Introduction

The offshore industry is heavily involved in the development of discoveries in deep- and ultra-deepwaters. These developments routinely involve a floating production facility and many utilise rigid steel risers in either vertically-tensioned free standing or catenary configurations. During their life, such risers are subjected to:

- Static loads from the riser submerged weight and functional loads such as from the contents pressure and temperature
- Quasi-static loads, ie, characterised by medium-long periods, generated by ocean current variations/eddies and by surface vessel motions
- Dynamic loads generated by short period actions such as wave motion and vortex induced vibration.

These loads may lead to a critical situation within the riser as a result of over-stressing, buckling, brittle fracture or fatigue failure. Consequently, it is essential that all loadings on the riser system are fully analysed to identify potential failure modes and to establish riser design criteria which minimise such risk.

In particular, vortex-induced vibrations can be severely detrimental to the integrity of slender tubular elements such as risers due to the severe fatigue impact associated with the cyclic stresses resulting from large amplitude vibrations.

Vortex induced vibration

What is VIV?

Vortex-induced vibration (VIV) occurs when the shedding frequencies of vortices generated by the current flow around the riser are able to interact or 'lock-in' with one or more natural modes of vibration of the riser.

This lock-in results in high frequency stress reversals at right angles to the current flow and results in cyclic, large amplitude cross-current oscillations of the riser. The natural frequencies of a riser are a function of riser length, axial load and mass per unit length. As none of these factors are readily modifiable to adjust the riser natural frequencies, the focus of VIV mitigation is upon minimisation of vortex shedding and/or upon disorganising the creation and shedding mechanism.
What are the risks from VIV?

The shedding of the vortices causes a forced vibration to the riser which critically decreases its fatigue life. The amplitude of vibration will resonate when the vortex shedding frequency is in line with the natural frequency of the riser system.

Riser system failure will be caused in a very short period of time due to severe fatigue damage while the vibration motion also significantly amplifies the global drag force of the riser system. Static stress and local buckling will be adversely affected due to the increase in drag. Since the fatigue life is related to static stress, the fatigue capacity of the riser system will also be adversely affected.

What options are available for VIV mitigation?

The principles behind current VIV mitigation devices are to mitigate the vortex shedding forces by minimising vortex formation and by disorganising the residual vortex shedding process. Current industry practice for VIV mitigation involves two approaches:

- Fairings. Streamlined fins which produce a smooth hydrodynamic shape on the riser and thereby modify and stabilise the confluence point at which the two entrainment layers from either side of the riser meet and interact.
- Strakes. The provision of fins or other protrusions on the riser surface with the intention of creating a turbulent transition of the boundary layer and disorganisation in the wake.

Each system has its own particular advantages and disadvantages. Strakes are simple, low-cost, easy-to-install, risk-free devices which are highly efficient in VIV mitigation efficiency but which create additional hydrodynamic drag.

Fairings give maximum possible VIV mitigation with lower drag than strakes. They are however expensive to manufacture, unwieldy to install, prone to storm damage and, not being omni-directional, are at risk of locking in a cross-current orientation in the event of failure of the weather-vaning bearings.

Strakes are the current industry standard solution for VIV mitigation.

VIV suppression strakes

Overview

VIV suppression strakes conventionally comprise a cylindrical body surrounding a riser with typically three triangular or trapezoidal profile helices on the riser outer diameter. Straps are employed to secure the system onto the riser.

Typical strake manufacturing options include injection moulding, rotational moulding and polyurethane (PU) casting, depending on the total quantity, service requirement, proposed installation method and lead time.

General construction

For efficiency of delivery packaging and ease of installation, there are typically three panels per riser circumference and the axial length is typically 1.4 metres. VIV suppression strakes will be secured by 3-4 titanium or Inconel bands, the number of bands depending on the riser outer diameter and the length of the product.

Mode of action

As observed from a bare riser, the initially symmetrical flow will develop to a highly fluctuating flow which will cause severe vibration. VIV suppression strakes are designed to promote flow separation at the tip of the strakes regardless of the flow direction. The locations of the tips induce consistently asymmetric flow, which disorganises vortex shedding and thereby minimises vortex-induced vibration. Hence, the arrangement of three helices is the most effective solution.
VIV suppression efficiency, drag and lift

As proven in tank tests, the suppression efficiency of Balmoral VIV suppression strakes exceeds 90%. The overall drag (CoD) is approximately 1.6.

