Trans IMarE, Vol 102, pp 205–215

Investigation into optimised design of flexible riser systems

***P A Brown, MSc, †A Soltanahmadi, MSc, PhD, *R Chandwani, BTech, MS, MASc, MASCE, MIPetE and ‡Prof I Larsen MSc, PhD**

*Zentech International Ltd, †Zentech International Ltd (now Earl & Wright Ltd) and ‡Royal Institute of Technology (now Zentech Belgium)

SYNOPSIS

During the last seven years, Zentech Consultants have been involved in a number of projects that may be broadly classified within the heading 'Analysis and Design of Flexible Riser Systems'. The basis for their involvement has been the development of an advanced analytical tool for detailed design and hydrodynamic response of these systems. This paper summarises some of the experience gained by Zentech over the last seven years and presents an investigation into optimisation techniques used during design of single and multiple flexible riser systems.

An introduction to this subject is given which addresses the reasons behind performing advanced analysis within the design procedure. The purpose and definition of flexible riser systems and the characteristics of flexible pipe are then presented followed by a discussion of the methodology commonly used within design. The analytical tools required during design are identified and guidelines are given for validation of these software packages. A series of case studies showing typical system analysis are then presented with emphasis on parameters used for system optimisation.

INTRODUCTION

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. These risers accommodate floating platform motion and hydrodynamic loading by being flexible. In North Sea 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 structural 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 – it is necessary to perform large deflection analysis of these tensile structures when they are subjected to dynamic boundary conditions and non-linear hydrodynamic loading. This 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.

It should be noted that the main emphasis in this paper is on practical aspects of design – the theoretical background to flexible riser system analysis is presented elsewhere,[1,2] and only a summary is presented here.

Mr Paul Brown graduated from the University of Exeter with a first class honours degree in Mathematics followed by an MSc degree in Offshore Engineering from Cranfield Institute of Technology. In 1984 he joined J P Kenny & Partners Limited as a pipeline engineer. He is now employed as a senior analyst at Zentech. Mr Brown joined Zentech in 1985 and has been involved in the design and analysis of flexible and rigid pipelines for the past four years.

Dr A Soltanahmadi took a BSc degree in Civil Engineering from Hatfield Polytechnic followed by MSc (Structures) and PhD (Offshore Engineering) degrees from the City University. His research was concerned with efficient numerical and experimental modelling of flexible riser systems. In 1987 he joined Zentech as a senior design engineer and since then he has been involved with the design of flexible risers and pipelines.

Mr R Chandwani, as a founder member and the managing director of Zentech, has been involved in development of software for the design and analysis of offshore structures with emphasis on non-linear and dynamic aspects, for the past 20 years. As a part of the R&D effort the company has developed a number of sophisticated analytical tools using finite element and finite difference techniques.

Professor Ian Larsen, as the head of the department of Water Resources Engineering at the Royal Institute of Technology, Stockholm, Sweden and a Senior Principal Consultant to Zentech, has been involved in R&D work connected with non-linear dynamic analysis of flexible and rigid pipelines for the past 15 years.

CHARACTERISTICS OF FLEXIBLE RISER SYSTEMS

The purpose of a flexible riser system is to transfer hydrocarbons or other fluids associated with oil production between a floating vessel and the seabed. A typical flexible riser system comprises of a continuous length of pipe attached at one end to a floating vessel, hanging in a catenary shape, and attached to some type of buoyant component positioned at some distance along the length and then approaching the seabed either smoothly or at a near vertical angle. Schematics showing typical configurations are presented in Fig 1.

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.[3] The pipe is therefore designed such 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:

1. tension dominated structure;
2. hydrodynamic loading due to waves and current;
3. dynamic boundary conditions due to movement of vessel;
4. pinned/clamped boundary conditions;
5. system can be partially in air/partially submerged;
6. possible connection to a subsurface body;
7. possible change in weight along length of system;
8. 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

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

Design criteria

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-seabed or riser-vessel and between the riser and other adjacent risers, cables or mooring systems.

Design parameters

The main problem in the 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 configuration (possible configurations are presented in Fig 1) is usually based on economic criteria, position of wells etc and can be considered as known. The length of riser, sizing of buoyancy components and system geometry need to be determined by the designer.

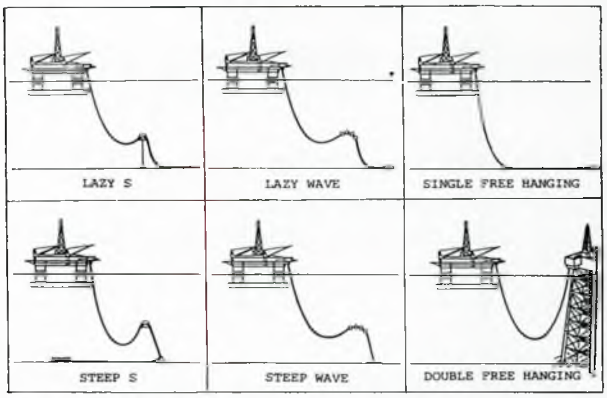

Fig 1: Typical types of flexible riser configuration

Design procedure

The first stage in the design of a flexible riser system is to determine an acceptable system layout. This 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 (ie system geometry and length) on the static curvature and tension. Based on the results of this parametric study, the designer 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 loadcases are considered. These loadcases combine different wave and current conditions, vessel positions and riser contents in order to provide 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 stage is presented in a separate publication.[4]

ANALYSIS TOOLS

Three distinct stages have been identified within the design procedure for flexible riser systems. The engineer must be supplied with the necessary tools to complete all three stages efficiently. Due to the complexity of the system, these tools correspond to computer-based solutions of the inherent equations of motion. Since each stage is essentially based on the same configuration, the most efficient package for the engineer to use will have common data input and result output modules for all three design stages. This approach reduces time and error on data input, since much of the system data is not changed between stages, and also reduces learning time since the engineer only has to familiarise himself with one software package. This approach has been adopted by the authors' company within the development programme for flexible riser analysis software.

Table I: Required characteristics of flexible riser analysis software during design

Design stage	*Required characteristics*
Determination of system layout	Static analysis; Quick study of range of system parameters; Current and vessel offset; Easy to change system geometry or weight.
Global dynamic response analysis	Specification and modelling of regular waves and vessel response; Realistic subsurface buoy and distributed buoyancy modelling; Fast result assessment.
Detailed design/analysis	Bendstiffener design; Assessment of clashing with vessel, mooring system etc; Random seastate analysis; Vortex shedding assessment; Disconnection assessment; Installation procedures.

Required software

The characteristics of the software required by the engineer during design of a flexible riser system are presented in Table I – this table is based on the three design stages identified previously. Following an intensive research, development and validation programme, the software package ‘FLEXRISER 4’ has been designed to perform all analyses required during design stages 1 and 2 and most of the analyses required within design stage 3.

There are two techniques available to the software developer for solution of the governing equation systems for design stages 1 – 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. The finite difference scheme has been implemented with ‘FLEXRISER 4’ for these reasons and one important consequence is that the package can be mounted and run on a Personal Computer (PC).

The ‘FLEXRISER 4’ package consists of two modules corresponding to static and dynamic analysis – each module uses a separate finite difference solution scheme. The static module, which can be used within design stage 1, is based on an energy minimisation technique to obtain the equilibrium configuration of single or multiple flexible riser systems. The effects of current, vessel offset and seabed friction can also be studied. The dynamic module, which can be used within design stages 2 and 3, uses an optimised implicit time integration solution scheme to predict the dynamic response of the system.

