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Design of Flexible Marine Risers in Deep and Shallow Water

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Abstract

This paper reviews the design methodology of marine riser systems and the analysis performed to substantiate the design corresponding to two field conditions in deep and shallow water.

The analytical and numerical tools adopted are capable of handling riser dynamic analysis for cases of survival, operation, interference, installation, and design life verification.

The results of computer analyses are presented in this paper in graphical form for the riser system selected in the two cases. Output includes envelopes of riser co-ordinates, axial force and time histories of forces and wave surface profiles. The obtained results highlight the significance of design parameters for the combined flow of waves and currents on the selection of riser configuration.

Introduction

The adoption of flexible pipe for marine risers as an integral part of offshore production systems is no longer viewed as exploratory in nature. Recent installations of key systems worldwide have proved the concept to be technically acceptable, economically attractive and often representing a unique solution.

Though flexible pipe as a marine product was introduced to the offshore market in the early seventies it was not till 1978 that flexible risers were specified and installed in the Enchova field offshore Brazil [1] as part of a floating production system.

Acceptance of flexible marine risers as components of floating production systems or for connection of export lines to a loading buoy as a viable long term engineering solution was up to recently dependent on the ability of the prospective user or the manufacturer to demonstrate the adequacy of the design configuration chosen. Such evaluation requires certain dynamic analytical models which could only be evaluated through model test or the luxury of full scale validation by actual experience in the field alone with simulated life cycle tests. The availability of such proven tools today along with extensive variety of tests performed so far on samples of the flexible pipe itself and the actual field experience in Enchova [1] Balmoral [2] Jolliet [3] and Green Canyon Block 29 [4] to mention a few, help remove the barriers of acceptance but not necessarily lower the guard in so far as the careful and lengthy design procedure which such an application calls for. Similar to other engineering technological breakthroughs, development often depends on the availability and ease of use of the analytical tools capable of properly simulating the behaviour of flexible marine riser in the ocean environment in which it is expected to operate survive, installed and removed if necessary. Life expectancy of 15 - 20 years in not uncommon and life cycle analysis is therefore required in addition to the above mentioned design criteria.
The most convincing proof of acceptance of flexible marine risers is best demonstrated if one reviews the outstanding projects currently committed to such engineering solutions in Brazil, Canada, Australia, South East China, North Sea and the Gulf of Mexico. Some projects require an extensive trade off study in order to compare the flexible and rigid pipe options, taking into consideration the product, its installation, removal, and its ability to survive the environment. Technology and economy each play a major role in such a comparison and the design often represent a rational compromise. The two cases selected for presentation and discussion in this paper are different, since it involves the design of a riser system for two extreme water depth condition one in over 2000ft and the other below 100ft. In either case a trade off study was not necessary, since flexible riser was the only rational solution available in such water depth and the associated environmental conditions on site. These cases were selected in order to illustrate the differences in riser configurations and the approach necessary to be taken in each case as well as to emphasise similarities, such as the temporary nature of the installation and the expected removal within a short time, reuse of system components and the consideration as later discussed.

In order to demonstrate the design methodology of such flexible risers, a short discussion of the design approach and the analytical tools available for it must be given first followed by the design verification stages which one should undertake as part of the riser analysis prior to discussing the effects on the pipe itself namely resulting stresses, and the product capabilities to withstand such loads.

The results of the analysis for the two cases are the essence of this paper. Typical outputs illustrating the critical aspects of the riser configuration selected and their sensitivity to the assumptions made in each of the analytical phases used are discussed.

**Flexible Riser Analysis and Design**

Flexible pipes and risers are critical components of offshore field developments because they provide the means of transferring fluids or power between subsea units and a topside floating platform or buoys. These risers accommodate floating platform motion and hydrodynamic loading by being flexible. In storm conditions they undergo large dynamic deflections and must remain in tension throughout their response. They are consequently manufactured to possess high structural axial stiffness and relatively low structural bending stiffness. These structural properties provide only a small resistance to lateral disturbances caused by wave and current induced hydrodynamic loadings. Their global dynamic behaviour can therefore be considered as more mechanical, or force dependent, than structural. In contrast, behaviour near the end connectors of a system is governed by local structure stiffness properties.

The design of a flexible riser system has to account for a combination of complex loading and motion phenomena. A major part of the design is therefore the system analysis where it is necessary to perform large deflection analysis of those tensile structures when subjected to dynamic boundary conditions and non-linear hydrodynamic loading. Such analysis must be performed by a software package which is fast enough to enable the engineer to adequately assess the effect of different parameters on the system and yet is rigorous in its structural modelling and solution of the inherent equations of motion [5][6].

