Observations of marine riser response show current-induced vortex-induced vibrations (VIV) to be a widely occurring phenomenon, with the potential to cause costly and environmentally damaging fatigue failures. In the deep waters of the Gulf of Mexico, West Africa and Brazil, for example, where oil and gas exploration and production continue apace, VIV may make the largest contribution to overall riser fatigue damage. Wave and vessel motion-related damage may remain at roughly the same level or even diminish as water depth increases, but currents can act over the full depth of the water column, which tends to make VIV more important in deeper water. This, and the fact that VIV of long risers is generally less well understood than other load effects, has led to an intensification of research activity in recent years.

Interaction and collision between risers in arrays has been a concern in riser design. Up to date, the usual practice has been to design the risers with sufficient spacing to avoid contact as they move about in the ocean current. Avoiding interaction has become more difficult and expensive as production moves to deeper water. Therefore, riser arrays with small spacing is advantageous from both a practical and economical point of view, and the industry is now considering to accept the occurrence of riser clashing.

MARINTEK has recently carried out several research projects that have focused on enhancing the understanding of the behaviour of long flexible marine risers in ocean currents. Innovative measurement techniques and cutting-edge analytical techniques have been developed. The services MARINTEK provides are capable of reducing the uncertainties in lifetime assessments of risers, pipelines and umbilicals, which could have a dramatic impact on the cost of developing new fields.

Recent projects on flow-induced vibrations include:
- High mode VIV
- Riser clashing
- Efficiency of strakes
- Galloping of riser bundles
- Fluttering instability of faired risers
- VIV tests on prototype umbilical
- Improvements and validation of the prediction tool VIVANA

In addition to deep-water riser research, this issue of MARINTEK Review also focuses, among others, on shallow water challenges. LNG tankers at offshore terminals in shallow water are exposed to non-linear wave effects that are not fully taken into account in numerical simulations.
High Mode VIV Model Tests

VIV of long risers is generally less well understood than other load effects and is a critical part of a floating production system, which means that this phenomenon is of great interest to the industry.

MARINTEK recently performed an extensive model test campaign in the Ocean Basin with a 38m long flexible riser, for the NDP (Norwegian Deepwater Programme). The model had an L/D (length-to-diameter ratio) of 1,400. The riser was tested without VIV suppression and with various strake arrangements.

There were three objectives:

(i) Acquire data to improve understanding of high-mode VIV of long risers in different current profiles.

(ii) Provide benchmark information for calibration and validation of codes that predict riser response.

(iii) Assess suppression effectiveness of strakes with different geometries and different percentage coverage over the riser length.

Testing was performed on an innovative new test rig that could simulate uniform and linearly sheared currents. The riser model used was made of composite fibre pipe, see Figure 1. A total of 64 strain gauges and 16 accelerometers were utilized, creating one of the most detailed instrumentation arrays used to date for measuring riser VIV response. The strain gauges were non-uniformly spaced, unlike in many earlier experiments.

During the planning of the test program, both inline and cross-flow responses were considered to be of importance with respect to fatigue. Indeed, this study documented that inline fatigue damage is as severe as cross-flow fatigue damage, as shown in Figure 2. However, industry analysis approaches generally ignore inline damage due to VIV.

The findings also indicate that the response character of a bare riser can be quite distinct from that of a riser partially or fully covered with helical strakes. An example is shown in Figure 3, which presents fatigue in different riser configurations vs. tow speed. The figure shows that helical strakes of different types can be effective in mitigating VIV fatigue of long risers; their performance is thus dependent on their geometry.

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Figure 1. Schematic of test rig (vertical view).

Figure 2: CF and IL fatigue vs. tow speed for a bare riser in uniform flow.

Figure 3. Maximum CF fatigue damage in uniform flow for a bare riser and two different strake geometries.
Interaction between Tensioned Risers

Interactions and collisions between risers in arrays are a source of concern in offshore developments. Common practice is to design riser systems to avoid contact between individual risers. In deep water, avoiding riser clashing becomes both expensive and technically cumbersome. MARINTEK has carried out a research project whose general objective was to improve our understanding of the physical mechanisms that drive riser clashing. Our findings will be used as input to new industry guidelines on riser system design.

The behaviour of a riser array in currents is an extremely complex hydroelastic problem that can be characterized in terms of motions in different time scales. Long periodic translations occur at low mode shapes (typically first mode, i.e. one half wave), while high-frequency VIV motions occur at much higher modes. The former response is denoted WIO (Wake Induced Oscillations). Flow separation and partial shielding between the cylinders can significantly modify the local fluid kinematics in amplitude, frequency and phase, compared to a single cylinder. The differences in excitation of adjacent cylinders may produce large relative motions that can bring them into contact.

