

Understanding the Response of Pipe-in-pipe Deepwater Riser Systems

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ABSTRACT

Pipe-in-pipe top tensioned risers, in the forms of TLP/Spar dry tree risers and freestanding hybrid risers, are used in numerous deepwater developments worldwide.

During the detail design of pipe-in-pipe systems, the complex interactions between the pipes are often misunderstood, leading to conservatism or possible errors in the estimation of the system fatigue life.

This paper aims to provide an explanatory note on the interaction response of pipe-in-pipe riser systems and the considerations that are required to assess the stress, fatigue and VIV response of such systems. The methods considered in this paper could also be applied to multi tube risers.

KEY WORDS: Risers; Pipe-in-pipe; Fatigue; VIV; Stresses

INTRODUCTION

The industry has seen an increasing number of application of multiple pipe risers, ranging from TLP/Spar dry tree riser and freestanding single line hybrid risers, in deepwater. All these designs have a fundamental design challenge of determining the response of two or multiple pipes within the system, in order to determine the extreme stress and fatigue life over the length of the riser.

In all pipe-in-pipe risers centraliser are included in the design between the pipes and are considered essential to reduce differential bending in the system. Also centralisers can stop propagation buckling, when one string is in compression.

Analysis of pipe-in-pipe risers is often performed considering an equivalent composite model forming a unique pipe, as analysis of a detailed dual pipe model is considered time consuming. This assumes that the equivalent pipe bending and tension are shared equally based on the bending and tension capacities of the pipes. Using a composite model is justified if the pipes have equivalent differential bending or that the bending moment of the system is small, therefore little fatigue

or minimal stresses in pipes is expected. However, for certain riser systems, where the bending moment is high near the top and bottom assembly of the structure, it is important that the interaction between the pipes is clearly understood.

In areas of high riser curvature, the presence of centralisers and/or contacts between pipes may lead to discrepancy in the local bending moment response compared to those predicted by using the equivalent composite model. Therefore a detailed FE analysis modeling the inner and outer pipes and interaction between them is necessary to determine the response of the individual pipes to insure that the local bending in one pipe is not under or over-conservative for extreme storm event or first order fatigue analysis. Results from this detailed analysis can then be used in conjunction with the equivalent model to achieve an accurate assessment of riser response.

A detailed model also enables the following centraliser design parameters to be considered:

- The maximum annular gap size requirement between the centralizer and the outer pipe.
- Number of centralisers.
- Optimisation of centralizer spacing.

The centralisers design parameters cannot be determined from the analysis of an equivalent pipe system. Usually the smaller the gap between the pipes, the better; the same applies for the spacing as the closer the centralisers are for each other, the more the pipe in pipe system will have a tendency to behave together uniformly. An example of centralizer design is given in Figure 1.

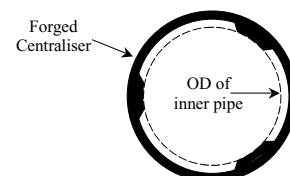


Figure 1 – Example of centraliser on outer pipe

Comparison between the equivalent pipe model and the detailed model leads to development of bending moment magnification factors which are used to understand to effect of the pipe-in-pipe system. Those

bending magnification factors can then be used to account for the error in the equivalent pipe system.

When considering a pipe-in-pipe system design, it is found that a high frequency, even with low relative bending moment the inner and outer riser pipes have can higher bending moment factor than that obtained for a lower wave frequency loading. Modelling techniques and considerations are described to correctly assess the impact of different type of environmental response.

EQUIVALENT PIPE-IN-PIPE MODELLING

When creating an equivalent model for a pipe-in-pipe system, the stiffness of the pipes is combined. This approach is fine assuming that the pipes are moving together uniformly under external and internal loading. The global motion of the equivalent model should therefore be close to the one of a real pipe in pipe system.

The combined stiffnesses (axial and bending respectively) for two pipe system are shown in (Eqs. 1~2). It should be noted that similar equations could be written for more than 2 multiple pipes.

$$EA = EA_1 + EA_2 \quad (1)$$

$$EI = EI_1 + EI_2 \quad (2)$$

where A is area, I the moment of inertia and E is the young modulus. The subscript 1 & 2 represent the outer and inner pipe respectively.

