INVESTIGATION ON VORTEX INDUCED OSCILLATIONS AND HELICAL STRAKES EFFECTIVENESS AT VERY HIGH INCIDENCE ANGLES

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ABSTRACT

The demand to develop steel catenary riser (SCR) technology for floating production systems requires the capability to predict and eventually reduce the vortex induced vibrations (VIV) of slender tubular structures when subjected to steady flows at high angles of incidence. The SCR looks to be a prime candidate for future deepwater developments, but the means of VIV suppression of such a structure within its other stringent design requirements is only in its development phase, particularly for harsh environments such as the Atlantic margin and West Africa. An in-house helical strake design has been developed to satisfy potential response mitigation requirements. A reduced scale model experimental programme has been undertaken, to better address the full scale open water test campaign, aimed to determine both the VIV response and the helical strakes effectiveness at very high incidence angles. The reduced scale tests were carried out by towing in a tank a *6 m* long, *0.152 m* diameter pipe model at different velocities and inclination angles. The full scale tests were carried out by towing in open water a *200 m* long, *0.274 m* diameter pipe model at different velocities and inclination angles. A description of the towing arrangement and relevant instrumentation of both the test programmes is given.

KEY WORDS: Helical strakes, steel catenary riser (SCR), suppression devices, vortex induced vibrations (VIV).

INTRODUCTION

The offshore industry is currently embarking upon new challenging deepwater projects involving floating production systems in harsh environments, such as West of Shetland and West Africa. Such developments require riser configurations that accommodate the vessel motions and environmental loading, such as *buoyant vertical* (often called *hybrid*), *simple catenary riser (SCR*), *or buoyant arch catenary risers.* Because of the water depth and diameter requirements, composite flexible pipe constructions cannot resist the collapse forces, and are being replaced by solid steel walled riser pipes.

During their life, the risers are subjected to:

- static loads, e.g. the submerged weight of the structure, the mean axial pulling force at the top end, internal fluid pressure and temperature;
- quasi-static actions, induced by phenomena which are characterised by periods of the order of *~100* seconds, e.g. the *long period* current variations and the fluctuations associated with large eddies;
- dynamic loads, generated by *short period* phenomena, such as short period vessel motions, the wave motions, and vortex induced vibrations (VIV).

VIV can be very detrimental due to the severe fatigue impact associated with the large amplitude vibrations, and is the reason for the investigation described in this paper.

To counteract the fatigue impact, VIV needs to be suppressed. Major research efforts have focused on VIV and suppression devices for slender tubulars subject to uniform flow along their length, for instance for vertical drilling risers. For catenary risers, the flow incidence is generally variable along the component axis and the description of the interaction between the fluid and the tubular component is extremely difficult. Velocity gradients can generate a multi-modal excitation where the tubular presents both excited stretches and damping zones (Griffin, 1985; Humphries, 1998; Vandiver, 1985,1993), and suppression devices that are satisfactory for certain excitation regimes may fail under different conditions (Jacobsen et al., 1996).

There was therefore considered to be a requirement to better understand the effect of VIV due to flow over inclined risers, and the ability of suppression devices under these conditions. This work was performed as part of the STRIDE JIP (Steel Risers in Deepwater Environments) sponsored by 15 oil companies and 5 engineering contractors.

VORTEX INDUCED VIBRATIONS

When water flows past bluff bodies, it causes the formation of large vortices, which are carried away by the current. For a circular cylinder, the vortices are shed periodically at a frequency given by:

$$f_s = St\,\frac{V}{D}$$

where:

St : Strouhal number,
V : flow velocity,
D : cylinder diameter.

The Strouhal number of a stationary circular cylinder is a function of Reynolds number and, to a lesser extent, of surface roughness and free stream turbulence. The alternate shedding of vortices generates a oscillating load transversally to the flow direction, with a frequency equal to the vortex shedding frequency. Resonance between the natural frequency of the cylinder and the vortex shedding induced loads will occur when the two frequencies approach each other.

The parameter commonly adopted to describe the vortex induced vibration phenomenon is the *reduced velocity,* defined as:

$$V_{r,n} = \frac{V}{f_n\ D}$$

where f_n is the cylinder n^{th} natural frequency.

