The Specialist Committee on Vortex Induced Vibrations Committee

## Final Report and Recommendations to the 25th ITTC

1. GENERAL

Whilst vortex induced vibrations can occur in both water and air, the present report focuses upon the subject of vortex induced responses of structures in water, due to the ITTC remits on ship and offshore structures in the marine environment.

1.1 Problem description

Vortex Induced Vibrations (VIV)

Bluff marine structural bodies such as the risers, free spanning pipelines and offshore platforms with cylindrical members (e.g. SPARs and semi-submersible) can undergo vortex shedding in ocean currents. The vortex shedding process and shed vortices induce periodic forces on the body which can cause the body to vibrate. The amplitude of vibration is dependent on many factors, including the level of structural damping, the relative mass of the body to the displaced water mass (the so-called "mass ratio"), the magnitude of the fluid forces, and the proximity of the vortex shedding frequency to the natural frequency of vibration of the body. The VIV is illustrated in Figure 1. For a fixed, rigid circular cylinder in a uniform flow directed normally to its axis, the vortex-shedding frequency (or Strouhal frequency) is given by $f_s = StU/D$, where St is the Strouhal number, U is the flow velocity, D is the cylinder's diameter. The Strouhal number is a function of the Reynolds number $Re = UD/\nu$ where ν is the kinematic viscosity . In the sub-critical range the value is around 0.2, in the critical range it varies and can be in the range 0.2 - 0.5. In the super-critical range it is typically around 0.2 - 0.3.
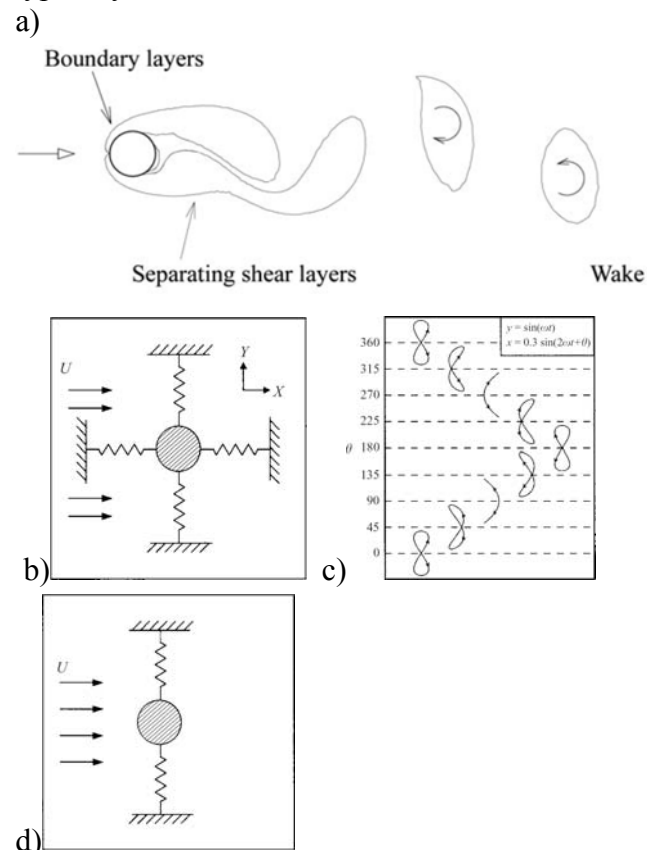
Figure 1 a) Vortex shedding due to boundary layer separation, which results in oscillating drag and lift forces on the body. For the idealised mass-spring setup shown in b), these oscillating drag and lift forces lead to response modes of the type shown in c). As the cross flow response is typically larger than the inline response, most studies concentrate on the cross-flow response illustrated by the test setup shown in d). Willden (2003) and Jauvtis and Williamson (2004).

Lock-in vibration

If the natural resonant frequency of the body is close to the Strouhal frequency *lock-in* or *synchronisation* may happen. In this case vortices are shed at the actual frequency of oscillation rather than the Strouhal frequency. In other words, it is the motion of the body that controls the frequency of vortex shedding. The frequency of oscillation may not be exactly equal to the expected calm-water resonant frequency of the cylinder either. This is because the process of forming and shedding vortices alters the cylinder's added mass. The change in added mass will be different from the still water value, causing the resonant frequency to shift somewhat too. The change in the added mass can be negative or positive, causing the natural frequency to increase or decrease. The damping will increase with increasing amplitude of oscillation and will cause the VIV amplitude to be moderate. Typical maximum amplitude is around one diameter. Marine structures have normally low mass ratio cylinders because of the higher density of water, in contrast to structures in air which normally have high mass ratios.

The lock-in phenomenon is illustrated in Figure 2 for a case with low mass ratio, with respect to the setup shown in Figure 1d). Note that, outside the reduced velocity band at which lock-in occurs, the vortex shedding is dominated by the Strouhal frequency.

1.2 Definitions

VIV – Vortex Induced Vibrations of various marine structures. Often used to describe the motion of structures such as risers, cables and free spanning pipelines, where the frequency is relatively high because of the small diameter (confer the Strouhal frequency, $f_s = St\ U/D$). The motions are often characterized by elastic (often bending) deformation of the structure.

VIM – Vortex Induced Motion. Normally used to describe vortex induced motion of offshore platforms with 1 to 6 degrees-of-freedom of rigid body motions. The frequency is relatively low because of the large cylinder diameter.

WIO – Wake Induced Oscillations. Downstream cylinder(s) in the wake of upstream cylinder(s) will experience forces which consist of two rather different frequency ranges with one frequency range around the Strouhal frequency and a much lower frequency range. Both type of forces can cause the down-stream cylinder(s) to oscillate. The first type of forces induces VIV-type responses whilst the low frequency forces give rise to large-amplitude wandering motions which are denoted as WIO.
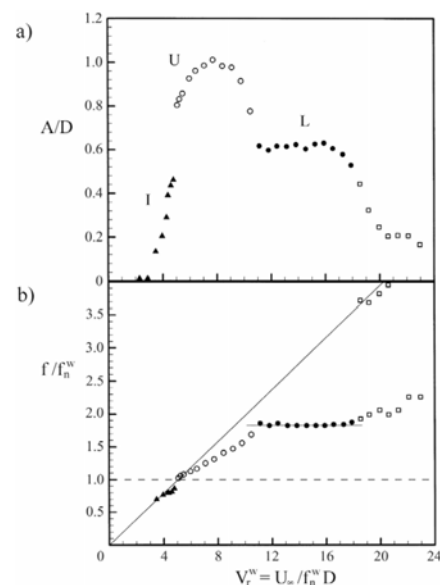
Figure 2 Cross-flow VIV behaviour of an elastically supported circular cylinder with low structural damping and low mass ratio for the setup shown in Figure 1d, Govardhan R. and Williamson Figure a) shows amplitude to diameter ration vs. reduced velocity (*Vr=U/(fnD)* where *fn*=natural frequency in still water) Figure b) show the oscillation and vortex shedding frequencies.

1.3 Membership and Meetings

The members of the Vortex Induced Vibrations Specialist Committee of the 25th International Towing Tank Conference are as follows:

- Halvor Lie, Division of Ship and Ocean Laboratory, MARINTEK, Norway. (Chairman).
- Elena Ciappi, Istituto Nazionale per Studi ed Esperienze di Architettura Navale, Italy.
- Shan Huang Naval Architecture and Marine Engineering, Universities of Glasgow & Strathclyde, UK.
- Chang-Kyu Rheem, Institute of Industrial Science, University of Tokyo, Japan.
- Don Spencer, Oceanic Consulting Corporation, Canada.
- Jung-Chun Suh, Seoul National University, Dept. of Naval Architecture and Ocean Engineering, Korea.
- Xiong-Liang Yao, Harbin Engineering University, Shipbuilding Engineering College, China.

