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Fluid-Solid Interaction Analysis Using a Coupling Library

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1. Introduction

Nuclear reactors involve various physical phenomena such as neutron transport, thermal fluid flow transport, and stress, strain, and deformation of solids, and these phenomena are generally influenced by each other. A typical example is a flow-induced vibration (FIV), which is a part of the Fluid-Solid Interaction (FSI).

At the boundary between the fluid and the solid, the fluid exerts a force on the solid, and the solid subjected to the force might be deformed according to the properties of the solid. Then, the boundary between the fluid and the solid moves, and the fluid flow changes accordingly, interacting with each other like this way. If there is a difference in temperature between the fluid and the solid, the heat flux is exchanged at the boundary between the fluid and the solid.

The advantage of the coupled analysis of FSI is that by simultaneously or sequentially performing flow analysis and structural analysis, complex procedures and constraints that can occur in individual analyses disappear, and the desired simulation result can be obtained effectively in a short time.

In particular, in case there happens large deformation of structures that can affect fluid flow and plastic deformation of the structure accumulates in real-time due to repetitive fluid flow, structural integrity may be affected by the deformation. For these cases, integrity cannot be properly evaluated with the structural analysis performed once after the flow analysis is completed.

Plastic deformation is an irreversible change that can accumulate at every moment. Therefore, structural analysis using temperature boundary conditions at a specific point in time cannot accurately simulate the plastic deformation pattern, and even if the temperature change pattern is known, it is difficult to assign the same temperature boundary conditions as the actual ones for structural analysis to the entire structure one by one and change it over time.

When a load such as pressure occurs in the structure due to the fluid flow, the load distribution and change pattern can be performed through coupled analysis. Therefore, when non-linear material plastic properties, complex shapes, and boundary conditions are considered, coupled analysis can improve the accuracy of structural integrity evaluation.

In this paper, an open-source coupling library to analyze FSI was verified for a simple case and then is applied for component design evaluation of sodium-cooled fast reactor.

2. Simulation Models

2.1 preCICE

An open-source preCICE (Precise Code Interaction Coupling Environment) is a library that can easily link various solver programs [1]. As shown in Fig. 1, preCICE can couple commercial codes, open-source codes, and in-house codes by using adapters. Coupling configuration is set by precice-config.xml file. The xml file has 5 parts for configuration which are composed of coupling data, mesh information for mapping, coupling participants, communication channel, and coupling schemes.

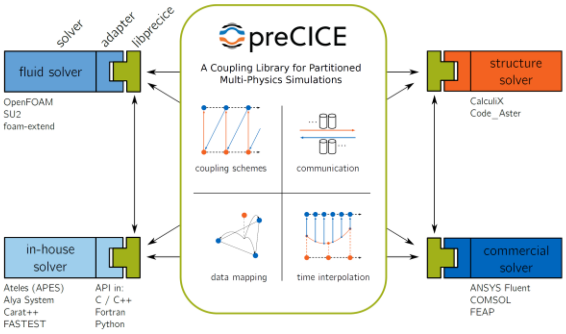

Fig. 1. Concept of preCICE library [1]

To connect each solver through preCICE, an adapter program can be developed for each solver. Adapter programs have already been provided for the flow solver, OpenFOAM [2], and the structural analysis solver, Calculix [3].

2.2 OpenFOAM

OpenFOAM (for "Open-source Field Operation And Manipulation") is a C++ toolbox for the development of customized numerical solvers, and pre-/post-processing utilities for the solution of continuum mechanics problems, most prominently including computational fluid dynamics (CFD) [2]. It has a large user base across most areas of engineering and science, from both commercial and academic organizations. OpenFOAM has an extensive range of features to solve anything from complex fluid flows involving chemical reactions, turbulence, and heat transfer, to acoustics, solid mechanics, and electromagnetics.