Assessment of the effects of vortex shedding is considered as a separate aspect of detailed analysis and design within the authors’ company. The lift forces induced by vortex shedding can be evaluated using a method first developed for vertical drilling risers,[5] and extended by one of the authors to randomly oriented flexible risers in wave and current flows.[6] This extension has been validated experimentally and shows promising results for future investigation and application. Some other aspects of detailed analysis and design have been reported in a separate publication and will not be repeated within this paper.[4]

Theoretical background

This paper is concerned with large deflection analysis of tensile structures subjected to dynamic boundary conditions and non-linear loading conditions. Analysis of flexible structures subjected to dynamic loading is performed in two stages: static analysis and dynamic analysis. The methods used in these two stages are described in other publications,[1,2] and only a brief summary is presented her.

The static equilibrium configuration of a system is computed using a dynamic relaxation technique incorporated with kinetic damping. In this technique the structure is initially laid in a horizontal plane. The ends are then lifted to the correct static positions and static loads are applied to the system. The riser is allowed to respond without viscous damping and each time a kinetic energy peak is detected all nodal velocity components are set to zero and the system is restarted. Eventually the kinetic energy of the system reduces to practically zero – the system is then in static equilibrium. The theory behind the static solution scheme is given by Soltanahmadi and Barnes.[2]

The characteristic equation governing the dynamic motion of a slender tubular structure in a three-dimensional frame of reference is presented in equation (1). The development of this equation of motion from basic principles is given elsewhere.[7,8]

$$m\ddot{\mathbf{r}} = -\frac{\partial^2}{\partial s^2}\left\{EI\frac{\partial \mathbf{t}}{\partial s}\right\} + \frac{\partial}{\partial s}\left\{(T - EI\kappa^2)\mathbf{t}\right\} + \mathbf{F}_d + \mathbf{F}_m + \mathbf{W} + \mathbf{R} \tag{1}$$

where
m is mass per unit length
$\ddot{\mathbf{r}}$ is structural acceleration
s is distance along pipe axis
EI is pipe bending stiffness
$\mathbf{t}$ is tangential vector along pipe axis
T is tension (effective)
κ is curvature
$\mathbf{F}_d$ is hydrodynamic drag force per unit length (see equation (2))
$\mathbf{F}_m$ is hydrodynamic inertia force per unit length (see equation (3))
$\mathbf{W}$ is weight per unit length (in air or submerged)
$\mathbf{R}$ is seabed reaction and friction force per unit length

Note that torsional terms may also be included in equation (1). The hydrodynamic drag force per unit length, $\mathbf{F}_d$, is evaluated and presented in equation (2) which shows the perpendicular component to the pipe axis. A similar expression is valid for the pipe tangential direction.

$$\mathbf{F}_d = \frac{1}{2}\rho C_d D\left|\mathbf{v}_n - \dot{\mathbf{r}}_n\right|(\mathbf{v}_n - \dot{\mathbf{r}}_n) \tag{2}$$

where
ρ is fluid density (seawater)
C_d is hydrodynamic drag coefficient (normal direction)
D is outside diameter of pipe
$\mathbf{v}_n$ is fluid velocity normal to the pipe axis (current + wave)
$\dot{\mathbf{r}}_n$ is structural velocity normal to the pipe axis

The hydrodynamic inertia force per unit length, $\mathbf{F}_m$, is presented in equation (3).

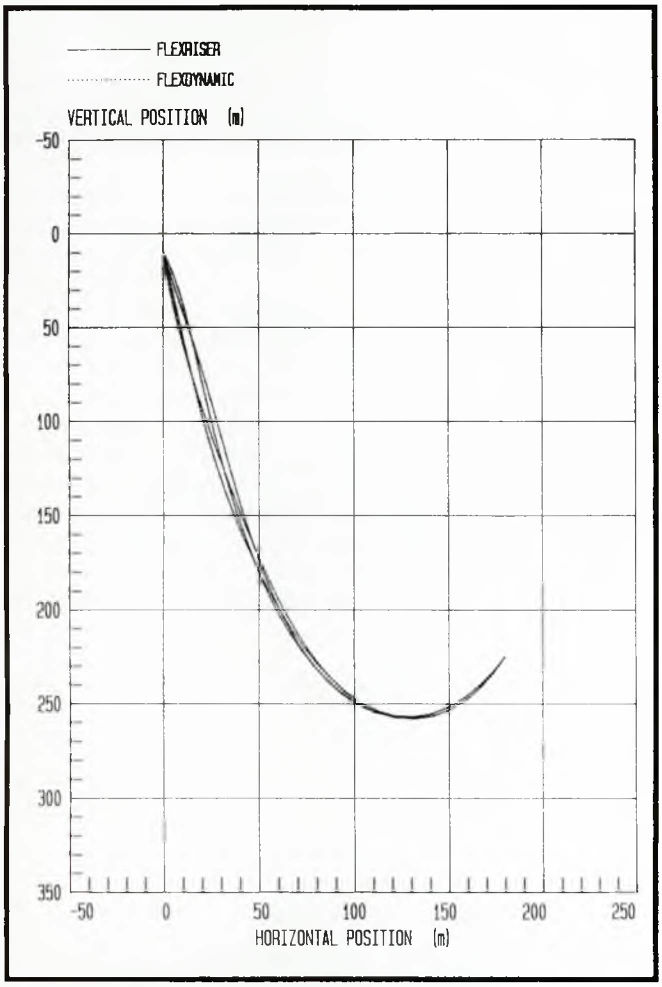

Fig 2: Comparison work for dynamic response of a double free hanging flexible riser with no floater motion

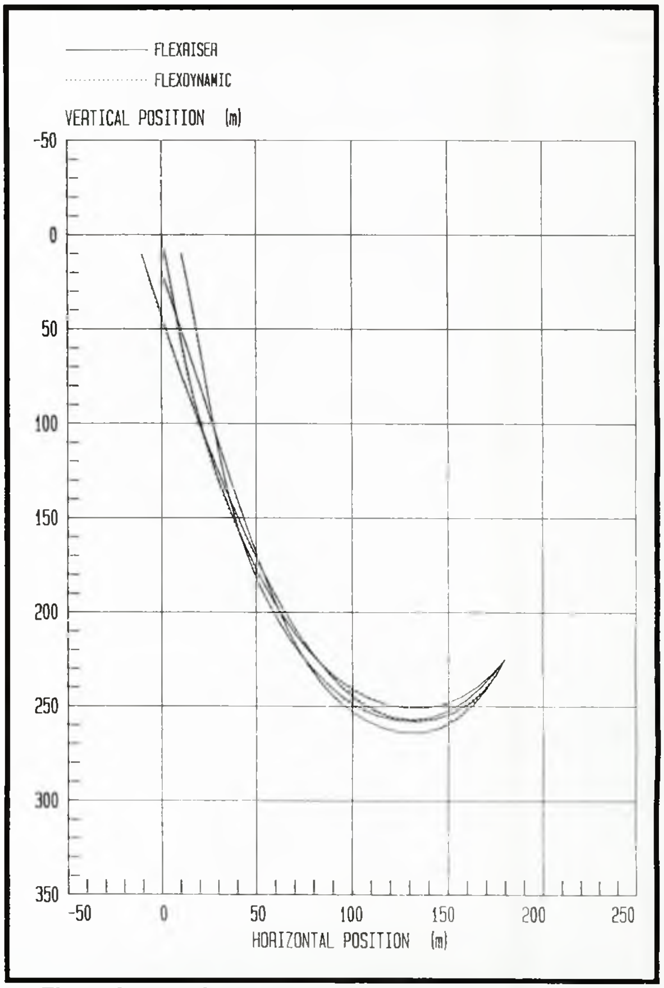

Fig 3: Comparison work for dynamic response of a double free hanging flexible riser with floater motion

$$\mathbf{F}_m = \rho A C_m \dot{\mathbf{v}}_n + \rho A (C_m - 1) \ddot{\mathbf{r}}_n \qquad (3)$$

where
A is external cross – sectional area of pipe
C_m is hydrodynamic inertia coefficient
$\dot{\mathbf{v}}_n$ is fluid acceleration normal to the pipe axis
$\ddot{\mathbf{r}}_n$ is structural acceleration normal to the pipe axis