Four committee meetings were held respectively at:

- Istituto Nazionale per Studi ed Esperienze di Architettura Navale, Italy, March 2006.
- Harbin Engineering University, China, September 2006.
- MARINTEK, Trondheim, Norway, October 2007.
- University of Tokyo, Japan, February 2008.

1.4 Tasks and Recommendations of the 24th ITTC

The original tasks recommended by the 24th ITTC were as follows.

- Conduct an in-depth review of Vortex Induced Vibration (VIV) and Vortex Induced Motion (VIM), including experimental and numerical modeling.

Identify and report on technology gaps and make recommendations for future work.
- Conduct an assessment of different prediction methods, and make recommendations on their application and limitations.
- Define and initiate a specific benchmark case study to be used to compare different experimental techniques. This could be based upon existing or new experiments.

2. REVIEW OF THE STATE OF THE ART

2.1 Ocean currents and measurement

Global ocean currents

Ocean waters are constantly on the move. Ocean currents can be divided into two types of flow based on the forces that drive them. Most currents in the upper layer of the ocean are driven by the wind. Density-induced mixing drives deeper currents, which is affected by long-term variability of climate. Climate controls salinity and temperature of the water, which has everything to do with density. Ocean currents contribute to the heat transport from the tropics to the poles, partially equalizing Earth surface temperatures, as well as influence climate and living conditions for plants and animals, even on land. They also affect the routes taken by ships as they carry goods across the sea, as well as the designs of offshore structures.

For large parts of the ocean the vertical water column can be divided into three parts according to the distribution of water temperature. In the upper zone (from the surface to a depth of 50 to 200 meters) the water is well mixed and the temperature is fairly constant. Below this zone (200 to 1000 meters) the temperature decreases rapidly. In the deep zone (below 1000 meters) the

temperature decreases slowly. Near the equator, and at mid-latitudes, the surface water is heated by the sun. Cooling of the water takes place at high latitudes, increasing the density and causing it to sink. Deep water then flows towards the tropics, and the warmer waters in the upper layer flow from the tropics towards higher latitudes.

Whereas the above global circulation transports water vertically and horizontally, the wind-driven circulation is considered to be mainly horizontal. The friction between the wind and the ocean surface transfers energy into the surface layer of the ocean, and the water in this layer starts to move. Friction forces between the moving water in the upper layer and the water immediately below, causes the water in the lower layer to move, and so on. It is the wind stress that is the major cause of the circulation in the upper few hundred meters of the oceans.

Effects of boundaries

The offshore oil and gas industry, still considered near the land in the scale of ocean dimensions, is steadily moving further away from the shoreline into ever deeper regions in the last ten years. Main features of the current flows in some regions around the world are of particular interest to the offshore industry, i.e. the Gulf of Mexico, the Norwegian Sea, West of Shetland, Brazil and West of Africa (Zavialova et al, 2002; Kaiser and Pulsipher, 2007). In these regions, the oil and gas developments are taking place on continental slopes, rather than the shallower continental shelves which have hitherto been the main areas for the offshore oil and gas developments. The continental shelf is the relatively flat plateau with the average inclination angle around 0.1 degrees. This plateau consists of sediments which have been eroded from the continent. Such sediments are constantly being transported from the shore towards the outer edge of the continental shelf, also referred to as the shelf break. Here the inclination of the bottom is increased many times. The continental slope is located between the shelf break and the deep ocean bottom and the average inclination angle is about 3 degrees (Cacchione and Pratson, 2004).

The dynamics of the current flows on a continental slope, or other sloping boundaries in the ocean, are complex and diverse due to the effects of bottom topography (Yttervik, 2005). During the work that was carried out to establish the metocean design basis for the development of the Foinhaven field on the continental slope west of Shetland, Grant et al (1995) found that the currents at the site were far more complex than those traditionally encountered by the oil industry in the shallower North Sea. Processes such as stratification, boundary layer dynamics, up and down-welling, breaking/overturning/reflection of internal waves and Ekman veering take place on the continental slope. These processes may interact, making such regions of the ocean a highly variable environment. The high variability near the continental slopes is of interest for the design and planning of marine structures to be placed and operated in such environments. For a general review of physical processes at ocean margins, see Huthnance (1995).

Measurements

Direct measurements of the ocean circulation provides information about the flow velocity at a finite number of fixed points in the ocean space, or, alternatively, about the positions of individual water particles in time domain. The common methods used are rotor current meters, acoustic current meters, and drifters.

Acoustic Doppler current profilers (ADCPs) can be mounted aboard ships or held in place by mooring lines. One ADCP can record the current velocity at several depths below or above its position in the water column (Sindlinger et al, 2005).

Records of flow speeds are obtained by emitting a series of short sound wave pulses, and then measuring and analysing the reflected signal from particles which travel with the flow. The method is thus based upon the assumption that particles which are suspended in the water follow the flow. Rotor current meters for direct measurements of the flow speed are based on counting the rotations of a propeller over a time span (Orvik and Skagseth, 2003). The orientation of the instrument relative to the current is always such that the flow is parallel to the propeller axis. This is achieved by allowing the instrument to rotate around a vertical axis, governed by a guiding vane. The Lagrangian flow field in an area can be studied by the use of instruments drifting along with the current. The drifters can stay at certain depths, go to the surface at regular intervals (or pre-programmed time instances) and report time, position, temperature and salinity via satellite, and then submerge to the pre-selected depth again.

Measurements of water properties, such as temperature and salinity, over an area and knowledge about some physical principles, combined with some assumptions and simplifications, may provide valuable information about the 3D flow field in the area. Such methods, i.e. estimating the current flows by measuring other parameters, are indirect. It is easier to measure water properties such as for example temperature, salinity and oxygen contents, than to measure the flow speed directly. Furthermore, it would be very expensive and time-consuming to use direct methods to establish the flow field in an entire oceanic region. The indirect methods are often used for the large scale flow in the ocean, but may not be suited for the current flows near shore and/or on continental margins.

Design current profile

High variability of the current presents new requirements to the way that the ocean

currents should be modelled by the offshore engineer. Reliable methods for obtaining design current conditions for a given deep water location have yet to be developed. For offshore structural design at a given location, design current profiles are often established based upon field measurements of the current velocities at a number of current meters arranged along a vertical line at the location. There are different methods for converting measured data into design current profiles. The more traditional use of exceedance profiles is formed by working on the measurement data as well as estimating extreme current speed at each current meter, using probabilities of occurrence fitted to the observed data. The current speeds at each depth are evaluated separately and then artificially combined to make profiles that bear little resemblance to true profiles. The exceedance current profiles typically take neither vertical coherence nor flow direction into account. This method has the built-in assumption that extreme current speeds occur simultaneously at all current meters. This assumption is generally not true, but the method is still used because it is believed to be conservative.