For the coupled fluid-structure analysis of the nuclear reactor, OpenFOAM was verified for basic examples such as incompressible flow, compressible flow, laminar flow, turbulence flow, and heat transfer and highly accurate analysis results comparable to those of the reference were obtained [4].

2.3 CalculiX

CalculiX is a free and open-source finite-element analysis application that uses an input format similar to Abaqus [3]. It has an implicit and explicit solver (CCX) and a pre-and post-processor (CGX).

Structural analysis code, CalculiX, has been validated by comparing with the Abaqus through structural analyses for representative examples such as cantilever beam, thermal expansion of a cylinder, thermal-structure analysis by convection and conduction, and reactor vessel ratcheting [4]. CalculiX when using a small number of elements with a first-order shape function may not produce good results but when using elements with a second-order shape function, regardless of the number of elements, it was confirmed that the results of Abaqus and CalculiX analysis were well matched [4].

3. Results

3.1 Turek-Hron case

To verify the accuracy of the preCICE library, flow analysis solver, and structure analysis solver, the Turek-Hron problem was simulated in which fluid flows around the flap attached to the cylinder are solved [5].

There are three verification cases as shown in Table 1 according to the physical properties of the fluid and structure for the shape of the same cylinder and flap.

Table I: Parameters for the Turek-Hron FSI cases

Parameter	FSI1	FSI2	FSI3
ρ^s [10^3 kg/m^3]	1	10	1
ν^s	0.4	0.4	0.4
μ^s [10^6 kg/ms^2]	0.5	0.5	2.0
ρ^f [10^3 kg/m^3]	1	1	1
ν^f [10^{-3} m^2/s]	1	1	1
$\bar{U}$ [m/s]	0.2	1	2
$\beta = \rho^s/\rho^f$	1	10	1
$Ae = E^s/(\rho^f \bar{U}^2)$	3.5x10^4	1.4x10^3	1.4x10^3
$Re = \bar{U}d/\nu^f$	20	100	200

In Table 1, ρ^s, ν^s, μ^s, E^s, ρ^f, ν^f, $\bar{U}$, and d refer to the density, Poison ratio, shear modulus, Young modulus of the solid, the density, viscosity, inlet average speed, and cylinder diameter of the fluid, respectively.

At the entrance of the flow channel, the velocity distribution is expressed as the following equation.

$$v^f(0,y) = 1.5\bar{U}\frac{y(H-y)}{(H/2)^2}$$

Here, y and H mean the vertical distance and height of a flow channel, respectively.

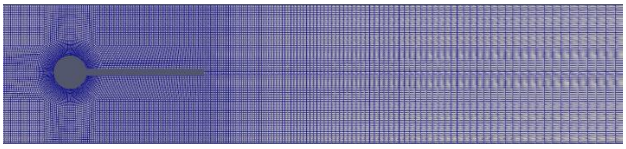

Fig. 2. A grid system of flow region

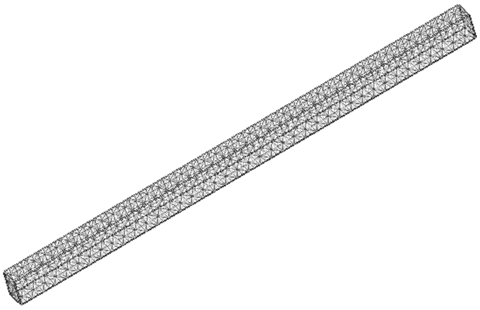

Fig. 3. A grid system of solid region

Figure 2 shows a grid system created using ‘blockMesh’ utility program. The entire area was composed of multiple blocks to generate structured grids. The number of grids generated is 20,969. Figure 3 is a grid system of a flap generated by ‘CGX’ program. The form of the elements used is C3D20R, the number of elements is 80, and the number of nodes is 773. The flow inlet conditions have different values depending on time and location, and a utility library called ‘groovyBC’ was used to apply the adequate velocity condition.