Resonance in the cross-flow direction can thus be expected when $f_s / f_n = V_r\ St$ equals *1,* that is, for sub-critical regimes *(St»0.20),* when the reduced velocity is approximately *5.* As the shedding mechanism locks onto the natural frequency of the cylinder, resonance occurs over a broad range of reduced velocities, typically from *~4* to *~9.* Experiments have shown that within the resonance region the phenomenon is self-limited with typical response amplitudes up to *~1.5* diameters.

VORTEX SUPPRESSION DEVICES

To prevent VIV lock on, it could be suggested to change the natural frequencies of the riser by structural modification, though this is largely impractical. Instead, it is better to inhibit the formation of vortices or disrupt their structured formation, through the application of the so-called *suppression devices.*

The different types of suppression devices are commonly grouped into four categories, namely *surface protrusions, shrouds, near wake stabilisers* and *streamlined fairings,* though it is common to merge the last two categories into a more general category called *fairings.* Shrouds provide a slotted second surface to the pipe, but are difficult to engineer for SCR's, and restrict riser inspection activities. Fairings must involve moving parts to enable them to rotate to suit the prevailing current direction, and are considered impractical for a typical *25* year subsea life requirement.

The most widely used technique to reduce VIV on cylindrical structures is the application of a surface protrusion type device, and in particular a *helical strake system*. This has been used many times on chimneys, process towers, and vertical marine risers, but never on the inclined sections of SCR's.

The large varieties of helical strakes are mainly defined by the height, the number of starts of the helix and the pitch of each helix. Though there is general agreement that the height of the strakes shall be between *0.1* and *0.15* times the diameter to ensure effectiveness without unacceptably high drag increase penalties. The optimum value for the other parameters is a matter of debate. A pitch of about five diameters has generally been accepted as optimal, but recent tests have shown that a pitch of *15* diameters may be just as effective (Jones and Lamb, 1992).

The following summary observations have been made in other investigations, though relating to cylinders where the flow is normal to the cylinder axis, which is predominantly not the case with an SCR:

- The drag coefficient of a cylinder fitted with strakes is independent of the Reynolds number, that is it keeps practically unchanged when going from sub-critical to critical and post-critical flow conditions (Cowdrey and Lawes, 1959).
- A strake coverage ratio of *80%* and even of *50%* of the cylinder gave large reduction of response amplitudes whereas a coverage ratio of *25%* was found to be inadequate (Vickery and Watkins, 1962).
- The effectiveness of helical strakes reduces for large values of the reduced velocity (Every and King, 1979).
- Turbulence in the incoming flow was found to reduce the effectiveness of helical strakes, from a reduction of over *80%* in amplitude for low turbulence levels, to a reduction of only 50% in amplitude for a turbulence level of *14%* (Gartshore et al., 1978).
- Helical strakes are capable of reducing vibrations both underwater and in air (Vickery and Watkins, 1962; Every et al., 1982).
- Suppression devices that are satisfactory for certain excitation regimes may fail under different conditions (Jacobsen et al., 1996).

REDUCED SCALE TESTS IN TOWING TANK

Objectives

The aim of the reduced scale model experimental programme was to collect data relevant to VIV response and helical strakes effectiveness at different incidence angles in a controlled environment. This work was also a learning exercise for the full scale open water test campaign, identifying areas of special interest, and developing instrumentation techniques.

Experimental Set-up

Test Facility. The tests were carried out in the towing tank facilities of the BMT/DERA Hydrodynamic Test Centre, at Gosport, Hampshire, UK. The tow tank was *270 m* long, *12 m* wide and *5 m* deep.

Pipe Models. The pipe models were made of Glass Reinforced Plastic (GRP). The outer diameter was *0.152 m* (*6")* and the model length *6 m,* thus giving a length-to-diameter ratio approximately equal to *40.* The pipe models, which were water filled, were practically neutrally buoyant. Pipe model geometric and structural characteristics are summarised in Table 1.

Model Support. A yoke structure was designed and built to provide a stiff and robust mounting for the test pipe, to be horizontally towed at *1 m* below water level (Figs. 1 and 2). The yoke structure was attached to the towing carriage, and could be rotated to provide different angles of inclination between the tow pipe and the towing direction, in order to establish the desired current angles relative to the cylinder axis. Fairings on the vertical struts of the yoke structure could be arranged to always face into the flow direction, as could a pair of vertical fences, included to help separate some of the turbulent flow around the end fittings from the main pipe span.

