Fluid-Structure Interactions Modelling of Pipe-In-Pipe Riser Systems Operating in Ocean Environments

E. Yettou, A. Derradji-Aouat & C.D. Williams
National Research Council Canada, Institute for Ocean Technology, St. John's, NL, Canada

ABSTRACT:

This paper is a part of a larger project to investigate the performance of a new pipe-in-pipe (PIP) riser design for operations in a harsh ocean environment. It is hypothesized that this new system will reduce Vortex-Induced Vibration (VIV) and show significant advantage in terms of fatigue life span. The mandate of the project covers both physical model testing and numerical predictions. A physical model for a PIP riser system was tested in air (for reference benchmark data) as well as in water. In this paper, the development of the numerical model, steps for validation and numerical results will be presented. In particular, the focus will be directed towards current issues associated with numerical modelling of Fluid-Structure Interactions (FSI) in a multi-physics environment (water, air, PIP-structure). The FSI Model was developed on the basis of the Arbitrary Lagrangian-Eulerian (ALE) numerical solution methodology. Comparisons of the numerical results with experimental results are given for validation.

1 INTRODUCTION

For floating offshore drilling structures, riser systems are crucial elements. Marine risers are used to transport oil, gas, water and mud from the producing field to a surface platform and back down for export through a subsea pipeline or a tanker loading system. Harsh environmental conditions off the coast of Newfoundland and Labrador impose more complexity in the design of actual riser systems. Under the influence of high winds, powerful waves, continuous water currents, ice floes and icebergs, risers are subjected to cyclic bending loads as well as axial loads due to their own weights. Exposure to this severe ocean environment accelerates fatigue, risk of premature failures, and shortens the operating life span of the of traditional industry risers.

Despite these harsh operating conditions, offshore oil and gas exploration has been moving into ever increasing water depths. One of the growing issues facing deepwater risers is Vortex Induced Vibration (VIV), or large amplitude oscillations, which occur when the local ocean currents produce vortex shedding and when the frequency of vortex shedding is approximately equal to the structure's natural frequency. VIV may make the largest contribution to overall deep-water riser fatigue damage. Extensive researches have been done to investigate VIV response of risers and several methods have been proposed for the fatigue life estimation of these structures (Iranpour et al. 2006). Many design and configuration solutions were proposed to reduce the effect of VIV on riser systems. For instance, an extensive riser systems testing program, focused on VIV, was carried out by Exxon Mobil (Frank et al. 2004, Tognarelli et al. 2004). The test program was directed towards investigating the effects of wave flow around cylindrical bodies. According to those studies, the presence of strakes on the riser causes a change in its frequency of vibration. Therefore, the overall life of the riser could be improved by adjusting the number of strakes and their percent coverage to attain the desired frequency.

Traditional pipe-in-pipe (PIP) riser systems are employed in offshore oil and gas production when steady thermal operating conditions are required to maintain flow-rates and to avoid hydrate plugging and wax appearance in deep cold-water environments. A PIP riser is comprised of concentric inner and outer pipes. The inner pipe, called the “conduit”, carries the production fluids and is insulated, while the outer pipe or “carrier” provides mechanical protection. Specially designed spacers are placed “strategically” at pre-calculated locations between the two pipes. Traditionally, the spacers are rigidly attached to both pipes (Bai 2001). For such riser systems, the literature review provided some insight into the overall industry experience “and the cumulative wisdom” to prevent VIV fatigue damage. For instance, a pre-tension applied to the inner pipe, a common industry practice, makes the pipe less susceptible to large amplitude vibrations. Also, insulation of the inner pipe may have a dual purpose. In addition to controlling the temperature of the inner pipe, it can act as a damper between the two concentric pipes. Annulus fluid fill and inner pipe coating could be very beneficial. The fluid fill such as a high viscosity mud, could slow flow line motion and act as natural viscous dampers (Derradji et al. 2006). Extensive experiments were carried out by Lim et al. (Lim et al. 2005) to obtain information on wave motion/PIP riser vibration interactions. Their test program included a parametric study to investigate the effects of the distance between the fixed spacers; issues associated with damping, due to annulus fill (with water or viscous types of mud), pre-tension of the inner flow lines and pipes friction effects were investigated.