A finite element model in riser string package such as Flexcom-3D [MCS,2003] for extreme storm or Flexcom-Modes 3D and Shear7 [Vandiver, Lee and Leverette,2005] for VIV fatigue analysis can be setup to determine the response of the system to environmental conditions. The equivalent pipe is modeled such as the outer drag properties of the equivalent pipe is associated to the outer pipe.

Then the tension and bending in the riser may obtain by de-compositing the stiffness of the two pipes as follows.

$$B_1 = \frac{B_T I_1}{I_1 + I_2} \quad (3)$$

$$B_2 = \frac{B_T I_2}{I_1 + I_2} \quad (4)$$

Where B_T and T_t are the bending moment and effective tension of the composite model respectively. This is only sharing out the bending according to the inertias of the pipes; hence the bending moment could be higher, in both cases.

$$T_1 = \frac{T_T A_1}{A_1 + A_2} \quad (5)$$

$$T_2 = \frac{T_T A_2}{A_1 + A_2} \quad (6)$$

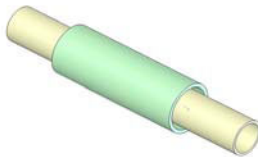


Figure 2 – Isometric View of a Pipe in Pipe System

These equations are assuming no pre-tensioning in the pipe initially but, can be adapted to take this fact into account.

Note that the assumption that the pipes move together is for some vertical riser system. For region of high bending, near the top and bottom or touch down point for SCRs, this will cause errors in the stresses and even more in the fatigue life assessment.

To obtain good prediction of the fatigue life, a detailed model need to be constructed or bounds on the error caused by using the equivalent pipe model. This model doesn't need to be used for the entire analysis, only to determine some general trends in the outer and inner pipes.

DETAILED PIPE-IN-PIPE MODELLING

A detailed model can be constructed of the pipe-in-pipe system. This includes the detail such as centraliser gaps, annulus gap, and centraliser arrangement. This allows optimisation of centraliser configurations, which includes spacing and required annular gap size of the centralisers.

Different possible tension configuration maybe considered, involving different pre-loads, in the individual pipes. From this model, tension and bending are calculated directly for the two pipes.

The disadvantage with pipe-in-pipe models is that they are more complex and requires longer running time for fatigue analysis and a detailed extreme and survival analysis. The advantage is that not the entire analysis needs to be run this way. A general pattern that is project specific can be analyzed and then applied to the rest of the analysis using a composite model.

The drag or the damping effect, of the inner pipe fluid is assumed to be minimal. This is more the case when the fluid is a gas, as it would be in the case of a gas lift line. For pipe-in-pipe risers, the annulus is usually not filled with fluid, except in damaged scenarios.

COMPARISON OF DETAILED AND EQUIVALENT PIPE-IN-PIPE MODELLING

In this section methods are defined to compare detailed and equivalent pipe-in-pipe models, which enables the understanding of the effect of centralisers to be considered and the difference over the equivalent pipe model to be established.

Bending Moment Magnification Factors (BMFs)

Detailed and equivalent models are considered with the same environmental loading conditions and same boundary conditions. The loading on the pipes are either due to an extreme storm, fatigue seastate or VIV fatigue oscillations.

To determine the relative response of the pipes, the bending moment magnification factor is defined for the inner and outer pipes by (Eqs. 7~8) [Yousun Li ,1997].

$$BMF_{inner} = \frac{Max \{ B_{inner - det ailed} (t) : \forall t \}}{Max \{ B_{inner - equivalent} (t) : \forall t \}} \quad (7)$$

$$BMF_{outer} = \frac{Max \{ B_{outer - det ailed} (t) : \forall t \}}{Max \{ B_{outer - equivalent} (t) : \forall t \}} \quad (8)$$

Where $B_{Inner-det ailed}$ and $B_{outer-det ailed}$ are the bending moments for

the detailed pipe in pipe model for the inner and outer pipes.

$B_{Inner-equivalent}$ and $B_{outer-equivalent}$ are the decompose bending moments for the equivalent pipe in pipe model.

Note that for accurate calculation of the BMFs, the equivalent and the composite model configurations need to be closely matched. Small bending moments tends to generate larger error in the BMF calculation (this is always the case when dividing small number by small numbers). This is especially the case for VIV analysis, where the modal response, in term of absolute bending is less than the extreme of wave fatigue analysis.