**Characteristics of Flexible Riser Systems**

Flexible pipe is defined as a composite of layered materials which form a pressure containing conduit. The pipe structure allows large deflection without a significant increase in bending stresses [7]. The pipe is therefore designed so that it has a low bending stiffness and can accommodate high internal and external pressures. The pipe construction will either be of a bonded type (whereby layers are bonded together using adhesive and are then vulcanised in an oven to form a homogeneous structure) or non-bonded (whereby individual layers remain
separated allowing internal relative movements). Typical materials used for construction include: polymers, textile, steel and fabrics.

From an engineering analysis point of view, the technical characteristics of a flexible riser system are:

- tension dominated structure;
- hydrodynamic loading due to waves and current;
- dynamic boundary condition due to movement of vessel;
- pinned/clamped boundary conditions;
- system can be partially in air / partially submerged;
- possible connection to a subsurface body;
- possible change in weight along length of system;
- possible surface contact at seabed.

On consideration of the above characteristics the main complexity in the analysis of flexible riser systems is due to non-linearities arising from hydrodynamic loading and dynamic boundary conditions.

**Design Methodology Criteria**

Efficient design of flexible riser systems is only made possible by using computer-based solution techniques. The basic steps required in design of a flexible riser system are set out in this section.

The design of flexible riser systems is usually based on allowable pipe curvatures and tensions, which are prescribed by the pipe manufacturer, and clearances between the riser and other structures and boundaries during its dynamic response. The allowable curvatures and tensions are based on full-scale test procedures and stress analysis carried out by the manufacturer and these limits ensure that the pipe is not over-stressed when responding to dynamic loads and vessel motions. The system is generally designed such that the pipe is always in tension throughout its dynamic response cycle. Minimum clearances are also specified to avoid clashing problems between riser and seabed or riser and vessel and between the riser or other adjacent risers, cables or mooring systems.

**Design Parameters and Procedures**

The main problem in design of flexible riser systems is that the number of design parameters is large. The environmental conditions, vessel motions and riser properties are usually well-defined. The main design parameters are therefore the choice of configuration, the length of riser, the system geometry and the sizing of buoyancy modules, subsurface buoy or arch. The choice of riser configuration is usually based on economic criteria, position of wells etc. and in most cases can be considered as known.

The length of riser, sizing of buoyancy components and system geometry need to be determined by the designer.

The first stage in the design of a flexible riser system is to determine an acceptable system layout. The first stage is based on static analysis and it is normal to carry out a parametric study to assess the effect of changing the design parameters (i.e., system geometry and length) on the static curvature and tension. Based on the results of this parametric study, the design selects a suitable range of system geometries and lengths that satisfy the design criteria. The parametric study will also assess the static effects of vessel offset (displacement of the top end) and current loading in different directions.
The second stage in the design procedure is to perform dynamic analysis of the system to assess the global dynamic response. A system layout and length is chosen from stage one and a series of dynamic load cases are then considered. These load cases combine different wave and current conditions, vessel positions and riser contents in order to prove an overall assessment of the riser suitability in operational and survival conditions. The corresponding analyses are then carried out and dynamic curvatures, tensions and clearances are checked against the design limits. The design may need to be modified at any stage of this procedure - it is therefore essential that the solution technique is fast.

The third stage in the design procedure is to perform detailed static and dynamic analyses of local areas to design particular components. This state is presented in a separate publication [8].

**Riser Configuration Selection**

Industry practice calls for several types of riser configurations which are typically used in conjunction with Floating Production/Loading Systems. The standard five configurations generally used are: Free-hanging Catenary, Lazy-S, Steep-S, Lazy Wave and Steep Wave. **Figure 1** illustrates the two types of configurations which are discussed in this paper.

Although dynamic response of a riser system to extreme and operational environmental conditions plays the key role in selection of a particular configuration, other important factors that should also be considered during this phase are:

- Interference with other riser systems and mooring lines
- Activity of other vessels in the vicinity
- Ease of laying and retrieval and future requirements of maintenance
- Inspection and work over operations.

The dynamic response of a particular riser system is directly related to the environmental loadings due to the combined wave-current field flow coupled with the interaction arising from the structural non-linear behaviour of the riser itself. The spatial and temporal distribution of the integral properties of wave such as mass, momentum, pressure and energy, set the ground for the selection of a particular riser configuration for a particular depth of water.