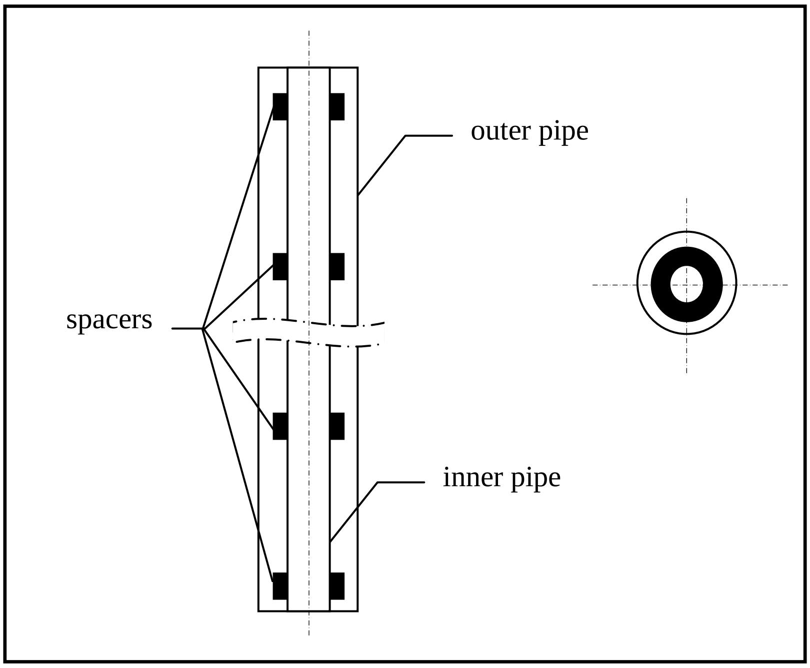

Figure 1. Simplified sketch of the pipe-in-pipe riser system

This work is a part of a larger project to investigate the performance of a new PIP riser design in the harsh ocean environment off the east coast of Canada. For this new PIP riser, spacers are designed to not be rigidly connected to both pipes. Therefore, the two pipes are allowed to move independently relative to each other (see figure 1). It is believed that this new design concept of the PIP riser will reduce large amplitude oscillations caused by VIV and thus, provide significant advantage in terms of structural performance, fatigue life span, costs and reliability; as compared to the traditional PIP riser designs (“traditional PIP system” refers to PIP system where the inner and the outer pipes are rigidly attached together at the spacers locations). The mandate of the new PIP riser design project covers both physical model testing and numerical predictions. A physical model for a PIP riser system was tested at the Institute for Ocean Technology of the National Research Council Canada (NRC-IOT). This paper deals with the predictive numerical approach. First, a preliminary FSI numerical model of the PIP riser system in air was developed. The solution was obtained using the LS-DYNA Arbitrary Lagrangian-Eulerian (ALE) penalty coupling algorithm. For validation, the numerical results were compared with both the classical Lagrangian numerical results (without FSI consideration) and the measured results from the actual PIP test program. In this validation/verification process, the focus was directed towards current issues and concerns associated with numerical modelling of Fluid Structures Interactions (FSI). Thereafter, using the multi-material capability within LS-DYNA, the FSI modelling of the actual PIP riser system in water was conducted.

This paper is divided into six sections. After an introduction in section 1, a brief discussion about the importance of the numerical prediction in ocean engineering is presented in section 2. Subsequently, section 3 gives a description of the preliminary model of the PIP riser in air. Comparisons of the numerical results with experimental data are given in section 4. Issues and concerns of the validation/verification procedure are highlighted as well. In section 5, discussions about future work of the FSI modelling of the PIP riser in water are presented. Finally, conclusions, propositions as well as the author’s views of the practical implications of the results are provided in section 6.