Note that for two pipe which always moves together, the BMFs value will be 1 and the greater the extent which the pipes do not move together the higher the factor will be. The length of time considered to be sufficient to define the BMF should be longer than the largest period of oscillation of the system.

Similar factors can be defined for the tension, but the impact of tension between the pipes is far less than the bending.

As an example, the bending moment near the top of a particular riser is taken for a composite model (and then derived to give inner and outer pipe bending moment) and a detailed model with an inner and outer pipe. A schematic plot of the bending moment decomposition is given in Figure 3. The associated BMF (7) is given in Figure 4.

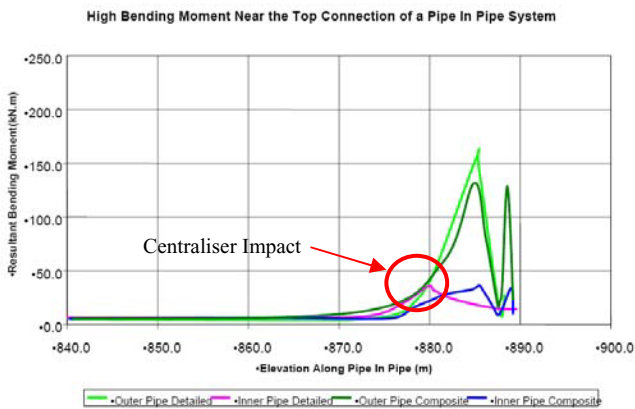


Figure 3 – Schematic view of Bending Moment Decomposition

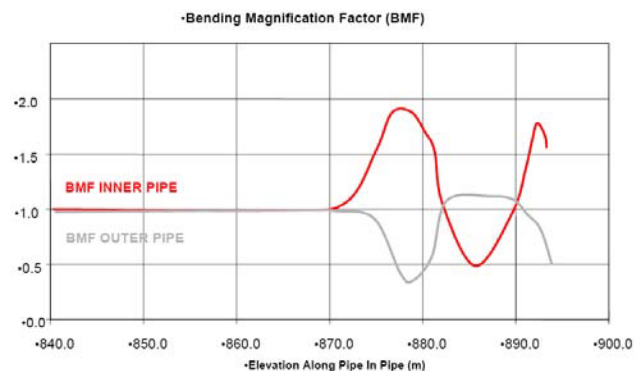


Figure 4 – Associated BMF of Figure 3

Example of BMF along riser

The following section present results of BMF along riser for case for extreme storm conditions, fatigue conditions and VIV conditions. The riser type considered for this analysis is pipe-in-pipe free standing riser which is free to rotate at the bottom and top of the riser under the air-can, [Hatton, McGrail and Walters 2002].

Shown in figure 5 and 6 are BMF calculations resulting from VIV modal oscillation of the first and second mode shapes of a possible riser. Shown in figure 7 is the BMF for Mode 5. These BMF are regular along the length of the riser and peak near the location of centralisers. The BMF are subject to errors as the location of the bending can shift due to centralizer positioning. This shift means that the composite bending moment might be divided by a very low actual bending moment generating some large errors in the BMF; this is especially true near the end of the riser where bending moment increases rapidly. Usually, once the concept of BMF is firmly understood, some threshold values can be added for very small bending moments. Shown in Table 1 is the peak BMF for mode shapes 1 to 5. This doesn't include the areas which have large errors in the BMF.

Mode Number	VIV BMF
1	1.10
2	1.08
3	1.09
4	1.24
5	1.21

Table 1 – VIV BMF

The amplitude of the modes shapes considered is approximately the same, but the higher modes have higher BMF, due to the increased frequency of oscillation.

Shown in figure 8 is an example of BMF distribution along riser for fatigue analysis, which was obtained by running a fatigue seastate with both models and calculating the BMF. The maximum BMF, obtained along the length of the riser is close to 1.1 near the ends. Areas of high BMF depend on the nature of the motion of the riser and what natural frequencies are excited. As many frequencies are excited the peaks along the riser don't follow a regular pattern. A few fatigue seastates are selected to obtain the bounding BMF for fatigue analysis. To be sure that the maximum bounding BMF is obtained, the sample seastates are chosen based on the maximum fatigue damage due to bending moment such that high, low and worst response frequencies are considered. The BMF due to wave motions are smaller than those due to VIV motions, as the frequency of oscillation is higher for VIV.