Concurrent current profiles which actually occur or are representative of currents which actually occur should be considered. An approach which attempts to represent concurrent profiles in an efficient way is the empirical orthogonal functions (EOFs). Use of EOFs is analogous to the modal analysis of structural dynamics, and the full set of EOFs can be re-combined to reproduce the original sequence of current profiles (Jeans et al, 2002). Other methods are given in Meling (2002), Donnelly and Vandiver (2003).

2.2 Semi-empirical VIV models

Semi-empirical models for VIV response analysis use the hydrodynamic force coefficients such as drag coefficient, lift coefficient, added mass coefficient and

hydrodynamic damping coefficient. These coefficients are normally obtained from rigid-cylinder model tests with forced motions. Comparisons of models can be found in Larsen and Halse (1997) and Chaplin et al. (2005).

ABAVIV solves the VIV response in the time domain by the use of published VIV models (Finn et al, 1999) and the finite element analyses code ABAQUS. Strouhal number and hydrodynamic force coefficients depend on the Reynolds number. The inline response is calculated by the use of Morison equation for the in-line component of the relative velocity.

LICengineering model (Hansen and Nedergaard, 1994) solves the in-line and cross-flow equation of motion in the time domain and finds the VIV response by modal superposition. The in-line and cross-flow solutions are weakly coupled. For each mode the reduced velocity is calculated along the line structure. An excitation zone is defined where the reduced velocity is within the interval 4.8 to 8. Vortex shedding correlation length is modelled as a function of the vibration amplitude. Inside the excitation zone, an unsteady VIV force and a negative damping term are considered in addition to structural and hydrodynamic damping forces. Outside the excitation zone, only structural and hydrodynamic damping forces are described as transverse forces. The total response in the cross-flow direction is found by linear superposition of the contributions from each mode. In this model the response from loads found for one mode is assumed to occur only for this mode. It means that the spatial load distribution is identical to the mode shape. So travelling waves and spatial attenuation along the structure span cannot be considered.

SHEAR7 (Vandiver, 1999, Lyons et al., 2003) is based on modal superposition and modal excitation regions combined with response-dependent lift coefficients. This

model is applied to solve the cross-flow vibration only. For each mode, zones of excitation are identified where the reduced velocity is within a certain range of the ideal lock-in condition. Elsewhere, the riser is considered to experience hydrodynamic damping. This model iteratively determines the correct combination of hydrodynamic damping, response and lift coefficient. For a given set of modal loads the total response is found by mode superposition. This model allows modal loads to excite all modes so that spatial attenuation can be taken into account. Time-varying effects such as a surface wave cannot be simulated in this model.

VICoMo (Moe et al., 2001) is based on the idea of complex modes. A single complex mode is applied to describe the VIV response. The VIV response is solved in MATLAB by means of an eigen-value solver. The hydrodynamic force coefficients are adjusted iteratively to match the response amplitude and frequency. This model uses the hydrodynamic force coefficients, as functions of reduced velocity, amplitude and Reynolds number, from section model tests on force harmonic motions of a cylinder in a plane normal to a steady, uniform current. In this model hydrodynamic force coefficients are applied with a strip theory method, in which flow interaction between neighbouring sections of the riser is neglected.

VIVA (Triantafyllou et al., 1994, Triantafyllou and Grosenbaugh, 1995, Triantafyllou, 2003) treats the overall response of a long marine cable as a sum of travelling waves of different frequencies. The waves travel along the cable and interact with other waves that were created nearby location. Because of the hydrodynamic damping, most waves only travel short distances before their effects become negligible. The response is assumed to be narrow-banded and it is described by a high frequency part and an envelope part (two-frequency representation of the response). Experiments were carried out to measure the hydrodynamic force

coefficients of rigid cylinders for different amplitudes of vibration and over a range of reduced velocities, and for modulation rates of frequency (beating oscillation). The drag coefficient depending on the VIV response is estimated by the measurements of Gopalkrishnan (1993). The solution of the dynamic equation for the cable is found using the Green's function approach. The model is based on the assumption that the correlation length is half the wavelength of the mode shape. This assumption may need to be examined carefully when multi-mode response occurs. In addition, the identification of beating parameters for cases involving more than two response frequencies may require further investigation.

VIVANA (MARINTEK, 2005, Larsen et al., 2001) is based on a three dimensional Finite Element Method (FEM) of the structure (by the use of the riser analysis software RIFLEX) and a VIV response analysis model with response-dependent lift and added mass coefficients that solves the dynamic equation of motion in the cross-flow direction. The mean in-line deflection is calculated by applying an amplification factor to the drag coefficient, to model the effect on the drag of transverse vibration. Response frequencies are identified while considering a frequency dependent hydrodynamic added mass along the structure. Response amplitudes are calculated by use of the discrete frequency response method. The excitation force model includes a lift coefficient that is a function of the response amplitude and the response frequency. Damping outside the excitation zone is introduced by high and low velocity damping terms. This model does not use mode superposition for dynamic analysis and can thus model both standing - and travelling wave behaviour; or a mixture of those two.

2.3 Wake Oscillator Models

Several wake–oscillator models have been proposed in the literature. The models generally have the following characteristics:

- the oscillator is self-exciting and self-limiting;
- the natural frequency of the oscillator is proportional to the free stream velocity such that the Strouhal relationship is satisfied;
- the cylinder motion interacts with the oscillator.

Starting from the pioneer works of Birkoff and Zarantanello (1957) and Bishop and Hassan (1964) who were the first to suggest the idea to use a van der Pol oscillator to represent the time-varying force, several improvements have been made to account for three dimensionality of the wake and to extend the analysis to flexible cylinders. A general characteristic common to all wake oscillator models is the choice of a representative wake quantity. However, differences exist in the assumed mechanisms through which this variable is coupled with the body motion. For a comprehensive review of this subject see Parkinson (1989), Gabbai and Benaroya (2005), Sarpkaya (2004), Dowell et al. (1995).

Focusing the attention first on cross-flow VIV, Hartlen and Curie (1970) developed the first so-called wake oscillator model that used the van der Pol oscillator equation for the cylinder wake modelling. In this model a van der Pol soft nonlinear oscillator for the lift force is coupled to the cylinder motion by a linear dependence on the cylinder velocity. With the appropriate choice of parameters, the Hartlen and Currie model qualitatively captures many of the features seen in experimental results. For instance, a large cylinder-oscillation amplitude resonance region occurs when the vortex-shedding frequency is near the natural frequency of the cylinder. The frequency of oscillation in this region is nearly constant at a value close to

the cylinder natural frequency. The hysteresis effects seen in the experimental results of Feng (1968) are also seen in the analysis of the Hartlen and Currie model by Ng et al. (2001) using multiple scales and bifurcation analyses.

Skop and Griffin (1973) modified the Hartlen and Currie model by introducing the dependence of the coefficients on some physical parameters of the system. Using these relationships, the authors were able to quantitatively predict the results of a different set of resonant vibration experiments found in the literature with reasonable accuracy. Iwan and Blevins (1974) introduced a hidden flow variable representing the average transverse component of fluid velocity within an arbitrary control volume.

Recently, the van der Pol oscillator was revisited for VIV prediction. Facchinetti et al. (2004a) verified the effect of the cylinder movement on the lift fluctuation via different type of coupling (displacement, velocity and acceleration). They came up with a formulation of the wake oscillator model that was qualitatively and, in some aspects, quantitatively reproducing some features of VIV observed experimentally for elastically-supported rigid cylinders. The original kernel form of the van der Pol equation has been reinterpreted and then applied in its 3D version. Wake oscillators have been continuously distributed along the spanwise extent of a slender structure and allowed to interact directly, in order to describe 3D features of vortex shedding from stationary structures and VIV of slender structures in uniform and sheared flow.

