DEVELOPMENT OF AN OPEN SOURCE TOOL FOR WATER HAMMER AND FLUID-STRUCTURE INTERACTION SIMULATION IN NUCLEAR REACTORS SYSTEMS

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1. Intoduction

Fluid-structure Interaction deals with the transfer of momentum and forces between a pipeline and its contained fluid. In this case, interaction mechanisms have to be taken into account. Three interaction (coupling) mechanisms occur during FSI in straight pipes [1-5]: Friction coupling is due to friction between pipe wall and the fluid; Poisson coupling relates the pressures in the fluid to the axial stresses in the pipe via the contraction or expansion of the pipe wall; Junction coupling takes place at pipe boundaries that can move, either in response to changes in fluid pressure or because of external excitation [5].

To accurately predict hydrodynamic loads in the fluid, as well as pipe stress and vibrations, the analyses of fluid and pipe movements must be conducted simultaneously in a coupled manner. This approach is referred in the literature as Fluid-structure Interaction (FSI). FSI has been the subject of intense research in recent years [2-10].

The called HT-FSI project (Hydraulic Transient with Fluid Structure Interaction) has been developed during the last 2 years in the Nuclear Engineering Center (CEENG) of Nuclear and Energy Research Institute (IPEN-CNEN). The main purpose of the HT-FSI Project is to develop an open source code to predict the main phenomena observed in single and two-phase water hammer transients in industrial piping systems, including specific nuclear reactors hydraulic systems. At final development, the code would be able to simulate the coupled problem of hydraulic transients and fluid-structure interaction by solving the one-dimensional six equation two-fluid model approximations. Pressures, stresses and displacements will be calculated in time in order to permit the analysis of pipeline and supports due to hydraulic transient generated by many different phenomena.

This paper present the concept of referred project, the main parts already developed and other parts that must be implemented.

All codes developed in this project are being developed in open source platform using the Python and C++ language, depending of specific calculation package. At final, the code will be available for users without charges but under certain specific distribution criteria, to be defined.

This paper is divided into three main parts: the first part of the paper deals with the general HT-FSI project design, the second one deals to show the main advances, and the third part deals to present the ongoing works.

2. The HT-FSI Project

With the objective of to develop a numerical tool for prediction the pipeline loads generated by hydraulic transients (or water hammer) the Hydraulic Transient with Fluid Structure Interaction project was purposed in order to give a more detailed information for designers when evaluating hydraulic pipeline systems of industrial or nuclear reactors.

The development of the computer code was initially proposed for simulations of several types of transients, whether in subcooled fluid flows or even saturated two-phase flows.

The final model proposed for thermo-hydraulic transients prediction is the two-fluid model of six one-dimensional equations with approximations of and calculation of forces and displacements in the pipeline. More complex models exists (14 equations), but according to the literature, the six equation model is sufficient to well predict al desired parameters.

For subcooled flow models, the Method of Characteristics (MOC) is used for solving the hyperbolic partial differential equations system, associated with finite differences and linear interpolations procedures.

For the saturated two-phase flow transient models, the Finite Volume Method (FVM) the main flow regimes being considered are: stratified, dispersed, and transitions. In this model the thermal non-equilibrium flow is modelled by a relaxation equation for the void fraction.

A more complete transient wall friction relaxation model will be applied. Piping deformation has been introduced in the equation system based on a development of the balance equations (mass, momentum and total energy) for a moving pipe cross-section.

Advanced numerical methods for hyperbolic conservation laws are included in order to damp down the numerical diffusion effects. A separate integration scheme enables to accurately integrate the stiff source terms.

The Fig. 1 show schematically the HT-FSI Project design.