The flow analysis solver transmits force to the structure analysis solver, and the structure analysis solver transmits displacement information to the flow analysis solver. Serial-implicit was used as a coupling scheme, and IQN-ILS was applied as an acceleration technique.

In this study, the FSI3 problem was analyzed, and the table calculated the displacement of the end of the flap over time is compared with the reference [5], as shown in Table 2.

Table II: y directional displacement of flap tip

Parameter	No. of cells	Displacement [x10^{-3} m]
Reference [5]	15,872	1.47±34.99
Present	20,969	1.48±33.78

It can be seen that it is well consistent with the results of the reference. Figure 4 shows the velocity fields at 11 and 11.1 seconds, and Figure 5 shows the pressure fields at 11 and 11.1 seconds. Vortex of flow occurs periodically at the rear end of the flap due to the vibration of the flap. Figures 6 show the stress distribution of the flap at 11 and 11.1 seconds. The figure was post-processed by reading the result file ‘flap.frd’ of CalculiX using ‘PrePoMax’ program.

Figure 7 shows the position of the end of the flap over time, and it can be seen that it vibrates at a constant amplitude after about 4 seconds.

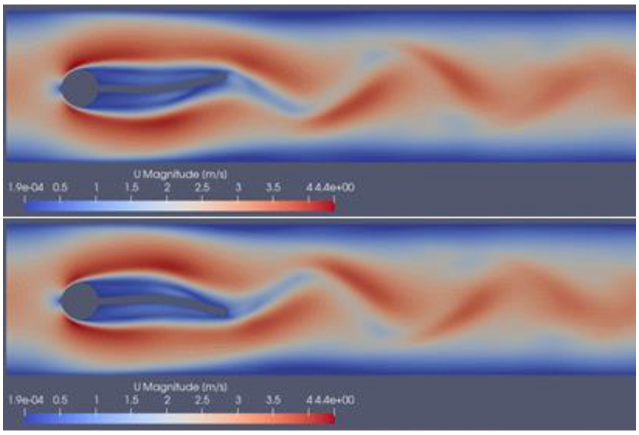

Fig. 4. Velocity field of FSI3 case (top:11s, bottom:11.1s)

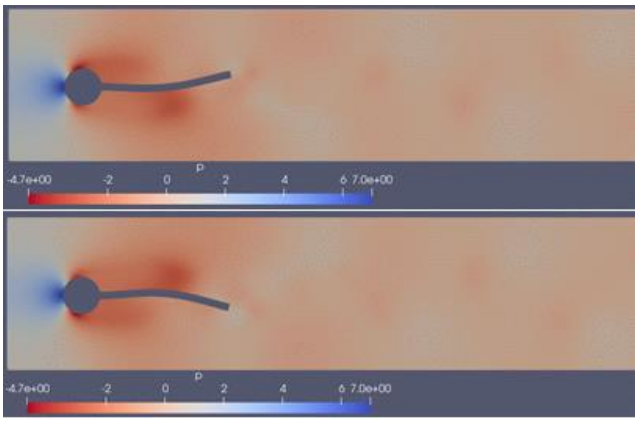

Fig. 5. Pressure field of FSI3 case (top:11s, bottom:11.1s)

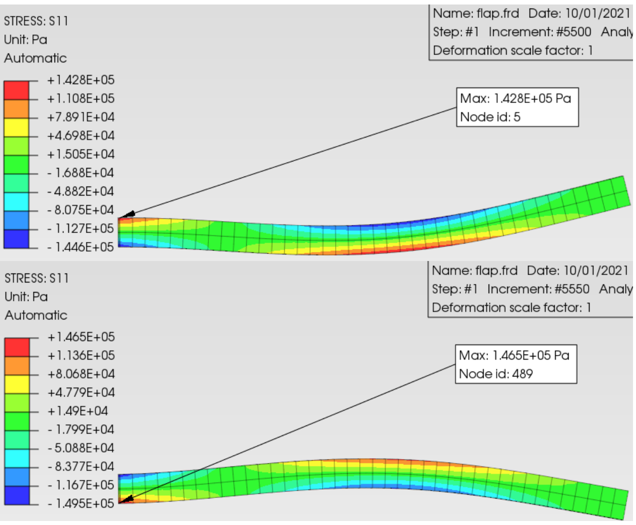

Fig. 6. Stress distribution of FSI3 case (top:11s, bottom:11.1s)