Skop and Balasubramanian (1997) presented a modified form of the Skop–Griffin model for flexible cylinders. The purpose of the model was to accurately capture the asymptotic, self-limiting structural response near zero structural damping. The fluctuating lift force is separated into two components: one component satisfying a van der Pol equation driven by the transverse motion of the cylinder, and the other component which is linearly proportional to the transverse velocity of the cylinder.

Krenk and Nielsen (1999) proposed a double oscillator model in which the mutual forcing terms are developed based on the premise that energy flows directly between the fluid and the structure. This means that the forcing terms correspond to the same flow of energy at all times.

Facchinetti et al. (2004b) extended their model to predict VIV and VIW (vortex induced waves) for cables and successfully predicted the experimental response behaviour of a towed cable. Mathelin and de Langre (2005) pushed further Facchinetti's work to predict VIV of cables subjected to sheared flows.

Violette et al. (2007), starting from the model of Facchinetti et al. (2004b) and Mathelin and de Langre (2005), applied the method to the study of the dynamics of cables and flexible beams and compared the results with that of direct numerical simulations (DNS) and experiments.

2.4 Computational Fluid Dynamics

Stationary cylinder

LES and DNS. Numerical simulations of the cylinder flow are largerly confined to 2D and 3D flows at relatively low Reynolds number. Recently, numerical simulations at higher Reynolds number (Re = 10^3 - 10^6) mostly large eddy simulations (LES), have been carried out due to the significant increase in the computing power. LES solution is recognised to be the most accurate of the calculation methods for Reynolds number that exceeds the present DNS capability.

As reported by Dong and Karniadakis (2005) the cylinder flow at Re = 3900 has become the canonical test case for LES. In particular Beudan and Moin (1994), although obtained results in a good agreement with experiments, exhibited an over-damping in the power spectral density at high wave numbers due to a significant numerical dissipation in the upwind scheme. Mittal and Moin (1997) showed that this phenomenon was better controlled using a central finite difference scheme. However in these two simulations the inertial range is not captured, while using a high-order method based on B-spline and zonal grid Kravchenko and Moin (2000) were able to describe the inertial range. Other references regarding numerical scheme adopted for the Re = 3900 case can be found in Dong and Karniadakis (2005).

Higher Reynolds number cylinder flow was studied by Jordan (2002) analysing the shear layer instability at Re = 8000 using an upwind finite difference scheme and a dynamic sub-grid model. This LES simulation captured several parameters correctly even if the lift coefficient is much lower than the one obtained experimentally. Another LES study was conducted by Kalro and Tezduyar (1997) for Re = 10000 using a stabilized finite element formulation and a Smagorinsky sub-grid model. In this case the Strouhal number and the drag coefficient are in fair agreement with the experimental data.

In order to evaluate the applicability of LES to Reynolds number value of practical interest, Bruer (2000) investigated a cylinder flow for Re = 14000 obtaining results in fair agreement with experimental data and Catalano et al. (2003) for Re= 5×10^5 to 2×10^6 obtaining reasonable results for the lower Re and very inaccurate results for the higher. Moreover, they compared the results of LES with those of Reynolds-averaged Navier-Stokes (RANS) simulations performed using the commercial code FLUENT. They concluded that LES is much more accurate than RANS.

Using DNS, Ma et al. (2000) studied the cylinder flow for Re = 3900, they employed a Fourier expansion and a spectral element discretization on un-structured mesh in the spanwise direction and streamwise cross flow planes and calculated the mean velocity profiles and power spectra which were in good agreement with experimental data. Comparing DNS and LES for the test case it can be concluded that the base pressure coefficient is a little lower with DNS while the recirculation bubble length is larger. Recently Dong and Karniadakis (2005), using spectral DNS, studied the 3D cylinder flow at Re = 10000 that represents the highest Reynolds number cylinder flow simulated by DNS. To avoid the increase of the computational effort they employed an efficient multilevel-type parallel algorithm in the computation. A spectral element discretization on unstructured grids in streamwise-crossflow planes and a Fourier spectral expansion in the spanwise direction was employed as well as a third-order accurate stable pressure correction-type scheme for the integration. The comparison with the experimental data showed a good agreement for the pressure coefficients at different angles and the Reynolds stresses.

RANS Recently Pinto et al. (2006) performed 3D simulations of the flow around a stationary cylinder with helical strakes at Re = 1.61×10^5 to understand the capability of an unsteady RANS code to predict the characteristics of the riser-fluid dynamic interaction within a reasonable computational time. The code used here is a finite volume, second-order solver, based on a pseudo-compressibility formulation of the Navier-Stokes equations. The unsteady flows are resolved with a dual-time technique, the Spalart-Almaras turbulence model is adopted and the volume discretisation is made by a Chimera algorithm. Comparisons of 2D and 3D simulations with available experimental data demonstrate the limitation of the 2D code to describe correctly the peculiarities of the wake vortex.

Oscillating cylinder

While a certain number of 2D numerical simulations on VIV can be found in the technical literature of the last 20 years, 3D simulations are quite limited and usually refer to low Reynolds number values and small aspect ratio. Recently, due to the significant increase in the computing power and in particular due to the use of parallel codes some 3D simulations of the flow about flexible or rigid cylinders which are forced or free to oscillate in both the flow and cross-flow directions have been carried out. Different computational approaches are adopted to describe the flow field. These include the discrete vortex method (DVM), LES, RANS, DNS and particular combinations of the four, for example, detached eddy simulation (DES).

DNS Blackburn et al. (2001) combined spectral 2D and 3D DNS and a PIV (Particle Image Velocimetry) experiment to study the flow past a freely vibrating rigid cylinder in cross flow direction at Re = 556. The incompressible Navier-Stokes equations are solved in an accelerating reference frame, and this simulation is coupled with a set of first-order ordinary differential equations that describe the motion of the cylinder. It was demonstrated that the 2D simulations, at least in absence of a turbulence model, are inadequate in predicting both the cylinder response and the vortex shedding mechanism even at this low Reynolds number. An extensive numerical work aimed to answer a number of questions on the characteristics of the turbulent wake behind rigid and elastic cylinders and their response in the lock-in regime to the hydrodynamic load is the one of Evangelinos and Karniadakis (1999). Using a parallel code they performed a 3D spectral DNS for the flow about a rigid oscillating cylinder and a flexible cylinder modelled as a cable, as well as a beam, at Re = 1000. On the basis of the study, Evangelinos et al. (2000) using the same code performed 3D

simulations of the Navier-Stokes equations coupled with the equation of the transverse motions of an elastic riser at Re = 1000. They analysed both a short and a long cylinders corresponding to L/D of 4π and 378, respectively. In particular they examined the difference between standing wave and travelling wave responses for the larger L/D ratio case which is more typical of longer risers.

Another important application of spectral DNS using a parallel code was performed by Lucor et al. (2001). They considered two shear profiles corresponding to a linear and to an exponential shear. The main difference between the two cases is that in linear shear the structural response resembles a standing wave pattern, whereas in the exponential shear case it resembles a mixed standing and travelling wave pattern. For the parameters considered, the linear shear led to a low-mode response while the exponential shear led to a multi-mode response with the participating modes as high as 12 and 14.