Equation (1) is solved at a series of points, or nodes, along the riser subject to dynamic boundary conditions on velocity and end orientation as prescribed in equations (4) and (5).

$$\dot{\mathbf{r}} = \dot{\mathbf{r}}_0(t) \qquad (4)$$

$$\mathbf{t} = \mathbf{t}_0(t) \qquad (5)$$

where
$\dot{\mathbf{r}}$ is structural velocity
$\dot{\mathbf{r}}_0(t)$ is prescribed structural velocity at boundary
$\mathbf{t}$ is tangential vector along pipe axis
$\mathbf{t}_0(t)$ is prescribed tangential vector along pipe axis at boundary
t is time

Solution of the equation of motion is achieved by using the computed static solution as the starting configuration for a dynamic solution scheme. This scheme uses an optimised finite difference technique incorporated with an implicit and therefore unconditionally stable time integration scheme. The derivatives in equation (1) are rewritten in finite difference form and a characteristic banded structure emerges in the matrices with a band width of five. This system may be efficiently solved for $\dot{\mathbf{r}}$ using a double sweep method.[9] The theory behind this scheme is also described elsewhere.[1]

Software validation

A flexible riser analysis package can be validated using the following four methods:

1. comparing with known theoretical solutions/checking result consistency using different modelling techniques;
2. comparing with results predicted by other software packages;
3. comparing with results predicted by experiment using scaled model tests;
4. comparing with results obtained from full-scale offshore tests.

Ideally, all the above methods should be used to validate a package. In practice, methods (1), (2) and (3) can be implemented with relative ease whereas method (4) requires complex monitoring equipment and therefore a large capital investment.

Known theoretical solutions used for software validation typically consist of simple static catenary or stretched catenary solutions. More detailed checks on boundary conditions and bending stiffness modelling can use simply supported beam

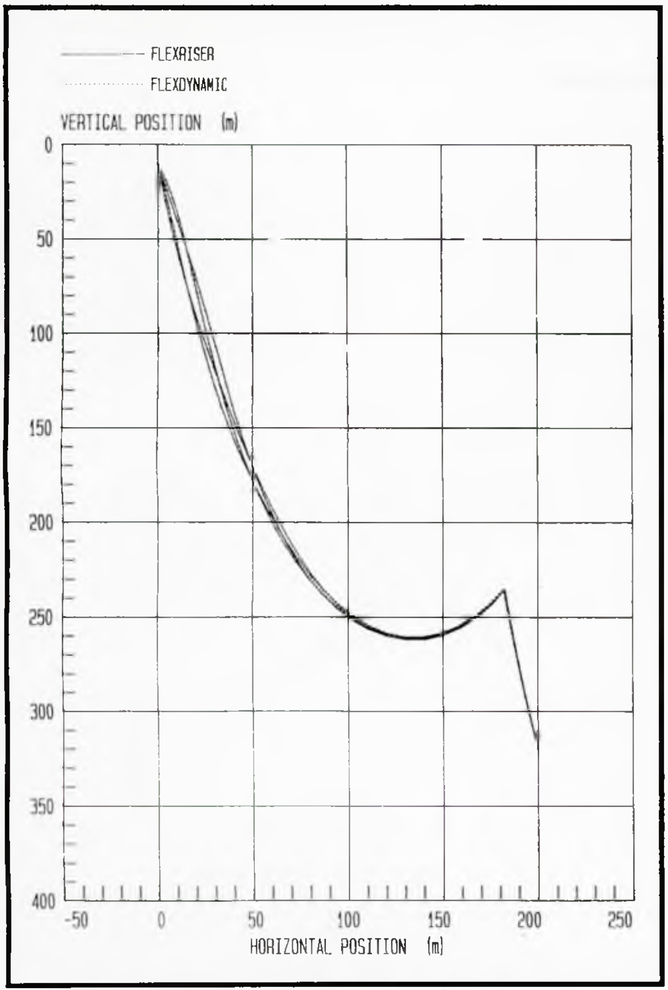

Fig 4: Comparison work for dynamic response of a steep-S flexible riser with no floater motion

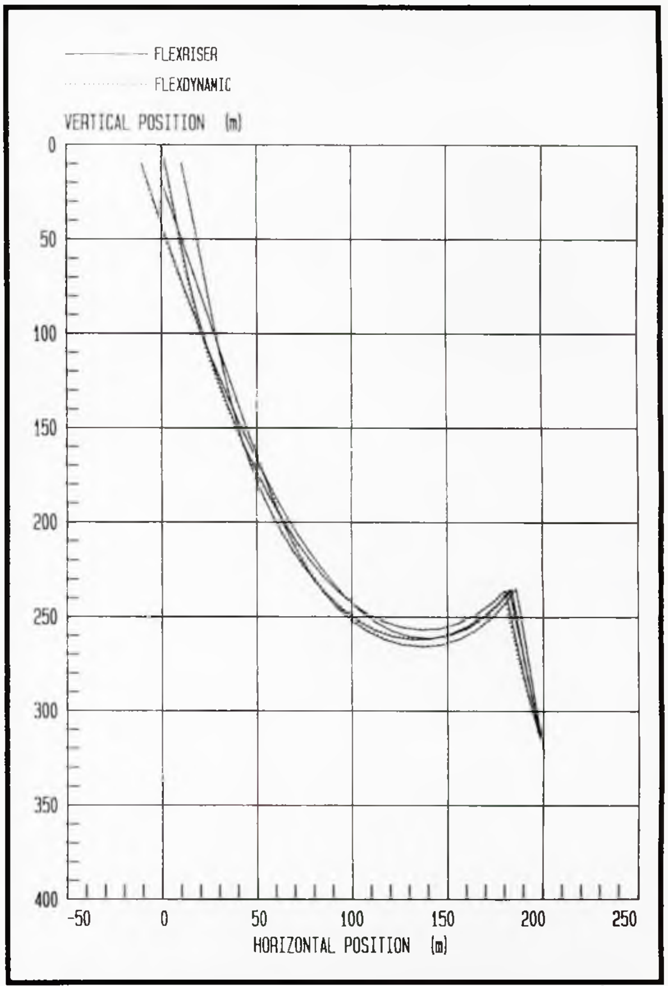

Fig 5: Comparison work for dynamic response of a steep-S flexible riser with floater motion

solutions and cantilever solutions. One example of assessment of result consistency between different modules within the same package is that of checking 3-dimensionality. This may be verified by considering a riser string hanging vertically down from a vessel with a disconnected lower end. Two analyses are performed with waves and current applied at 0 and 45°. The response in each case should be identical and should lie in vertical planes at 0 and 45° respectively.