3.2 IHX sodium drainpipe case

In the IHX of PGSFR, a drainpipe [6] was installed for sodium drain on the IHX tube side. As shown in Fig. 8, a long drainpipe with a small diameter was installed at the center of the IHX inner pipe, and designed to be supported by the upper bend part of the inner pipe and the lower part of the lower tube sheet.

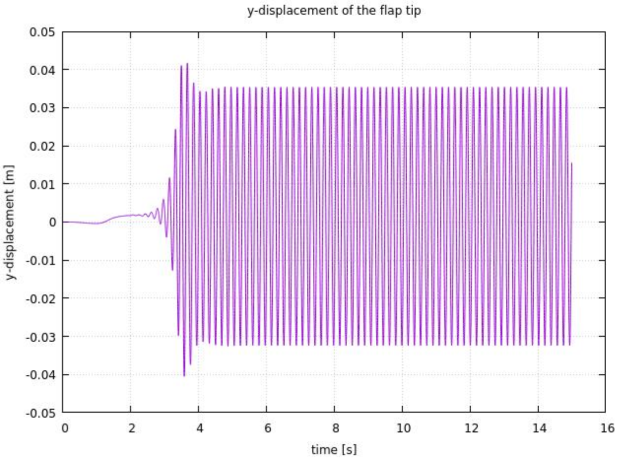

Fig. 7. Displacement of flap tip as a function of time

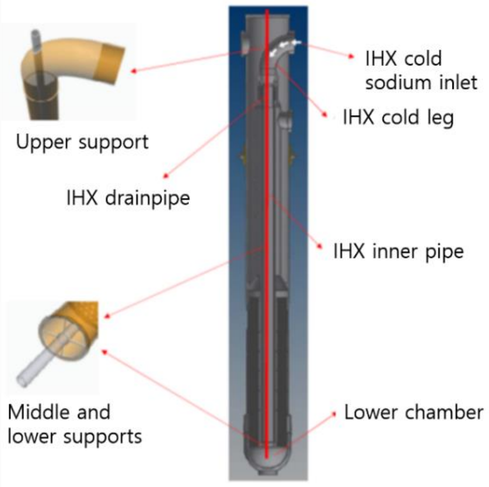

Fig. 8. Schematic of a IHX drainpipe

However, at the low-temperature sodium inlet, sodium passes through the drainpipe at an angle of almost 45 degrees, so the possibility of resonance according to the separated flow behind the drainpipe was evaluated [6]. To avoid low-frequency resonance, a guide has been proposed to install two or more support structures between the upper and lower supports.

However, apart from resonance, vibration due to flow separation may occur in the drainpipe, and the resulting instability of flow may adversely affect the structural integrity of the IHX. Therefore, the design of the IHX sodium drainpipe was evaluated by applying the FSI analysis technique using the preCICE coupling method verified above to this problem.

‘Salome’ program [8] was used as a shape modeling program for the surface grid and then the surface grid was stored in the STL format, and finally, a volume grid was created using the 'snapyHexMesh’ utility program.

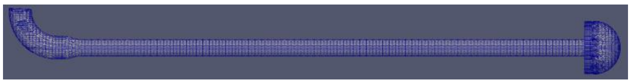

Fig. 9. A grid system of the IHX drainpipe

Figure 9 shows a grid system for flow analysis. In the grid system of the drainpipe, after generating a STEP file in Salome, the grid and boundary conditions were set in the 'PrePoMax' program. A grid can also be created in Salome, saved in unv format, read from PrePoMax, and saved in the input format of CaluliX input files. C3D10 was applied to elements of the grid for structural analysis, and 74,947 elements were generated.