The pipe was attached to the rig via universal ball joints at either end. A hydraulic cylinder was attached to one end to provide an axial tension of *1 ton* on the pipe. This was monitored and recorded by a pressure transducer near the cylinder. The hydraulic system included a nitrogen accumulator to maintain a reasonably constant mean tension on the pipe regardless of pipe deflection due to drag. To measure the drag, steel block gauges containing linear voltage displacement transducers (LVDT) were used, two at each end. All of these features were enclosed within smooth fairing structures to reduce rig end effects.

Vortex Suppression Device. 2H Offshore designed and manufactured the helical suppression system used in the tests. The system consisted of extruded lengths with a properly shaped section with *0.15 D* height. These lengths were manufactured from 80 shore hardness nitrile rubber and wrapped around the pipe to form a three-start helix with a *5D* pitch (Fig. 3).

Model Instrumentation. In order to monitor the VIV response, the pipe models were fitted with strain gauges and/or accelerometers. Details are as follows:

All Pipes

- Drag through LVDT block gauges
- Axial tension through hydraulic cylinder pressure
- Carriage speed through carriage instrumentation
- In-line and cross-flow vibration from strain gauges
- In-line and cross flow vibration from accelerometers
- Video monitoring from above and behind the test pipe

Strain gauges were arranged as 2 half-bridge pairs at each axial location. Relevant wiring was routed along the lee side of the pipe. Accelerometers used were monolithic chip IC devices, configured to pick up cross-flow and in-line pipe vibration. All instrumentation was logged through dedicated conditioning units to a PC running Labtech Notebook, with the sampling rate set at *30 Hz.*

The drag forces acting on the test cylinder were measured by four block gauges mounted on the vertical struts between which the cylinder was mounted. The total drag was found as the sum of the forces measured by the four block gauges.

Test Program. Tests for both the bare and straked pipe models were performed at inclination angles of *0°, 15°, 30°* and *45°*. Angles are defined with respect to the normal to the model axis, i.e. *0°* represents a normal flow. To adequately delineate the response curve, tests were executed for a discrete number of velocities within the synchronisation region of the *1st* mode. A test matrix detailing the towing velocities is shown in Table 2.

Free Vibration Test. The *1st* natural frequency was obtained by striking the pipe model sharply with a wooden beam. The pipe model condition was as it would be during the tow tests, that is submerged, water filled and under tension. The *1st* natural frequency was found to be *3.2 Hz,* which compared well with the analytically evaluated frequency of *3.0 Hz.*

Results

General. The results presented here are limited to the *30º* inclination tests, due to JIP restrictions, and focused on the cross-flow vibrations. Significant in-line vibration occurred in concomitance with large cross-flow vibrations. The cross-flow response amplitudes, normalised with the outer diameter of the test cylinder, are plotted as a function of the reduced velocity, for both the bare and straked models. The reduced velocity is evaluated on the basis of the velocity component normal to the pipe model axis and the pipe model *1st* natural frequency.

Bare Pipe Response. The cross-flow response curves for the various tested bare pipe models are shown in Fig. 4, for an inclination of *30º.* The response amplitudes experienced by the bare pipe are between *0.5* and *0.7* diameters, which is quite low if compared with the values predicted by analysis of *1.0-1.2* diameters.

Straked Pipe Response. The cross-flow response curves for the various tested straked pipe models are shown in Fig. 4, for an inclination of *30º.* The effectiveness of the tested strakes in reducing VIV response amplitudes is considerable within the whole synchronisation region of the first mode.

FULL SCALE TESTS IN OPEN WATER

Objectives

The objective of the full scale open water test campaign was to evaluate the VIV response of a very slender pipe string at high Reynolds numbers (up to $5x10^5$) at different angles of inclination to the current. In particular, the aim was to investigate the response at very high angles of incidence (up to *75º* to vertical), the effectiveness of the helical strakes in reducing the VIV response in such conditions, and the influence of the deflected shape of the model on the response.

The above data is intended to improve the understanding of the VIV phenomenon, the strake design and coverage requirements, and eventually allow the development of VIV design guidance.

Experimental Set-up

Test Facility. The two models were constructed and assembled on a quay at Risaviga bay, Tananger, near Stavanger, Norway. Then the models were successively launched and towed to Boknafjorden, about *14 nautical miles* northern of Tananger, where the tests were carried out.

Pipe Models. The pipe models were made of API-B grade steel. The outer diameter was *0.274 m (10.75")* and the model length *200 m,* thus giving a length-to-diameter ratio approximately equal to *726.* Pipe model geometric and structural characteristics are summarised in Table 3.

