirical models are still the technique currently used in the design of marine risers. Large scatter between different codes in the fatigue damage prediction is observed leading the designers to adopt extremely large factors of safety. There is a demand for systematic comparisons with full scale data.
- Among low order models, the wake oscillator has received a renewed attention. Sophisticated wake oscillator models have been developed in last three years but most of the results obtained show only a qualitative agreement with experimental observations.

3.1.3 Experimental studies

- There is still a lack of high Reynolds number model test and full scale measurement data devoted to the determination of the coefficients used in the semi-empirical codes.
- For validation of prediction tools and for further research of VIV new experiments are needed for both single and multiple flexible cylinders at moderate and high Reynolds numbers. These tests should be performed for both bare cylinders and for cylinders with suppression devices, such as strakes and fairings.
- Some flow field measurements performed by PIV technique are available for validation of numerical codes. However, new experimental campaigns should be performed specifically devoted to CFD validation at high Reynolds number for the isolated cylinder and at low and high Re for the multiple cylinder configurations.

3.2 Benchmark study

The committee recommends ITTC to continue and complete the Benchmark study in the next ITTC period. The benchmark study has been initiated and is undergoing in some member institutes. Given the critical importance of the subject to offshore engineering and the challenging nature of the subject to many towing tank organisations around the world, continuing efforts in this area are imperative. It is recommended that ITTC should establish cooperation with OMAE on the benchmark activity, where ITTC can provide valuable experimental data to OMAE.

3.3 Nomenclature

A nomenclature is included in the review.

Abbreviations

2D	Two dimensional
3D	Three dimensional
CF	Cross-flow
CFD	Computational fluid dynamics
IL	In-line
VIV	Vortex induced vibration
VIM	Vortex induced motion

Roman symbols

A	Displacement amplitude
A_e	External cross-section area
C_a	Added mass coefficient
C_e	Excitation coefficient, i.e. force coefficient in phase with cylinder velocity
C_D	Drag coefficient
C_L	Lift coefficient
D	Cylinder diameter
E	Modulus of elasticity
EI	Bending stiffness of a cylinder
f_0	Natural frequency in still water
f_{osc}	Oscillation frequency
f_s	Vortex shedding frequency
f_w	Frequency of the oscillatory flow
$\hat{f}$	Non-dimensional frequency, $\frac{f_{osc}D}{U}$
g	Acceleration of gravity
h	Submergence depth
k	Characteristic size of roughness
K_s	Stability parameter, $K_s = \frac{4\pi m_e \zeta}{\rho D^2}$
KC	Keulegan-Carpenter number, $KC = \frac{U_w}{f_w D}$
L	Cylinder length
m_a	Hydrodynamic mass per unit length, $m_a = C_a A_e \rho$. For a circular cylinder, $m_a = C_a \frac{\pi}{4} D^2 \rho$
m_s	Mass per unit length (including internal fluid)
m_e	Effective mass per unit length, $m_e = m_a + m_s$
$\overline{m}$	Mass ratio, $\overline{m} = \frac{m_s}{m_a}$
F_n	Froude number, $F_n = \frac{U}{\sqrt{gh}}$
R_e	Reynolds number, $\frac{DU}{\upsilon}$
S_t	Strouhal number, $\frac{f_s D}{U}$
T	Tension
T_{osc}	Oscillation period
U	Flow velocity
U_w	Maximum of oscillatory flow velocity
V_r	Reduced velocity, $\frac{U}{f_0 D}$
$V_{r,osc}$	Reduced velocity (oscillating cylinder), $\frac{1}{\hat{f}}$

Greek symbols

ς	Damping ratio
μ	Viscosity
υ	Kinematic viscosity
ρ	Density of fluid
Φ	Mode shape

3.4 Guide Line

The committee recommends that the guide line should be completed during the next ITTC period.

4. REFERENCES

Assi, G. R. S., Bearman, P. W. and Kitney, N. (2009): "Low drag solutions for suppressing VIV of circular cylinders", Journal of Fluids and Structures, Vol. 25, pp 666-675.

Atluri, S., Rao, V. K. and Dalton, C., 2009, "A numerical investigation of the near-wake structure in the variable frequency forced oscillation of a circular cylinder", Journal of Fluids and Structures, Vol. 25, pp. 229-244.

Baek, H. and Karniadakis, G.E., 2009, "Suppressing vortex-induced vibrations via passive means", Journal of Fluids and Structures, Vol. 25 , pp. 848-866.

Beynet, P., Shilling, R., Campbell, M., "Full Scale VIV Response Measured of a Drill Pipe in Gulf of Mexico Loop Currents", Proceedings of 27th Conference Offshore Mechanics and Arctic Engineering. OMAE2008-57610

Borazjani, I. and Sotiropoulos, F., 2009, " Vortex induced vibrations of two cylinders in tandem arrangement in the proximity-wake interference region", Journal of Fluid Mechanics, Vol. 621, pp. 321-364.

Carmo, B.S., Sherwin, S.J., Bearman, P.W. and Willden R.H.J., 2011, " Flow-induced vibration of a circular cylinder subjected to wake interference at low Reynolds number", Journal of Fluids and Structures, in press.

