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Vortex induced vibrations measured in service in the Foinaven dynamic umbilical, and lessons from prediction

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Abstract

The Foinaven Umbilical Monitoring System (FUMS) has been provided to measure the stresses in a subsea umbilical of the Foinaven floating production facility. The FUMS provides high-quality data for vortex induced vibrations. A novel approach has been adopted to clearly demonstrate the variation with time of the contributions of umbilical excitation at mooring system, wave, and vortex shedding frequencies. The Foinaven case is of particular interest owing to the existence of strong currents which may be substantially sheared, and the large number of modes of vibration which may be induced by vortex shedding. This paper presents some of the responses measured, and makes comparison with vortex induced vibration predictions. The predictions include drag coefficient amplification resulting from VIV, which is important for the design of future umbilicals owing to its influence on the total hydrodynamic load, and on station keeping of the vessel. Comments on design assumptions for estimation of vortex induced vibration are included.

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1. Introduction

For floating production systems the umbilical is a critical component for the control of subsea operations. It provides electrical and hydraulic power and signals to the subsea components in the system from the surface vessel. It will be subject to dynamic and static loads throughout its anticipated 20 years or so service life.

Relatively high frequency Vortex Induced Vibrations are a possible source of damage to marine risers, umbilicals, and moorings. However, this phenomenon has not apparently been significant for flexible risers and umbilicals in the North Sea. The reasons for this have been considered to be in part owing to the complex shape of the umbilical (compared with a vertical riser), substantial structural and hydrodynamic damping, and less extreme currents.

The Foinaven Umbilical Monitoring System (FUMS) measures the stresses in one of the two subsea umbilicals of the relatively deep water (465 m) Foinaven floating production facility (FPSO), Fig. 1. This is a new area of exploitation extended from the North Sea to the Atlantic margin, west of Shetland.

High-quality data recorded by FUMS have been available from March 1997 to date. The system provides information on the relative effects of vessel motion, and current (including VIV) on the stresses in the Drilling Centre 2 (DC2) dynamic umbilical. The stresses are derived using a specially designed curvature sensor, which acts at the entry of the umbilical into the underside of the vessel's connection turret (Fig. 2), and measurement of top tension. Additional sensors monitor turret heave, pitch and roll (aligned with the umbilical), turret surge and sway, heading, and significant

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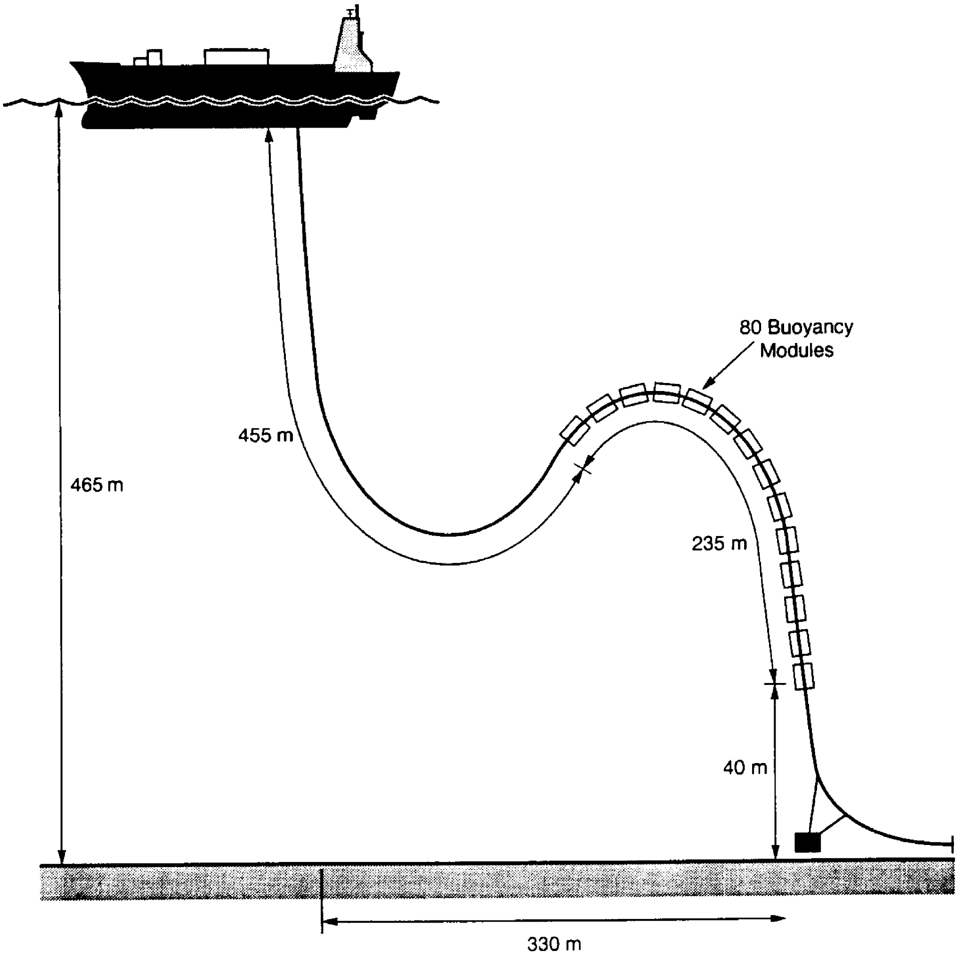

Fig. 1. Umbilical configuration.

wave height. Some of the effects observed on Foinaven have already been described in several technical papers (Lyons et al., 1998a, b, 1999). This paper presents the results from further studies funded by the Norwegian Deepwater Programme (NDP) comparing some of the data gathered and predictions using global, and VIV models. Of particular significance is the impact of VIV on C_d (drag coefficient) amplification for the extreme response of the umbilical in the global sense. Estimates of this are presented, as are comments on various aspects of design, including structural damping, and lift coefficient values.

2. Curvature measurement

The curvature sensor is deployed in a spare 5/8″ (16 mm) hydraulic control hose in the umbilical. It measures curvature in two orthogonal directions (X and Y), in the region of the umbilical bend stiffener (see Fig. 2). It is terminated at the FPSO connector deck level and extends through the vessel depth to the measurement region below the vessel keel. Curvature with direction is detected using strain gauges configured in pairs to ensure tension and temperature effects are eliminated.