Methods for predicting the probability of riser clashing and the resulting loads are welcomed by the industry. An important part of the process of developing a theoretical tool is validation. This must be done by comparing theoretical results with full-scale measurements or scaled model tests. As a part of the Norwegian Deepwater Programme (NDP), MARINTEK has performed a research project on riser interaction, comprising model tests and analyses of dual riser interaction in uniform flow. The tests were performed in Towing tank No. III at MARINTEK.

A sketch of the basic set-up is shown in Figure 1. Two 10 m-long flexible riser models with an L/D of 500 were tested simultaneously. Dense arrays of high-quality novel instrumentation were installed on the models. Both bare risers and risers with VIV suppression devices were tested, as were bumper elements attached to the risers. Riser spacing, inflow angle and current speed were systematically varied. A total of 310 tests were performed.

Advanced analysis methods were used to interpret the measurements. In particular, the scope of the investigation included i) describing the spatial distribution of riser clashing, ii) to compute the relative velocity at clashing, and iii) computing the riser VIV and WIO.

Figure 2 shows images of the VIV motion of straked risers in in-line (IL) and cross-flow directions (CF) for the upstream (blue) and downstream riser (red). It was found that when a straked riser resides in the wake of another riser, the strakes lose some of their ability to suppress VIV.

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Figure 1. Experimental set-up.

Figure 2. Snapshots of in-line and cross-flow VIV motion of straked risers.
The umbilical consists of several internal hydraulic pipes bound together with electrical and fibre-optic control cables and will be used to control the subsea gas field from shore. During a period before burial, free spans are believed to be critical with respect to VIV-induced fatigue. We therefore carried out a test programme whose primary objective was to verify VIV-induced stresses in the most critical pipe.

The umbilical was heavily instrumented to acquire records of bending and axial strain and lateral acceleration in both cross-flow and in-line directions at several stations. Two separate instrumented cores were installed inside the full-scale umbilical, in each hydraulic tube (see Figure 2) one with accelerometers and one with fibre-optic strain gauges.

The umbilical was towed from a carriage above the Ocean Basin (Figure 1) at speeds ranging from 0.3 to 2.5 m/s, corresponding to Reynolds numbers 30 000 - 260 000. The test programme gave results valid for prototype conditions, with high quality and consistent measurements that gave a very good insight into the behaviour of the umbilical. Figure 3 shows an example of cross-flow response. The figure to the left shows the standard deviation of the modal weight factors, based on using accelerations as input, bending moment signals as input or both. The next figure shows the displacements along the umbilical, where it can clearly be seen that 2nd mode dominates in this case. The next figure shows the standard deviation of the displacements along the umbilical, the solid line indicates the results obtained from a modal analysis, while the circles are results found by double integration of the acceleration signals. The displacement was also measured directly by means of a linear spring/force transducer at one location (green circle), also showing excellent agreement with the other results. The last figure shows the standard deviation of curvature versus umbilical length. The curvature is proportional to the bending stress and indicates thus the influence on fatigue. The results obtained from modal analysis (solid line) agree well with the results found directly from the bending moment transducers (stars).

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**Stress and Fatigue Analysis of Umbilicals**

In cooperation with Nexans Norway a.s. and several oil companies, MARINTEK is currently launching a joint industry project (JIP) called Stress and Fatigue Analysis of Umbilicals, which focuses on software development, verification testing and case studies of deepwater umbilicals.

In cooperation with Nexans Norway a.s., MARINTEK has already developed the state-of-the-art software tool UFLEX2D for detailed 2D-analysis of complex umbilical cross-section designs. One of the primary objectives of the new project is to extend the 2D description to 3D, allowing the study of longitudinal effects that are of special importance for stress and fatigue analysis of deepwater umbilicals, such as:

- End effects and friction interactions
- Radial reaction forces at bending stiffeners/restrictors
- Kinking due to coupling between tension/compression, torsion and bending
- Load-sharing between structural elements during installation and in riser configurations

Planned start-up is June 2005 and the JIP will run for three years.

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**Figure 1. Test set up for the tow tests of prototype umbilical.**

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**Figure 2. Umbilical showing instrument wires before they were cast-in by epoxy.**

Figure 2. Umbilical showing instrument wires before they were cast-in by epoxy.
Systematic Investigation of Efficiency of Helical Strakes

Vortex-induced vibrations play a critical role in inducing fatigue in offshore risers, pipelines and other tubular members. The suppression of VIV is essential to minimize the risk of premature failure. MARINTEK has carried out a systematic parametric study of the efficiency of different helical strake configurations. The results will provide valuable input for the selection of VIV suppression devices for flexible risers and umbilicals.