Cheng, Y., Xu, L., Lambrakos, K.F. and Muriby, K., 2009, " Investigation of VIV fatigue prediction for a top tensioned riser", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Cunha, S. B., Matt, C. G. C., Morooka, C. K., Franciss, R. and Tsukada, R. I. (2009): "Pipeline VIV: Analytical Solution, Experiments and Parameter Identification", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Gabbai, R.D. and Benaroya, H., 2008, " A first-principles derivation procedure for wake-body models in vortex induced vibration: a proof-of-concept", Journal of Sound and Vibration, Vol. 312, pp. 19-38.

Hao, Z., Zhou, T., Wang, W. and Tan, S. K. (2010): "Experimental Studies of Vortex Structures in the Wake of a Cylinder with Helical Strakes", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Hagatun, K., Steinkjer, O. and Lie, H. (2010): "Hybrid riser solution for harsh environments", Proceedings of Deep Offshore Technology International.

He, C., Duan, Z. and Ou, J., 2010, "Numerical simulation of vortex-induced vibrations on a flexible riser in uniform currents", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Hong, S., Choi, J. S., Kim, H. W., Yeu, T. K., Kim, J. H., Kim, Y. S. and Rheem, C. K. (2011): "Experimental Study on Vortex-Induced Vibration of a Long Flexible Pipe in Sheared Flows", Proceeding of 9th ISOPE Ocean Mining Symposium 2011 (to be published).

Huang, K., Chen, H.C. and Chen, C.R., 2009a, "Vertical riser VIV simulation in uniform current ", Proceedings of the 19th International Offshore and Polar Engineering Conference.

Huang, K., Chen, H.C. and Chen, C.R., 2009b, "Vertical riser VIV simulation in sheared current ", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Huang, S., Khorasanchi, M., Herfjord, K., 2011, "VDrag Amplification of Long Flexible

Riser Models Undergoing Multi-mode VIV in Uniform Currents", Journal of Fluid Mechanics, Vol. 27, pp. 342-353.

Huera-Huarte, F. J., Bearman, P. W., 2011, "Vortex and Wake-induced Vibration of Tandem Arrangement of Two Flexible Circular Cylinders With Near Wake Interaction", Journal of Fluid Mechanics, Vol. 27, pp. 193-211.

Irani, M.B., Perryman, S., Brewer, J. and McNeill, S., 2008, " Vortex induced motions of the Horn Mountain truss spar", Proceedings of 27th Conference Offshore Mechanics and Arctic Engineering.

Kim, Y. C., Suzuki, F. and Rheem, C. K. (2009): "VIV Response of a Flexible Cylinder under Locally Strong Sheared Flow", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Korkischko, I., Meneghini, J. R., 2010, " Experimenal Investigation of Flow-induced Vibration on Isolated and Tandem Circular Cylinders fitted with Strakes", Journal of Fluid Mechanics, Vol. 26, pp. 611-625.

Larsen, C. M., Wu, J. and Lie, H. (2010): "On the Understanding of Non-Stationary VIV of Slender Beams", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Li, T., Zhang, J. and Zhang, W., 2010, "Nonlinear characteristics of vortex-induced vibration at low Reynolds number", Commun Nonlinear Sci Numerical Simulation, in press.

Lie, H., Larsen, C. M., Kaasen, K. E., 2008, "Frequency domain model for prediction of stochastic vortex induced vibrations for deep water risers", Proceedings of 27th Conference Offshore Mechanics and Arctic Engineering. OMAE2008-57566

Liu, N., Cheng, Y. M., Wilde, J., Burke, R. and Lambrakos, K. F. (2009): "Time Domain VIV Analysis of a Free Standing Hybrid Riser", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Moreau, F. and Huang, S. (2010): "Model Testing on Cross-Flow Vortex-Induced Vibration in Combined In-Line Current and Oscillatory Flows", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Mukundan, H., Modarres-Sadeghi, Y., Dahl, J.M., Hover, F.S. and Triantafyllou, M.S., 2009, " Monitoring VIV fatigue damage on marine risers", Journal of Fluids and Structures, Vol. 25 , pp. 617-628.

Ogink, R.H.M. and Metrikine, A.V., 2010, " A wake oscillator with frequency dependent coupling for the modeling of vortex induced vibration", Journal of Sound and Vibration, Vol. 329, pp. 5452-5473.

Prasanth, T.K. and Mittal, S., 2008, "Vortex induced vibrations of a circular cylinder at low Reynolds numbers", Journal of Fluid Mechanics , Vol. 594, pp. 463-491.

Prasanth, T. K. and Mittal, S., 2009, " Flow induced oscillation of two circular cylinders in tandem arrangement at low Re", Journal of Fluids and Structures, Vol. 25, pp. 1029-1049.