2.1. Data acquisition

This utilizes two separate 486 processing units. The main unit samples 16 channels of analogue data at 20 samples/second/channel, for a total of 8192 samples per channel. Hence each sampling period is just under 7 min. The 20 Hz

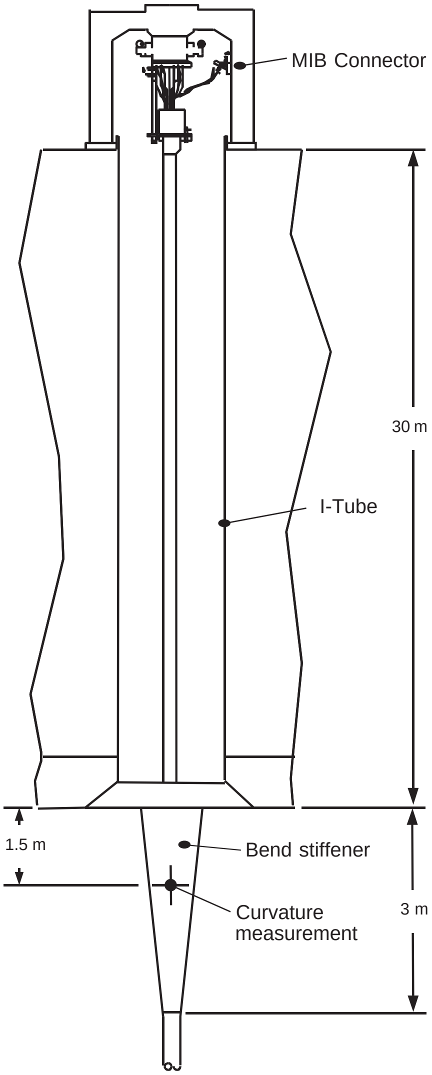

Fig. 2. Umbilical exit from turret.

sampling was chosen to deal with the anticipated maximum 3 Hz vortex induced vibration frequencies. The 7 min sampling period being adequate to cope with several cycles of surge and sway.

Subsequent to acquisition, the data are processed, which includes marking for quality, calculation of statistical values, incrementation of rainflow tables (fatigue cycle counting), and storage of time series if preset thresholds have been exceeded. This takes of the order of 3 min to complete, before acquisition of the next set of data. Hence, statistical data are updated at approximately 10 min intervals.

2.2. Umbilical configuration

A significant feature of this design is that 4 outer layers of armoring were required to achieve a compatible weight/diameter ratio with the associated ten risers for which an analogous behaviour might be expected, Fig. 3. This figure also shows the hydraulic and chemical injection hoses, and central electrical conductors. Buoyancy (flotation) modules of 0.92 m diameter distributed as shown in Fig. 1 enable the pliant wave configuration. Physical details are given in Table 1.

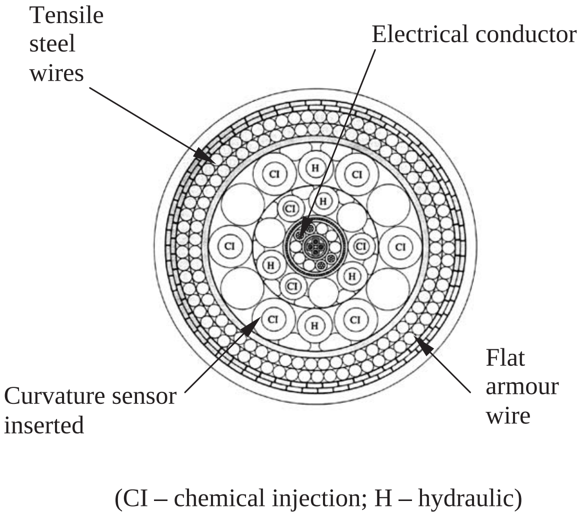

Fig. 3. Umbilical cross-section (CI—chemical injection; H—hydraulic).

Table 1
Umbilical physical details

D	Outer diameter	0.185 m
EA		1.4 GN
EI		30 kPa
M	Mass/m in air	77.7 kg/m
A	Cross-sectional area	0.02688 m^2
E	Young's modulus	52.1 GPa
I	Second moment of area	5.76×10^{-7} m^4

2.3. Measured VIV

Statistical data gathered include the maximum, mean, minimum, and standard deviations of measurands mentioned above (Figs. 4 and 5). Also Acoustic Doppler Current Profiling (ADCP) data are available at 10 min intervals, and so it is possible to make comparison with these and the curvature measurements which had been recorded in frequency bands representing mooring system (M1), wave (vessel motion) (M2), and VIV frequencies (M3 and M4), see Table 2.

The choice of cut-off frequencies for each of the bands was based on the general expectation of frequency range for each of the types of dynamic response indicated, i.e., mooring system (M1) being of the order of minutes; vessel motions (M2) dependent on wave periods with significant energy to excite vessel response; higher frequencies than M1 and M2 which are owing to other causes (principally VIV). The initial choice of (VIV) frequency bands M3 and M4 was made on the expectation that VIV might be expected principally in the band of M3, whilst possible higher frequencies might be a consequence of 'noise'. M4 has been used to discern what little noise exists. More recently the M3 range has been altered to include the full range of 'VIV' frequencies from 2 to 10 Hz (such that the M4 'caps' are included in a full VIV response).

Plainly in reality there is likely to be some overlap in the bands for these different effects. In practice, by reference to the additional motions and environmental measurements, it has been possible with this filtering arrangement to easily discern the effects of these different influences. VIV for the Foinaven umbilical configuration occurs principally owing to current effects. This is evident from the M3 and M4 standard deviation responses for curvature, which are closely correlated with measured currents. The standard deviation (which is the r.m.s. plus any offset) is used as a measure of the total dynamic response (within the frequency band). This VIV relationship with current is clearly demonstrated in Fig. 5 (comparing figure part (c) with (e), in which the peaks of vibration match with peaks in current speed).

Large motions of the FPSO have been shown in this study as capable of inducing VIV. However, there is some evidence from the data that vessel motions tend to reduce the current induced VIV response, which was anticipated since the relative flow is more disrupted (less correlated) along the umbilical with time, Lyons and Fang (1991), and Fang and Lyons (1991).