A significant increase of the Reynolds number was achieved by Dong and Karniadakis (2005) using spectral DNS. They simulated the flow about a forced oscillating cylinder in the cross-flow direction at Re = 10000 obtaining drag and lift coefficients in fair agreement with experimental data. The computational cost associated with this significant increase in Reynolds number is attempted by employing an efficient multilevel-type parallel algorithm. Recently Lucor and Triantafyllou (2006) studied the vortex induced vibration modes of a riser placed in cross-flow. Also in this case two inflow velocity profiles are tested: uniform and exponential shear. Using their 3D spectral DNS code they characterised the complex mode mixtures of travelling and standing waves.

LES Al-Jamal and Dalton (2004) performed a 2D LES for the flow about a freely vibrating cylinder in 1DOF. It is

suggested that 2D calculation can give a reasonable estimation of global parameters such as drag and lift coefficient because cylinder oscillation causes the correlation length of the wake vortices to increase which diminishes the 3D influence of vortex shedding. They performed a parametric analysis, firstly varying the Reynolds number for a fixed cylinder natural frequency in order to determine the Reynolds value leading to the maximum oscillation amplitude. In a second step, the cylinder natural frequency was varied while the Reynolds number was fixed to its critical value in order to examine the vibration response at a fixed value of the vortex shedding frequency.

More recently, Willden and Graham (2004) using a hybrid Eulerian-Lagrangian Vortex-in-Cell method and a LES Smagorinsky model to capture the effects of turbulent length scales at high Reynolds numbers, conducted a quasi 3D simulations using strip theory for a long flexible pipe (with the length to diameter ratio L/D at 1544) at Re = 2.84×10^5 subjected to a uniform current profile. A linear Finite Element implementation of Bernoulli-Euler bending beam equations is used to model the transverse riser pipe response. A parametric analysis was performed varying the pipe's mass ratio (the ratio of the pipe's mass to the mass of fluid displaced by it) to study its effect on the vibration response. The results of this analysis showed a multi-mode response for mass ratio values lower than three because the fluid, via its added mass, is able to excite modes whose natural frequencies differed from the excitation frequency. It was also recognised that this effect decrease with increasing mass ratio.

Tutar and Holdo (2000) conducted 2D and 3D LES simulations of the flow past a cylinder forced to oscillate in the cross flow direction at Re = 24000 using the Smagorinsky model for the unresolved scales and a damping term in the cylinder wake. Although it was demonstrated that 3D simulations agree better with experimental data a quite large discrepancy in the pressure coefficient is still observed.

Recently, Pontaza and Chen (2006) studied the flow past a cylinder freely to vibrate in two DOF using a LES Smagorinsky model to account for unresolved scales in the flow field at Re = 10^5. This work contains the first published 3D results for two DOF VIV.

DVM The discrete vortex method is a Lagrangian numerical scheme for simulating two-dimensional, incompressible and viscous fluid flow. The advantage in using this numerical scheme is the drastic reduction of the computational time although extension to three dimensional case is not feasible. Yamamoto et al. (2004) developed a quasi-three-dimensional approach evaluating the hydrodynamic forces in two-dimensional strips and coupling those strips through a three-dimensional structural calculations using a finite element model based on the Euler- Bernoulli beam theory. The DVM employs the stream function-based boundary integral method and incorporates the growing core size method in order to model the diffusion of vortices. The induced velocities of the vortices are calculated through the Biot-Savart law. The numerical structural model is based on the studies of Patel and Witz (1991) and Ferrari (1998). A general equation of motion is solved through a numerical integration scheme in the time domain. The static solution is obtained first and the stiffness matrix is used as an average approximation for the dynamic analysis. The results obtained for a marine risers for Re = 10^4 to 10^5 showed a good agreement with experimental data. The main disagreements are related to the maximum amplitude of oscillation and hysterisis not correctly modelled by the simulations.

Another application of the DVM was developed by Zhou et al. (1999) for the flow around an elastic cylinder at Re = 200. An important aspect of the work is to bypass the

Biot-Savart law. By projecting the vorticity from the vortices onto a fixed mesh, the velocity field can be calculated through the use of Poisson equation for the stream function. This discrete vortex method provides substantial savings to the computational time required, however, it makes the method grid-dependent.

RANS Guilmineu and Queutey (2002) used a two-dimensional finite volume code in conjunction with a k-ω RANS solution to represent the 1-DOF response of a cylinder with low mass-damping at Reynolds number ranging between 900 and 15000. The calculated results compared with experimental data of Khalak and Williamson (1996) at Re = 3700 correctly predicted the 2P mode in the upper branch and the maximum amplitude of oscillation. Pan et. al (2007), using a similar numerical scheme for the same test conditions of the Khalak and Williamson (1996) experiments, conducted an in-depth analysis about the influence of the Reynolds-averaging procedure on the appearance of the upper branch in the riser response.

Commercial codes. Recently a commercial code ACUSOLVE was widely used to analyse complex problem related to VIV and VIM. In particular in the recent OMAE2006 conference several papers analyse different aspects of the VIV problems with different tools included in Acusolve. Essentially this tool is a Finite Element solver based on the Galerkin/Least Squares formulation and it is second order accurate in space and in time. Moreover it contains the P_FSI module to solve the coupled problem and to evaluate the structural response. Within this code, Constantinides and Oakley (2006) analysed a bare and a straked cylinder freely to oscillate in transverse direction and compared the results of a 3D RANS and a 3D DES model at Re = 2×10^5 to 1×10^6 with measurements. Moreover, Constantinides et al. (2006) analysed the response of an array of 20 straked risers placed just under the hard tank of a truss spar while Holmes et al. (2006)

using 3D DES simulate the response of a flexible risers free to move in horizontal direction using modal analysis without taking into account the hydro-elastic interaction.

Finally two works can be cited regarding VIM; the first by Thiagarajan et al. (2005) which presented a 2D DES at Re=5×10^4 to 1×10^5 considering the effect of strakes in the suppression of motion of cylinder. Atluri et al. (2006) performed a DES simulation of the flow about a Truss Spar in order to analyse the effect of strakes with different configurations.

2.5 Structural model

For semi-empirical VIV analyses, the structural models can be analytically explicit modes or modes solved numerically by the use of finite-difference or finite-element method.

SHEAR7 is a mode superposition program, which evaluates which modes are likely to be excited by vortex shedding and estimates the steady state, cross-flow, VIV response in uniform or sheared flows. It is capable of evaluating multi-mode, non lock-in response, as well as single mode lock-in response. The program evaluates natural frequencies and mode shapes of cables and beams with linearly varying or slowly varying tension and with a variety of boundary conditions, including cantilevers and free hanging risers.

VIVA predicts the riser response by assuming harmonic response consisting of complex modes, i.e. modes whose amplitude and phase vary along the riser length, so they may be standing waves, travelling waves or a combination of the two. This allows for energy to travel along the riser, i.e. regions along the span are excited by the local flow, while other regions dissipate the energy, which must travel between these regions. The user can use the internal solver of VIVA to find the natural frequencies and modes. The

riser in VIVA is modelled as a straight, tensioned beam, using second order finite differences as the numerical scheme.

The lumped mass approach can be an attractive alternative due to its inherent efficiency. Bending is approximated by rotational springs, and this formulation has been demonstrated to be fully viable for structures not dominated by flexural rigidity, such as flexible risers and cables. Its simplicity permits a shorter development period.