Rustad, A. M., Kallekleiv, A. J., Sødahl, N., "Recommended Practice on Riser Interface", OTC 20066, Houston, Texas, 2009

Shi, C., Manuel, L., Tognarelli, M. A. and Botros, T. (2010): "On the Vortex-Induced Vibration Response of a Model Riser and Location of Sensors for Fatigue Damage Prediction", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Soni, P. K. (2008): Hydrodynamic Coefficients for Vortex-Induced Vibrations of Flexible Beams, PhD thesis, Department of marine technology, NTNU, Trondheim, Norway.

Soni, P. K., Larsen, C. M. and Wu, J. (2009): "Hydrodynamic Coefficients for Vortex-Induced Vibrations of Slender Beams", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Soni, P. K. and Larsen, C. M. (2009): "Vortex Pattern Comparison for Periodic and Harmonic Combined CF and IL Forced Oscillations", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Soni, P. K. and Larsen, C. M. (2010): "Response of Pipelines under VIV: Experimental Investigation", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Springer, M., Jaiman R.K., Cosgrove, S. and Constantinides, Y., 2009, " Numerical modelling of vortex-induced vibrations of two flexible risers", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Srinil, N., Wiercigroch, M. and O'Brien, P., 2009, "Reduced-order modelling of vortex-induced vibration of catenary riser", Ocean Engineering, Vol. 36, pp. 1404-1414.

Srinil, N., 2010, "Multi-mode interactions in vortex-induced vibrations of flexible curved/straight structures with geometric nonlinearities", Journal of Fluids and Structures, Vol. 26, pp. 1098-1122.

Srivilairit, T, Manuel, L., 2009, "Vortex-Induced Vibration and Coincident Current Velocity Profiles for a Deepwater Drilling Riser", Journal of Offshore Mechanics and Artic Engineering, Vol. 131.

Sumner, D., 2010, "Two circular cylinders in cross-flow: A review", Journal of Fluids and Structures, Vol. 26, pp. 849-899.

Szwalek, J. and Larsen, C. M. (2009): "Reynolds Number Effects on Hydrodynamic Coefficients of Pure In-Line and Pure Cross-Flow Vortex Induced Vibrations", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Tang, G. Q., Lu, L., Teng, B., Park, H. I., Song, J. N. and Zhang, J. Q. (2010): "Laboratory Investigation on the In-Line Dynamic Characteristic of Long Flexible Riser under Vortex-Induced Vibration", Proceedings of 9th ISOPE Pacific/Asia Offshore Mechanics Symposium.

Tognarelli, M.A., Yin, F., Campbell, M. and Achanta, V., 2009, "Benchmarking on SHEAR7V4.5: Comparisons to full scale drilling riser viv data and legacy analysis", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.

Tognarelli, M.A., Taggart, S., Campbell, M., 2008, "Actual VIV Fatigue Response of Full Scale Drilling Risers: With and Without Suppression Devices", Proceedings of 27th Conference Offshore Mechanics and Arctic Engineering, OAME2008-57046

Vandiver, J. K., Jaiswal, V. and Jhingran, V. (2009): "Insights on vortex-induced, traveling waves on long risers", Journal of Fluids and Structures, Vol. 25, pp 641-653.

Violette, R., de Langre, E. and Szydlowski, J., 2010, "A linear stability approach to vortex-induced vibrations and waves", Journal of Fluids and Structures, Vol. 26, pp. 442-466.

Wanderley, J., Souza, G., Sphaier S. and Levi, C., 2008, "Vortex-induced vibration of an elastically mounted circular cylinder using an upwind TVD two-dimensional numerical scheme", Ocean Engineering , Vol. 35, pp. 1533-1544.

Wu, J., Larsen, C. M. and Lie, H. (2010b): "Estimation of Hydrodynamic Coefficients for VIV of Slender Beam at High Mode Orders", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Wu, H., Sun, D. P., Lu, L., Teng, B., Zhang, J. Q. and Xie, B. (2010a): "Suppressing Vortex-Induced Vibrations of Long Flexible Riser by Multiple Control Rods", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Wu, W., Saint-Marcoux, J., Blevins, R. D., Quiggin, P., 2008, "Innovative 3-D Implementation of Riser Wake Interference Assessment", Paper No. ISOPE-2008-MWU10. Proceedings of 18th ISOPE Conference, Vancouver, Canada.

Xu, W.H., Zeng, X.H. and Wu, Y.X., 2008, "High aspect ratio (L/D) riser VIV prediction using wake oscillator model", Ocean Engineering, Vol. 35, pp. 1769-1774.

Xu, W.H., Wu, Y. and Yu, J., 2010, "A new wake oscillator model for predicting vortex induced vibrations of a circular cylinder", Journal of Hydrodynamics, Vol. 22(3), pp. 381-386.

Yin, D. and Larsen, C. M. (2010): "On Determination of VIV Coefficients under Shear Flow Condition", Proceedings of 29th Conference Offshore Mechanics and Arctic Engineering.

Zhang, Y. B., Meng, F. S., and Guo, H. (2009): "Experimental Investigation of Vortex-Induced Vibration Responses of Tension Riser Transporting Fluid", Proceedings of 28th Conference Offshore Mechanics and Arctic Engineering.