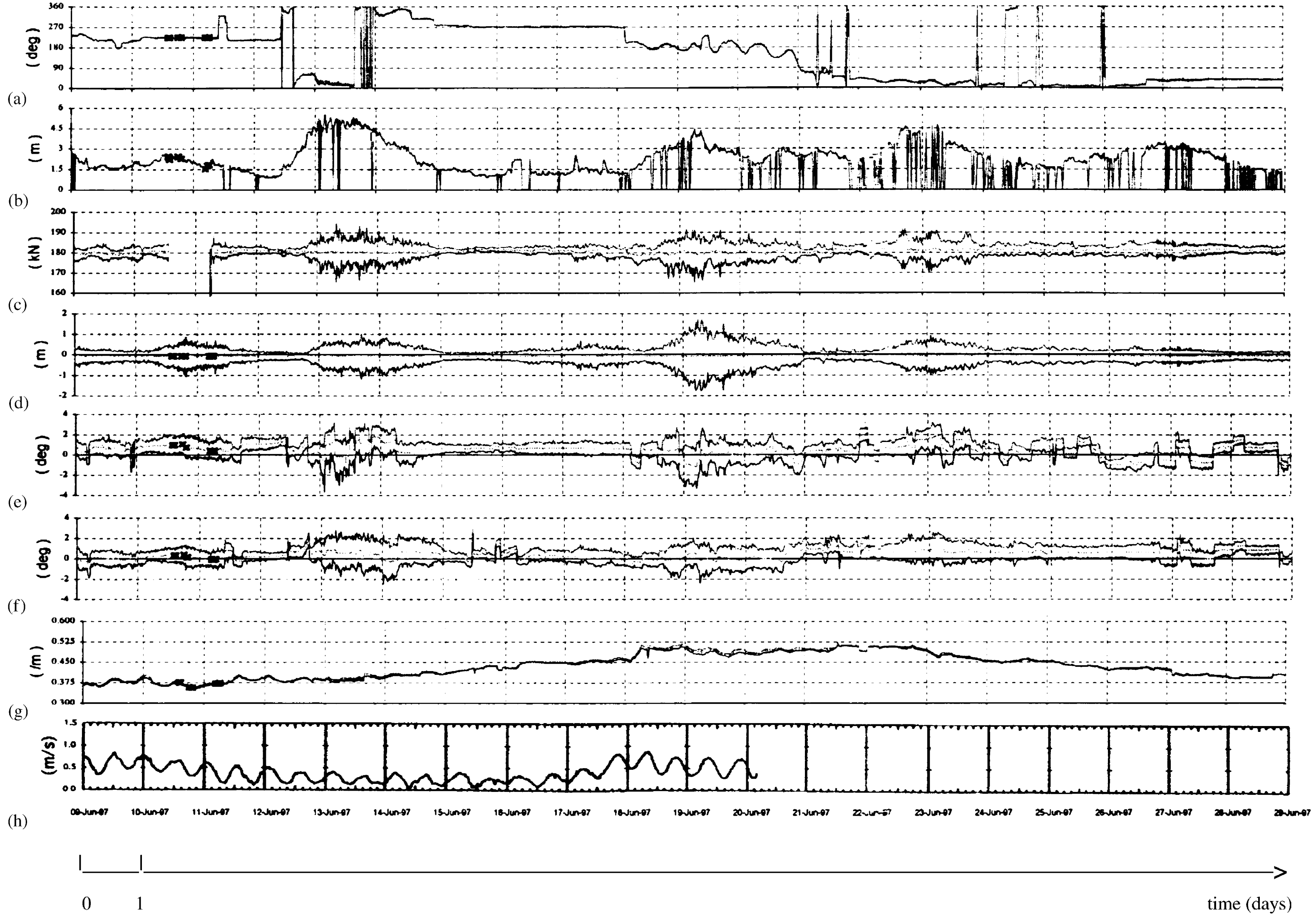

Fig. 4. Maximum, mean, minimum log histories: 9 June 1997 to 29 June 1997: (a) heading, (b) significant wave height, (c) tension, (d) heave, (e) roll, (f) pitch, (g) curvature, (h) current at 220 m depth.

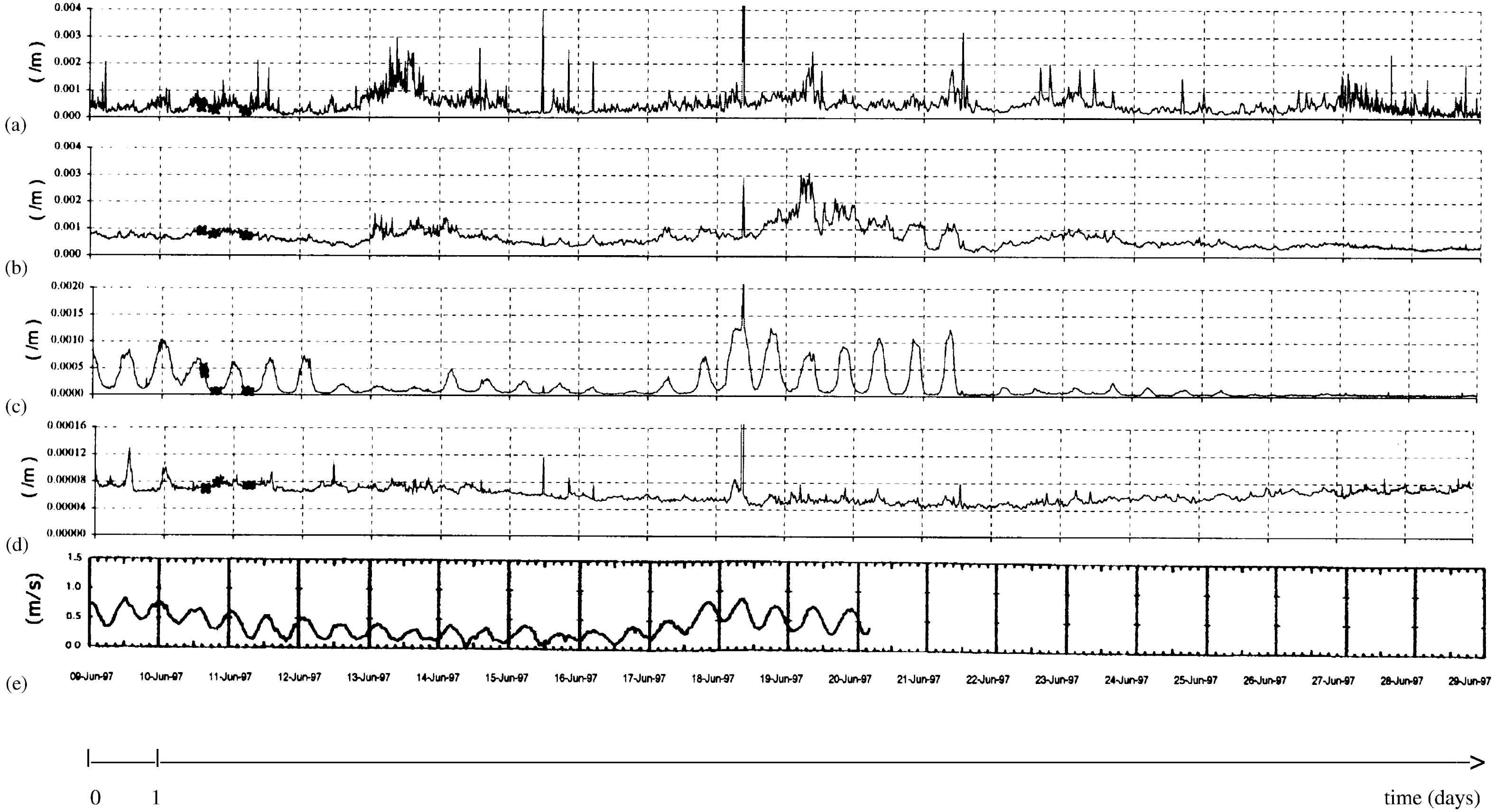

Fig. 5. Standard deviation log histories: 9 June 1997 to 29 June 1997: (a) curvature M1 filter (0–0.05 Hz), (b) curvature M2 filter (0.05–0.5 Hz), (c) curvature M3 filter (0.5–2 Hz), (d) curvature M4 filter (2–10 Hz), (e) current at 220 m depth.

Table 2
Frequency filtering bands

Descriptor	Interest	Low pass (Hz)	High pass (Hz)	Low pass (s)	High pass (s)
M1	Mooring	0.05	0.00	20.0	
M2	Wave	0.5	0.05	2.0	20.0
M3	VIV1	2.0	0.5	0.5	2.0
M4	VIV2	10.0	2.0	0.1	0.5

Note that frequency band VIV2 (M4) should be viewed as the extra component of M3, and so where M3 peaks appear to be decapitated it is appropriate to look to M4 for the missing cap (Fig. 5). All the caps are very small.

3. VIV analysis

3.1. General

There are several VIV computer programs available which have the potential for prediction for flexible catenary risers and umbilicals. Each has its own attractions, and limitations. Of those available from the authors of this paper: VIVALL, Lyons (2001); VIVANA, Larsen et al. (2000); and SHEAR 7 Version 3.0, Vandiver (1999). It was decided to use the latter as part of the NDP study since an earlier version of this code had been used in the design of the umbilical system, and was of benefit in providing subsequent comparison with the measured data.