VIV suppression strake design

Key features: pitch, height, shape

The fundamental parameter is hydrodynamic diameter, D, which is typically the riser outer diameter in addition to the material thickness of the strake body. Since the hydrodynamic diameter indicates the actual wet circumference, D is the reference dimension of most of the other parameters and engineering coefficients.

The primary design parameters are pitch length and strake height. The pitch length is the length of one complete helix turn, which is usually 15D - 15 times the hydrodynamic diameter - to 17D for riser application and 5D for buoyancy modules and large structures. Strake height is the height of the strake profile of the helix in the radial direction, which is typically 0.2D.

The shape of the strake profile is typically triangular or occasionally trapezoidal. Generally speaking, triangular profile is more efficient and provides lower drag and higher VIV suppression efficiency.
VIV suppression strake design software
The leading VIV response prediction software is 'Shear 7', which carries out a global analysis of the fatigue damage rate and the drag implication due to VIV on risers.

In order to carry out a more detailed fluid analysis, Balmoral has adopted a computational fluid dynamics (CFD) package, ‘ANSYS CFX’. Flow characteristics in a relatively microscopic level, such as flow separation and vortex shedding, are easily simulated and visualised allowing Balmoral to optimise the product design with respect to fluid dynamic performance.

On the structural side, a finite element analysis (FEA) package, ‘ANSYS Workbench’, has been adopted to verify the tensioning system which ensures that VIV suppression strakes will not slip throughout the entire service life, even in the event of riser coating diameter reductions as a result of creep.

Balmoral computational capacity is extended to fluid-structure interaction (FSI), which is a combined application of FEA and CFD. Typical one way FSI application includes transferring hydrodynamic pressure due to impact of ocean current from CFD simulation to FEA simulation for stress analysis. Two-way FSI simulation is a feedback loop between FEA and CFD, ie, feeding hydrodynamic load from CFD to FEA, then feeding structural deformation from FEA back to CFD.

The velocity contour and velocity vector shown in figures 3 and 4 are typical CFD output enabling the visualisation of the flow pattern, ie, flow separation at the tip of the strake and wake behind the riser.

Coefficient of drag and pressure distribution is also easily computed.

Effect of strake fin features on suppression efficiency, drag and lift
Other than the critical feature, strake height, the strake profile is also driven by the base ratio and the tip fillet of the strake profile. The base ratio is the base width of the profile which is perpendicular to the strake height. Typically, base ratio would be ideally below half of the strake height to ensure flow separation.

Similarly, the tip fillet has to be optimised.

Generally speaking, decrease in strake height would lead to decrease in drag and decrease in VIV suppression efficiency. The combination of strake height of 0.2D, base ratio of 0.5SH and tip fillet of 0.05SH will strike the optimum balance between drag and VIV suppression efficiency.

Attachment system design
The VIV suppression strake is secured with titanium or Inconel banding due to their superior corrosion resistance and strength properties. Installation loads would be carefully calculated to ensure the system will not slip along the riser due to hydrodynamic force, riser contraction, material creep and material shrinkage due to temperature change and hydrostatic pressure.

Banding specification may be defined by project requirements.
Materials used in strake construction
Depending on the manufacturing process, the material options are polyethylene (PE) or polyurethane (PU). The actual grade of material may be specified by the client or selected by Balmoral to suit project service requirements, installation method and required quantities.

Accommodation of riser diameter variation
The required circumferential clearance between individual strake panels is calculated to allow for manufacturing tolerance of the riser and service life coating diameter changes. This clearance ensures that strake panels do not overlap during installation and ensures the strakes do not slip during service life.

Adaptability
Balmoral’s VIV suppression strake design can accommodate local diameter changes resulting from field joint coating over-builds, for example. The Balmoral strake design can also be incorporated into other Balmoral products including buoyancy modules, insulation covers, and pipeline protection systems.