2 NUMERICAL MODELLING OF FLUID-STRUCTURE INTERACTIONS

Marine and offshore engineering problems are complex in nature and the use of a single set of analytical equations, such as “closed form solutions”, may not be adequate enough to describe all physical processes of the problem (Office of Naval Research 2000). Moreover, usually in such problems, system analysis is taking precedence over the traditional component analysis. For instance, in an offshore system that is made up of several structural components, the effect of the behaviour of one component on the global system needs to be investigated. This is propelled by the need for an overall fragility “design safety” and consequence analyses of complex structures (Casciatti et al. 1991). Therefore, understanding and dealing with the weakness (or weaknesses) of the whole system is needed. Nowadays, in ocean engineering, a coupled numerical approach, involving computational structural dynamics (CSD) and computational fluid dynamics (CFD), is needed (Erno 1985). Offshore and marine engineering models are becoming increasingly large and complex. Numerical modelling has become a multi-disciplinary and multi-physics approach, whereby the CFD and CSD are combined “in a hybrid manner” to analyze offshore engineering problems from both points of view concurrently. The hydrodynamic effects on the overall structure behaviour cannot be either ignored or just added to the structural analysis using superimposition principles since offshore CSD/CFD problems are nonlinear. A whole fluid-structure interaction model taking into account the hydroelasticity effect (the instantaneous coupling between different fluids and structures mediums) has to be generally considered. As a result, the emerging numerical predictive methods and particularly the Fluid-Structure Interaction (FSI) modelling becomes a significant alternative in marine and offshore engineering. In addition to its ability to give an insight of complex multiphysics engineering problems, it enables researchers and scientists to experiment with a wide range of “what-if” scenarios for risk assessments, accident scenario investigations and fragility analyses.

However, the true value of any computational model is determined by both the accuracy of the results and the ability to interpret all of the significant information contained in those results. To a large extent, the accuracy of the results can be assured via verification and validation analyses (V&V analyses), also known as numerical uncertainty analyses. Subsequently, V&V analysis is imperative to gaining an acceptable level of confidence in the computation output (Stern et al. 2001). Benchmarking of the numerical results against data from physical experiments is the most direct and effective way for a system validation.

At the Institute for Ocean Technology (IOT) of the National Research Council Canada (NRC), the willingness to integrate the predictive numerical methods, and particularly the Fluid-Structure interactions (FSI) modelling, in the different research projects becomes increasingly necessary (Derradji A. 2003). For this aim, the Marine Dynamics Virtual Laboratory (MDVL) is being developed. The MDVL is a virtual replica of the physical towing tank facility at the NRC-IOT. It is intended that the MDVL will be used to conduct numerical tests (same scenarios and ship manoeuvres as those conducted in the physical test facility) at lower cost, much faster test schedules, and much more complex testing programs (Derradji A. 2001).

The present work falls within the scope of this goal to integrate predictive numerical methods for the analysis of complex multiphysics ocean engineering problems. The software used in this study uses the commercial packages ANSYS (www.ansys.com) and LS-DYNA (www.lstc.com). The former is essentially used to build the geometry and perform meshing while the latter is used as a solver. LS-DYNA has both a CFD Navier-Stokes solution technique and a fluid–structure interactions capability. It deals, also, with collisions, explosions, disaster simulations and general structural dynamic problems. Such dynamic events could be modeled into LS-DYNA in many ways, including pure Lagrangian, coupled Lagrange and Euler, and Smooth Particle Hydrodynamics (SPH) methods (Hallquist 2005). For the present study, the SPH method was discarded because of the expected increase in calculation time associated with this algorithm. A pure Lagrangian approach is discarded as well, since the numerical problems due to element distortion would limit its applicability to simulate water motion around the riser. The multi-material Eulerian formulation combined with an Arbitrary Eulerian-Lagrangian (ALE) coupling algorithm was used as it is the most mature methodology and is thought to produce the best results.

3 DESCRIPTION OF THE NUMERICAL MODEL OF THE PIPE-IN-PIPE RISER

The PIP geometry was generated on ANSYS using its Boolean operations and its primitive volumes library. Manual mesh option was chosen; this option is preferred in the case where the user needs to change the mesh resolution. Solid elements were used only for the spacers. All other structural elements were meshed using shell elements. Note also, that the mesh of the inner pipe, the outer pipe and the spacers was chosen to be of about the same dimensions. Top and bottom plates were added to close the ends of the inner and the outer pipe in order to replicate the conditions in the experiments. Pin systems (cylindrical articulation) were added at the top of the pipes, too. Figure 2 presents some details of the geometry at the top of the PIP where the pins are located. Note that all structural materials are rigid except for the inner pipe, the outer pipe and the spacers.