Empirical models are today almost exclusively based on the assumption that VIV will appear as a response at discrete frequencies. Vandiver and Chung (1988) applied stochastic models in an early version of his SHEAR program, and also Triantafyllou et al. (1994) for VIV analysis of cables. The model published by Le Cunff et al. (1999) has a stochastic option, but is to the authors' knowledge the only model of this kind in use today. Discrete frequency models are seen both as time domain procedures; Finn et al. (1999), Fossati et al. (1999) and Le Cunff et al. (1999), and frequency domain models like SHEAR7, Vandiver and Li (1999); VIVA, Triantafyllou et al. (1999) and ViCoMo, Moe et al. (2001). The model published by Larsen and Beck (1986) is based on a direct modal response method and is different from other models in that sense that no load or damping model is used. The method adopted by Lyons and Patel (1986) which is the basis for VIVALL is a frequency and time domain semi-empirical hybrid, similar in some respects to SHEAR7, but using a drag coefficient formulation for damping rather than lift. It is capable of dealing with combined wave and vessel motions, as well as sheared currents.

SHEAR7 V3.0, is a frequency domain mode superposition program. The power-in region for each responding mode is determined by finding the location on the riser where the predicted vortex shedding frequency on the riser equals the natural frequency of the mode. A power-in region for that mode is defined for all flow velocities which have reduced velocities within a range of 20–30% of the ideal lock-in reduced velocity. All other portions of the riser for each mode are considered sources of hydrodynamic damping. A reduced velocity dependent hydrodynamic damping model is used to compute the modal damping for each mode with a power-in region. The dynamic lift force excitation is assumed to be at the natural frequency of the mode and is applied only in the power-in region.

The lift coefficient depends on the ratio of the local response amplitude to diameter, A/D. In Version 3.0 of the program, which was used in this study, the lift coefficient varies approximately linearly from 0.12 at an A/D of 0.0, to 0.65 at an A/D of 0.15, and then rises slowly to 0.68 at an A/D of 0.3. In this study the A/D never exceeded 0.25 peak or 0.18 r.m.s. Hence the lift coefficient was between 0.12 and 0.68. With better calibration data, more recent versions of SHEAR7 have increased the initial value of the lift coefficient to 0.5 at zero amplitude.

SHEAR7 iteratively determines the correct combination of hydrodynamic damping, response and lift coefficient. The response of many modes are determined at each power-in zone frequency. The total response at each frequency is determined, keeping track of the correct phase angles of each mode at all locations. Then the total local responses are determined by adding the local mean square response at each frequency, and then taking the square root.

3.1.1. Transfer functions from curvature to displacement

Since curvature is measured here rather than displacements, it was necessary to convert these to displacements for comparison with the VIV predictions. This was obtained by constructing a transfer function between curvature at the instrumented positions within the bending stiffener and dynamic response amplitudes for the umbilical. Two computer programs were used for this purpose, RIFLEX, Fylling et al. (1998), and RISANA, Larsen (1997). RIFLEX is a finite element program designed for nonlinear analysis of three-dimensional slender marine structures, and was used for global analysis of the umbilical. This model had, however, a simplified representation of the bending stiffener and was therefore not suited to provide the transfer function. RISANA is a simpler two-dimensional finite element program that can perform dynamic analyses of linear structures. A local RISANA model with a correct distribution of stiffness within the tapered bending stiffener was established and tuned to give identical eigenfrequencies and modal wavelengths as for the global model. By exciting this model at varying frequencies, both curvature and response amplitudes of the umbilical were found, and hence also the transfer function between them.

One such approximate frequency dependent transfer function which relates to the sensing location for the VIV frequency range considered may be expressed as

$$H(f) = \mathit{Displacement}(\mathrm{m})/\mathit{curvature}(\mathrm{m}^{-1}) = 19/f(\mathrm{Hz}).$$

This is shown graphically in Fig. 6.

The transfer functions were used to estimate the response spectra of the VIV amplitude using the VIV curvature spectra obtained from the time series data. An example displacement spectrum is shown in Fig. 7. In general the upcrossing frequency of the response amplitude in all VIV cases analysed fell between 0.45 and 0.63 Hz. At the typical average upcrossing frequency of 0.475 Hz seen in the VIV data, the transfer function value is approximately 40 m^2.

R.m.s. values of the VIV response were computed by taking the square root of the sum of the mean square values in the x and y directions at each sensor location. The mean square values were obtained by integrating the displacement response spectra.

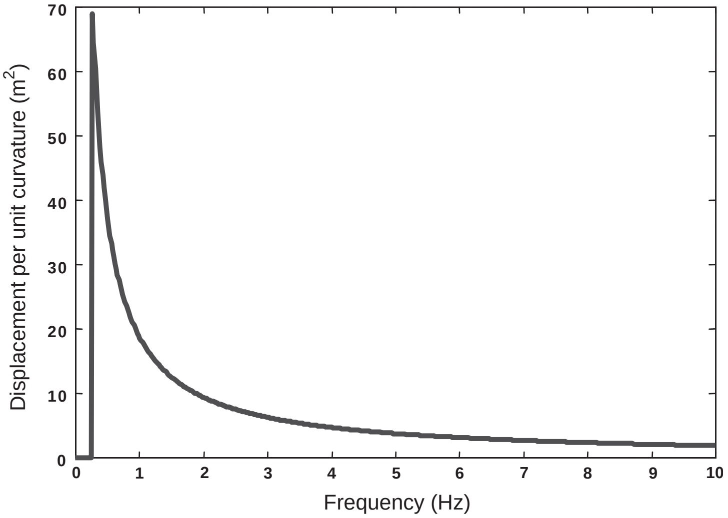

Fig. 6. Curvature to displacement frequency transfer function.

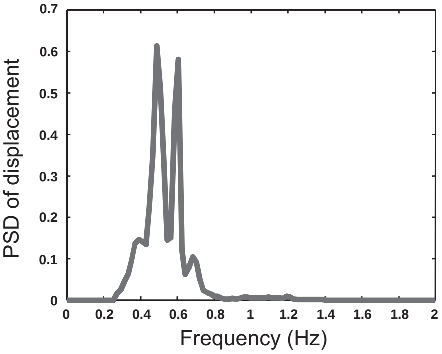

Fig. 7. Example displacement spectrum (Case 7) showing most significant VIV peaks at 0.47 and 0.6 Hz.

Table 3
Summary of cases examined for VIV measured data

Case	Form	$Heave_{\mathrm{r.m.s.}}$ (m)	H_{sig} (m)	Max. current (m/s)	VIV $A/D_{\mathrm{r.m.s.}}$	VIV upcrossing frequency (Hz)	VIV C_d amplifier
1a	Calm	0.04	0.8	<0.1	No VIV	No VIV	No VIV
1b	Current only	0.04	1.9	0.66	0.17	0.57	1.52
4	Heavy seas only	1.6	2.1	0.305	0.16	0.45	1.50
7	Current only	0.16	2.4	0.86	0.18	0.47	1.54
8a	Combined seas and current	0.64	7.2	0.56	0.15	0.47	1.48
8b	Combined seas and current	0.72	7.1	0.84	0.14	0.63	1.46

H_{sig} is significant wave height (mean of highest third).