A detailed comparison between results predicted by independent software packages gives confidence in the programming and modelling techniques within the packages. Any significant deviations must be caused either by programming errors or by one package having a more refined model of a particular aspect than the other. This type of comparison is essential for assessment of different modelling techniques and identification of errors.

A two-stage procedure to perform a detailed comparison of two flexible riser analysis programs is now presented. The first stage involves consideration of a simple riser system without subsurface buoy or distributed buoyancy. Comparisons are made of the following results:

1. static equilibrium configuration;
2. static equilibrium configuration with current loading and platform offset;
3. dynamic response due to wave/current induced hydrodynamic loading;
4. dynamic response due to vessel motion and wave/current induced hydrodynamic loading.

The second stage of the comparison procedure consists of repeating the above analyses for a system with a particular feature, for example a subsurface buoy or distributed buoyancy section.

Over the last seven years, the 'FLEXRISER' package has undergone a series of successful comparisons with other software packages based on finite element and finite difference solution techniques. Most of these comparisons have been carried out independently by operators or engineering contractors. The authors' company has also carried out a detailed inhouse comparison with the specialist program 'FLEXDYNAMIC'.[6] This program is also based on a finite difference technique but adopts entirely different solution methods than 'FLEXRISER'. A summary of this comparison is now presented - the comparison is based on a 'Steep-S' flexible riser configuration (Fig 1).

The first stage of the comparison procedure considers the length of riser between floater and subsurface buoy. Dynamic analyses are performed with and without floater motion for six wave periods and results are presented and compared within Figs 2 and 3 respectively. These figures show four riser positions within the last wave period of the analyses. The results predicted by 'FLEXRISER 4' and 'FLEXDYNAMIC' are shown as full and dotted lines respectively. Similarly, Figs 4 and 5 show corresponding comparisons for the complete 'Steep-S' configuration using the same hydrodynamic loading and vessel motions. The comparisons show that results from both packages are in close agreement.