Consider a progressive wave moving in the positive horizontal axis (**figure 2**). For simplicity considering small amplitude wave theory, the wave kinetic energy concentration averaged over one wave period at any elevation above the bottom is given by:

\[ \text{KE}(s) = \frac{a^2 \rho g k^3}{\sigma^2 (\cosh[kh])^2} \]

\[ \text{KE}(s) / \text{KE}(h) = \frac{\cosh[2ks]}{\cosh[2kh]} \]

Equation (2) is plotted in **figure 3** for the case of h/L=0.05 (conventional shallow water limit). The figure shows that for the case of shallow water waves the energy concentration is nearly uniform with depth, while for case of deep water waves the energy is concentrated near the surface.

It should be highlighted that the effects due to wave-currents interaction should always be considered in design and analysis as it might cause a significant change in the magnitude and distribution of fluid forces. This change of fluid forces could be dramatic, as seen by Ismail [9], in coastal waters not only due to the strong current shear but also due to the characteristics of
shoaling waters. The parameters which also usually sensitive to wave-current interaction effects, include hydrodynamic force coefficients, current velocity profiles and relative direction of waves and currents.

To illustrate the suitability of a particular configuration for a particular water depth, two riser design cases were studied in deep and shallow waters. The results of these studies are in the following section. The computer analyses were carried out at Wellstream's engineering offices using computer program Zenriser developed by Zentech, London.

Analysis Tools and Validation

Three distinct stages have been previously identified as essential for the design procedures of flexible riser systems. The designer must be provided with the necessary tools to complete all three stages efficiently. Due to the complexity of the system, these tools have to be computer-based solutions of the inherent equations of motion. Since each design stage is essentially based on the same configuration, the most efficient package to use will have common data input and result output modules for all 3 design stages. This approach reduces time and error on data input, since much of the system data is not changed between stages. Several software packages are commercially available which basically meet the design approach outlined above. While the obvious approach to analysis might be to select one such program to simplify and speed the design through familiarization with that particular program, it has been learned that as a result of some differences in methodology and approach to the analytical solution, more than one program is often required to validate and investigate specific results which are particularly sensitive to assumptions and input data used by the particular program selected. While general agreement exists between three of the programs which were evaluated, some differences may show up particularly in sensitive areas.

Two techniques are generally available and acceptable for solutions of the governing equations systems for design stages 1 to 3. These techniques are the finite difference and finite element schemes. Both methods are equally applicable to solution of flexible riser problems however the finite difference scheme has distinct advantages in terms of both speed of solution and computer memory requirements, particularly when performing random seastate analysis. One of the programs used namely Flexriser by Zentech [10] is based on finite differences, direct space and time discretization of governing equations, the other two programs, Flexcom-3D by M.C.S. and Seaflex [10] by Marintek are based on finite element method and the virtual work principle. Though the above two approaches to solution of the governing equation system may distinguish the one program from the other two, numerous other aspects of the mechanical behavior of flexible risers must be considered and treated numerically leaving extensive room for substantial differences between the two solutions both using the same method of analysis namely finite element. Such consideration, for example, due to non-linearities, may result from large rotations and displacements, large differences between the bending verses axial and torsional stiffness, contact with other rigid surface which may lead to interference, contact with the seabed and last but not least, modeling of the hydrodynamic loading.

A general software evaluation project flexible riser system analysis was reported in [10] and included three of the programs mentioned about or close versions of it. Static and dynamic analysis of two typical riser configurations using four different software packages all designed to provide cost effective engineering solutions was given in [10]. All programs were three dimensional, capable of handing axial, bending and torsional stiffness, regular and irregular waves, seabed friction and use compatible input and output data presentation.

The main evaluation of the four software packages evolved a lazy S configuration in 77m water depth, with the current and wave headings assumed to be perpendicular to the plane of the catenaries in mean position. The results of all programs were within plus or minus 10% of each other. It should also be noted that analysis obtained by a "cable elements" 3-D program
was used as a basis for comparison and yielded a reasonable "mean" for all four programs. An additional analysis comparing results from just two of the programs for J tube riser clamped on a layover arch was also given in [10]. It was concluded in [10] that for most standard riser configurations the programs evaluated as well as other dynamic programs using more simplified approach seem to yield similar results for tensions, angular deflection, bending radius and other relevant parameters. This conclusion agreed with an earlier one in [11] both advocating the use of simplified programs in general and more elaborate approach for riser configurations where bending and torsional behaviour could be critical. A combination of an efficient general analysis program with a capability to investigate specific detail when circumstances call for is not generally available within one commercial software package. However, the use of two or even three such packages as part of the design process in conjunction with a sensitivity analysis to critical inputs could most likely yield satisfactory engineering solution in most cases.