3.1.2. Data analysis

Time series data were available at only selected times. Statistical summaries of the data were available at all times and were used to find interesting cases for time series analysis and to understand problems with various sensors.

The time series records of curvature have static and dynamic content from a variety of causes, including waves, current, and vessel motion. The VIV contribution to the dynamic response may be separated from that due to other causes by high pass filtering. The curvature response spectra were computed after high pass filtering the curvature time series data with a 9 pole Butterworth filter with a cut-off frequency of 0.25 Hz. All contributions to the measured curvature above this frequency were assumed to have come from VIV origins.

3.2. Case studies for comparison

The cases which were analysed were chosen so as to cover a variety of field conditions, including calm (1a), current only (1b and 7), heavy seas only (4), and combined seas and current (8a, b). The heavy seas only Case 4, was chosen to verify that significant vessel heave could alone cause VIV in the absence of significant current. This was verified.

The availability of measured current profiles from ADCP current meters provided the basis for prediction of VIV response. These predictions included both $A/D_{\mathrm{r.m.s.}}$ and C_d amplification. SHEAR7 was not designed to handle unsteady, motion-induced VIV. Therefore, only steady currents were assumed in the analysis. From estimates of the $A/D_{\mathrm{r.m.s.}}$ response, the drag coefficient amplification factor was computed (see for example Fig. 14) and passed back to the global FEM.

The cases were selected to give a variety of sea-state and current combinations. As shown in Table 3, the $A/D_{\mathrm{r.m.s.}}$ response did not exceed 0.2 diameters of the umbilical for any of the cases.

The cases with both current and significant vessel heave have slightly smaller response than with current only. For example compare 1b to 8a or 7 to 8b. From this it is postulated that a rapidly time varying velocity component tends to disrupt the VIV that would normally result from a steady current. All cases with vessel motion, including those with current, have less total VIV response than the current only cases. This conclusion is based on a small sample of data, and further analysis will be carried out in future to further verify this assertion.

Current profiles for Cases 1a, 1b, 7 and 8 are shown in Figs. 8–10. At the Foinaven site the currents are relatively fast with significant shear owing to the effects of the Gulf and Arctic streams at different levels. The twice-daily effects of changing current are evident from the VIV response and current velocities, as seen in Fig. 5 where the M3 and M4 standard deviation (dynamic components) of curvature VIV peaks and troughs match with those of the 10-min averaged mean water depth current speed. Whilst the current does swing through 360° the predominant effect is from SW to NE and vice versa. This is in the direction of the plane in which the umbilical lies. With the current direction in the plane of the mean curvature of the umbilical, the dominant VIV response was perpendicular to the current. For this reason the VIV analyses presented here only consider the out-of-plane modal response.

3.3. Results

Fig. 11 is a typical predicted $A/D_{\mathrm{r.m.s.}}$ response for Case 7. In this analysis VIV excitation was assumed to exist only on the small diameter portion of the umbilical without flotation. This is the top 62% of the length of the umbilical. At the time of the analysis, SHEAR7 V3.0 could not model two different hydrodynamic diameters in the same run.

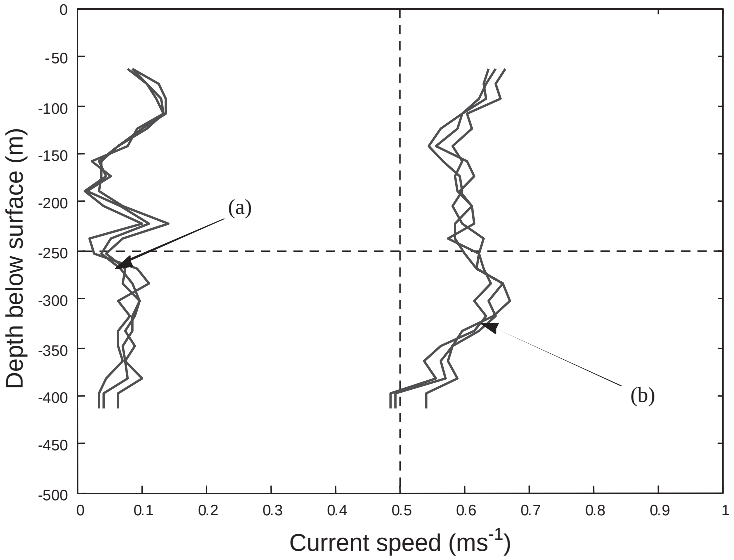

Fig. 8. Current profiles Cases 1a and 1b.

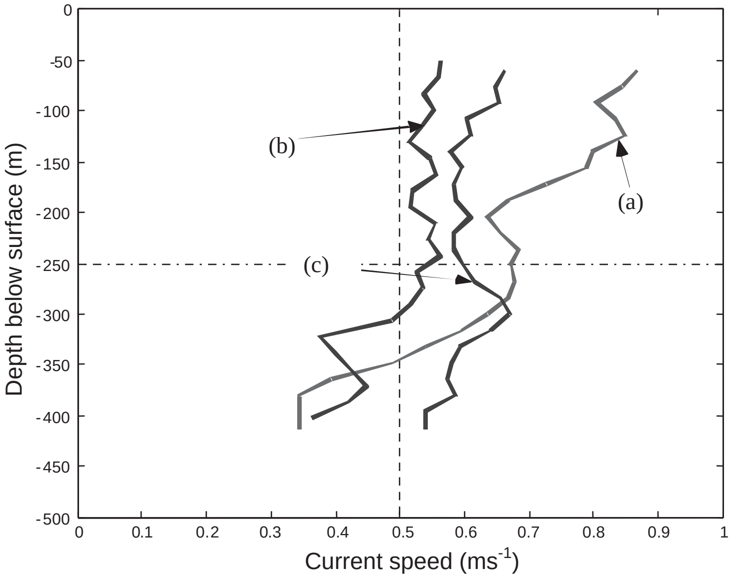

Fig. 9. Current profiles Cases 1b, 7, and 8a.