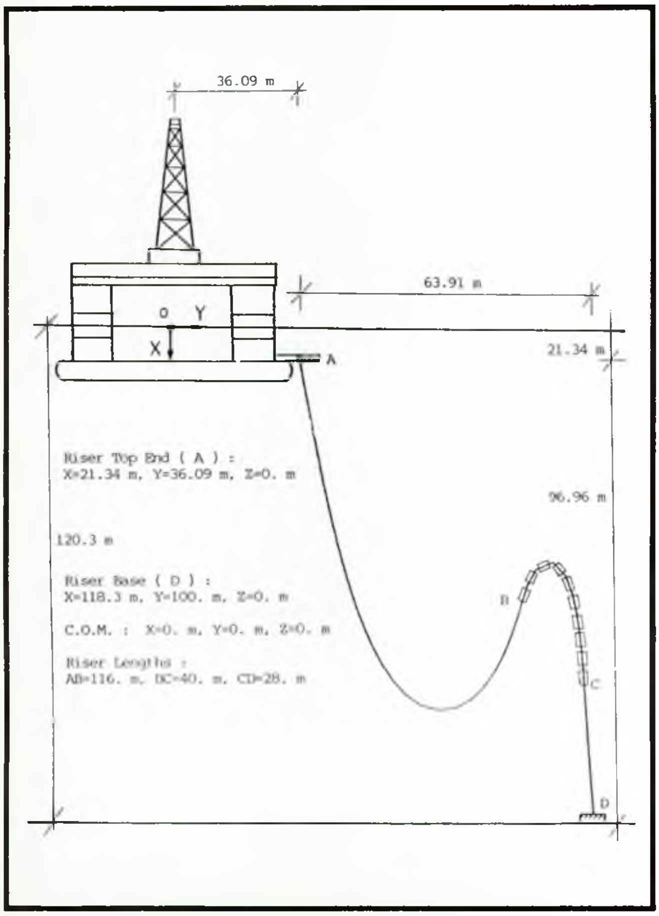

Fig 6: Steep wave configuration; layout

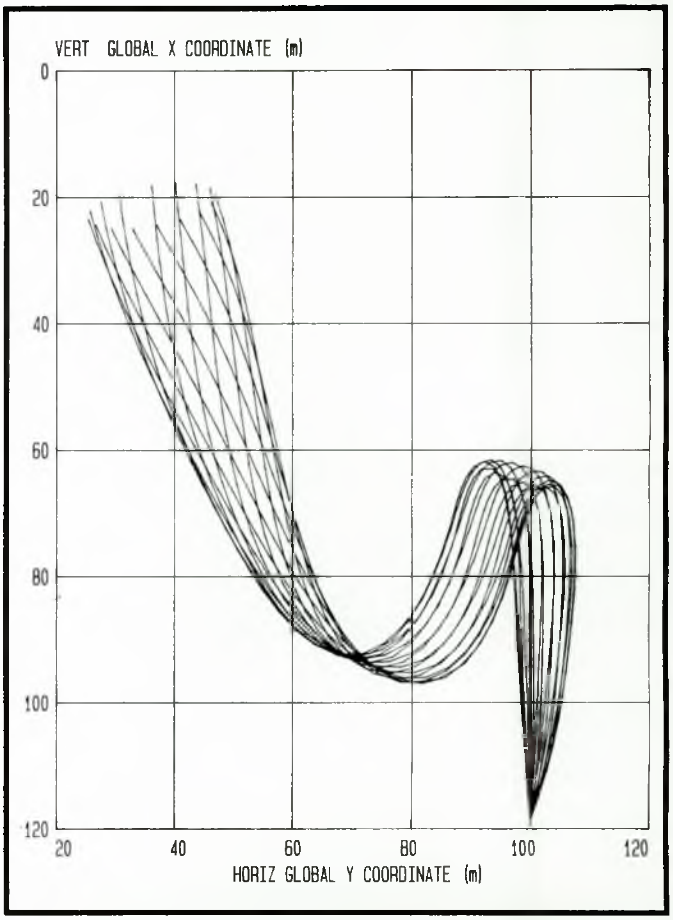

Fig 7: Steep wave configuration; snapshots

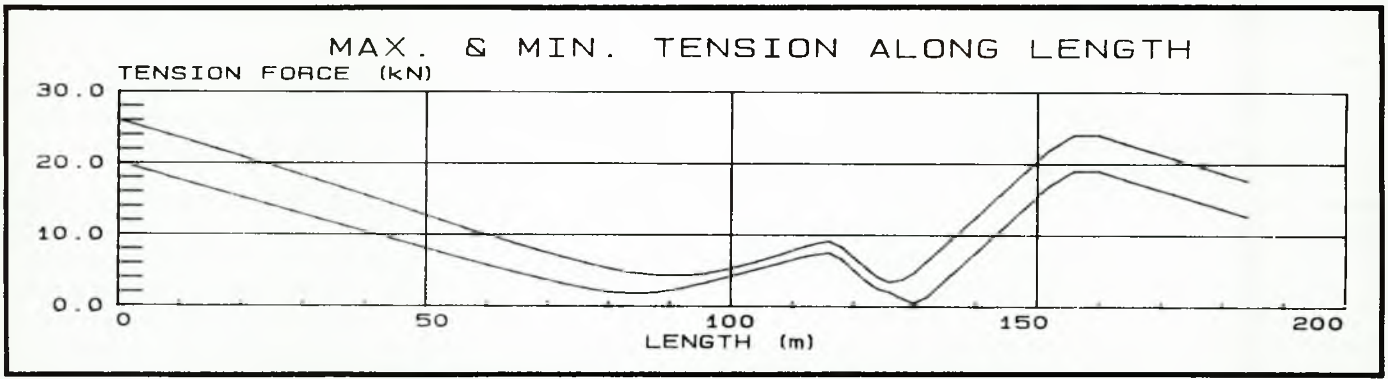

Fig 8: Steep wave configuration; envelopes of tension

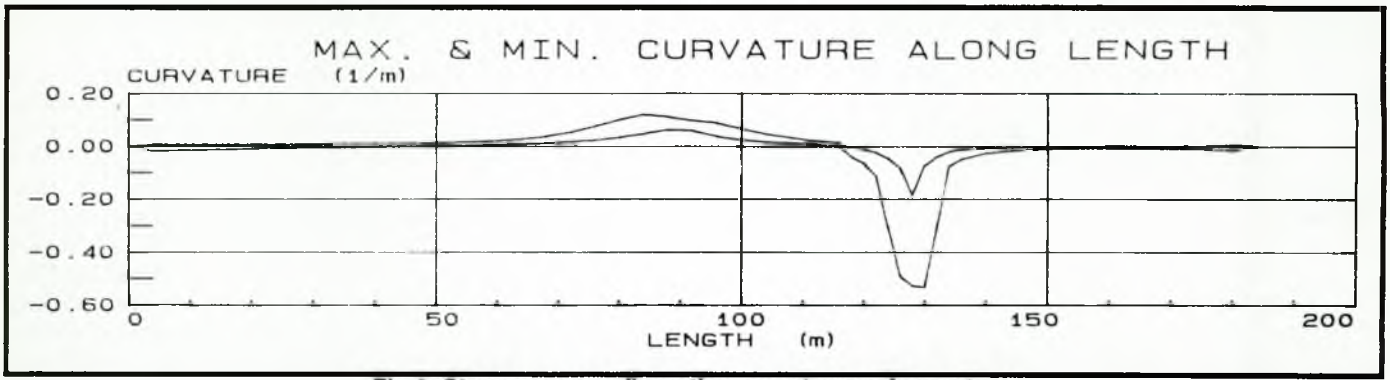

Fig 9: Steep wave configuration; envelopes of curvature

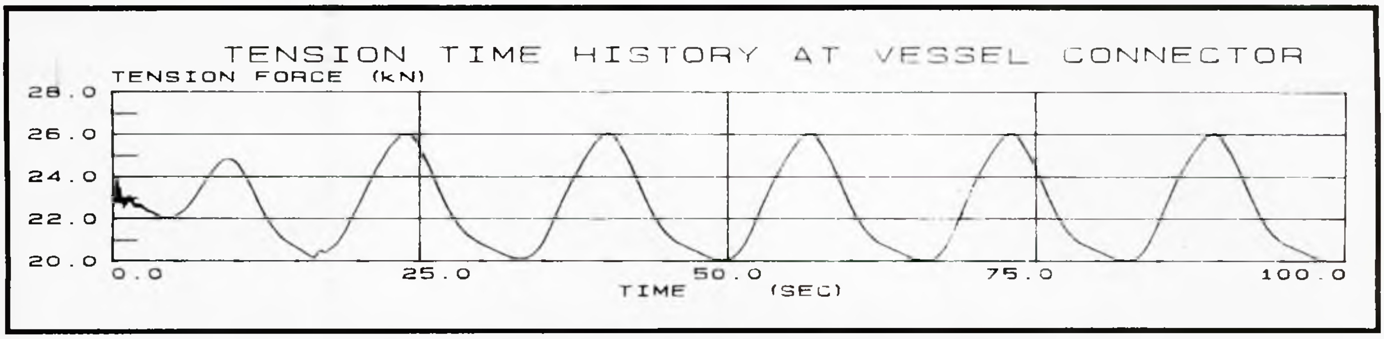

Fig 10: Steep wave configuration ; time history of tension

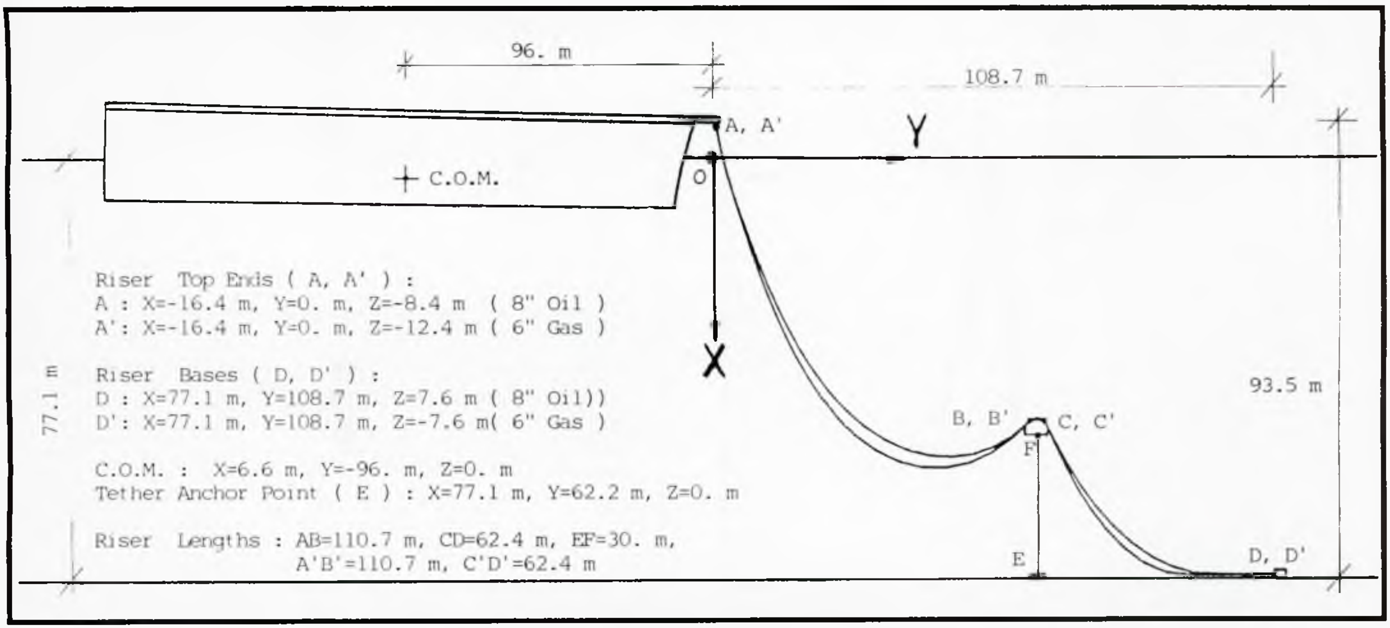

Fig 11: Multiline lazy-S configuration; layout

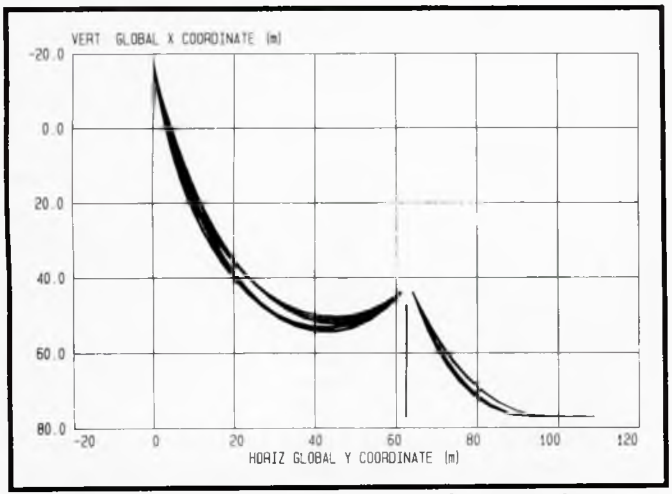

Fig 12: Multiline lazy-S configuration snapshots (side view)