Helical strakes are often installed in order to mitigate VIV. The strakes are screw-like protrusions that are wrapped around the cylinders to suppress flow vortices by shortening their correlation lengths. The efficiency of the helical strakes is dependent on the height of the protrusion and the pitch of the helical, i.e. the length of a full wrap around the cylinder. A drawback of the helical strakes is that they may increase drag on pipe sections. They will also increase the fabrication and installation cost.

When helical strakes are being installed, we strive to combine the best possible VIV suppression with the least possible increase in drag. As a part of the Norwegian Deepwater Programme, MARINTEK has studied the efficiency of different helical strake configurations in terms of 2D model tests. Rigid models were elastically mounted in a set-up where they were free to move in the cross-flow direction, but restricted in the in-line direction. The cylinders investigated were 2 m long, with diameters varying from 76 mm to 114 mm. A systematic parametric study was performed, with strake pitch-to-diameter ratio ranging from 5 to 17.5, and strake height-to-diameter ratio from 0.10 to 0.25. Both 3-start and 4-start strakes were tested. Each configuration was tested for a wide range of reduced velocities ranging from 3 to 30. Figure 1 shows some of the cylinders tested.

The measurements focused on cross-flow vibrations as well as drag forces on the cylinders. In order to investigate the physics of straked cylinders in current, PIV measurements were made.

Although all strake configurations mitigated the VIV, large differences in efficiency were found. The most important parameter for strake efficiency is the strake height. At the highest reduced velocities, a “galloping” type of behaviour was seen.

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MARINTEK Includes PIV Measurements in Model Testing

PIV: Particle Image Velocimetry for assessing fluid kinematics

Particle Image Velocimetry (PIV) is a measurement technique that provides velocity fields from consequent digitized images. Digital cameras and laser lighting synchronized with a computer provide high accuracy and repeatability. PIV, as of today, is regarded as a well-established measurement technique capable of bringing significant progress to applied fluid mechanics. 3D velocity vectors may be obtained by using two cameras at different relative angles (Figure 1).

PIV is useful in many areas, and provides both qualitative and quantitative information. Examples of direct usage are:

- Evaluation of wave loads and sloshing loads – important for design of ships and offshore structures.

Examples of more theoretical character are:

- Validation and verification of theoretical/numerical models – important for improvement of simulation tools.

Examples of sloshing and VIV are shown in Figures 1 and 2.

NTNU, in cooperation with MARINTEK, has

Cont. on page 6
Shallow Water Effects
LNG Terminal Hydrodynamics

New offshore LNG terminals are being developed worldwide. They are usually installed in shallow waters, for which reason special effects must be taken into account. In particular, floater hydrodynamics, e.g. for a LNG carrier, need to be paid special attention. This includes such influences as nonlinear wave effects, increased slow-drift forces, and changes in added mass and damping.

Furthermore, multi-body interactions add to the complexity of the problem, and numerical modelling is not straightforward. For this reason, model tests play an important role in software validation as well as operation and design verification. During the past few years, MARINTEK has carried out experimental studies on a number of terminal projects.

Slow-drift forces in shallow water
In shallow waters, slow-drift forces in irregular waves increase. This is due to the greater interaction between waves with different periods, which are known as off-diagonal contributions in Quadratic Transfer Functions (QTFs). Thus modelling by the frequently used Newman’s approximation will be non-conservative. Validation by model tests is recommended, especially for multi-body cases, but also in general.

Low-frequency bound waves and kinematics
Nonlinear contributions in wave elevation and particle kinematics increase in shallow water. It is well known that wave crests become sharper and troughs flatter. For floaters, the low-frequency (LF) group-induced wave components are of greatest interest. In steep waves, LF contributions can become quite large, with a corresponding large set-down current.

Barge motions in shallow water
Motion characteristics can change significantly in shallow waters. MARINTEK has carried out model tests for Statoil to verify the in-docking operation of a barge to be installed at the Snøhvit Melkøya terminal. The change in wave-induced heave and roll motion characteristics with the change in water depth was of particular interest. As well as the model of the barge itself, a model of the dock and of the nearby shore and sea bottom were also included.

MARINTEK Includes PIV Measurements in Model Testing ... Cont. from page 5

Invested in state-of-the-art PIV equipment. The set-up includes software, two high-speed cameras and a pulsing laser. MARINTEK has used PIV measurements in several model testing projects, and plans to increase the use in future.