Therefore, in the analysis shown here, the entire umbilical was assumed to have the diameter 0.185 m. This was assumed, because the strongest VIV excitation will occur in the strongest current region, near the top of the umbilical where the diameter is small. No excitation was allowed in the flotation region, which leads to negligible error because the current was very small in that region. The strong excitation near the top results in high-frequency vibration waves travelling down the riser from the top as shown in Fig. 12. This figure is an example of the travelling wave behaviour of riser response to excitation near the top end. In this example a vortex shedding frequency of 0.547 Hz was used, which corresponds to the natural frequency of the 35th mode and is excited by vortex shedding at a current speed of approximately 0.55 m/s, such as in Case 1b. Since the SHEAR7 model was not intended to model excitation on the flotation region this prediction is quantitatively valid only in the bare portion of the umbilical. However, once the vibration waves enter the flotation region they will damp out quickly as shown in the figure. Also since the important component of current velocity is that normal to the umbilical, the effective velocity reduces with increasing umbilical

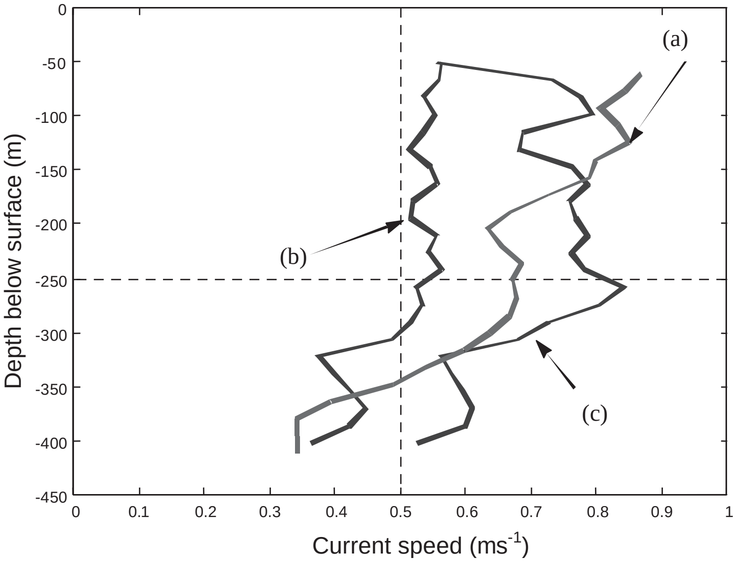

Fig. 10. Current profiles Cases 8a, 8b, and 7.

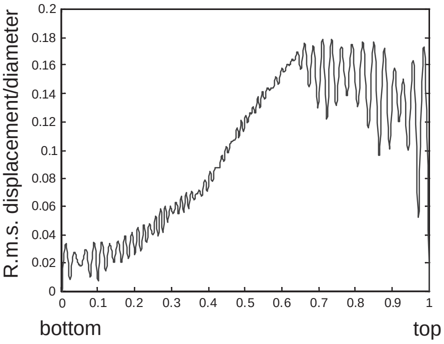

Fig. 11. Prediction of $A/D_{\mathrm{r.m.s.}}$ (Case 7).

inclination, which is substantial for much of the flotation region. This reduces the possibility of VIV excitation for the frequencies identified. Thus in the region with flotation, Fig. 12 is qualitatively accurate.

The very irregular diameter in the flotation region will suppress significant VIV. Although some response from the flotation region is possible, lack of experimental data for such structures prevents making a quantitative prediction of the amount. Some facts are known about the likely VIV characteristics of the flotation region, which are described here. Firstly, any VIV would be at very low frequency, due to the large diameter of the floats and due to the low expected Strouhal number. It has been experimentally established by many authors that for cylinders with L/D ratios less than 40, the Strouhal number decreases with the L/D, arriving at approximately 0.1 for L/D values less than 10 (Pantazopoulos, 1994).

The region will also have significantly greater hydrodynamic damping (at the frequencies corresponding to the excitation on the small diameter regions of the riser) because of the larger diameter in the flotation region. Due to the low expected VIV frequencies from the flotation region, it would not be possible to separate curvature caused by waves and vessel motion from that resulting from VIV on the flotation. In examining the curvature data for cases with current and calm seas no obvious VIV was present at frequencies that would be associated with VIV on the flotation. It is concluded here that for this particular umbilical, VIV on the flotation region is not a significant factor in VIV related fatigue or drag coefficient enhancement.

In this particular analysis the structural damping was set at 0.5% of critical. An added mass coefficient of 2.0 (with respect to the small umbilical diameter) was used to give the overall umbilical the correct average mass per unit length,

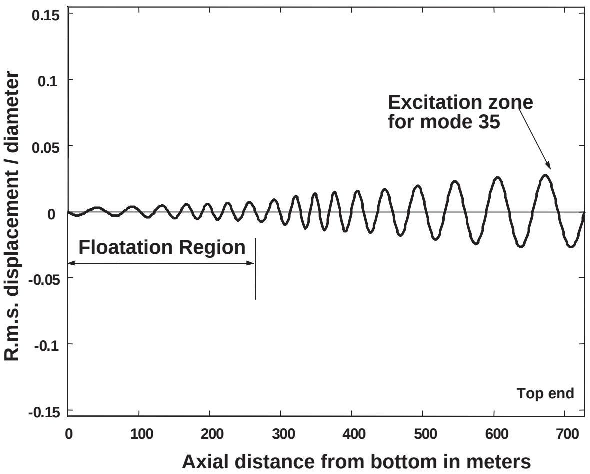

Fig. 12. Example prediction of wave propagation in response to VIV excitation near the top end at 0.547 Hz (mode 35).

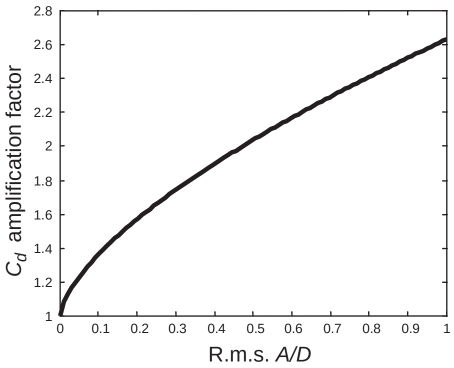

Fig. 13. C_d amplification as a function of VIV displacement (from experiment, Vandiver, 1983).

due to the presence of the flotation. This was necessary because the mass of the flotation was not included in the structural mass per unit length in the input data. An added mass coefficient of 1.0 was also tried with no significant difference in the predicted VIV behaviour.

SHEAR7 requires use of a lift coefficient table to determine the lift coefficient. As described earlier, the lift coefficient is a function of the response A/D, which makes iteration necessary. This lift coefficient table was increased by a factor of 1.08 to raise the predicted response to 0.18 diameters. Such a correction is less than the error in the measurements and in the transfer function from curvature to displacement and should not be considered significant. Thus the average lift coefficient for the dominant responding mode was approximately 0.65.

The displacement data cited in this paper are not accurate enough to be used as a basis for refining the accuracy of the program SHEAR7. However, the program is constantly being refined as additional data become available. The program is intentionally conservative, so as not to give overly optimistic estimates of fatigue life.

4. Drag enhancement

The amplification factor calculated is a function of $A/D_{\mathrm{r.m.s.}}$ as given below and plotted in Fig. 13

$$C_{d,\mathrm{amp}} = 1.0 + 1.637(A/D_{\mathrm{r.m.s.}})^{0.65}.$$

This is an empirical curve, derived from measured drag forces on a flexible steel pipe ($L = 22.86\,\mathrm{m}$, $D = 0.04\,\mathrm{m}$) excited by tidal current with VIV in modes 1–3, Vandiver (1983). There are other similar curves published by a variety

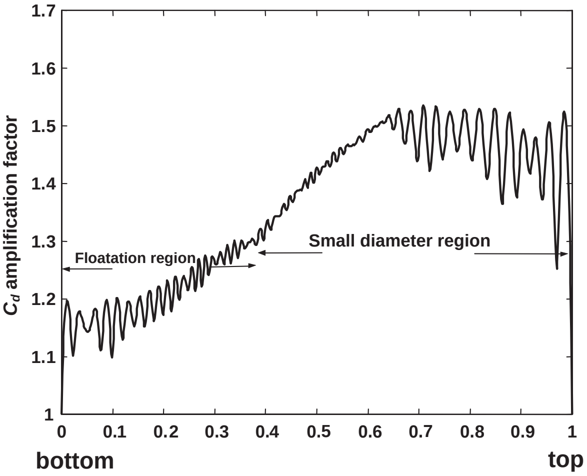

Fig. 14. Estimate of the mean C_d amplification factor (maximum current Case 7).

of authors, though most use a single degree of freedom oscillator, e.g., Griffin and Ramberg (1982), or driven cylinder data from laboratory experiments.