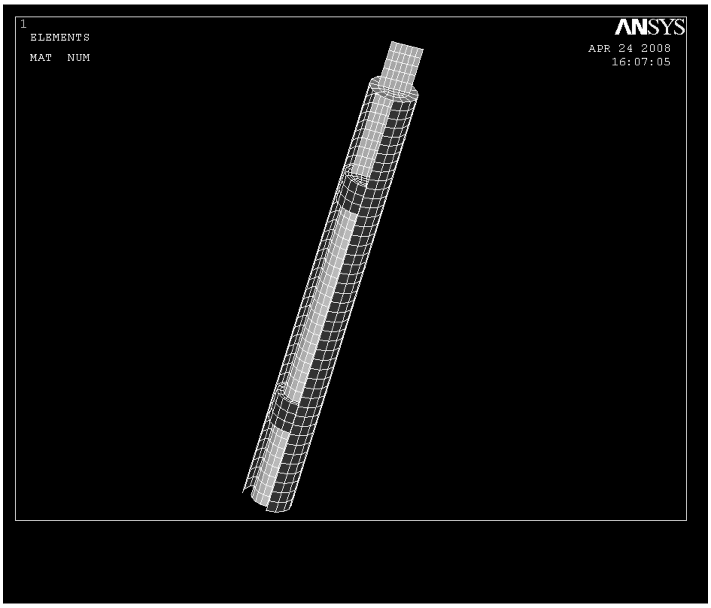

Figure 2. Design details of the top of the PIP including the pin system and top plates.

Once, the structural part was built, the fluid part is generated using rectangular volume geometry. Since the preliminary model is intended to simulate coupling between the structure and air only (as fluid), the Eulerian or ALE geometry (fluid part) could be relatively small. Thus, the dimensions of the fluid block were chosen so that the structural part remains inside the Eulerian mesh throughout the whole simulation. Figure 3 shows the entire finite elements model performed on ANSYS (the Eulerian mesh was cut in half to show the Lagrangian mesh inside). Table 1 summarizes all the significant information about the model at the pre-processing stage.

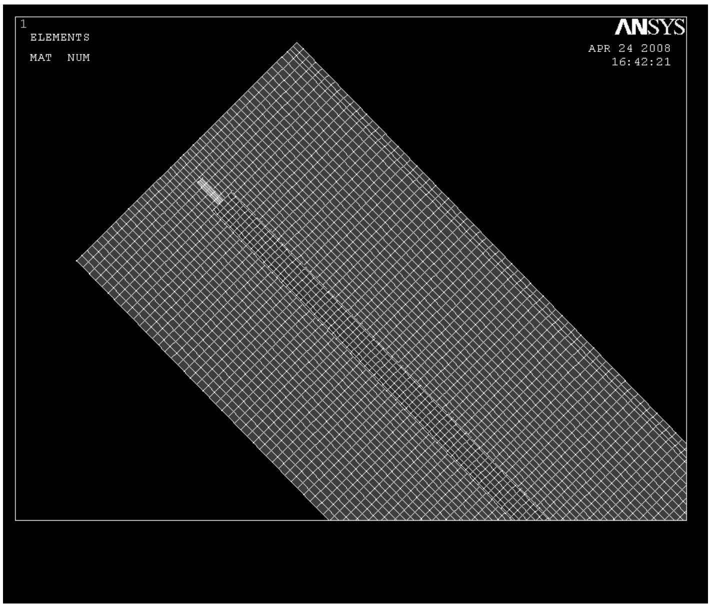

Figure 3. The whole FSI model: The PIP or the Lagrangian structure, inside the fluid part of the ALE mesh.

Table 1: General pre-processing parameters

Parameters	Description
Number of Lagrangian nodes (PIP structure)	5995
Number of Eulerian nodes (fluid)	54496
Total number of nodes in the model	60491
Number of Lagrangian elements (PIP structure)	5828
Number of Eulerian elements (fluid)	46410
Total number of elements in the model	52238

Once the finite elements model was built on ANSYS, a k-file is created. The k-file is an LS-DYNA input file that contains a list of LS-DYNA commands, with a proper format. This k-file needs to be manually modified to add and adjust the different contact and coupling parameters. Then, the k-file is processed by LS-DYNA and the output data are analyzed using the post-processing tools.

4 VALIDATION AND VERIFICATION

The validation/verification process was carried out in two stages. The first step consists of validating the contact definition between the spacers and the outer pipe, while, the second step is carried out to validate the coupling definition or the interaction between the Lagrangian mesh of the outer pipe (structure) and the ALE mesh (fluid). For that matter, experimental data from the test in air were first compared to the numerical results obtained from a classical Lagrangian model (without any FSI coupling consideration). Thus, for this first comparison, the numerical model consists of the PIP riser structure only with real material properties and dynamic loading (the ALE mesh containing air was omitted). Table 2 below presents all the important parameters of this numerical simulation. As is shown in Figures 4 and 5, satisfactory correlations between experimental data and numerical results were achieved.