2.6   Validation of prediction models

The validation of numerical codes for the evaluation of the coupled mechanism of VIV would need experimental validation of some empirical assumption adopted to reduce the computational effort as well as, for the case of CFD codes, an intrinsic validation of the numerical scheme adopted. Unfortunately most of the experimental data available contain some uncertainties related to the experimental inflow profiles, instrumentations and in general test conditions.

To analyse the capability of different numerical tools to predict VIV, a comparison between laboratory measurements and blind predictions of eleven different numerical models was performed by Chaplin et al. (2005). The test case consisted of the in-line and cross-flow motion of a vertical riser in a stepped current. Different measurements and simulations were performed varying the current speed and the pre-tension of the model riser. The eleven prediction methods used in the blind comparison can be divided into the following three different groups: *i)* two-dimensional CFD codes based on strip theory (NorskHydro, USP, DeepFlow and VIVIC) solving the flow around a riser on a large number of horizontal planes over its length. At each time step the position of the riser changed by the flow-induced force is updated; *ii)* two time domain codes (Orcina Vortex

Tracking and Orcina Wake Oscillator) that use simplified and less CPU-demanding approaches for the computation of the hydrodynamic forces on the riser; and *iii)* five hybrid codes using data from measurements on rigid cylinders undergoing vortex-induced or forced vibrations to identify the response amplitude of the modes which are most likely to be excited.

A brief description of these numerical tools can be found in Chaplin et al. (2005). The conclusions of the comparison can be summarised in the following points:

- in general, empirical models were more successful in predicting cross-flow displacements and curvatures than codes based on CFD; the overall ratios between predictions and measurements were around 95% for the empirical models and 75% for the CFD based codes;

- there is a big spread of the results regarding cross-flow curvature predictions and almost all are not conservative;

- The in-line displacement is underestimated by all numerical models; the average ratios between predictions and measurements were between 135% and 175%;

- the in-line curvature can be calculated only by codes based on CFD but it is in very poor agreement with the measurements.

It is therefore concluded that, although in the last 10 years the agreement of the predictions of several different numerical models and the model test data available has been considerably improved, the gap between the numerical models and experiments remains large.

2.7   Experimental Methods

Experimental research on VIV has been comprehensive, particularly in the last decade, and it is impossible to review this work in

detail within the limited space of the report. In the following a brief review will be given. The reader may also confer the review papers of Bearman (1984), Williamson & Govardhan (2004), Sarpkaya (2004) and Lie and Larsen (2006) and relevant text books such as Blevins (1990) and Sumer and Fredsøe (1997).

On one hand, VIV may have a large impact on the fatigue life of deepwater risers and pipelines exposed to ocean currents, and on the othe, VIV is less well understood in comparison with other load effects. These two aspects have been the motivation for a strong and concerted research effort undertaken during the last decade or so. One important contribution to the research on VIV of risers and pipelines is model testing. The experimental work on VIV has been substantial and the tests can be divided into two different types:

- 2D tests of rigid cylinders with various geometric shapes (e.g. bare cylinders, straked and with fairings) that are elastically mounted or forced to oscillate, and towed in still water.
- 3D tests of long flexible pipes with varying geometries and boundary conditions. The test arrangements have made it possible to create various flow conditions and current profiles.

The typical objectives of such experimental studies are as follows.

- To study the behaviour of bluff body subjected to cross flow.
- To determine force coefficients that can be applied in semi-empirical prediction tools.
- To establish experimental data which can be used to benchmark prediction tools such as semi-empirical and CFD tools.

2D Tests

Free vibration test are normally used to study the cross-flow displacement (single degree-of-freedom) vs. reduced velocity e.g.

Feng (1968) and Vikestad (1998). Results from such studies show that resonance of the cylinder will occur over a regime of the reduced velocity in the range typically from 4 to 8. The maximum amplitude will be about one diameter for systems with low structural damping. The VIV response of the cylinder which is allowed to move in both the in-line (IL) and cross-flow (CF) directions is also studied, e.g. Huse et al. (2002) and Williamson et al. (2004). The comparison between the SDOF and the two DOF experiments shows that the cross-flow motion depends on the in-line motions. In Huse's study the natural frequency in IL direction is 1.5 and 2 times larger than the natural frequency in CF direction, while the natural frequencies are the same in the two directions in Williamson's study. The first study shows that the CF motion generally tends to be reduced when in-line motions are present. The second study reports some cases with large CF amplitude of 1.5 diameter when IL motion is allowed. The free vibration tests can also be used for studying different mitigation devices such as strakes (Baarholm and Lie, 2005) and fairings (Slocum et al., 2004).

Several tests with forced motion have been performed, where most tests have been done with sinusoidal cross-flow motion only (Sarpkaya, 1978; Staubli, 1983; Gopalkrishnan, 1993). Gopalkrishnan (1993) also carried out tests with amplitude modulated motion. Aronsen (2005) studied the forced in-line motions and some combined IL and CF motion tests. The lift and added mass coefficients, together with the in-line time-averaged drag coefficient are the most important results from these forced motion tests. These coefficients are required as the input data to semi-empirical VIV prediction tools.

To study the riser interaction, small-scale experiments of rigid cylinders in close proximity have been reported by Haritos and He (1993) for the cylinders exposed to wave

flow and by Herfjord and Bryndum (2001) for the cylinders exposed to current loading.

Most 2D tests are done at sub-critical Reynolds numbers, but there are also some results from full-scale Reynolds numbers tests. Ding et al. (2004) presented results from a 2D test program (cross-flow motion only) of bare and straked cylinders at full scale Reynolds numbers. Lift and damping characteristics from forced test are presented together with amplitude-to-diameter ratios vs. reduced velocity for free vibration tests. The VIV response of the bare cylinders shows pronounced sensitivity to Reynolds numbers and roughness when Reynolds numbers are in the critical region. Amplitudes of response can be as large as twice the cylinder diameter for smooth bare cylinders in certain Reynolds number regions. For a large roughness cylinder the displacement amplitudes are more similar to the amplitudes found for sub-critical Reynolds numbers.

3D Tests

In contrast to 2D tests, the model tests of long flexible risers or pipelines make it possible to study VIV under more realistic conditions, where the current flow along the model may vary both in magnitude and direction and where the structure can respond in several degree-of-freedoms (modes) in both cross-flow and in-line direction. However a disadvantage of this type of studies is that they often are done for lower Reynolds numbers (typically in the subcritical regime) than prototype Reynolds numbers which is typically around 10^6.

Some riser VIV test programmes have been conducted in towing tanks (Lie et al., 1997; Chaplin et al., 2004) or in an in-door ocean basin (Trim et al., 2005) or in a flume tank (Marcollo and Hinwood, 2002). In these studies the test conditions, i.e. the current profile, the set-up and instrumentation, are relative easy to control, but the cylinder model is relative small. MARINTEK

conducted in the period 2000 to 2004 four VIV test programmes on free spanning pipelines. Here longer free spans than traditionally used by the industry and multi-spans were studied. A result of these tests is that it is possible to increase the design length of the free spans, see DNV-RP-F105, Feb. 2006, App. A.

An alternative type of testing is large scale testing which is typically conducted out-door in a lake (Vandiver et al., 2005), in a fjord (Huse et al., 1998) or at sea (Vandiver et al., 2006). The test conditions in these tests are more realistic compared to full scale conditions, but less controlled with respect to flow conditions, test set-up, etc. They are also generally more expensive than the small scale testing.

