Development of Fluid-Structure Interaction Program for the Mercury Target

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Japan Atomic Energy Research Institute (JAERI) is promoting to construct the liquid mercury target as a neutron scattering experiment facility. The liquid mercury target is planed to receive MW class proton pulse beam and high intensity spallation reactions occur in the target generating neutrons. Under such condition, high density heat is released and consequently strong pressure wave is generated. Thus the pressure wave propagates through mercury and reflects on the container of target made of hard stainless steel. Then it is considered that an erosion of the wall might be caused by the cavitation. In fact, some experiments show that pit type scratch is created on the wall when strong pressure wave reflects on it. If the phenomenon happens in mercury target, it makes the life span of container shorter. Since the pressure wave propagation and the wall deformation have influence with each other in this phenomenon, a coupled simulation study is needed in order to reveal the process of the scratch generation. In this report, a simulation of the interaction between the pressure wave propagation of the liquid mercury and the wall deformation is carried out in order to investigate the possibility of the cavitation in the mercury target. In our project of the year 2003, the fluid-structure interaction program was developed and the fine meshes of the mercury target was generated. Then this large scale model was applied to simulate the interaction between the pressure wave propagation and the wall deformation.

Keywords: mercury target, pressure wave propagation, wall deformation, coupled simulation, fluid-structure interaction

1. Project outline

As a plan of the high power proton accelerator project, the mercury target, which is used for neutron sources in high density neutron scattering laboratory, will be constructed. The structure of the mercury target is a pipe like channel made by SUS316 in which liquid mercury circulates. The protons come from the perpendicular direction to the flow channel and collide with the target. Then mercury emits neutrons due to the nuclear fission caused by the collisions with protons. High density energy release by the nuclear fission causes strong shock waves inside the mercury target. Recent experiments in the shock wave reflection at the liquid-solid interface revealed that the outer wall suffers fine damages due to cavitations after the deep impact by shock waves into the wall. Thus, not only the shock wave pressure but also the cavity damage should be considered in the construction plan of the mercury target.

2. Simulation programs

2.1. Fluid model

In our fluid program, the finite volume method is adopted in order to simulate dynamics of compressible thermal fluids. The mercury target geometry is discretized by a regular grid with three dimensional generalized coordinate. The advective term is differenciated by the first order upwind scheme or the central difference scheme or the TVD scheme. The time integration is carried out by the HSMAC scheme and the BiCGSTAB iterative solver is implemented for solving the Poisson's equation. The complete set of equations are composed of the mass, the kinetic momentum and the energy conservation equations with the equation of state for liquid mercury. This set enable us to simulate liquid mercury dynamics inside the mercury target.

2.2. Solid model

For dynamics of elastic solids, the finite element method is adopted in order to simulate dynamics of elastic solids. The geometry of the wall of the mercury target container is discretized by isotropic shell element with four nodes. The lumped mass matrix is adopted and the explicit time marching can be carried out by the central difference method. This solid model is described by the elastic body equation and kinetic boundary condition and geometric boundary condition.

2.3. Weakly coupling

In order to evaluate the effect of the interaction between the pressure wave propagation and the wall deformation, so called weakly coupling method is adopted here. The fluid program receives the displacements of nodes at the target wall from the solid program. After that, metrics of the generalized coordinate such as Jacobian and boundary flow velocity are renewed. On the other hand, the solid program receives the pressure of meshes near the target wall from the fluid program. The solid program transfers the receiving pressure at the wall into the nodal loads. Such data communications between the fluid program and the solid program are executed every time step. These procedures are all implemented by the standard MPI libraries.

3. Results

First of all, the fine meshes of the mercury target was generated as shown in Fig. 1. The number of the mesh for fluid is beyond 1,000,000 cells and the number of the mesh for solid is about 10,000 elements. Using this large scale model and our own fluid-structure interaction program above, the interaction between the pressure wave propagation and the wall deformation in the mercury target was carried out.

Next, an initial pressure distribution was given as shown in Fig. 2. Then pressure propagates through the liquid mercury and reflects on the wall. Then the wall deformation due to the pressure was observed. Fig.3 shows the wall deformation after 1.0e-4 sec.

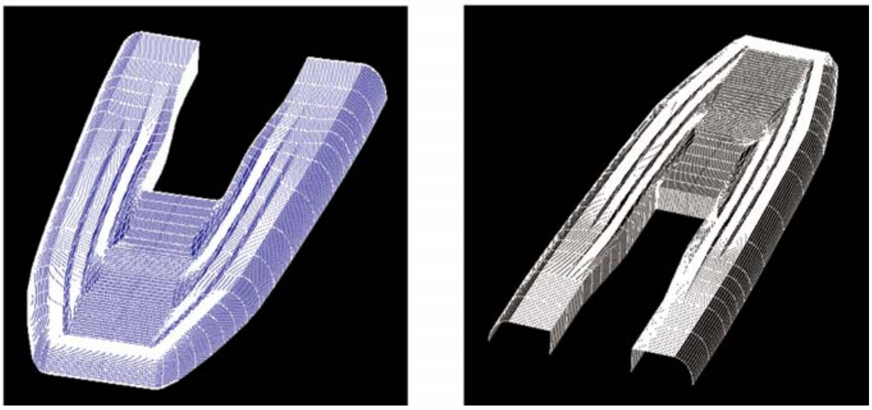

Fig. 1 mesh of fluid (left) and mesh of solid (right)

