Update on the Design of Steel Catenary Riser Systems

S. Hatton

UPDATE ON THE DESIGN OF STEEL CATENARY RISER SYSTEMS

By Stephen A Hatton, 2H Offshore Engineering Ltd

Introduction

The concept of the steel catenary riser is now well established in the industry. The technology has advanced through numerous studies and JIPs and there are now 4 installations, with more planned in Brazil and Gulf of Mexico in the near future. Steel catenaries are believed by many in the industry to be cost-effective riser solutions that enable deepwater developments. But how mature is the technology? What are the key design issues? How does it compare against competing technologies and what are the future development requirements of the technology?

The steel catenary concept is inherently simple. Lay a pipeline on the seabed and simply pick up the end and connect to the production vessel forming a free hanging 'simple' catenary. The beauty of this concept is that it allows the pipeline to be extended to the vessel using standard grade steel, which is cheap. Additionally the riser can be installed using the same lay vessel as the pipeline, saving a dedicated mobilisation.

This arrangement may lead people to the conclusion that deepwater riser systems will in fact be simpler and cheaper than shallow water systems where costly flexible pipe must be considered. However, when steel catenary arrangements are engineered at a detailed level a more complex and costly design emerges. Key issues such as VIV, TDP interaction, thermal insulation/process flow assurance and requirements for weld and inspection quality can cause significant technical complication.

The STRIDE (Steel Risers for Deepwater Environments) JIP was established in 1997 by 2H Offshore Engineering with the objectives of better understanding key issues. The JIP is supported by 20 participants and has been funded to a total of $2.5million. The scope of the JIP covers the following activities:

- Riser basic sizing and parametric studies
- Global analysis methods
- Codes and Standards
- Installation methods
- VIV analysis and testing
- Touch down point analysis methods and testing
- Material assessment and fabrication requirements

The initial thrust of the JIP was aimed at large diameter risers and extreme environments such as West of Shetland. However, this has now been extended to other environments such as West Africa where there is considerable industry interest.

Author Summary

Stephen Hatton is a graduate of Newcastle Upon Tyne University and has 15 years experience in subsea equipment and riser systems design. He worked for Cameron Offshore Engineering for 7 years where he was Engineering Manager and was involved in the design of subsea trees, manifolds, flowline connection systems TLP, drilling and workover riser systems.

In January 1993 he was jointly responsible for establishing 2H Offshore Engineering where he has continued his involvement with riser systems design and analysis. 2H Offshore Engineering is an independent Engineering consultancy that specialises in riser system design and particularly the development of riser systems for deep and ultra deep water floating production.

Learn more at www.2hoffshore.com
Basic Sizing and Codes and Standards

There are two principle steel catenary riser configurations, see Figure 1 and 2: the Simple Catenary Riser (SCR) and the Wave Catenary Riser (WCR). The former is used for TLPs and Spars where motions are small or for other vessel types where the environment is very mild. The WCR is proposed for catenary moored vessels such as FPSO and may be configured even for environments such as found West of Shetland.

Recommendations for initial pipe sizing of these systems generally follows that used for flowline and pipeline systems [1,2] covering burst, collapse and buckling criteria. However, due to the dynamic nature of these systems, wall thickness increases are often required, to increase the weight in water, to achieve an acceptable response. This is particularly the case for harsh environments and where significant vessel motions are expected.

Basic configurations may be established by considering the near case loading condition i.e. when the vessel is offset closest to the TDP. The riser length may be estimated using simple geometric considerations.

Simple Catenary Riser

- Total Riser Length = \((\text{Water Depth} - \text{MBR} \times A) / \cos \theta + (0.5 \times \pi \times \text{MBR} \times A)\)

Wave Catenary Riser

- Total Riser Length = \((\text{Water Depth} - \text{MBR} \times A) / \cos \theta + (2.5 \times \pi \times \text{MBR} \times A)\)
- Start of Riser Buoyancy = \((\text{Water Depth} - \text{MBR} \times A) / \cos \theta + (\pi \times \text{MBR} \times A)\)
- Buoyancy Length = \((\pi \times \text{MBR} \times A / 2)\)
- Buoyancy Upthrust = \(2 \times (\text{Pipe} + \text{Contents Weight})\)

Notes

- \(A = \) a factor between 1.0 and 1.2 depending on severity of environment (1.0 for mild environments and 1.2 for severe environments)
- \(\theta = \) Riser top angle to vertical, typically between 10 and 20 degrees depending on severity of environment and water depth
- \(\text{MBR} = \) minimum bend radius based on 80% material yield strength (typically API grade X65-N80)
- An additional pipe length of approximately 750m should be included in both cases to allow for TDP movement between near and far offset conditions.