A flexible riser analysis package should ideally be validated using the following four sources:

(a) Comparing with generalized theoretical solutions and checking result consistency using different modeling techniques;
(b) Comparing with results predicted by compatible software packages;
(c) Comparing with results predicted by experiment using scaled model tests;
(d) Comparing with results obtained from full-scale offshore tests.

Ideally, all the above methods should be used to validate a package. In practice, (a) (b), and (c) can be implemented with relative ease whereas (d) requires complex monitoring equipment therefore a large capital investment. A recent attempt to illustrate such a validation was presented in [12]. Results of full scale measurement were reasonably correlated with the numerical model yielding the same order of magnitude values at frequencies corresponding to the numerical model capabilities. Vortex shedding effects were not accounted for in the numerical model used in [12].

It is apparent from the above, that to achieve a a flexible riser system design, one must use a suitable computer software package to perform static and dynamic analysis. Such a package should form the basis of 3 distinct design stages - determination of system layout, dynamic global response analysis and detailed localized analysis and details design.

A study of the effects of variation of a certain parameter on the system dynamic response can be useful and sometimes essential to assessing trends and investigate what seems to be 'trouble spots'. This type of analysis allows the designer to make intelligent estimates of dynamic magnifications for other similar configurations and load cases.

Furthermore, the sensitivity of the system response to small variations in environmental loads and vessel displacements can also be analysed and studied. This facilitates determination of the system dynamic response to small changes in forcing function magnitude and definition and thus identifies the possible existence of critical dynamic magnification trends.

**Engineering Analysis and Design Verification**

With any one or more of the software packages available as a design tool the successful completion and verification of a flexible riser depends to a large extent on the methodology developed by the designer in using such software.

Static and dynamic analysis of the riser system are carried out to determine the layout and demonstrate the full feasibility of the riser systems under all operating modes. The same type of analysis is also applied to the riser and the remaining static pipe life work for configurations likely to be encountered during riser installation and pipe layout phase.
The static and dynamic response analysis of the flexible pipe presented in this paper simulates the dynamic behaviour of single and multiple flexible riser systems subjected to hydrodynamic loading and vessel motion. The software utilised a 3-dimensional non-linear analysis approach in the time domain. The software was used for feasibility and conceptual studies, as well as for global and detail design for installation and operating conditions. It was also used for an interference analysis to determine clearances between risers, mooring lines, pipe protection against abrasion as a result of interaction with the seabed, design of pull-in tubes clearances, and similar potential obstructions.

The software is applicable for both the preliminary static analysis to determine system layout and general configuration as well as for the full dynamic response analysis.

The scope of work generally consists of four phases:

- Phase I: Riser Configuration Design and Analysis for Survival and Marginal Operation Conditions
- Phase II: Interference Study
- Phase III: Installation Analysis
- Phase IV: Fatigue Analysis Input Data Preparation

The above applies to all flexible pipe components used as part of the riser system, which require design verification.

The above engineering design approach was applied to two specific riser configurations representing two extreme water depth conditions, i.e., 600m and 40m: The first a Free-hanging catenary riser and the second a Steep Wave riser with buoyancy. These two cases were selected since it represents a design challenge on the one hand and a case where flexible riser is the only acceptable engineering solution.

The results of the analysis, including the input data, output in tabular and graphical form along with interpretation of the results is presented in the following section.

**Presentation and Interpretation of Results**

In order to illustrate the potential and limitations of adopting specific riser configurations in a particular water depth, the results of riser dynamics analyses for two riser configurations in deep water and shallow water are presented. The computer analyses were conducted at Wellstream’s engineering office and made use of the Flexriser personal computer program developed by Zentech, U.K.