VIV mitigation becomes even more crucial when the hydrodynamic diameter increases due to attached components.

Fin alignment
The spigots on the ends of the assembled strake panels are carefully engineered to ensure the helices are continuous along the riser in order to ensure that overall drag is minimised and VIV suppression efficiency is maximised.

Strake coverage
Strake coverage is usually determined by the client depending on the dynamic riser analysis.

Prevention of marine biofouling
Biofouling is the deposition and development of marine organisms of all sizes and types upon a submerged substrate such as a VIV mitigation strake.

Depending upon local environmental conditions including water temperature, salinity, flow patterns, light levels, nutrient concentration, etc, the fouling layer may contain microfoulers such as bacteria, fungi and algae and macrofoulers including hydroids, seaweeds, molluscs and barnacles.

The nature and extent of biofouling varies with water depth: hard fouling such as barnacles and molluscs typically occurs, often in massive thicknesses, from the splash-zone to 30-60msw whilst soft fouling, such as algae and bacterial slimes, predominate in the 60-120msw depth band. Biofouling beyond 120msw is only observed in exceptional situations, such as in the localised regions where deepwater corals such as Lophelia pertusa occur.

The normal mode of action of antifouling coatings is to prevent the initial deposition of the microbial biofilm which facilitates subsequent settlement and attachment of macrofouling organisms. There are two recognised approaches to antifouling which are relevant to the low current velocity environment of a steel catenary riser:

- Toxic surface, onto which biofouling species cannot attach and survive. Toxic surface systems do not release significant concentrations of toxic species into the marine environment.
- Biocide slow release coatings, where the binder resin slowly dissolves or hydrolyses to release a biocidally-active chemical into the immediate near-surface environment.
Balmoral provides coatings of both types: its own toxic surface system ‘Balmoral CuNiClad™’, based on copper-nickel granules, and a proprietary biocide slow release system, Jotun SeaQuantum Ultra S’. The choice between these systems is primarily based on client preference and local environmental restrictions. Both systems are capable of providing 25 year, maintenance-free antifouling service.

**Design for abrasion service**

In the vast majority of service situations, VIV mitigation stakes are not subjected to abrasive contact with the external environment. The only service condition where abrasion may need to be considered is for VIV strakes installed on the touchdown section of the riser. Where the seabed at the touchdown location is comprised entirely of colloidal clays, no special consideration is usually given to potential abrasion. Where the seabed is of coarse sand, is rocky or includes deepwater corals such as *Lophelia pertusa*, then abrasion resistance may drive material selection.

As the touchdown zone is relatively short in length, premium materials with recognised superior abrasion resistance are routinely used. High abrasion resistance PU elastomers of the types typically used for abrasion protection of flexible flowlines are normal for this type of service.

**Strake design and material selection for S-lay**

The majority of risers with VIV mitigation strakes are now installed either by J-lay or reel-lay. In both of these situations the strakes are subjected to, at most, minor mechanical loadings from rollers, etc.

Spool-pieces carrying VIV strakes are normally craned into position so, again, mechanical loadings from installation equipment are minimal. In all of these cases no special consideration requires to be given to VIV strake design or material selection to accommodate installation.

There remains, however, a minor but still significant percentage of strake-carrying risers which are installed by S-lay. With this installation method significant, sometimes massive, loadings are exerted upon the VIV strakes by the stinger roller boxes. These potentially damaging loadings are accommodated in the strake design process by:

- **Design of the strake fin.** The standard hollow triangular fin on roto-moulded LLDPE and injection-moulded HDPE may suffer irreversible distortion and possible splitting from the compressive loadings exerted by the stinger rollers. Narrowing the fin width down to the narrow trapezoidal design allows the fin to fold over under roller loadings. Under normal circumstances the fin will recover to essentially its original configuration. Triangular fins manufactured from polyurethane elastomer are more tolerant of stinger roller loadings however even here it is standard practice to utilise a narrow trapezoidal fin and to design the strake body to facilitate fin fold over.