Global Analysis Methods

Analysis of steel catenary risers should be conducted using a time domain FE program. This is necessary as a result of the complex non-linear behaviour of these systems. Areas of particular interest are the touch down point and the connection to the vessel. The designer should establish a load case matrix considering combinations of current, waves, vessel motions and offsets, riser contents, operating pressures and ensure that for all load cases riser response is within code limits. This assessment may be conducted using regular or random sea analysis methods.

It is normal that following preliminary analysis, optimisation of the initial configuration is required. With an SCR changing the wall thickness, top angle, material grade may be considered. With the WCR, the size and distribution of the buoyancy can also be considered. Of course wall thickness and material variations can be considered locally rather than along the whole riser length.
At the TDP and in the sag and arches of the WCR, extreme stresses are often bending dominated, particularly for near case load condition. It has been normal practice to limit extreme storm equivalent stresses to 0.8 of yield. However, as a large proportion of the riser stress at these locations is displacement controlled and are self limiting, i.e. local yielding relieves the condition that causes the stress, API and DnV allow higher secondary bending stresses to be considered.

Following storm analysis, a fatigue assessment should be conducted. Establishing the fatigue life of a catenary riser is not trivial. The analysis is best conducted in the time domain to account for non-linear effects and must take into account issues such as seabed interaction and environmental directionality. In addition to the first order fatigue, damage due to second order vessel motions and VIV must also be established. VIV damage is an area of some uncertainty and is an area of investigation in the Stride JIP.

**VIV Analysis**

Cross-flow vibration of risers in steady current flow is an important factor in the design of all rigid riser systems. Flow past a riser pipe can shed alternating vortices that put an oscillating force on the riser. If the shedding frequency is similar to a natural vibration frequency of the riser, the riser may resonate, leading to high fatigue damage. This is true of all marine risers in currents, and catenary risers have the added complication that they present a variety of angles to incident current, and can resonate at a large number of closely spaced current speeds.

High levels of VIV fatigue damage can be accumulated in relatively short periods of time in the severe currents encountered in most of the deepwater development areas world-wide. Suppression devices, such as helical strakes or fairings may be needed to prevent unacceptable levels of fatigue damage. These devices can have a significant influence on riser cost both in terms of materials and installation time. Reliable predictions of VIV response are needed to ensure that premature failures do not occur and that undue expense in specification of suppression devices is not incurred.

**VIV Analysis Methods**

A detailed review of current VIV analysis methods is given in reference [3]. Of these methods, only a few are commercially available to the riser designer, including the DnV Rules [2] and the analysis programs SHEAR7 [4] and VIVA both developed at MIT under separate JIP's. The guidance provided by DnV enables prediction of the response of uniform risers in uniform current flows. This approach is unsuitable for many developments where highly sheared current profiles are experienced. The program SHEAR7 accounts for variation in current speed through the depth and enables prediction of multi-mode VIV response of a uniform riser in sheared or uniform current and has been extensively validated using model tests. While SHEAR7 was developed for analysis of nominally straight, top-tensioned risers, such as drilling risers and TLP production risers, it is also considered applicable to steel catenary risers. Though some inaccuracies may exist at low modes of vibration, the program is considered suitable for prediction of higher mode response which generally produce the greatest contribution to fatigue damage. The most recent technique to become commercially available is the programme VIVA, also developed at MIT. This can account for the effects of varying riser section along the length, and is currently being validated using tank test data.