Tow Configuration. The tow configuration is depicted in Fig. 5. The model pipe is suspended from its top end to the trailing tug through a *40 m* long wire, and from its bottom end to a leading tug through a *winch wire.* The winch wire length could be varied, by either paying out or reeling in, in order to achieve the required nominal model inclination angles. A *15 ton* clump weight was suspended at the model bottom to force a node for the model VIV response. Finally, a *300 m* vessel-to-vessel *tow wire* maintained the distance between the two tugs. During towing, the leading tug provided the trusting force, while the trailing boat powered in reverse to maintain the tow wire tight.

Vortex Suppression Device. 2H Offshore designed and manufactured the helical suppression system used in the tests. The system consisted of extruded lengths with a properly shaped section with *0.15 D* height. These lengths were manufactured from 80 shore hardness nitrile rubber and wrapped around the pipe to form a three-start helix with a *15 D* pitch. The hand of the strake helixes was reversed in correspondence of model lifting support points, i.e. every *24 m,* to minimise the induced deflection effects during inclined tow operations (Fig. 6).

Model Instrumentation. In order to monitor the VIV response, each pipe model was fitted with 1 rotational accelerometer logger and 40 linear accelerometer loggers. The units were strapped to the models on the lee side to the tow, to minimise interference with the

VIV phenomena, and they were fitted equally spaced along the pipe axis, i.e. a logger every *5 m*, with the angular accelerometer logger at the model midspan. The loggers were designed and built by 2H, self contained units approximately *11 cm* diameter and *23 cm* height (Fig. 7). The core of the device is a set of three monolithic IC accelerometers, measuring *±5g* in three mutually orthogonal directions. These sensors were mounted inside the pods in such a way that, when the loggers were fitted to the pipe models, their measuring directions were aligned with the model cross-flow (transverse), in-line and axis directions. Prior to installation, all the loggers were synchronised with the same PC clock, which was constantly updated by radio link to an atomic clock transmission. Sample rate was *10 Hz,* and data was logged continuously and stored within the unit built-in 40 MB memory. The relevant data were unloaded after the test execution and model retrieval. Two of the loggers, one at about *20 m* from the model top end and the other at about *0.5 m* from the bottom end, were hardwired to the trailing tug logging station, to allow real time monitoring of the model response.

Additional instrumentation consisted of a pressure transducer, two load cells, and an electro-magnetic flow meter, all hardwired to the trailing tug. The pressure transducer measured the pressure at the model bottom end, to indicate the vertical position of the end. Of the two load cells, one provided the wire tension to the top of the pipe, and the other the winch wire tension to the bottom. Finally, the flow meter was to be suspended from the trail tug at a location away from the vessel wakes, to monitor the tow velocity. This was only partly successful, and velocity measurement was mainly from the Global Positioning System (DGPS). The sampling rate of all the hardwired instrumentation could be varied through the onboard computer, and was usually set at *30 Hz.*

Onboard Instrumentation. The onboard instrumentation was installed on the trailing tug, with an umbilical to the top of the pipe. It consisted of one PC with a *Windows 95®* Operating System, connected to two data acquisition *instruNet®* boxes where the instrumentation wiring was converging, and running *DASYTEC®* data acquisition software *DASYLab®*, to allow real time monitoring.

Test Program. Tests for both the bare and straked pipes were performed at pipe inclination angles of *30°*, *45º*, *60º* and *75°*. Angles are defined by the nominal pipe axis direction with respect to the vertical. A test matrix detailing the towing velocities is shown in Table 4.

Results

General. The results presented here are limited to some of the *30º* inclination tests, due to JIP restrictions, and focused on the measured transverse accelerations. In particular, the time histories of the measured transverse accelerations as measured by the top hardwired pod, are plotted for towing speeds of *4* and *5 knot.*

Bare Pipe Response. The time histories of the transverse accelerations measured by the top hardwired pod during the bare pipe model tests at 30º inclination are plotted in Figs. 8 and 9, for towing speeds of *4* and *5 knots* respectively.

Straked Pipe Response. The time histories of the transverse accelerations measured by the top hardwired pod during the straked pipe model tests at 30º inclination are plotted in Figs. 10 and 11, for towing speeds of *4* and *5 knots* respectively.

CONCLUSIONS

Detailed consideration of the results from these test programmes is ongoing within the STRIDE JIP, and the overall findings are subjected to JIP restrictions at this time. Nevertheless, it is worth to mention some aspects emerged during the experimental campaign.