Shell has performed a number of VIV test programmes including bare riser, riser models with strakes and/or with fairing (Allen and Henning, 2001) where a riser model with various cross sections was towed in a horizontal rotating rig at up to full scale Reynolds numbers.

In several studies it has been documented that IL fatigue can be as high as CF fatigue and in some cases even higher (Baarholm et al., 2006; Trim et al., 2005; Tognarelli et al., 2004). Analysts should be aware of this behaviour when using prediction programs that account for only the cross-flow VIV and its associated fatigue damage.

Vandiver et al. (2006) reported significant vibration in long flexible cylinders at the expected Strouhal frequency and also at two and three times the Strouhal frequency (referred to as higher harmonics). The total fatigue damage rate including the higher harmonics is shown to be significantly larger than the damage rate due to the vibration of the Strouhal frequency alone.

Deepwater catenary risers are significantly curved in the static equilibrium. This

complicates the VIV behaviour compared to vertical or nearly vertical risers, and implies that structural vibrations in the directions tangential and normal to the static equilibrium position of the riser are coupled. Typical the sheared ocean current profile has the largest speed near the surface. However since the riser tension normally will have a significant reduction near the sea bed the largest bending stresses due to VIV will occur near touch down point. The touchdown point is not fixed to the sea bed and necessarily travels along the seabed and thereby changing the length of the riser. This effect makes the structural vibrations significantly nonlinear. A second important nonlinear phenomenon is caused by the soil-riser interaction at seabottom and the geotechnical characteristics (soft vs. hard sand/clay) may affect the local pipe stresses at sea bottom. However, whether the soil hysteresis will reduce the VIV because of its damping contribution is at present not known. A model test of a steel catenary riser performed in the 10 m deep towing tank is reported by Halse et al. (1999). The riser was tested in wave, current and a combination of wave and current. The current was simulated by towing the riser model by use of a carriage. The catenary riser plane was parallel to the towing direction in one set-up, but was also given an angle of 23 degrees relative to towing direction. A VIV model testing of a generic catenary riser was conducted at MARINTEK's Towing Tank as a part of the joint industry project STRIDE Phase 4. The objective was to obtain experimental data on the VIV response of a Steel Catenary Riser when the riser is exposed to current with various velocities and incoming directions. A carriage in the towing tank towed the riser model, where both current velocity and inclination angle between the current and the riser were systematically varied. Limited analyses of recorded data were done related to the test program. Some results have been presented by Moe et al. (2004).

Riser interaction studies where two or more flexible riser models are interfering, and some times clashing, are reported by Duggal and Niedzwecki (1994), Baarholm et al. (2005) and Huse and Kleiven (2000). The first one studied wave-riser interaction, while the other two studied the behaviour of riser arrays in current and the riser clashing induced impact loads. The behaviour of a riser array in current is a highly complicated hydro-elastic problem that can be characterized by motions in different time scales. Long periodic translations occur at low mode shapes and high frequency VIV motion occurs at much higher modes. The former response is often denoted as Wake Induced Oscillations. Huse (1996) describes a series of model experiments in a Norwegian fjord to determine criteria for on-set condition of the collisions between risers of a deep sea TLP. A cluster of 10 individual model risers of 44.39 m were tested. With a length scale factor of 30, this corresponds to 1332 m prototype scale. The current was modelled using the natural tidal current in the fjord.

In a series of papers (Wu et al., 2002 and 2003, Huang and Wu, 2003) the interaction between two top tensioned risers with one placed in the wake of another is considered, in particular, the onset condition of WIO. The loss of stability, i.e. the onset of WIO, of two top tensioned risers in currents is characterized by a so-called stationary bifurcation. It should be emphasized that the main cause of the stability loss and its ensuing large-amplitude low-frequency motions is believed to be the time-averaged nonlinear force field which the downstream riser is subject to in the wake.

VIM tests

Spar platforms in their various forms – classic, truss, cell – have been adopted by the offshore industry for deep and ultra-deepwater oil and gas production because they are resistant to heave motions in waves. However, their circular cylindrical shape makes them susceptible to Vortex-Induced-Motions, or VIM.

There have been a number of publications on spar VIM model testing procedures and results over the past few years (Finn et al, 2003, Finnigan et al, 2005, Halkyard et al, 2006). Most tests allowing for full 6 DOF response to date have been done under sub-critical Reynolds Number conditions.

Finnigan and Roddier (2007) completed a series of model tests to investigate the effect of Reynolds Number and hull appurtenances on spar VIM for a vertically moored 6DOF truss spar hull model with strakes. Tests were done at both sub- and super-critical Reynolds Numbers, with matching Froude Numbers. In order to assess the importance of appurtenances (chains, pipes and anodes) and current heading on strake effectiveness, tests were done with several sets of appurtenances, and at various headings and reduced velocities.

Cueva et al (2006) performed the first experimental evaluation of the VIM of mono-column type floating platforms. It was discovered that the VIM of the mono-column type platforms presents higher amplitudes for Vr > 8. In accordance with other VIM studies, a strong influence of the heading in VIM was noted, increasing the maximum cross flow amplitude from 0.8D to 1.2D.

3. ASSESSMENT OF PREDICTION METHODS

3.1 Introduction

The discussion will be brief and general because of the very limited benchmark data available and a great deal of uncertainties in both the experiment and the numerical prediction methods.

3.2 Prediction Methods

Semi-empirical method

Semi-empirical method is the most practical VIV response prediction method at the present time. Simulation codes have been improved and predicted responses less scattered than before (Larsen and Halse, 1997) and Chaplin et al. (2005)). Semi-empirical method, however, still has limitations. Most methods are based on low mode experiment and sub-critical Reynolds number flow, and predict only cross-flow response. Simulation predicts improved responses on low modal cases in uniform and mild sheared 2D flows, however improvements are needed for other cases. Semi-empirical method often predicts regular response even though experiments often show irregular response. It is difficult to treat strakes and fairings with this method.

Wake Oscillator Model

Wake oscillator models are still used to simulate VIV. One of the main advantages of the phenomenological approaches, because of the simplicity of the models, is the small computational time. This would allow undertaking large parametrical studies of VIV of long risers that are needed for practical designs. Moreover, in terms of applications to cases of high Reynolds number, it is only needed to incorporate the dependence of the coefficients on Reynolds number that can be known from 2D experimental results. On the other side, it is clear that this method cannot provide refined results on the wake structure such as those obtained by numerical simulations. An important issue is also the range of applicability of this kind of models. By nature, all empirical (or phenomenological) models make use of experimental data from simple experiments to predict more complex cases. Systematic validation and the search for a physical understanding of the elementary mechanisms that take place in VIV are of the utmost

importance to assess the range of applicability (Violette at al., 2007).

Computional Fluid Dynamics

3-D direct numerical simulations with the use of spectral methods that allow a sensible reduction of the CPU time is recognised to be the most accurate numerical method in predicting VIV. However, up to date, the computational resources are inadequate to simulate case of practical interest i.e. high Reynolds number flow and large aspect ratio. In fact, although the significant increase in the computing power and in particular the use of parallel codes have allowed 3D simulations of the flow about flexible or elastically supported cylinder, the Reynolds number achieved with this type of methods is usually of the order of 10^3.