Fig. 13 gives an amplification of 1.5–1.55 for $A/D_{\mathrm{r.m.s.}}$ from 0.15 to 0.2 diameters. Fig. 14 shows the C_d amplification factor for the $A/D_{\mathrm{r.m.s.}}$ shown in Fig. 11. From this a conservative amplification factor of 1.6 appears to be appropriate for the small diameter regions. The mean C_d on the floats as configured on Foinaven will only increase by a small amount due to VIV related motion. An amplification of 1.2 in the flotation region should suffice for design purposes. The staggered layout of the flotation on the Foinaven umbilical is very good for discouraging VIV. The uneven diameters, and the low aspect ratio (length/diameter) of the floats, both serve to reduce the VIV. Little data exists to support a more precise prediction of C_d in the flotation region.

5. Discussion

5.1. Modelling

The geometry of pliant wave umbilicals (and risers) is more complex than that of vertical tensioned members. Consequently, these umbilicals require more attention to the way in which they are modelled if accurate responses (particularly VIV) are to be obtained.

Particular attention must be paid to (a) distribution of mass and hydrodynamic diameter, (b) identification of potential VIV power-in active regions, (c) identification of potential VIV energy dissipative regions. The principal concern for these is with the provision of buoyancy aids.

The limitations of the computer code used must be recognized. Potential difficulties of such codes include (but are by no means limited to) (a) ability to cope with variations in properties along the umbilical (e.g., mass, diameter, relative flow velocity, various coefficients, effective tension, bending stiffness), (b) ability to generate or import eigenfrequencies/modes, (c) ability to deal with a sufficiently high number of modes, (d) ability to consider added mass as an anisotropic mass, both for the bare umbilical and for sections with buoyancy modules (this modelling feature is of importance when computing eigenfrequencies/modes of the umbilical in its plane, relevant for current perpendicular to this plane).

Having recognized the deficiencies it may still be possible to proceed to provide meaningful results. One strategy which has been successfully used has been to consider the regions with and without buoyancy aids differently. In this arrangement the bare umbilical alone is assumed to be capable of VIV excitation. The section with flotation collars is assumed to be capable only of energy dissipation.

Whilst it may not be possible to model the umbilical with variations in diameter it may be possible to perform the analysis as follows.

The entire umbilical may be assumed to have the bare diameter. This may be assumed, because the strongest VIV excitation will occur in the strongest current region, near the top of the umbilical where the diameter is small. This will result in high-frequency vibration waves travelling down the riser from the top. If the VIV model is not intended to model excitation on the flotation region this prediction is quantitatively valid only in the bare portion of the umbilical. However, once the vibration waves enter the flotation region they will damp out quickly.

The very irregular diameter in the flotation region will suppress significant VIV. Although some response from the flotation region is possible, lack of experimental data for such structures prevents a quantitative prediction of the amount.

Some facts are known about the likely VIV characteristics of the flotation region: (a) Any VIV would be at very low frequency, due to the large diameter of the floats and due to the low expected Strouhal number; (b) the Strouhal number would be low due to the very low aspect ratio of the floats; (c) The region will also have significant hydrodynamic damping at locally generated VIV frequencies, due to the large local variations in diameter; (d) The region will have large damping at the high frequencies of waves propagating down the umbilical from high current regions.

Owing to the low expected VIV frequencies from the flotation region, it would not be possible to separate curvature caused by waves and (if suspended from a vessel) its motion, from that resulting from VIV on the flotation section since these would be of similar frequency.

In examining the curvature data from Foinaven for the response from currents with calm seas, no obvious flotation region VIV was present. For this particular umbilical, VIV of the flotation region is not a significant factor in VIV related fatigue or drag coefficient enhancement.

5.2. *Structural damping*

Estimates of likely suitable structural damping values have relied upon tests on flexible risers, and cables, which have been of relatively short lengths (tens of metres).

One of the authors (Vandiver) has conducted tests on a 13 m long horizontal power cable sample, with a diameter of 0.14 m and under a tension of 40 kN. The resulting damping ratio was approximately 1.5% at 3 Hz for vibration of the first asymmetric mode.

Fang and Lyons (1992) reported on a wide range of tests on a 10 m long, 2 inch flexible riser in free-hanging and catenary configurations from 1st to 3rd mode of vibration at ambient and elevated temperatures. This indicated damping ratios of 2.5–25%. These values are too high for application for umbilicals, which are substantially longer than this, and at higher tensions. It has been shown (Fang and Lyons, 1996; Brown et al., 1996) that damping decreases at higher tensions, and depends on wavelength and curvature (mode). This work has shown the rate at which damping increases with length appears to be very rapid. However, it is difficult to extend the existing data to accurate values of structural damping for lengths much in excess of 50 m.

Previously, Lyons and Fang (1991) showed that fluid damping over passive regions is expected in general to be an order of magnitude higher than structural damping. As a consequence the choice of a low value of structural damping is appropriate and should lead to reasonable estimates of VIV. The development of SHEAR7 has included considerable attention to damping models. In sheared flows, hydrodynamic damping is always much larger than the structural damping ratios for metals. For steel 0.3% structural damping is common. For umbilicals the amount of damping data under realistic tensions and lengths is sparse. However, a very conservative value would be 0.5%, which will be small compared to the hydrodynamic contributions and is also likely to be less than the true structural damping value for umbilicals with multiple layers and materials.

5.3. *Lift coefficients*

Lift coefficients are of necessity functions of A/D, roughness, Reynolds number, and reduced velocity. At this time there is inadequate data to fully calibrate programs such as SHEAR7, especially at Reynolds numbers above 10^5 or at large values of roughness. As data become available, the models used in the programs will be improved. In this study the lift coefficient curve in SHEAR7 had to be slightly modified (8%) to achieve agreement between typical measured and predicted values. This was within the measurement accuracy of the curvature data. Furthermore the transfer function conversion from curvature to displacement amplitude was also only an approximate model.

6. Conclusions

VIV response of umbilicals is significantly different to that of tensioned vertical risers. Whereas for tensioned vertical risers the VIV response is found in the frequencies from the fundamental upwards, for dynamic umbilicals (and flexible risers) the VIV modes of interest are much higher, and are unlikely to include those modes near the fundamental. Generally the response of umbilicals will be more complicated than that of tensioned vertical risers, in particular owing to their global geometry, large tension variations, and construction with varying diameters. It is possible that some of the modes of VIV interest will be in the frequency band of vessel motions and waves. It is more likely that those VIV responses of interest will however be of higher frequencies than these.