In particular, as regards the reduced scale tests, it came out that:

- the tests spanned the critical interaction regime, as indicated by the experienced drag coefficients;
- the tested helical strakes proved to be effective in suppressing the *1st* mode of the VIV response, even at the higher inclination angles;
- single hand helical strakes provided an appreciable displacing force on the test pipes when subjected to inclined flows, arching them transversally either upwards or downwards, depending on the hand of the helix.

As regards the full scale tests, the transverse accelerations experienced by the bare pipe are significantly reduced compared with what is foreseen by standard VIV prediction codes. Work is ongoing to establish whether the test set-up was causing damping of the vortex induced oscillations, or whether this is a realistic finding. The effectiveness of the tested strakes in reducing VIV response is generally considerable.

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REDUCED SCALE PIPE MODEL		
Outer diameter	D	0.1524 m
Wall thickness	t	4.15 mm
Length	L	6 m
Length ratio	L/D	~40
Young’s modulus	E	2.80×10^{10} N/m^2
Density		1800 kg/m^3

Table 1 – Reduced scale tests: pipe model geometric and structural characteristics.

ANGLE	PIPE 1 - BARE	PIPE 2 - BARE	PIPE 3 - BARE	PIPE 3A - BARE	PIPE 2 - STRAKED
0 deg	0.6 – 3.7 m/s	0.6 – 4.6 m/s	1.75 – 2.5 m/s	2.0 – 3.0 m/s	0.6 – 3.7 m/s
15 deg	0.6 – 3.8 m/s	-	-	-	0.6 – 3.8 m/s
30 deg	0.7 – 4.2 m/s	0.7 – 3.4 m/s	2.0 – 3.2 m/s	2.0 – 3.2 m/s	0.7 – 4.2 m/s
45 deg	0.8 – 4.5 m/s	0.8 – 4.5 m/s	-	-	0.8 – 4.5 m/s

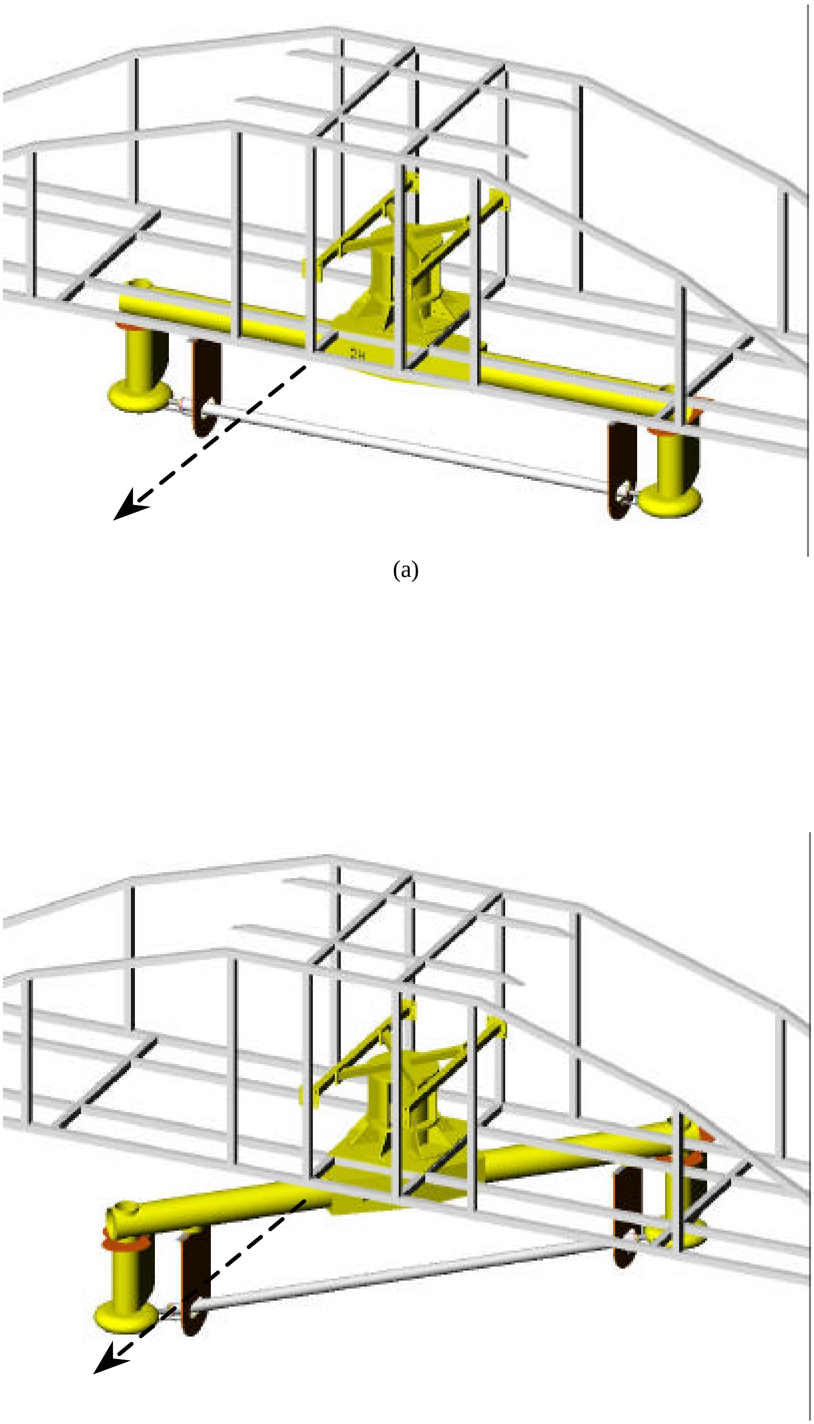
Table 2 – Reduced scale tests: synthetic test matrix.