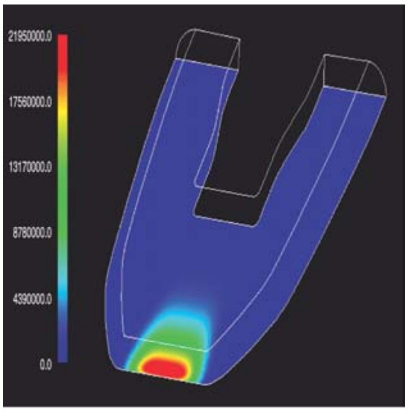

Fig. 2 Initial pressure distribution

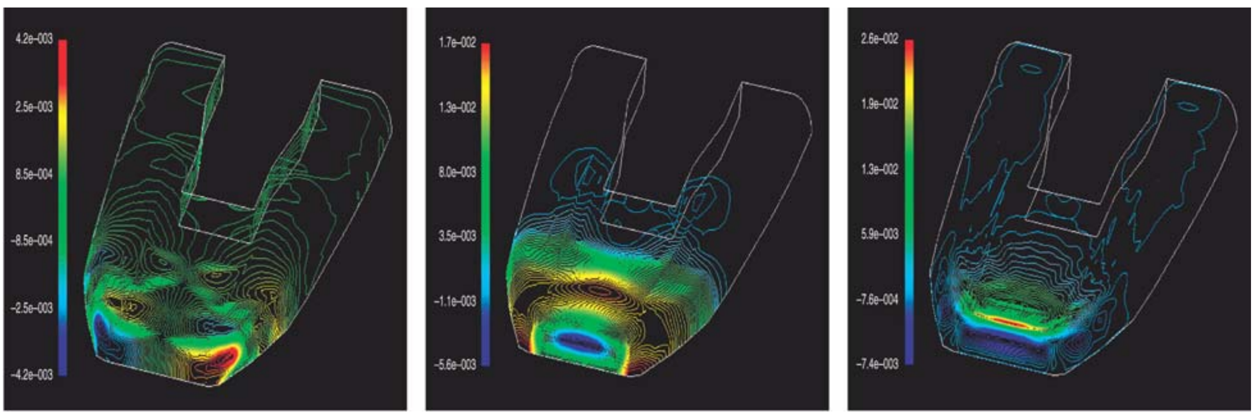

Fig. 3 Wall deformation (x-direction, y-direction and z-direction displacements)

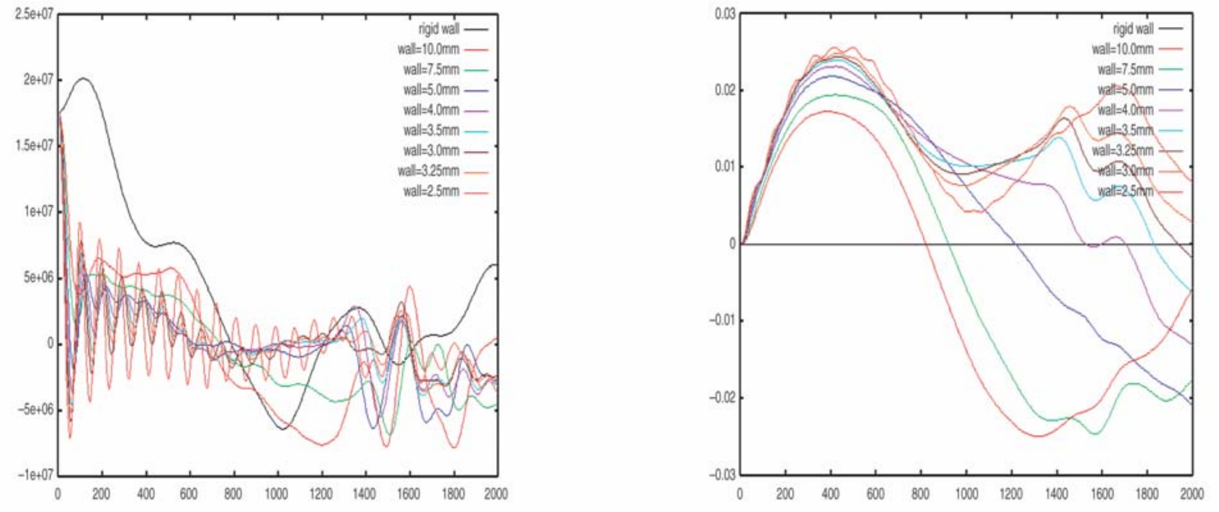

Fig. 4 Time histories of the pressure (left) and the displacement (right)

By changing such parameter as thickness of the target wall, comparison of the simulation results was performed. Fig. 4 shows that time histories of the pressure near the target wall and the displacement of the wall. In the case that wall thickness is smaller than 5.0 mm, pressure near the wall is reduced rapidly and negative pressure is reached there. From the results above, it is found that the wall deformation causes a rapid reduction of pressure near the wall and this implies the possibility of the cavitation.

4. Vectorization and Parallelization

The parallelization was implemented by the domain decomposition method and the vectorization was implemented by taking the vector length as long as possible. In particular, the Jagged diagonal storage, which is a storage format of matrix elements, was adopted in the solid program by using PARCEL (Parallel Computing Elements) which is a mathematical libraries for parallel computing developed by CCSE / JAERI. As a result, mean vectorized operation ratio of the fluid-structure program exceeds over 98%.

5. Future works

In order to evaluate the cavitation effect, it is needed to simulate the behavior of the bubbles in the liquid mercury. As the project of the year 2004, bubble dynamics model will be coupled with our fluid-structure program. The interaction among the pressure wave propagation, the wall deformation and the bubble dynamics model will be carried out to advance the coupling simulation method.

Reference

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