In order to obtain estimates of long term VIV fatigue damage, analysis must be conducted with a number of current profiles of varying severity, typically based on exceedence level. The fatigue damage obtained assuming continuous application of each profile is then factored according to the assumed duration of the profile, and the total long term damage is given by the sum of the factored damage from each profile. As the more severe current profiles generally produce greater rates of fatigue damage, a more refined selection of profiles is required amongst the low exceedence levels.

Whilst VIV is recognised as a significant problem area, the confidence levels in the available prediction tools is limited. This arises from software limitations, which cannot handle:

- Change in incidence angle along length
- Changes in structural properties with depth
- Change in buoyancy diameter along risers
- Non-monotonic current distribution
- Current direction variation with depth
• Seabed interaction
• Strake design and effectiveness
• Vessel motions and riser tension variation
• Wave loading

In each of the above areas, the riser designer must make simplifying assumptions in order to produce estimates of VIV response. Out of necessity, such assumptions must err on the side of conservatism. However, due to the lack of available data the levels of conservatism may not be understood even when parametric analysis is conducted, and enhancements to analytical tools are needed in order that these uncertainties can be quantified and undue conservatism avoided. As part of the STRIDE JIP VIV tank testing and large scale open water testing have been conducted with the objective of better understanding riser VIV response and qualification of VIV prediction codes.

VIV Tank Testing

A test program was initiated to look at the VIV response of cylinders at different angles to incident water flow, and the success of vibration suppression devices at the different angles.

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. 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, Figures 3, 4 and 5. 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. The model cylinder was towed at different constant speeds to establish the variation in reduced velocity.

Each model “riser” was made of glass reinforced plastic (GRP) of outer diameter 0.152 m (6”) and length 6 m. The pipe was practically neutrally buoyant. 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, and this was monitored and recorded by a pressure transducer near the cylinder. The hydraulic system included a nitrogen accumulator to maintain a near constant mean tension on the pipe regardless of pipe deflection due to drag, or VIV.

The pipes were fitted with strain gauges and accelerometers that could monitor both in-line and cross-flow vibration. Where possible, wiring and instrumentation were placed along the lee side of the pipe to avoid interference with the flow over the pipe.

Drag was measured using displacement block gauges at each end of the test pipe.

Tests for both the bare and straked pipes were performed at pipe inclination angles of 0°, 15°, 30° and 45°. Angles are defined with respect to the normal to the flow, i.e. 0° is modeling a vertical section of the riser in a horizontal current. At each angle, a set of tows was performed at different velocities, typically from 0.6m/s to 4.5m/s, corresponding to Reynolds between 0.8x10^5 to 6.1 x 10^5, which spans the critical Reynolds regime.

VIV Tank Testing - Results and Conclusions

Certain results and conclusions are restricted within the JIP agreement. Others are detailed below:

• The pipe was excited in first and second modes at frequencies corresponding with analytical prediction

• The results suggest that it is reasonable to take the flow at an angle and resolve it normal to the pipe for angles up to 30 degrees on the bare pipe. This was not apparent at 45°, where VIV amplitude response was larger than on all other tests. This may have been due to rig end effects, which was one of the reasons for the large scale tests described below (open water tests).

• The mean drag coefficient, averaged over the whole test pipe, varied from 1.5 to 0.3 over the velocity range, indicating the critical Reynolds number regime. The straked riser mean drag coefficient was found to be between 1.35 and 1.6 for all tests.
• The strake configuration used was effective at suppressing mode 1 VIV, providing 95% amplitude suppression for all angles within current simulations up to 2.5m/s.

• The strake effectiveness was found to increase at the higher angles, in contradiction to the findings of other investigations.

• Single hand rotation helical strakes can provide a significant torque as riser angle increases. This could provide a displacing force on a catenary shaped riser.

Open Water Test Programme

Further to the tank testing program an ambitious open water test program has been completed in December 1998.

The objectives for this test program were as follows:

• Evaluate the VIV response of a long pipe string (200m) at high Reynolds numbers (to $5 \times 10^5$) at different angles of inclination to the current.

• Investigate response at high angles of incidence up to 75 degrees.

• Determine response of curved risers e.g. catenary shapes.

• Determine effect of tension variation due to first order vessel motion.

The above data is intended to allow the following:

• Provide data to benchmark VIV prediction software.