FULL SCALE PIPE MODEL		
Outer diameter	D	0.2738 m
Wall thickness	t	9.55 mm
Length	L	198.8 m
Length ratio	L/D	~726
Young’s modulus	E	2.07×10^{11} N/m^2
Density		7850 kg/m^3

Table 3 – Full scale tests: pipe model geometric and structural characteristics.

ANGLE	PIPE 1 - BARE	PIPE 2 - STRAKED
30 deg	1.0 - 2.0 - 3.0 - 4.0 - 5.0 knot	1.0 - 2.0 - 3.0 - 4.0 - 5.0 knot
45 deg	1.0 - 2.0 - 3.0 - 4.0 - 5.0 knot	1.0 - 2.0 - 3.0 - 4.0 - 5.0 knot
60 deg	1.0 - 2.0 - 3.0 - 4.0 knot	1.0 - 2.0 - 3.0 - 4.0 - 5.0 knot
75 deg	1.0 - 2.0 - 3.0 - 4.0 - 5.0 knot	1.0 - 2.0 - 3.0 - 4.0 - 5.0 knot

Table 4 – Full scale tests: test matrix



(a)

(b)

Fig. 1 – Reduced scale tests: tow rig at *0º* and *45º* inclination.

Fig. 2 - Reduced scale tests: tow gantry.

Fig. 3 - Reduced scale tests: straked pipe model.

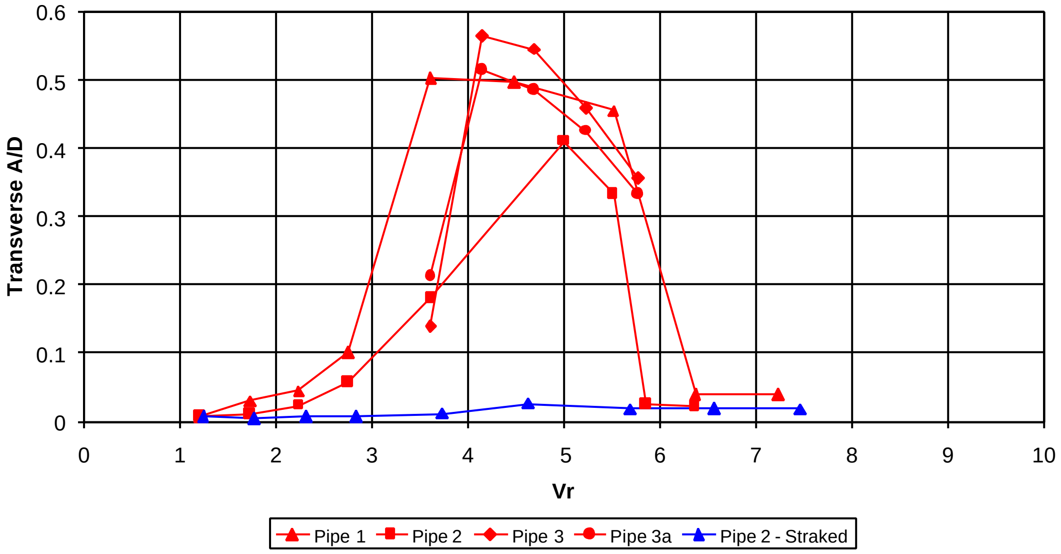


Fig. 4 - Reduced scale tests: cross-flow response at mid point of bare and straked models at *30°* inclination vs. reduced velocity.