Comparison with results obtained from experimental work using scaled models can also give confidence in a computer package. The specialist program 'FLEXDYNAMIC', which has been extensively validated against 'FLEXRISER', has also been validated by one of the authors,^{6} against a series of model tests within a wave flume. Details of these tests and general guidelines for testing scaled models of flexible riser systems within wave flumes and current channels are presented within this reference.

The best validation for a software package is by comparison with results obtained from full-scale tests. Unfortunately, this method is very costly and is very difficult to implement due to the problems of measuring response data within an offshore environment.

EXAMPLE ANALYSIS

The analysis of two practical flexible riser systems is presented. The first system considered consists of a flexible riser with subsurface distributed buoyant modules attached down the riser length ('Steep Wave'). The system is subjected to wave and current flow in the direction defined from vessel to seabed connector and vessel excitation at the top end.

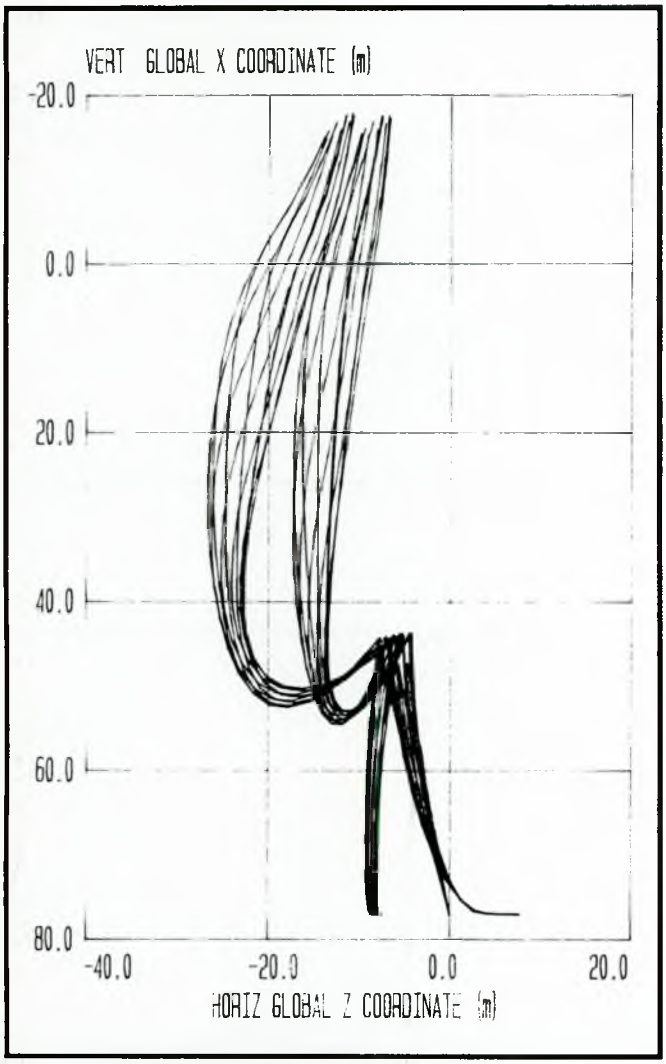

Fig 13: Multiline lazy-S configuration snapshots (end view)

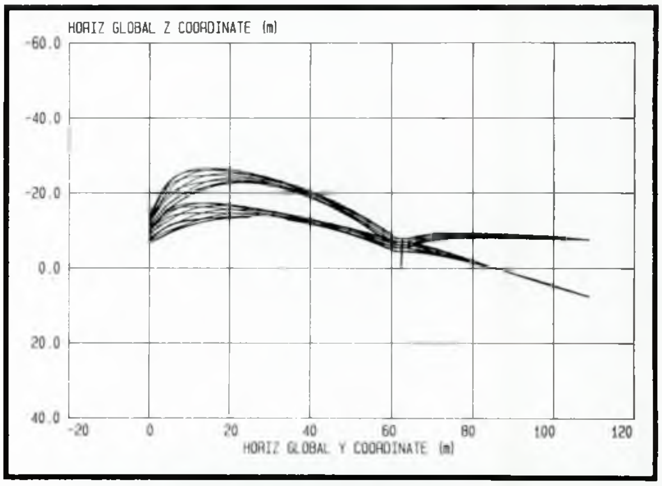

Fig 14: Multiline lazy-S configuration snapshots (plan view)

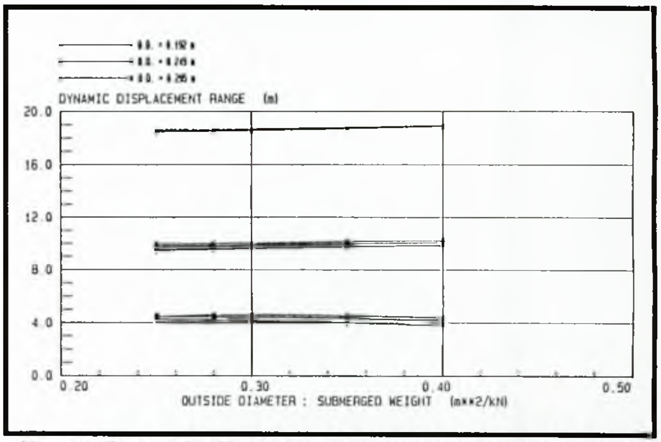

Fig 15: Dynamic displacement range vs hydrodynamic response ratio

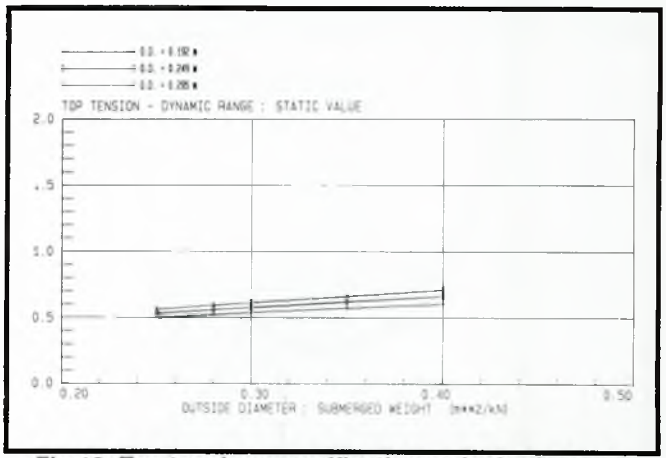

Fig 16: Top tension magnification vs hydrodynamic response ratio

A schematic of the system layout and key data is presented in Fig 6. Typical results from dynamic analysis are presented in Figs 7 – 10. The response of the system during a wave cycle is presented in Fig 7 – this type of diagram is called a 'snapshot'. The extreme values of tension and curvature along the length of the riser system during a wave cycle are presented in Figs 8 and 9 respectively. The time variation of tension at the vessel end of the system is presented in Fig 10.