• Better understanding of strake design and coverage requirements.

• Development of VIV design guidance.

• Optimisation of STRIDE Phase I riser configurations.

Once again the current was simulated by towing the riser in still water. To obtain sufficient water depth without significant ambient currents, the testing was performed in Bokna Fjord in Norway.

The test arrangement is illustrated in Figure 6, with a 200m riser towed between 2 tugs and rigged to allow a variety of angles and catenary shapes to be configured. 2 Pipe strings were tested, each welded from 10.75” OD, 3/8” wall steel pipe.

One of the pipes was fitted with VIV suppression strakes, the other left bare. The strake profile was scaled on the successful profile used for the 6” Tank Tests tests at Haslar, but configured to provide a 3-start helix with 15D pitch, which has previously been shown to be effective for multi-mode VIV suppression on vertical tubulars.

In order to monitor loads and vibration on test, each pipe was fitted 2H data logger units fixed at 40 locations along each pipe, positioned on the lee side from the incident flow, Figure 7. These are stand-alone devices and log time, temperature, and tri-axial acceleration at 5-10Hz. Two of these loggers were also hard-wired back to the rear tug to be monitored on line. Stand alone loggers were required because of the amount of data to be simultaneously recorded, and the impracticality of logging this at the station on the tug. They also minimised the hard-wiring and umbilical requirements, and improved the level redundancy in the system.

This data is currently being back-analysed and will provide a better understanding of riser VIV response and allow validation of VIV prediction software. The work will allow a higher level of design confidence, meaning less conservative and lower cost riser designs.

Design for Thermal Insulation

The need for high levels of thermal insulation on deepwater risers has only recently become fully apparent. The increasing use of subsea completions tied-back, often many kilometres, to FPSO’s requires careful attention to process flow assurance in order that arrival temperatures and transient cool-down duration are achieved. This is necessary to prevent hydrates and wax deposition. Recent projects have rejected the use of steel catenary risers in preference to hybrid risers, which although
much more costly than a simple catenary, offer very high levels of thermal insulation due to the large volume of syntactic foam.

Experience shows that often 50-100mm thickness of a good quality thermal insulation coating (<0.6 W/mK) is required to achieve realistic levels of thermal performance. Alternatively, there is increasing consideration given to pipe-in-pipe riser systems where an annulus between an inner and outer pipe is filled with a thermal insulating material. However, both these arrangements can have problems achieving acceptable dynamic response due to the relatively light weight in water and high drag diameter of these systems.

The effect of thermal insulation coatings has been the subject of a number of studies which conclude that peak stresses at the critical TDP increase 15-30% for SCRs and 10-15% for WCR for a 50mm thick thermal coating. Consequently, if high thermal insulation levels are required, a thicker riser wall may be required simply to increase the riser weight in water. Whilst steel is relatively cheap, the main problems are a reduced ID which may require the use of a larger OD and higher welding and installation costs. Additionally, the cost of the thermal insulation material is high.

It is concluded that the specification of thermal coatings must be carefully considered requiring an optimum combination of coating density, thickness and heat transfer coefficient along the riser length.

**Riser Seabed Touch Down Point**

The response of the riser at the seabed touch down point (TDP) and the interaction with the seabed is complex. Until recently most analysis was conducted assuming the seabed is rigid or that it exhibits a linear stiffness. However, these assumptions are not necessarily conservative. There is evidence that risers can trench to significant depth, 2-3 diameters, in certain conditions. The formation of the trench is not well understood but is thought to be a combination between soil deformation and remoulding, soil liquefaction and sediment transport. Once a trench is formed there is a possibility that the trench may back fill burying the pipe and over time consolidate. Subsequent extreme vessel offsets may then result in higher stresses to that calculated on a rigid seabed since the pipe must be sheared out of the soil and additionally high suction forces may need to be overcome. This concentrates curvature immediately above the TDP causing higher stresses resulting in possible overstressing and higher fatigue damage rate.

Understanding of the above problem is compounded by the many different seabed conditions, vessel motion characteristics, riser type and environmental conditions. The net effect is that it is currently difficult to accurately quantify these effects. Work is ongoing in STRIDE to investigate these effects both through analysis and testing techniques. A better understanding is required before we can confidently predict and optimise riser fatigue.