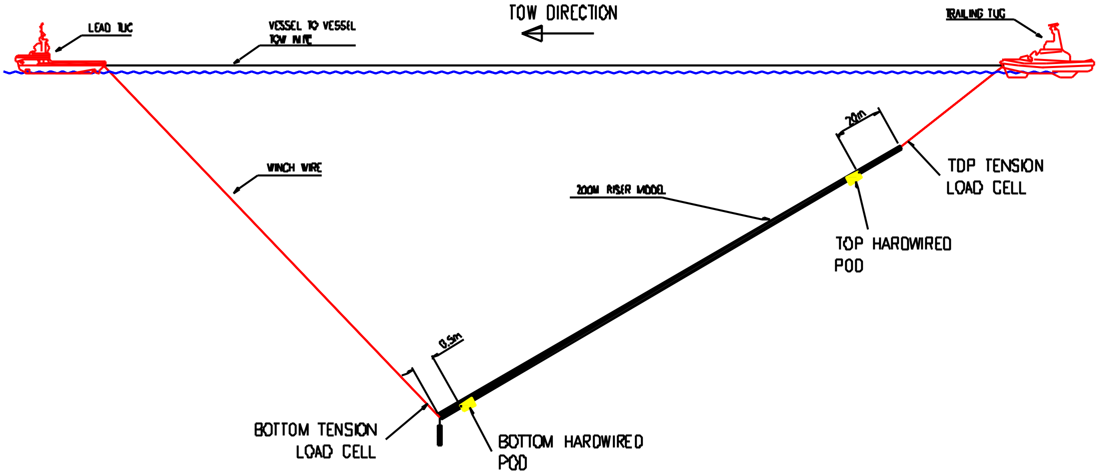


Fig. 5 - Full scale tests: tow set-up.

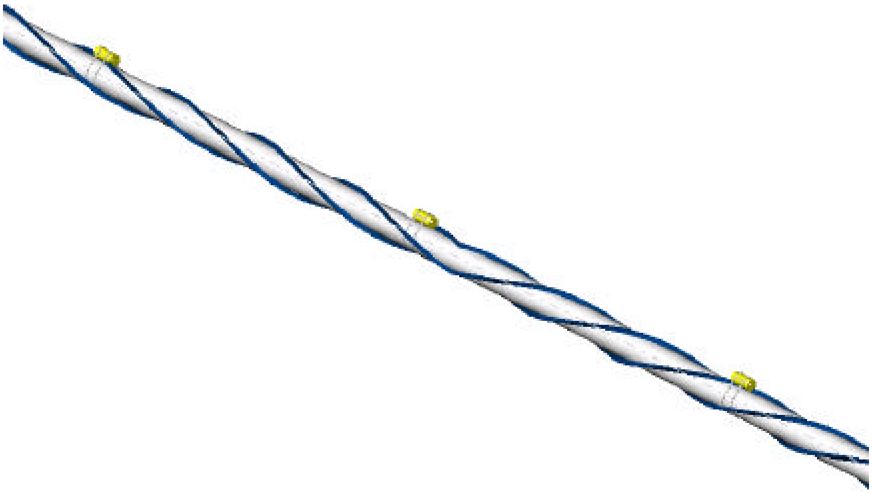


Fig. 6 - Full scale tests: strake *handing.*

Fig. 7 - Full scale tests: accelerometer data logger.

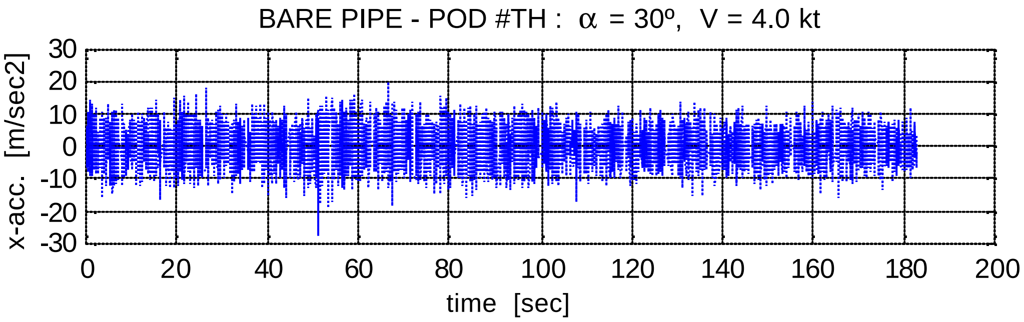


Fig. 8 - Full scale tests: transverse acceleration measured by the top hardwired pod during the bare pipe model test at *30°* inclination and *4 knot* towing speed.