VIV response for the Foinaven dynamic umbilical has been shown to be timewise broadband with no $A/D_{\mathrm{r.m.s.}}$ values greater than 0.2 having been measured to date. However, most VIV energy has been shown to be within an identifiable range (0.45–0.63 Hz), which is outside the range normally considered for wave and vessel motion. VIV response has been shown to generally decrease beyond this identifiable range with increasing mode number (Lyons et al., 1998a, b).

It is significant that single frequency VIV response was never observed on this umbilical. This supports the argument that riser response at high mode numbers in sheared flow is unlikely to exhibit single mode dominated response. This will result in lower maximum response amplitudes than is observed on low mode number drilling risers.

VIV can regularly exist if the current conditions permit. This is true in deeper waters where waves and vessel motion are less likely to disrupt the extent of vortex sheets owing to current. It may generally be expected that current will be the prime driver for VIV. VIV as a consequence of large wave and vessel motion has also been demonstrated for the Foinaven umbilical. This at present is considered to occur in practice less often for deep water umbilicals than current driven VIV, and so its effect is likely to be of less overall significance to design.

There is some evidence from the Foinaven data that vessel motions tend to reduce the current induced VIV response, which was anticipated since the relative flow is more disrupted (less correlated) along the umbilical (Fang and Lyons, 1991).

Many of the comments are directly transferable to flexible risers. From these it is evident that the FUMS has enabled us to be in a better position in respect of how we should be dealing with both global and VIV analyses.

The work reported here has been limited in the extent of the number of cases examined. Plainly there is a lot to be learnt from the data such as FUMS can provide. Technology is advancing, and it is now possible to design a data gathering system, which provides more detail on the umbilical response through more of its length. It is hoped that in the not-too-distant future we will have been able to implement this technology with pliant wave umbilicals and risers to improve our understanding of their response in greater detail.

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References

Brown, D.T., Lyons, G.J., Lin, H.M., 1996. Effects of catenary mooring line damping, Final report for ULOS Managed Programme of research in reducing the uncertainties in offshore structures. EPSRC/MTD, UK.

Fang, J., Lyons, G.J., 1991. Application of a general prediction method for vortex induced vibrations of catenary risers. ISOPE, Proceedings of First International Offshore and Polar Engineering Conference, Vol. III, Edinburgh, pp. 354–361.

Fang, J., Lyons, G.J., 1992. Structural damping behaviour of flexible risers. Journal of Marine Structures, Design, Construction and Safety 5, 162–192.

Fang, J., Lyons, G.J., 1996. Structural damping of tensioned pipes with reference to cables. Journal of Sound and Vibration 193, 891–907.

Finn, L., Lambrakos, K., Maher, J., 1999. Time domain prediction of riser VIV. Proceedings of Fourth International Conference on Advances in Riser Technologies.

Fossati, F., Guaita, P., Resta, F., Diana, G., Ferdenzi, R., 1999. Deepwater drilling riser subjected to vortex induced vibrations—time domain code verification. Report from ENI/Agip and Politecnico di Milano, Italy.

Fylling, I.J., Larsen, C.M., Sødahl, N., Passano, E., Bech, A., Engseth, A.G., Lie, H., Ormberg, H. 1998. RIFLEX—User's Manual, Revised Version 1998-09-24. MARINTEK Report STF70 F95218, Trondheim, Norway.

Griffin, O.M., Ramberg, S.E., 1982. Some recent studies of vortex shedding with application to marine tubulars and risers. Proceedings of ASME 104, 2–13.

Larsen, C.M., 1997. RISANA—a computer program for static and dynamic riser analysis, input description. Department of Marine Structures, Norwegian University of Science and Technology, Trondheim, Norway.

Larsen, C.M., Beck, A., 1986. Stress analysis of marine risers under lock-in conditions. Proceedings of Fifth OMAE Conference, Tokyo, Japan.

Larsen, C.M., et al., 2000. VIVANA—Theory Manual. MARINTEK 513102.21.01, Trondheim, Norway.

Le Cunff, C., Biolley, F., Durand, A., 1999. Prediction of the response of a structure to vortex-induced vibrations: comparison of a modal and a wave approach, Proceedings of the OMAE Conference, OMAE99/OFT-4072, St. John's, Canada, pp. 19–26.

Lyons, G.J., 2001. VIVALL—Theory Manual. BPP Technical Services Ltd., Report No. TS01/R/0501.GJL1, London, UK.

Lyons, G.J., Patel, M.H., 1986. A prediction technique for vortex induced transverse response of marine risers and tethers. Journal of Sound and Vibration 111, 467–487.

Lyons, G.J., Fang, J., 1991. Vortex induced vibrations of tensioned and catenary marine risers. Paper C416/042, Proceedings of International Conference on Flow Induced Vibrations, Brighton, UK, IMechE, pp. 75–86, ISBN 0-85298-764-1.

Lyons, G.J., Cook, H.H., Ashworth, M., 1998a. High frequency motion components in a large dynamic duty umbilical. In: Kashiwagi, et al. (Eds.), International Conference on Hydroelasticity in Marine Technology, RIAM, Kyushu University, Japan, 1998, pp. 273–282, ISBN 4-87780-001-8.

Lyons, G.J., Brown, D.T., Cook, H.H., Walls, B., Barnay, G., 1998b. The Foinaven umbilical performance monitoring system—a new approach. OTC 8883, Proceedings of Offshore Technology Conference, Houston, TX, USA, 669–680.

Lyons, G.J., Walls, B., Cook, H.H., 1999. Dynamic umbilical performance—results from Foinaven. Proceedings of the Third European Conference on Flexible Pipes, Umbilicals and Marine Cables—MARINFLEX 99. Bentham Press, London, UK, pp. 14.1–14.19, ISBN 1-874612-29-3.

Moe, G., Arntsen, Ø., Hoen, C., 2001. VIV analysis of risers by complex modes. Proceedings of the ISOPE Conference, Stavanger, Norway, pp. 426–430.

Pantazopoulos, 1994. Vortex-induced vibration parameters: critical review. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Vol. 1, pp. 199–255.

Triantafyllou, M., Gopalkrishnan, R., Grosenbaugh, M.A., 1994. Vortex Induced vibrations in a sheared flow: a new predictive method. Proceedings of the International Conference on Hydroelasticity in Marine Technology, Trondheim, Norway, pp. 31–37.

Triantafyllou, M., Tein, D., Ambrose, B.D., 1999. Pragmatic riser VIV analysis. Proceedings of the Offshore Technology Conference, OTC10931, Houston, TX, USA, pp. 419–426.

Vandiver, J.K., 1983. Drag coefficients of long flexible cylinders. Proceedings of the Offshore Technology Conference, OTC4490, Houston, TX, USA, pp. 405–414.

Vandiver, J.K., 1999. User Guide for SHEAR7. Massachusetts Institute of Technology, Department of Ocean Engineering, Cambridge, MA, USA.

Vandiver, J.K., Chung, T.-Y., 1988. Predicted and measured response of flexible cylinders in sheared flow. Proceedings of the ASME Winter Annual Meeting, Symposium on Flow-Induced Vibration, Chicago, USA.

Vandiver, J.K., Li, L., 1999. SHEAR7 Program Theory Manual. Massachusetts Institute of Technology, Department of Ocean Engineering, Cambridge, MA, USA.