Shown in figure 9 is an example of BMF distribution along the length of a riser for extreme storm analysis. This is obtained by running the model both for wave loading and current, that corresponds to an extreme event. A maximum BMF of 1.2 occurs along the length and 1.3 at the ends. As for the fatigue analysis BMF determination, only a few extreme loading cases are considered to bound the BMF for extreme loading looking at the maximum stress along the length of the pipe.

It should be noted that a BMF of 1.3 means that the ratio between the equivalent bending moment and real pipe system shows that the bending should be in fact 30% higher, but, for fatigue purpose, this increase of 30% should generate around $1.3^3=2.2$ time more fatigue damage at the location, hence the fatigue life is out by a factor 2. For a BMF of 2.0 in harsher environment or riser configuration, the fatigue life could be 8 times more damaging.

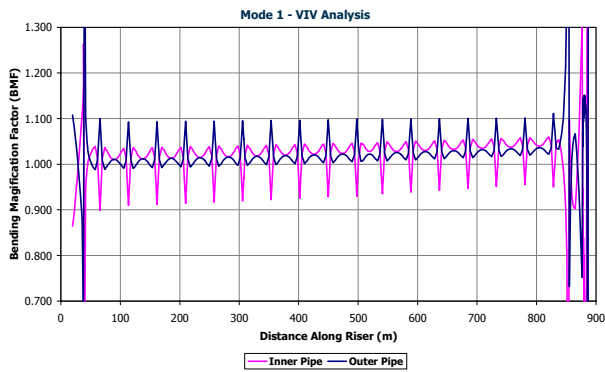


Figure 5 – Mode 1 – VIV Analysis

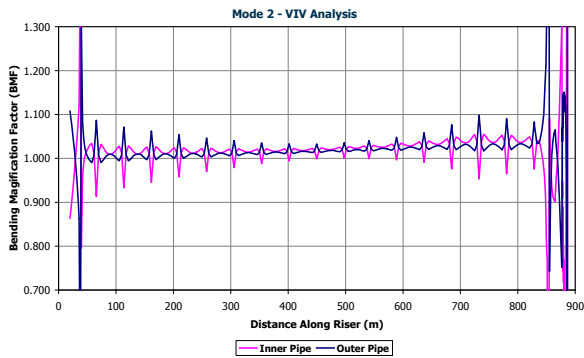


Figure 6 – Mode 2 – VIV Analysis

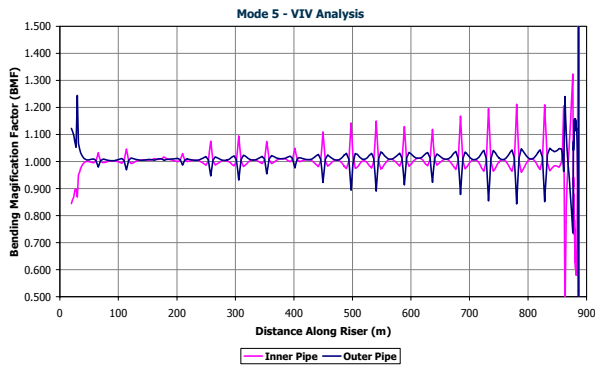


Figure 7 – Mode 5 – VIV Analysis

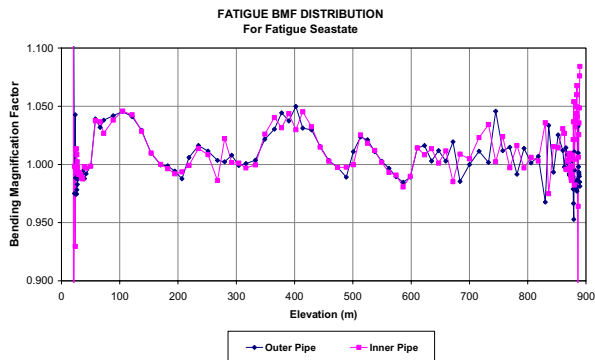


Figure 8 – Wave Fatigue BMF Distribution

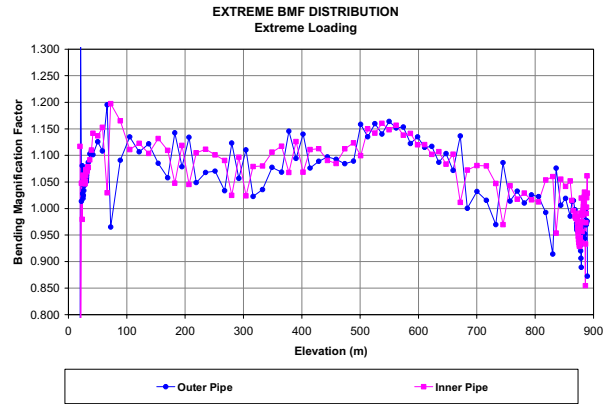


Figure 9 – Extreme Loading BMF Distribution

Note also that for large movements of the riser, the system response of the pipe-in-pipe behavior is more together. Small movement of the riser induces large bending moment factors (BMF) particularly in the case of VIV. Also note that at the location of the centraliser the bending moment is higher as the impact of the centraliser cause local bending in the pipes.

Centraliser Design Parameters

The effect of the centraliser spacing and annular gap size can be considered and compared via this method, to determine, what gap size is required and what gap size can become critical to a riser design. The minimum gap that can be achieved for a centraliser gap is dependent on the tolerance of the pipe manufactured, which could be about 5mm.

The closer the gap between the pipes and the more the centralisers will 'force' the inner pipe to move with the outer pipe, reducing the BMFs, but the response of these parameters is non-linear and is depend on the configuration geometry.

BMF Trends

Shown in Table 2 is a summary of the trends due to BMF parameters. It should be noted that the response to parameters is non-linear due to the nature of the geometries involved. Also, centralisers spacing and gap size will be limited by installation considerations and fabrication tolerances.

Effect	Response
Closer centraliser gap	Decreases BMF, pipes movement is more together.