Flow conditions [7] of SALUS IHX were used as the inlet condition of IHX low-temperature sodium. Sodium passing through the lower chamber passes through the lower tube sheet and suffers a rapid pressure loss due to a decrease in the flow area. The lower tube sheet was treated with porous media. 'topoSetDict' program was used to select the location of porous media. For this area, the pressure loss was modeled by fvOptions.

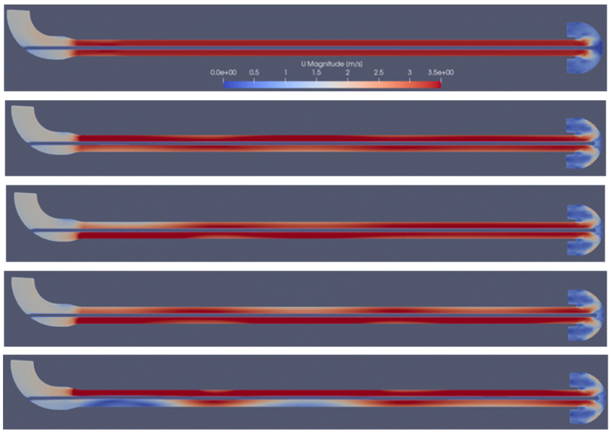

Fig. 10. Flow field of IHX drainpipe (time=0.1, 0.9, 1.0, 1.1, 1.2s from top)

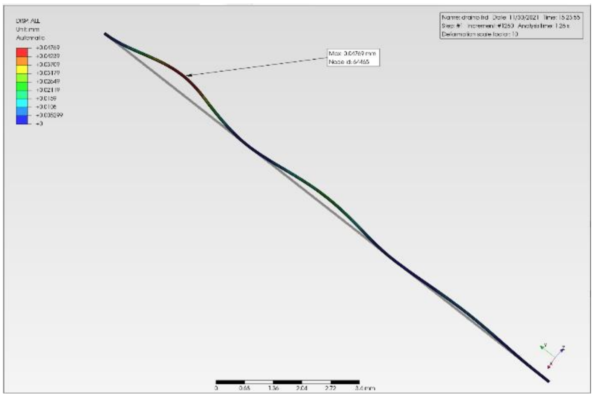

Fig. 11. Displacement of IHX drainpipe after 1.25s due to FSI (x10 magnified displacement)

Figure 10 shows the flow field around the drainpipe up to 1.2 seconds after analysis starts. It was observed that the flow gradually began to be biased to one side according to the interaction between the flow and the pipe, and the flow became unstable.

Figure 11 shows a 10 times magnified displacement view of the drainpipe, and it can be seen that the displacement of the pipe occurs between one support point and another support point. The maximum displacement of the pipe after 1.25 seconds was calculated to be about 50 mm. The maximum stress appears at the back of the part in contact with the flow. Since the sodium drainpipe of IHX can vibrate due to FSI which may weaken the supporting parts of the drainpipe, a more detailed design evaluation is required.

4. Conclusion

preCICE for fluid-structure linkage was validated through a fluid-structure interaction of a horizontal flap attached to a cylinder. Using the preCICE coupling library, the sodium drainpipe installed in IHX was evaluated whether it is stable for vibration induced by flow separation around it. It was observed that vibration of the drainpipe due to fluid-structure interaction is not small and it can weaken the supporting parts of the drainpipe. Therefore, a more detailed design evaluation is required. Through this study, a coupled fluid-structure analysis system using open-source programs was established. Through various validation examples, the methodology, accuracy, and validity of the program were confirmed.

ACKNOWLEDGEMENT

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