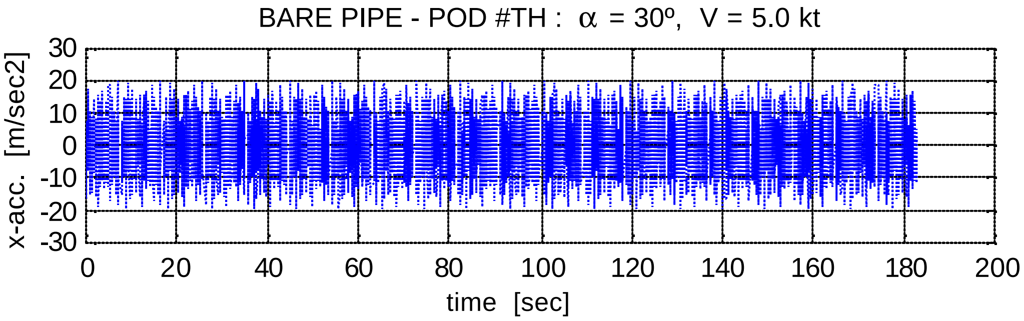


Fig. 9 - Full scale tests: transverse acceleration measured by the top hardwired pod during the bare pipe model test at *30°* inclination and *5 knot* towing speed.

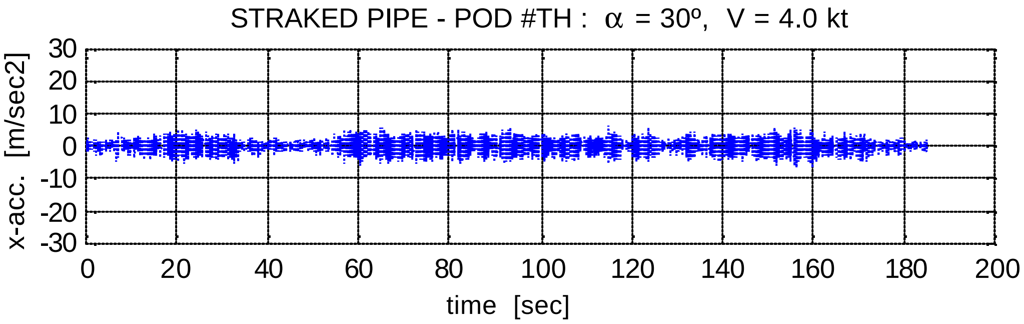


Fig. 10 - Full scale tests: transverse acceleration measured by the top hardwired pod during the straked pipe model test at *30°* inclination and *4 knot* towing speed.

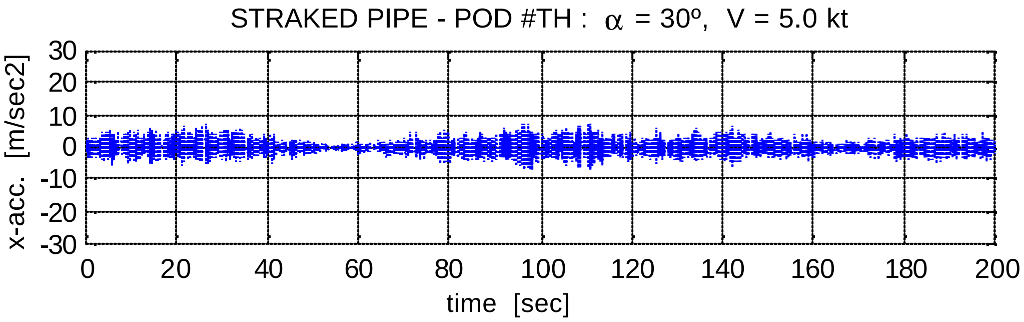


Fig. 11 - Full scale tests: transverse acceleration measured by the top hardwired pod during the straked pipe model test at *30°* inclination and *5 knot* towing speed.