Centraliser spacing along the riser length	Decreases BMF, pipe movement more together, but after certain size, little improvement is gained.
Increase Frequency	Increases BMFs,
Increase Amplitude	Can increase or decrease BMF depending on the gap size

Table 2 – Response to Changing Centraliser Parameters

ANALYSIS OF PIPE-IN-PIPE RISERS

The use of BMFs can be turned into an analysis methodology, by considering the BMF scaling for the different loading cases of extreme storm, long-term fatigue and VIV fatigue. The BMFs allows us to obtain maximum stress and fatigue lives of the system.

The following methods can be considered for pipe-in-pipe riser systems,:

- Equivalent pipe analysis (If the pipes behavior is homogeneous)
- Equivalent pipe analysis, combined some-cases BMF determine and applied to results.
- Detailed pipe-in-pipe analysis, when the BMFs obtained are large and the results are highly critical. This would require large amount of computational time, consideration or a reduced load case matrix.

The equivalent pipe analysis is only suitable for riser systems that have large motions such that the centralisers are in contact most of the time and the fatigue lives are not critical

The equivalent pipe analysis combined with detailed modeling and BMFs allows for the consideration of the pipe-in-pipe aspects of the riser, while not requiring that the whole analysis is carried out for all risers in consideration and all load cases. For cases where the BMFs are high and the fatigue lives is critical, it is still recommended that a full detailed pipe in pipe analysis is conducted to remove conservatism in the BMFs approach as the BMFs values used for the entire analysis are in fact 'envelopes' of the worst BMFs considered.

CONCLUSIONS

The definition of the BMF enables to find out the extent to which the pipe-in-pipe deviates from an equivalent single pipe riser. Thus

enabling determination of the importance or critically of the centraliser configuration and the extent at which it impacts the stresses and the fatigue life response of the system.

ACKNOWLEDGEMENTS

The authors would like acknowledge Frank Lim, Simon Luffrum and Hugh Howells for useful discussion.

REFERENCES

- Hatton, S, J McGrail and D Walters (2002) "Recent Developments in Free Standing Riser Technology"- *3rd Workshop on Subsea Pipelines, Rio de Janeiro Brazil.*
- Li, Y (1997) "The Concept of Multitube Moment Factors in a Riser System and its Applications," *OTC008519.*
- MCS (2003) "Flexcom-3D Three Dimensional Non-linear Time Domain Offshore Analysis Software". *MCS International, Version 6.1.9.*
- Vandiver, JK, Li.Lee, S.Leverette, H Marcollo (2005). "User Guide for Shear7", Atlantia Offshore.
- Young, WC (1989) "Roark's Formulas for Stress & Strain" Sixth Ed, McGraw Hill.