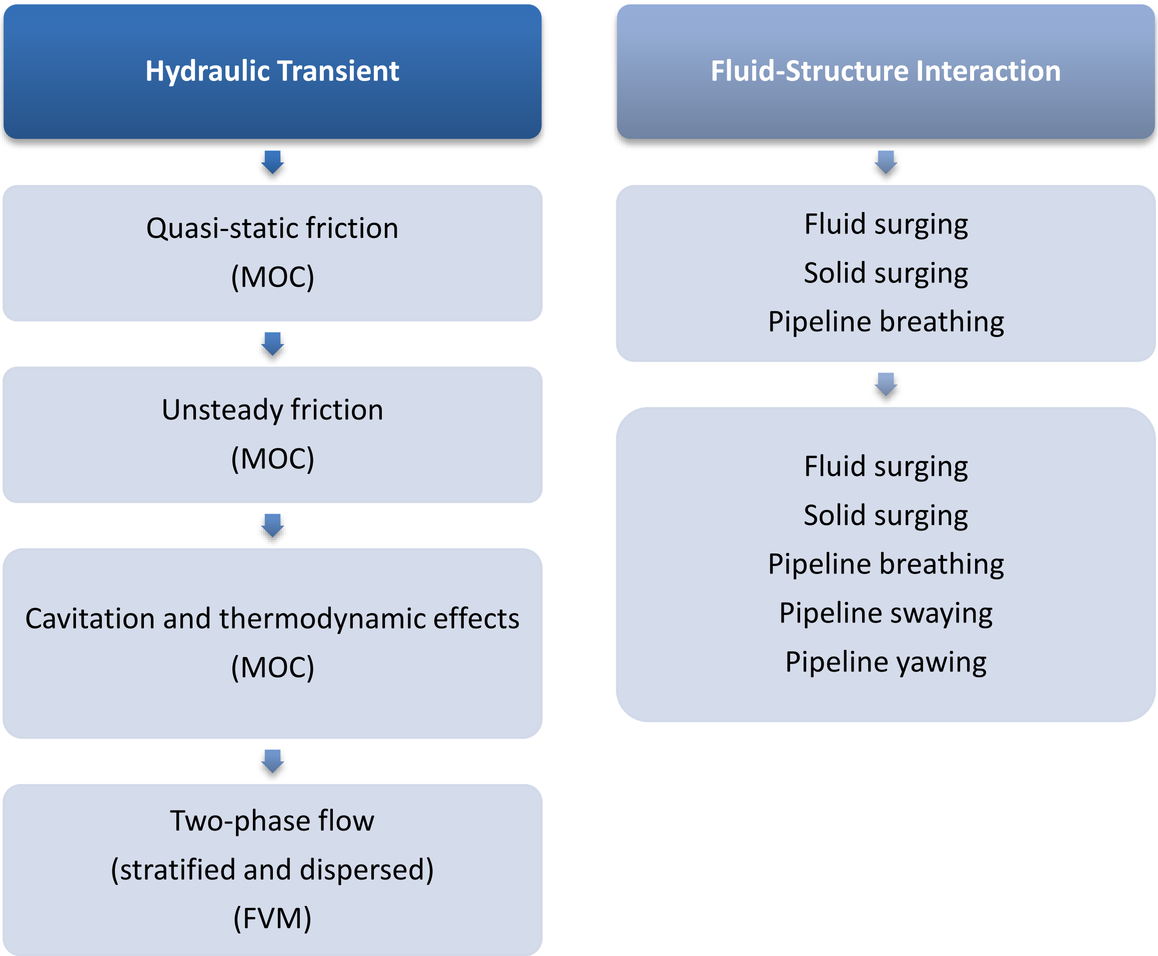

FIG. 1. HT-FSI Project design.

3. Advances of computer codes

The first code developed (FSI_01) [x] calculates the effects of hydraulic transients on the fluid (elastic model), for a simply reservoir-tube-valve system. The codes, developed set of mathematical equations that describe the phenomenon of hydraulic transient and fluid interaction models are composed of an input module, a pre-processing module (solving the equations) and a post processing module that will supply the variables of interest. It was developed in the C++ language, and are able to fluid-structure in a fluid transport pipeline.

Numerical simulation of hydraulic transients (with and without FSI) is generally based on one-dimensional mathematical models composed of differential equations and empirical coupling equations specific to singularities.

For the fluid component it solves the continuity and momentum equations for the fluid, in the axial and radial directions. As for the structure, the two-dimensional (axial and radial) stress-strain equations are solved.

The liquid and pipe coupling equations are determined by boundary conditions that represent the contact between the liquid and the pipe wall.

Externally to the tube there is also the condition of ambient pressure. The dynamic conditions provide the pressures of the fluid acting on the tube wall and the kinematic conditions prescribe the interaction between the liquid and the tube.

The equations that govern this phenomenon can be solved in the domains of time and space. The influence of fluid and structure characteristics is great on the result, that is, on the prediction of pressures, frequencies, efforts and displacements.

The method also needs correlations that are obtained empirically, that is, they depend on the performance of experiments.

The classical methods of resolution, restricting the focus to transient solutions in the time domain, are the Method of Characteristics (MOC), Finite Element Method (FEM), or a combination of these methods [x]. Another method used is that of Glimm in conjunction with an operator decomposition technique.

The four equation (and more simplified) model for hydraulic transient with fluid structure interaction has been develop and validated by analytical and experimental results.

Equations (1), (2), (4) and (5) form a pair of hyperbolic equations of partial derivatives.