Table 2: Parameters of the classical Lagrangian finite elements model (the PIP structure part only)

Parameters	Description
Number of nodes	5995
Number of elements	5828
Elements types used in the model	Shell and solid elements
Materials	- Elastic with Ey=0.689E+11 Pa - Elastic with Ey=0.125E+08 Pa (spacers) - Rigid with Ey=0.689E+11 Pa
Loading	- Sinusoidal velocity (x direction) with an amplitude of 2*PI*0.4*0.184 m/s and a frequency of 0.4 Hz - Gravity 9.81 m/s2
Contact	Yes
Coupling	No (no ALE mesh and no coupling)

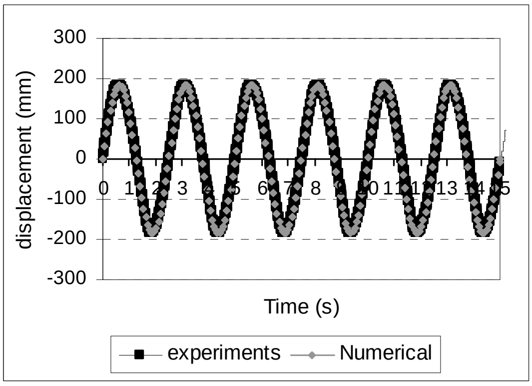

Figure 4. X-Displacement vs time history of the displacement of the top of the riser.

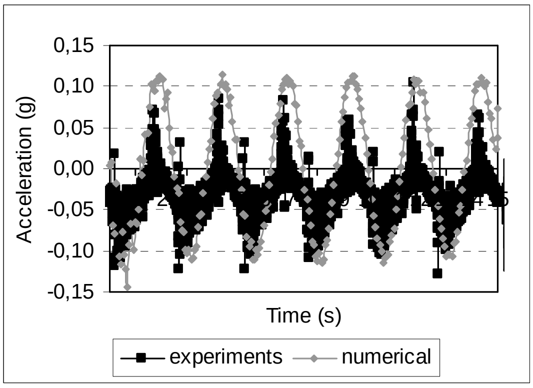

Figure 5. X-Acceleration vs time history of the bottom of the riser.

This preliminary validation/verification step was conducted mainly to improve contact definition. Once the contact was properly defined, the ALE mesh was added and the coupling between the structure (the PIP) and the fluid (air) was activated. However, when adding the coupling, the calculation time increases considerably. So, for reasons of saving calculation time, the Young's moduli of the structural parts were set to smaller values. Typically, we used a reduced value of 0.689E+08 Pa for Aluminum parts (all solid parts except the spacers) and 0.125E+08 Pa for the spacers. Doing that, we reduced calculation time by more than 90%. This modification allowed us to adjust all the coupling parameters so as to produce useful FSI simulation results. However, for more realistic results to be compared to the experiments, we have no choice but to set the Young's modulus to its real value that is 1000 times larger than the above-mentioned value. Table 3 below gives all the important parameters of the FSI finite elements model.

Table 3: Parameters of the FSI finite elements model (with coupling consideration)

Parameters	Description
Number of Lagrangian nodes	5995
Number of Lagrangian elements	5828
Number of ALE nodes	54496
Number of ALE elements	46410
Total number of nodes in the model	60491
Total number of elements in the model	52238
Elements types used in the model	Shell, Solid and Solid_ALE Elements
Materials for structure parts	- Elastic with Ey=0.689E+08 Pa - Elastic with Ey=0.125E+05 Pa (spacers) - Rigid with Ey=0.689E+08 Pa
Materials for fluid parts	- MAT_NULL (density of air =1.29)

	- EOS_LINEAR_POLYNOMIAL (C4=C5=0.4)
Loading	- Sinusoidal velocity (x-direction) with an amplitude of 2*PI*0.4*0.184 m/s and a frequency of 0.4 Hz - Gravity 9.81 m/s2
Contact	Yes
Coupling	Yes

The results of the above FSI model were compared to the results of the pure Lagrangian simulation (without ALE mesh and without coupling definition). This comparison shows a satisfactory correlation as can be seen in Figures 6 and 7. This correlation confirms that the coupling definition is acceptable and reliable to use in future numerical modelling of the PIP riser in air and water.