**Free-hanging Catenary**

A free-hanging catenary configuration was adopted for riser systems in two design cases which have similar overall design parameters but very different water depths at the respective project sites. The first case is in 600m water depth and the second on in 90m water depth. **Table 1** illustrates the main design parameters used as input for the computer analyses. For the first case, **Figure 4** shows a snapshot of the riser configuration and the distribution of axial force along the length of the riser depicting a small amount of compression near the seabed. Also shown are the time variation of the axial force, near the sea bottom. In contrast to this, for the 90m water depth case, **figure 5** shows an appreciable amount of compressive force in the riser near the seabed. To maintain the stability of a flexible riser system, it is imperative that the riser pipe remains in tension throughout its operational life. Because of the development of this excessive amount of compressive force in the pipe in shallow waters it can be safely concluded that free-hanging catenary configuration is unsuitable for shallow water depths. Studies have also shown that sometimes even in deep water locations, because of
heavy seas and the resulting heave motion of the vessel, appreciable amount of compression in the riser pipe near the seabed in free- hanging catenary configurations might also occur. To mitigate the effects of this loss of tension in the riser pipe which could adversely affect the service life of the pipe, one of the following measures may be adopted:

- Increase departure angle of the riser at the end connector at the floater level.
- Increase the weight of the riser pipe section near the seabed by wrapping with some heavy material.
- Modify the vessel to reduce the heave motion.
- Attach a subsurface buoy.

Each of the above remedies could be viewed as a possible solution depending on the technical and economical constraints of the project in general and the riser system in particular.

**Steep Wave**

Dynamic riser analyses were also conducted for a design of a single oil export system in a 40m water depth site. An extensive analysis was carried out prior to arriving at the proposed steep riser configuration (either 6-inch or 8-inch flexible pipe diameter) which resulted in many unacceptable configurations primarily due to the riser inability to withstand the environmental conditions imposed, extreme wave heights of 15m for the 1 year-storm and 20m for the 100 year-storm. The analyses showed that any Lazy or Free-hanging system are not feasible at all. Moreover, the need to eliminate the Steep S configuration, as an alternative, became apparent when the sensitivity of the riser dynamic response to the intensity of additional buoyancy distribution was determined. Thus, the Steep Wave was left as the only feasible configuration for the riser of this oil export system. For the Steep Wave riser, the distribution of buoyancy along the riser was determined (figure 6) to prevent any buckling instability an to reduce any excessive angle at the riser base. A snapshot of the riser configuration under the dynamic effects of waves and currents is shown in figure 7 for both cases of far and near field. The corresponding axial tension force along the Steep Wave riser is shown on figure 8.

It is apparent that the Steep wave configuration, though a natural choice for extreme conditions as in the case above, does not necessarily offer an overall solution to all problems of flexible riser design.

**Conclusions**

For the design cases of flexible marine risers in deep and shallow water considered in this paper, it was evident that the most apparent riser configuration does not necessarily provide the appropriate solution. The deep water case emphasises a solution based on a simple riser configuration to facilitate modularity and hence ease of installation and removal. In the shallow-water case, the design is a more complex riser configuration due to the severe environment loads requiring particular design configuration loads. Both cases represent new frontiers for use of flexible pipe as marine risers.

The sensitivity of the riser dynamic response, in particular configuration, to environmental data and vessel/floater motion data warrants a careful review of design basis prior to the dynamic analysis and design of marine risers.
Nomenclature

\( a = \text{wave amplitude} \)
\( g = \text{acceleration of gravity} \)
\( k = \text{wave number, } ( \frac{2\pi}{L} ); L \text{ wave length} \)
\( L = \text{Wave Length} \)
\( s = \text{elevation above sea bottom} \)
\( T = \text{Wave Period} \)
\( \rho = \text{fluid density} \)
\( \sigma = \text{wave frequency, } ( \frac{2\pi}{T} ) \)

References

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Table 1 - Data for catenary and steep wave risers

![Diagram](image)

Figure 1 - Study cases of two flexible riser configurations
Figure 2 - Ratio of wave kinetic energy at s/h to kinetic energy at s/h=1.0

Figure 3 - Vertical pressure distribution within a progressive wave
Figure 4 - Typical results of free hanging riser analysis in 625m water depth
Figure 5 - Typical results of free hanging riser analysis in 90m water depth
Total riser length, $L$: 65m
Length, Top to buoy start, $S_1$: 40m
Horizontal separation, $H$: 40m
Length, Buoy start to buoy end, $S_2$: 10m
Vertical separation, $V$: 33.5m
Length, Buoy start to buoy end, $S_3$: 15m
Buoyancy per unit length, $B_2$: 1.37kN/m
Length, Buoy end to base, $S_4$: 0m
Buoyancy per unit length, $B_3$: 2.29kN/m
Riser diameter: 6in

Figure 6 - Design configuration of steep wave riser

Figure 7 - X-Y snapshot of steep wave riser configuration

Figure 8 - Tension and curvature distribution along a steep wave riser