- **Selection of strake material.** The material property requirements of particular importance in accommodating stinger roller loadings include high tensile strength, high elongation at break/yield, high flexural strength, high tear strength, good abrasion resistance and good resilience. In all of these requirements, elastomeric materials typically exhibit superior performance to polyolefin thermoplastics. Standard and high abrasion resistance polyurethane elastomers are suitable for S-lay VIV strakes. Where massive strake quantities mitigate against the use of polyurethane, plastomer thermoplastics, processed by injection moulding as per HDPE, may be used. These materials have flexural properties comparable with EPDM rubbers and are characterised by outstanding toughness and flex-cracking resistance.
Material qualification

International standards
There are no international standards directly relating to the qualification of materials for VIV suppression strakes. Individual operators or main contractors generally identify the testing requirements in project documentation.

In many cases the testing requirements are based on those given in API Spec 17L1- ‘Specification for flexible pipe ancillary equipment’, or its draft ISO equivalent ISO/DIS 13628-16, Sec 22 ‘Mechanical protection systems’, even though VIV suppressions strakes are currently only used on rigid piping.

The API Specification 17L requirements are supplemented by testing specifically relevant to VIV suppression strakes in fatigue resistance, for example, or project-specific requirements including antifouling system performance and adhesion.

Balmoral has qualified its VIV strake materials against a master schedule compiled from testing requirements in API Spec 17L1 Sec 22 and all client VIV suppression strake specifications received to date.

Short term properties for each of the candidate materials for Balmoral VIV mitigation strakes are shown in table 1 overleaf.
Table 1: Short-term material property summary