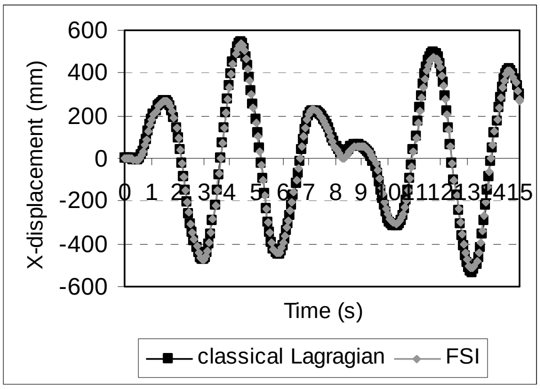

Figure 6. X-displacement vs time of the bottom of the riser.

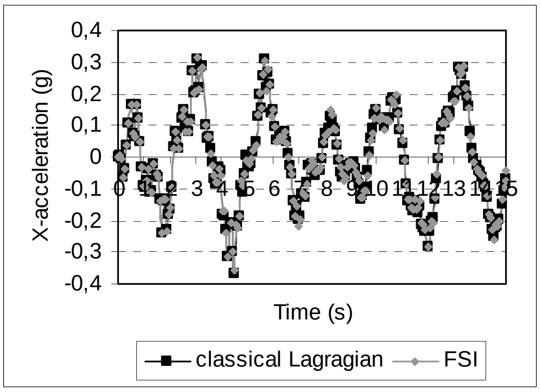

Figure 7. X-acceleration vs time of the bottom of the riser.

It should be noted that, to have this satisfactory correlation, many adjustments of the coupling parameters were needed. Particularly, using the penalty coupling method, increasing the number of coupling points and decreasing the minimum volume fraction of the coupled ALE element to activate coupling earlier than it was in the default configuration, are the main and the most important results for the studied case.

5 DISCUSSION AND FUTURE WORK

The first validation/verification step presented above enabled us to verify that the FSI modelling that occurs between the outer pipe and the fluid (in this case, air only) gives satisfactory results. Therefore, we can now move to the second step to simulate the oscillatory motion of the riser in water using the multi-material capability of LS-DYNA. The Eulerian mesh will contain thus two different fluid materials (water and air). A slight modification of the input k-file is obviously needed. However, the most important parameters of the coupling will remain unchanged. It should be remembered, besides, that the Young's moduli of the structural parts have been reduced by about 1000 times. Thus, the obtained results do not reflect the real behaviour of the riser. However, this allows us to save calculation time which is necessary as a first step to adjust all the parameters of FSI modelling. Once satisfactory results have been achieved, it would be possible, then, to apply the suitable materials properties to obtain results that reflect reality. However, to model the PIP riser in water and to have results that reflect reality and can be compared with experimental data, not only the actual materials properties should be used, but also, we should probably increase the dimension of the Eulerian mesh containing fluid. Indeed, this will decrease the effect of any water waves which may be reflected from the boundaries of the mesh, which, in turn, could slightly alter the quality of the results. The increase of the Eulerian mesh dimensions must, however, be carried out according to a compromise between the quality of the results and the calculation time. Since a larger number of elements will increase the calculation time without necessarily providing numerical results with a significantly higher quality, therefore a mesh optimization study over the quality of the results is needed. Usually, in

FSI modelling the extent of the Eulerian domain in a given direction should be at least 5 times the amplitude of the motion of the structural part in the same direction. However, this is not an inflexible rule since it depends on the nature of the motion, the material properties, the desired result, etc. Also, one of the major issues of FSI numerical modelling and the large number of elements required in such models is computer-processing power. The power of computers and how they are used are two of the most important concerns of FSI numerical modelling. LS-DYNA offers the opportunity to use its massively parallel processing (MPP) algorithm that can be, sometimes, a valuable alternative; this will be the focus of future work in this area.

6 CONCLUSIONS

In this paper some initial results have been shown from a FSI (fluid-structure interaction) model of a pipe-in-pipe structure for which extensive experimental results are available. By judicious choice of finite-element, multi-physics modelling and ALE (arbitrary Lagrangian-Eulerian) methodology and the combined use of ANSYS and LS-DYNA software, a preliminary validation and verification has been achieved. Indications are that future work with this model may require additional computer resources and the use of parallel-processing algorithms.

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