Several studies using different numerical tools for comparative 2D and 3D numerical simulations (see for example Tutar and Holdo, 2000) have led the conclusion that the 3D representation produced a better agreement with experimental data. However, a 2-D calculation does allow for a reasonably accurate estimate of global parameters such as the drag and lift coefficients. The negative aspect of doing a 2D calculation is that the influence of the span-wise wake turbulence is omitted. In fact, the 2D representation is more realistic for an oscillating cylinder than for a stationary one because the transverse oscillation causes the correlation length of the wake vortices to increase which diminishes the 3D influence of vortex shedding (Al-Jamal and Dalton, 2004).

LES is the numerical method used for high Reynolds number flows that exceed the actual DNS capabilities. However any 3D turbulence model is inadequate to capture the full effects of the flow. Thus, a LES model either 2D or 3D is not capable of calculating the full flow past a stationary cylinder, much less an oscillating one. Although LES provide

a much deeper insight in the wake-boundary-layer interaction mechanism compared to RANS simulation, as was noted by Sarpkaya (2004), RANS codes are more robust, less time consuming and have been applied as practical design analysis tools with reliable solutions. Up to date RANS simulations in VIV are limited to the cross-flow oscillations of an elastically mounted rigid cylinder in a uniform flow at Reynolds number up to 15,000. It was demonstrated that the upper branch appearing at low value of the mass-damping parameter is not kept. Notwithstanding, the fluid forces, cylinder response and the vortex mode in the wake are in good agreement with the experimental results. Comparisons between different turbulence models and extension to 3D simulations are needed.

3.3   Experiment Methods

Many experiment data are available for low Reynolds number, but there is a need for quality test data at high Reynolds numbers. Many uncertainties are still remaining, such as the flow behavior (e.g. by PIV) around cylinder, the effect of wave and current on VIV, the effect of wave/heave induced VIV and the effect of inclination angle between current and cylinder. It is also needed to evaluate the effects of marine growth, turbulence of the ocean currents, the effects of free surface and sea bed on VIV, and to determine scaling laws and effects. In particular for high Reynolds number cases, we need to investigate the effects of surface roughness.

Forced motion or elastic mounted rigid cylinder experiment: VIV responses are sensitive to experiment set-up, damping, motion path and turbulence in water. In-line and cross-flow responses influence each other. Many experiments with bare cylinders have been done, but less on cylinders with

auxiliary lines, strakes and fairings, and other non-circular cross sections.

3D experiment with elastic cylinder: VIV responses have been often measured on low mode and sub-critical Reynolds number flow. Experiments are needed for higher modal response and critical/over-critical Reynolds number flow. There are many data on uniform and linear shear 2D flow, but a few on other 2D sheared profiles and 3D flow. We need to understand the effect from stiffness caused by tension vs. bending stiffness and the effect from boundary conditions (e.g. shoulder effects in free span pipelines, SCR interaction with sea bed).

Full-scale experiment: Only limited full-scale data are available and it is desirable to conduct more full-scale measurements. Synchronizing of data, current measurements and logging of other relevant data (e.g. tension and mass along the riser) should be considered. It is also needed to study and improve the accuracy of measurement instruments, e.g. strain gauges, accelerometers, angel rate sensors, load cells.

4. TECHNICAL CONCLUSIONS

The ITTC VIV Specialist Committee has produced a draft report covering all three pre-stipulated tasks. The following key conclusions can be drawn from the report.

4.1 General trends

- The offshore oil and gas industry has a strong focus on VIV because VIV can be a detrimental factor in offshore field developments with potential huge economic losses, particularly in deep water. Marine risers, free spanning pipelines, tethers and floating vessels are typical structures subjected to VIV.
- VIV is characterized as a difficult subject

with a complex structural-hydrodynamic interaction. The phenomenon is generally less well understood than other marine loading processes. Thus the VIV prediction is considered to be correspondingly less accurate.
- During the last decade there has been a great deal of VIV focused research activities, both in the industry and in the academia.

4.2 Prediction methods

The prediction methods comprise a large variation in methods where the two main groups are CFD and semi-empirical methods. The status of these two groups are:
- CFD is still considered as a research tool with a prohibitive demand for CPU and large uncertainties. However, this is probably the method yet to realize its potential in the future.
- Semi-empirical prediction methods are currently used in the design of marine risers and other slender structures. In the last decade the methods have been improved and the prediction of response for low modal cases when exposed to 2D uniform and mildly sheared currents appear to be adequate. For other cases with higher modal responses (the number of participating modes are in excess of 10) and more complex current profiles the methods need further improvements.
- Only the cross-flow VIV response is normally dealt with. It is recommended to incorporate the in-line response in future models.

4.3 Experimental studies

- Model testing is important for the determination of the coefficients used in the semi-empirical codes.
- Model testing is important for verification of numerical methods. However, it should be noted that in

model tests there are relatively large uncertainties of various parameters (such as Reynolds number, 3D current, IL effect) and their influences on VIV are not well understood.

- Most of the experiments are done in the sub-critical Reynolds number regime. There is a lack of data for higher, full-scale Reynolds number regime. There is a demand for full-scale measured data with coherent high quality environmental and response data.

- The experimental results depend on the test set-up, but there exist no recommendations/guidelines on VIV experiments.

4.4 Suggestion to further activities

The 25th ITTC VIV Specialist Committee concludes that the committee continue the present activity for one more term of three years. The tasks for the committee are proposed as follows.

- Define and initiate a benchmark model test study, where results from various experiments will be compared. The recommended test set-up compromises a rigid cylinder which is elastically mounted and free to move. A possible test set-up is shown in Figure 3, though different test set-ups are permissible. The test conditions will be specified for all the participants, e.g. L/D, cylinder mass ratio, Reynolds number and reduced velocity ranges.

- OMAE has an ongoing activity for benchmarking VIV, where results from numerical prediction will be compared with experimental results. It is recommended that ITTC should establish cooperation with OMAE on the benchmark activity, where ITTC can provide valuable experimental data to OMAE. Initial discussion for such cooperation has already been undertaken.

- Evaluate the need for guidelines and recommended practice on VIV

experiment.

- Evaluate the need for defining and standardizing VIV related nomenclatures

- Update the VIV review in order to include an assessment of experimental and numerical prediction models and the proposed benchmark study activity of ITTC VIV Specialist Committee and OAME.
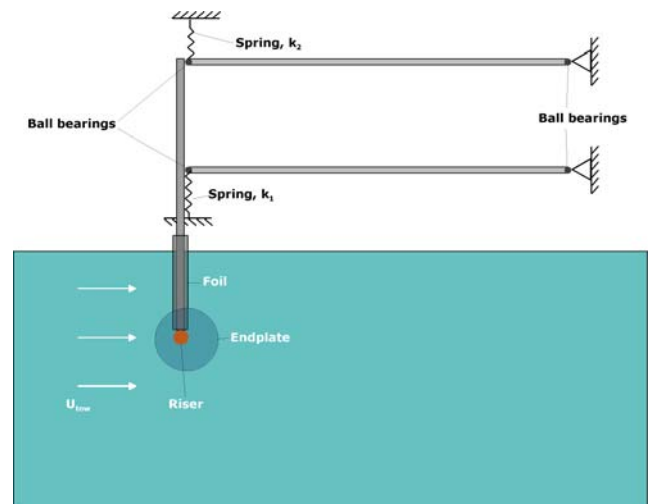
Figure 3 Principal sketch of a test apparatus that can be used in the proposed benchmark study

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