The second system considered consists of two different flexible risers connected to a single common subsurface buoy ('Lazy-S'). A schematic of the system layout is presented in Fig 11. The system is subjected to wave and current flow perpendicular to its plane and corresponding vessel excitation.

The dynamic response of the system during a wave cycle is presented as a series of 'snapshot' diagrams in Figs 12, 13 and 14. These figures show the system response from the side, end and plan views respectively.

OPTIMISED DESIGN

It is very useful in design to be able to assess the magnification of static tensions, angles, radii and deflections due to dynamic loading conditions. As a preliminary to this type of assessment, an investigation can be made into the effects of changing a particular parameter on the system response. This section shows results from a typical dynamic parametric study of a 'Steep-S' configuration and presents the results as magni-

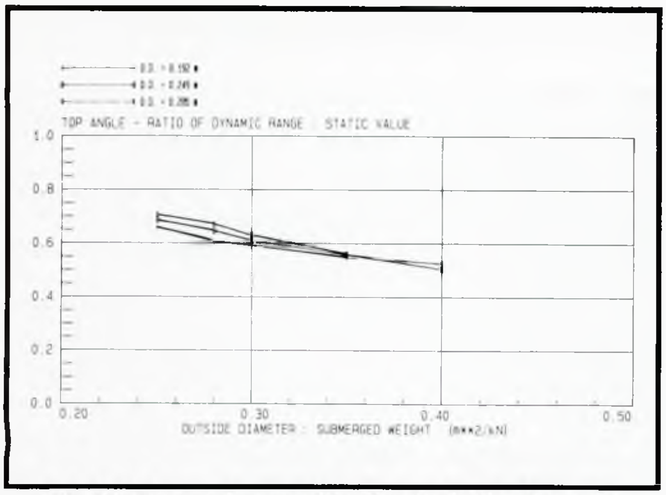

Fig 17: Top angle magnification vs hydrodynamic response ratio

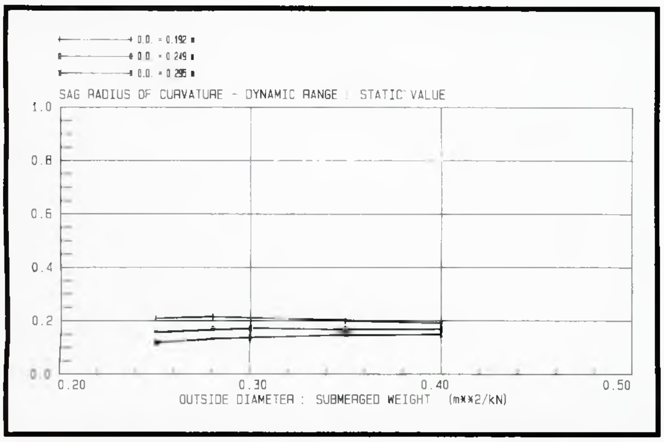

Fig 18: Sag tension magnification vs hydrodynamic response ratio

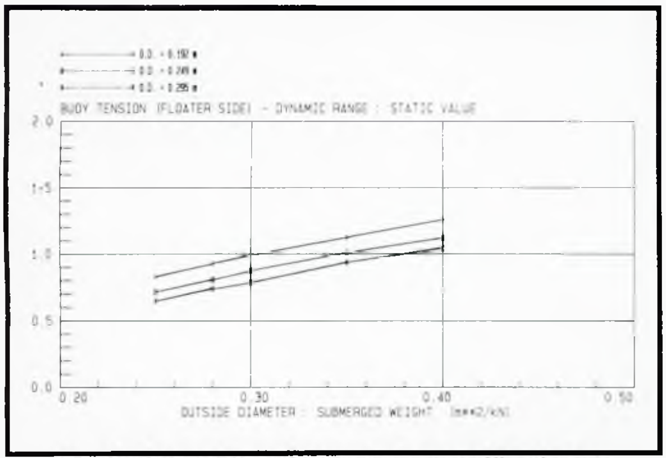

Fig 19: Sag radius of curvature magnification vs hydrodynamic response ratio

fication factors to be applied to static values. It is emphasised that these graphs are valid only for the particular 'Steep-S' configuration chosen and are presented here only in order to give an example of this type of study.

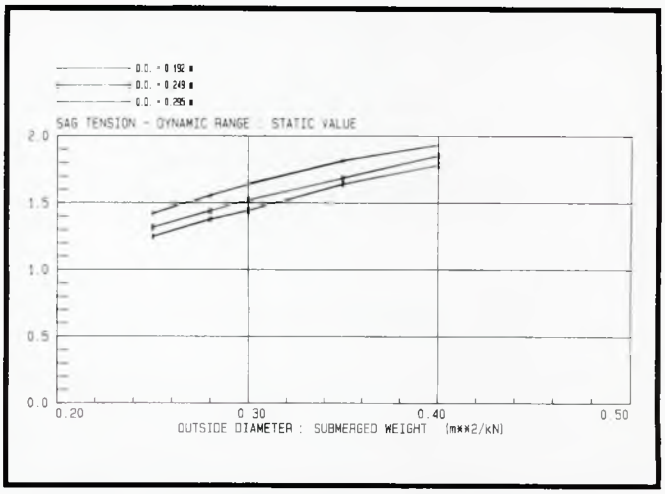

Fig 20: Buoy tension (floater side) magnification vs hydrodynamic response ratio

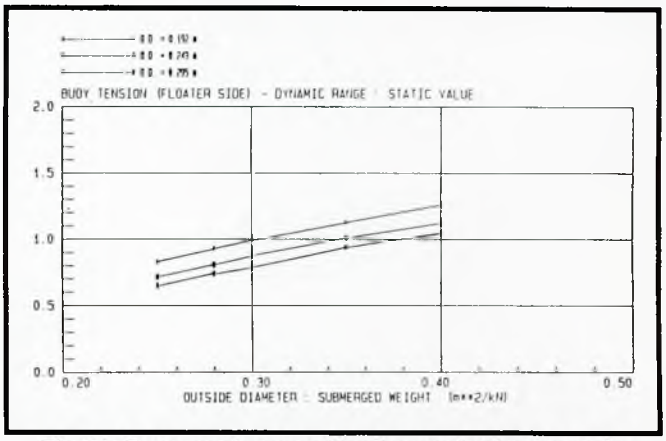

Fig 21: Base angle magnification vs hydrodynamic response ratio

A total of 15 dynamic regular wave analyses have been performed on a 'Steep-S' configuration. The parameter selected for variation is called the 'Hydrodynamic Response Ratio' which is defined as the ratio of riser outside diameter to riser submerged weight. This parameter is chosen to reflect drag loading, via the outside diameter, and resistance to drag loading, via the effective weight and therefore the tension. Five values of the Hydrodynamic Response Ratio have been selected and, for each value, three riser outside diameters have been studied. The only data changed between analyses is, therefore, the outside diameter or submerged weight - all other data remains constant.