The figures illustrate examples of its use at MARINTEK and NTNU. Figure 1 shows the 3D velocity field behind a horizontal cylinder under towing (VIV tests). The vortices shed by the cylinder are seen. Colours indicate the velocity component perpendicular to the plane. Figure 2 shows velocity vectors obtained from sloshing experiments. Figure 3 presents run-up on a fixed, vertical circular column.

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In the MARINTEK WaveLand JIP Phase 2, state-of-the-art engineering tools have been systematically validated against a wide range of experimental data, and new knowledge has been implemented into improved guidelines for industry use. Introductory CFD studies have also been carried out. The JIP participants included Statoil, HSE (UK), NDP, ABB (USA), Deepwater Technology Group Pte, DNV, AkerKvaerner, Complex Flow Design AS and MARINTEK.

Wave amplification and air-gap
Predictions of wave amplification around and between platform legs were made by second-order diffraction-radiation panel modelling. Convergence studies were made to assure numerically stable results. A single fixed column, an array of fixed columns, a three-column GBS, and a floating semi were considered. Comparisons were made to model test data in regular and irregular waves, in various wave steepnesses. Linear diffraction theory was found to significantly under-predict the amplification, while improved agreement was obtained with the second-order models. In steep waves, additional effects grow larger, and further corrections are needed in some cases to avoid obvious errors. Systematic trends have been interpreted and documented in guidelines.

Wave-in-deck impact
A simplified and efficient method for the prediction of deck-impact loads has been established. The approach is based on the conservation of momentum, similar to Kaplan’s approach but extended to 3D and including effects from second-order diffraction due to the submerged hull. The diffracted vertical wave kinematics are essential. Comparisons with experiments with a GBS show good agreement.

Further Work
Phase 3 of the JIP is currently in preparation. Findings from Phase 2 will form the basis for the development of robust and practical procedures, and more comparisons to model test data on impact loads will be included. Systematic studies on the use and validation of CFD codes are also planned, where the cases from Phase 2 will be considered. Validation against new 3-D PIV flow measurements will be included. CFD results will also provide useful additional input to the practical procedures.

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Taking the Effect of Ocean Current Variability into Account

There is wide variability in the current flow near continental slopes around the world. Strong current events have been recorded at several locations. The mechanisms responsible for this high variability are still far from being fully understood, but internal waves, boundary layer turbulence, surface winds and turbidity currents are all processes capable of causing such conditions. There are also variations in the flow higher in the water column. This variability is caused by jets, meanders, eddies and various types of instabilities.

During the past few years, the offshore industry has moved from the continental shelf to ever deeper waters. Along with this shift in water depth, there has also been a shift in technology. Solutions for field development have changed from various types of fixed structures in shallow water, via different types of floating or tethered structures in intermediate to deep waters, to pure sub-sea developments at some deepwater locations. It is believed that this tendency will increase the demand for advanced marine operations for installation and maintenance. Due to the complexity of such operations, and the long distance from the surface to the sea bed, marine operations in deep water will be considerably more time-consuming than in shallower waters. It is quite possible that local current flows will have time to change significantly in the course of such operations. Abrupt changes in the flow could also result in unforeseen and, possibly, unwanted events when a difficult task near the seabed is being performed.

Traditionally, it has been common practice in the offshore engineering community to treat the current flow on a field as a profile which is constant. This simplification is acceptable for shallow to intermediate water depths (50-500 meters), where the effect of the current tends to be considerably less than that of waves. As depth increases, however, the loading imposed by the current will assume greater importance, and the current modeling should be more refined in such cases.

This background makes it clear that there is a need to establish well formulated and relevant design conditions for marine structures/operations in variable current environments. Methods for predicting strong current events, or estimating the probability that such events occur, should also be sought. These tasks offer a considerable challenge to the offshore engineering community. Contributions from physical oceanography, mathematics/statistics and information technology must be combined to meet this challenge, and MARINTEK is currently in the process of preparing a research project for this purpose. Some activities which will be considered for inclusion in the project are listed below:

- Collection and analysis of ocean current data (speed, direction, temperature).
- Studies of critical current conditions for various types of structures, and various combinations of environmental loading (current, wind, waves).
- Synoptic observations of geophysical parameters (waves, wind, current, atmospheric pressure, etc.).
- Techniques for establishing joint probability distributions of waves, wind and current conditions.
- Further development and improvement of numerical tools and methods (algorithms and computer technology) for direct calculations and prediction of ocean currents.

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Illustrations of various current phenomena

- Time and space varying current.
- Travelling “turbulence vortex” passing the floater.
- Current downdraft.