Method of the Characteristics (MOC) [10] transforms these equations into total differential equations.

$$\frac{\partial V}{\partial t} + g\frac{\partial H}{\partial x} = -f\frac{V_{rel}|V_{rel}|}{4R} \tag{1}$$

$$\frac{\partial V}{\partial x} + \frac{g}{a_f^2}\frac{\partial H}{\partial t} = 2\mu\frac{\partial \dot{u}_x}{\partial x} \tag{2}$$

The governing equations for the axial motion of the pipe are provided by the momentum balance and the stress-strain relation. The pipe is described by its axial velocity ($\dot{u}_x$) and axial stress (σ_x) [6].

$$\frac{\partial \dot{u}_x}{\partial t} - \frac{1}{\rho_t}\frac{\partial \sigma_x}{\partial x} = f\frac{\rho_f A_f}{\rho_t A_t}\frac{V_{rel}|V_{rel}|}{4R} + g\,\mathrm{sen}\theta \tag{3}$$

$$\frac{\partial \dot{u}_x}{\partial x} - \frac{1}{\rho_t a_t^2}\frac{\partial \sigma_x}{\partial t} = -\rho_f g\frac{\mu R}{Ee}\frac{\partial H}{\partial t} \tag{4}$$

Equations (1) and (2) are coupled via terms proportional to the friction coefficient, f. Equations (3) and (4) are coupled via terms proportional to Poisson's ratio. These terms represent the Poisson coupling. These terms govern the friction coupling. Junction coupling is a result of local forces and therefore modelled via boundary conditions. The friction is modelled as if the flow were steady.

After *MOC* procedure, the so called equations of compatibility are obtained. The *MOC* is a powerful method to deal with wave phenomena. With respect to water hammer the method has many advantages: stability is firmly established, boundary conditions can be programmed easily, and complex systems can be handled. Initial condition (time = 0) and boundary conditions are set to the solution of the equation system in time. Boundary conditions can be reservoir, expansions, contractions, valves, nozzles, curves, pipe ends, etc.

The Fig. 2 shows the simplified scheme purposed for the FSI_01 code.[11]

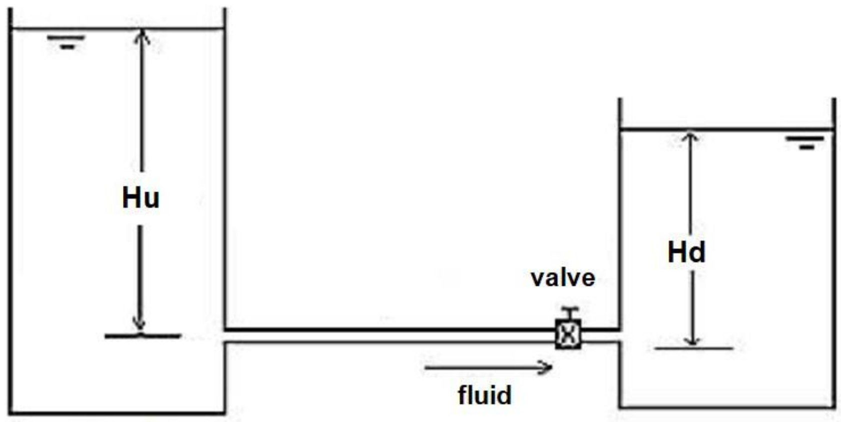

FIG. 2. Reservoir-Tube-Valve scheme [10].

Figure 3 show the validation results of FSI_01 against exactly solution [11] for Delft Hydraulics Benchmark Problem A. Fluid pressure, pipe wall stress and Fluid Velocity are calculated at valve section. There is good agreement between exactly solution and FSI_01 results.