The results from these 15 analyses are combined and presented graphically. All graphs plot the Hydrodynamic Response Ratio along the horizontal axis. Figure 15 shows the dynamic displacement range (maximum value minus minimum value) at different positions along the riser system as a function of the Hydrodynamic Response Ratio. Figures 16 to 21 are all presented with a vertical axis defined as the ratio of the dynamic range of the result quantity to the static value of the result quantity. Figures 16 and 17 present top tension and top angle magnification. Figures 18 and 19 present sag tension and sag radius magnification. Note that, in Fig 18, the sag tension magnification approaches 2.0 for an increasing Hydrodynamic

Response Ratio. This criterion typically indicates compression in the sag region of the system for large values of the Hydrodynamic Response Ratio. Figure 20 presents tension magnification at the buoy on the floater side and Fig 21 shows angle magnification at the riser base. These graphs present suggestions for parameters to use in the assessment and determination of general trends in dynamic magnification of static results.

CONCLUSIONS

Efficient flexible riser system design is made possible by using a computer software package to perform static and dynamic analyses. This package should form the basis of three distinct design stages: determination of system layout, dynamic global response analysis and detailed analysis/design. A study into the effects of variation of a certain parameter on the system dynamic response can be useful in assessing trends. This type of study allows the engineer to make informed estimates of dynamic magnifications for other similar configurations and loadcases.

REFERENCES

1. P A Brown, R Chandwani and I Larsen, 'Flexible riser dynamics modelled in 3-dimensions', Proc Int Conf on Mobile Offshore Structures, The City University, London, (1987).
2. A Soltanahmadi and M R Barnes, 'Dynamic response and modelling of flexible risers', Proc Int Conf on Non-Conventional Structures, Inst of Civil Eng, London, (1987).
3. American Petroleum Institute, 'RP17b – Recommended practice for flexible pipe', Houston, (1987).
4. P A Brown, A Soltanahmadi and R Chandwani, 'Problems encountered in detailed design of flexible riser systems', Int Seminar on Flexible Risers, University College, London, (1989).
5. F Rajabi, M F Zedan and A Mangiavacchi, 'Vortex-shedding induced dynamic response of marine risers', *J Energy Resource Technol*, Trans ASME, Vol 106, pp 214–221, (1984).
6. A Soltanahmadi, 'Dynamics of flexible riser systems', PhD Thesis, The City University, (1988).
7. R P Nordgren, 'On computation of the motion of elastic rods', *J Applied Mechanics*, pp 777–780, (Sept 1974).
8. D L Garrett, 'Dynamic analysis of slender rods', *J Energy Resource Technol*, Trans ASME, Vol 104, (Dec 1982).
9. M B Abbott, 'Computational hydraulics', Pitman, London, (1979).

Discussion

A Rose (Brown & Root Vickers) Figures 1 and 6 show risers connected at deck level and at pontoon level. In practice there are advantages and disadvantages, such as riser wear and emergency disconnect and recovery, associated with the position of the riser connection and these are considered on a case by case basis.

Is the program capable of analysing both cases and, assuming it is, what additional complexity is required when dealing with the deck edge connected system? It is not quite clear from the paper whether waves are considered only as excitation for vessel motions or whether the action of waves on individual risers passing through the wave zone is taken into account.

The authors state the need for tension to be maintained at all times; their opinion on minimum allowable tension would be appreciated.

In his verbal presentation, Professor Larsen gave a clear, albeit brief, description of the background mathematics. Could this be included in the final printed version?

P A Brown *et al* (Zentech International Ltd) Mr Rose's comments on advantages/disadvantages of connecting flexible risers at deck/pontoon level are valid. A riser connected at deck level is subjected to significantly high wave/current induced forces leading to an increase in the connector loads, the size of the required bend stiffener and the possibility of clashing at pontoon level. However the advantages of a 'dry' deck connector which is easily accessible during installation and operation generally outweigh the technical disadvantages which can be accounted for within design. The opposite story applies to a pontoon-connected riser. The program 'flexriser' automatically models both of the above situations. The difference in modelling arises primarily from the instantaneous wave surface profile. This boundary defines a change in weight of the pipe, from the submerged weight to the weight in air, and the application of hydrodynamic forces, in particular drag loading. Modelling of the wave- and current-induced velocity fields within this zone requires particular attention in some designs. The action of waves on the pipe itself is accounted for along its whole length including the wave zone.

The minimum tension allowable during dynamic response of a flexible riser system cannot be specified as a single value since it is dependent on the structural properties of the pipe being considered. For example, the minimum allowable tension for a 2 in gas lift line would be different from that applicable for a 10 in oil export line.

A brief theoretical background to this subject is presented within the paper together with references to publications containing the background mathematics.

Dr R M Carson (Orcina Ltd) May I congratulate the authors on their clear description of their analysis method; I particularly appreciated the presentation of the riser equations in terms of the simple wave equation solutions.

As a supplier of similar software, Orcina goes through a similar validation exercise. Among the theoretical solutions, we have found the classical solution of the vibration of a beam-column particularly useful, as it allows the program to be checked with respect to a wide range of parameters. Turning to the comparisons with tank tests, we too have made intercomparisons with selected results of the JIP study referred to by Mr Brown. We have found reasonable agreement on the whole. Like the authors, however, we have found particular cases where a marked discrepancy seems to be attributable to phase angle errors in the experiment results, and there are also individual cases where the recorded top tension seems inconsistent with elementary dynamics. This points to the general importance of running tank tests in parallel with theoretical support, when each becomes a check and validation of the other.

I would like to ask whether the authors use an isotropic seabed friction coefficient, or provide for variations in the principal directions? Given that the static solution is indeterminate in the presence of friction, can they elaborate on their method of assigning a starting position for dynamic analysis?

On the question of the merits of finite element and finite difference methods, may I suggest that perhaps too much has been made of this in the past. In both cases we are simply discretising the general partial differential equation prior to solution, and the difference is primarily in the stage of the solution at which this is done. Do the authors agree?

In the context of random seas, the authors mentioned the use of long simulation runs of up to 1h. This implies the use of statistics derived from the simulated run. There are of course problems in the derivation of long-term statistics from such a run, if the random input is synthesised from a finite number of components (see Tucker *et al*, Applied Ocean Research, Vol 6, Part 2, p 118, 1984). Further problems arise in extrapolating the statistics of non-linear processes. Would the authors like to comment on this aspect of the analysis?

P A Brown et al (Zentech International Ltd) Dr Carson's suggestion to use a beam-column model as a validation exercise is appreciated. The authors agree that parallel theoretical support is essential during model test comparisons.

Regarding seabed friction, the authors have incorporated a model within 'flexriser' which allows for different friction coefficients in the pipe lateral and axial directions. As pointed out by Dr Carson, the static solution is indeterminate in the presence of friction. Nevertheless, in the design of a riser system, it is typically the extreme configurations which are of importance and this must be considered when performing any analysis with friction. The starting position for dynamic analysis is controlled directly by the user of 'flexriser' via previous analyses. This could, for example, correspond to using the static configuration with the floater in the normal operating position as the starting position. One alternative would be to model the installation procedure using 'flexriser' and use this installed configuration as a starting position for further analysis.

In the authors' experience, comparisons between packages based on finite difference and finite element methods have shown that both methods are equally applicable to prediction of flexible riser system response (see Boef *et al*, Fifth Intl Conf on Floating Production Systems, London, Oct 1989).

The authors agree that there are problems in extrapolating statistics of non-linear processes. The prediction of service life of a flexible pipe is considered a vast topic in its own right and will not be elaborated on within this reply.