**Pipe Material and Welding Considerations**

Steel catenary risers are fatigue sensitive structures. To achieve required fatigue lives (10 times service life) high quality materials and fatigue details are required. Locations with minimum fatigue life are typically the welds near the TDP and for the WCR in sagbend and arch. Single side girth welds are used to connect the pipe sections. These have a fatigue performance equivalent to an F2 S-N detail however, there is only limited fatigue data for single-side girth welds of direct relevance to risers. Available data indicates that Class E S-N design curve may well be more appropriate but this relies on achieving a good quality weld root and good pipe-end alignment being maintained.

It should be appreciated that even with high quality NDT inspection experience shows that there is a 1 in 2 chance of missing a weld root flaw as big as 2mm deep by 12mm long. Such weld root defects will significantly reduce fatigue life. Automated tungsten inert gas weld roots (TIG or GTAW) are in general preferred to manual metal arc (MMA or SMAW) as riser weld fatigue failures would be expected to emanate from the weld root (ID) not the cap.

Reeling is seen to be a very cost effective method for SCR installation as is routinely used for steel flowlines. However, existing knowledge relating to fatigue and fracture performance of reeled pipe is very limited. Some experimental and predictive data on weld flaw extension during reeling is available,
but needs validation for catenary riser applications, which are higher strength and subject to greater weld/parent strength mismatch.

Significant plastic strain and weld/pipe strength mismatch are not currently accounted for in the industry design and assessment procedures. Data to confirm applicability in these conditions is needed. Residual stresses remaining in a reeled riser pipe are likely to be complex, and may effect fatigue and fracture performance.

A material documentation program is currently being conducted by TWI to investigate the effect of plastic deformation on the fatigue performance of welded joints. The material documentation program covers:

- Full scale fatigue tests on strained and unstrained welded pipes
- Fatigue tests on strip specimens taken from strained welded pipes
- Residual stress measurements on strained welded pipe
- Fatigue crack growth measurements on strained and unstrained welded pipe in air and product environments
- Measurements of weld flaw extension during reeling
- Material property changes as a result of straining
- Validation of flaw assessment procedures for high plastic strained welds and weld strength mismatch
- Definition of flaw acceptance criteria

An alternative to welding that is also currently being developed is that of threading the riser pipes together using casing or modified casing connections. Whilst these types of coupling have relatively high stress concentration factors (3.0-4.0), the elimination of welding allows B S-N curve to be adopted in the design process. Consequently, high fatigue lives can be achieved despite the high SCF. Additionally, the riser can be assembled quickly and reliably offshore using industry standard procedures.

Conclusions

The concept that steel catenary risers are simple low cost solutions for deepwater developments is unfortunately incorrect. It is true that they have the potential to be significantly cheaper than flexible risers and also that they extend the feasible diameter and depth ratios beyond what flexible risers can currently offer. However, the technology is neither mature nor simple. Whilst we continue to improve our technical capabilities and confidence levels, we still have much to learn. The participants involved in the STRIDE JIP have enthusiastically supported this process. However, it is true that installation of full scale risers may ultimately be the only way to answer some of the complex issues involved.

Whilst we are confident that current work on VIV, TDP and materials will ultimately lead to a better understanding and ability to better design and optimise steel catenary systems, thermal insulation requirements may be the factor that limits future applications, particularly for production riser applications. It is possible that acceptable thermal performance may be better achieved by application of active heating systems rather than insulation. This will require a further level of development particularly of pipe in pipe systems and lead to arrangements with increased cost and complexity.
REFERENCES


Figure 1 – Simple Catenary Riser

- Plan Length: 0.75-1.5 Depth
- Mean Top Angle: 10-25 degrees
- Simple Catenary
- TDP (Touch Down Point)

Figure 2 – Wave Catenary Risers

- Lazy Wave Catenary
Figure 3 – Tank Test Tow Rig at 45° Inclination

Figure 4 – Tank Tests - Straked Pipe
Figure 5 – Predicted Pipe Shapes (Flexcom3D)

Figure 6 – 2H Vibration loggers