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<tr>
<td>1</td>
<td>Density</td>
<td>Room temp 23 ± 2ºC</td>
<td>ISO 1183-3 1999 Methods for determining the density of non-cellular plastics - Part 3: Gas pyknometer method</td>
<td>1149 kg/m³</td>
<td>1116 kg/m³</td>
<td>956 kg/m³</td>
<td>917 kg/m³</td>
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<td>Hardness</td>
<td>Room temp 23 ± 2ºC</td>
<td>ASTM D2240 Standard test method for rubber property - Durometer hardness</td>
<td>85 Shore A</td>
<td>85 Shore A</td>
<td>62 Shore D</td>
<td>55 Shore D</td>
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<td>Resilience</td>
<td>Room temp 23 ± 2ºC</td>
<td>D 2632-96 Rubber property resilience by vertical rebound</td>
<td>35%</td>
<td>24%</td>
<td>22%</td>
<td>16%</td>
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<td>Melting point</td>
<td>N/A</td>
<td>ASTM D3418-03 Transition temperatures and enthalpies of fusion and crystallization of polymers by differential scanning calorimetry</td>
<td>N/A for PU</td>
<td>N/A for PU</td>
<td>139ºC</td>
<td>135ºC</td>
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<td>5</td>
<td>Tensile strength</td>
<td>Various temps 4/RT/40/70/90ºC</td>
<td>(1) ISO 37 Rubber, vulcanized or thermoplastic - determination of tensile stress - Strain properties (2) BS EN ISO 527-2 Determination of tensile properties</td>
<td>Standard used (1) 13.0 MPa at 4ºC 12.0 MPa at 23ºC 13.0 MPa at 40ºC 11.0 MPa at 70ºC 10.0 MPa at 90ºC</td>
<td>Standard used (1) 14.6 MPa at 4ºC 18.3 MPa at 23ºC 16.6 MPa at 40ºC 16.9 MPa at 70ºC 15.1 MPa at 90ºC</td>
<td>Standard used (2) 24.0 MPa at 4ºC 22.0 MPa at 23ºC 16.0 MPa at 40ºC 10.0 MPa at 70ºC 7.0 MPa at 90ºC</td>
<td>Standard used (2) 14.4 MPa at 4ºC 11.9 MPa at 23ºC 8.9 MPa at 40ºC 7.2 MPa at 70ºC 5.2 MPa at 90ºC</td>
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<td>6</td>
<td>Tensile EAB</td>
<td>Various temps 4/RT/40/70/90ºC</td>
<td>(1) ISO 37 Rubber, vulcanized or thermoplastic - determination of tensile stress - Strain properties (2) BS EN ISO 527-2 Determination of tensile properties</td>
<td>Standard used (1) 172 % at 4ºC 168 % at 23ºC 196 % at 40ºC 179 % at 70ºC 143 % at 90ºC</td>
<td>Standard used (1) 228 % at 4ºC 407 % at 23ºC 358 % at 40ºC 387 % at 70ºC 371 % at 90ºC</td>
<td>Standard used (2) 9% at 4ºC 11% at 20ºC 11% at 40ºC 11% at 50ºC 10% at 90ºC</td>
<td>Standard used (2) 11 % at 4ºC 12 % at 20ºC 16 % at 40ºC 42 % at 70ºC 44 % at 90ºC</td>
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<td>7</td>
<td>Tensile modulus</td>
<td>Various temps (See results) 4/RT/40/70/90ºC</td>
<td>(1) ISO 37 Rubber, vulcanized or thermoplastic - determination of tensile stress - Strain properties (2) BS EN ISO 527-2 Determination of tensile properties</td>
<td>Standard used (1) 16.0 MPa at 4ºC 16.0 MPa at 23ºC 15.0 MPa at 40ºC 16.0 MPa at 70ºC 17.0 MPa at 90ºC</td>
<td>Standard used (1) 12.6 MPa at 4ºC 12.1 MPa at 23ºC 15.6 MPa at 40ºC 14.2 MPa at 70ºC 14.2 MPa at 90ºC</td>
<td>Standard used (2) 1603 MPa at 4ºC 1446 MPa at 20ºC 980 MPa at 40ºC 511 MPa at 70ºC 298 MPa at 90ºC</td>
<td>Standard used (2) 666 MPa at 4ºC 526 MPa at 20ºC 314 MPa at 40ºC 238 MPa at 70ºC 154 MPa at 90ºC</td>
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<td>Tear strength</td>
<td>Various temps (See results) 4/RT/40/70/90ºC</td>
<td>BS ISO 34-1 2004: Rubber vulcanised or thermoplastic – Determination of tear strength – Pt 1 Trouser, angle &amp; crescent test pieces</td>
<td>63 N/mm at 4ºC 46 N/mm at 23ºC 41 N/mm at 40ºC 37 N/mm at 70ºC 32 N/mm at 90ºC</td>
<td>58.0 N/mm at 4ºC 57.0 N/mm at 23ºC 53.5 N/mm at 40ºC 50.2 N/mm at 70ºC 37.2 N/mm at 90ºC</td>
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<td>Compressive strength</td>
<td>Room temp 23 ± 2ºC</td>
<td>ASTM D695 Standard test method for compressive properties of rigid plastics, compressive properties, compressive strength, modulus of elasticity, plastics</td>
<td>N/A for flexible (High elongation PU's)</td>
<td>N/A for flexible (High elongation PU's)</td>
<td>24 MPa</td>
<td>11 MPa</td>
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<td>Compressive strain</td>
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<td>N/A for flexible (High elongation PU's)</td>
<td>N/A for flexible (High elongation PU's)</td>
<td>18%</td>
<td>16%</td>
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<tr>
<td>11</td>
<td>Compressive modulus</td>
<td>Room temp 23 ± 2ºC</td>
<td>ASTM D695 Standard test method for compressive properties of rigid plastics, compressive properties, compressive strength, modulus of elasticity, plastics</td>
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<td>N/A for flexible (High elongation PU's)</td>
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<td>Abrasion resistance</td>
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<td>Taber H22 1000g = 21.4mg loss DIN 165 mm³ - loss dry DIN 160 mm³ - loss wet</td>
<td>23ºC Taber H22 - 1000g 15 mg loss</td>
<td>4 mg loss  H22 500 cycles, 1000 g</td>
<td>24.2 mg Loss H22 500 cycles, 1000 g</td>
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<td>Charpy impact strength</td>
<td>Room temp 23 ± 2ºC</td>
<td>ISO 179-1-2010 Determination of Charpy impact properties</td>
<td>N/A for flexible (High elongation PU's)</td>
<td>N/A for flexible (High elongation PU's)</td>
<td>4 kJ/m²</td>
<td>90 kJ/m² (BGLR 1401)</td>
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