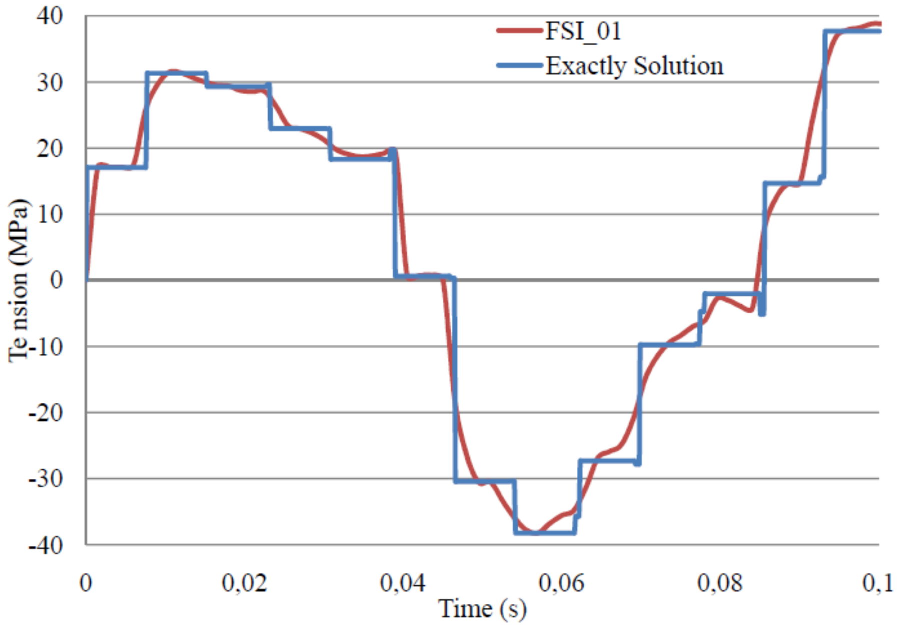

FIG. 3. Validating results against exactly solution. Pipe axial Tension at valve section for Delft Hydraulics Benchmark Problem A. Valve free to move. Tc = 0.[11]

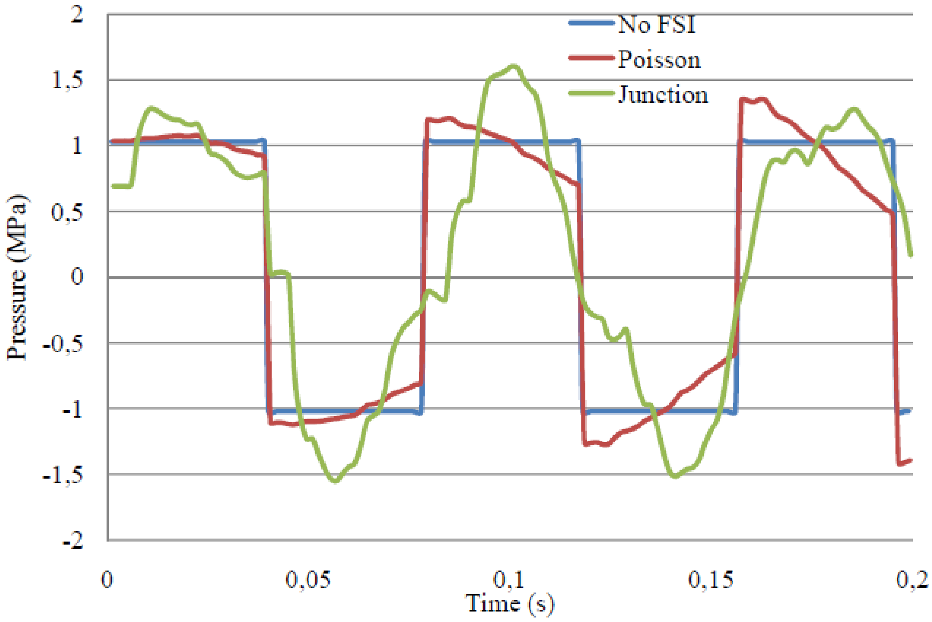

FIG. 4. Classic water hammer result, Poisson coupling, and Poisson and junction coupling. Pressure at valve for Delft Hydraulics Benchmark Problem A. Valve free to move. Tc=0.[11]

The first code developed in the vicinity of HT-FSI project showed good agreement with analytical and experimental results. Pre-processing and post processing modules are being in development in order to make the code more user friendly.

4. Ongoing codes

Next project's steps are the development of the following codes:

(a) One dimensional six equation thermal-hydraulic transient and fluid-structure interaction with unsteady friction;
(b) One dimensional six equation thermal-hydraulic transient and fluid-structure interaction with cavitation and unsteady friction;
(c) One dimensional six equation thermal-hydraulic two-fluid transient and fluid-structure interaction for dispersed and separated vapor-liquid flows with unsteady friction;

The codes mentioned before are in development by master degree students. The integration of pre and post-processing modules with all codes must, finally, to compose the planed HT-FSI code.

One of the main challenges of this project is the experimental data to validate the codes. Cooperation with other research centers will be carried out to stablish a database in order to guarantee the good code's behavior.

Qualified codes like RELAP 5 will be also used for validation of all codes mentioned.

5. Licences

The final HT-FSI numerical code will be available for all users after the complete tests. No charge will be required, but the license model used for this project (actually in study) will require previous authorization.

6. Conclusions

The HT-FSI will be a free tool for predicting thermal-hydraulic transients and fluid structure interaction in industrial and nuclear reactor systems with good accuracy. Engineers and designers will have a free important tool for pipeline and supports hydraulic and stress analysis.

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