Fluid-Structure Interaction Analysis of Closing Valves Using Abaqus/Explicit coupled with SC/Tetra

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Abstract: *There is increasing demand for high speed solenoid valves in Nabtesco products. To design high speed solenoid valves, drag force on the valve body must be reduced so the valve works faster. As valve speed increases, the valve body rebounds higher on the valve seat and this causes unintended extra valve actuations. This is a vital issue for precise fluid control.*

Rebound is caused by elastic deformation. Flow in the valve case influences valve body movement and vice versa, so fluid-structure interaction analyses, instead of sequentially coupled analyses, were conducted to reproduce these phenomena. Cross-linked dynamic structural analyses using Abaqus/Explicit and unsteady fluid analyses using SC/Tetra were executed using the SIMULIA Co-Simulation Engine. The mesh size in the fluid analyses was one of the key factors for stable calculations. The analysis results were in good agreement with experimental results. This method proved that changing the valve body shape makes movement faster and reduces rebound.

Keywords: *Fluid-Structure Interaction, FSI, Valve, Abaqus/Explicit, SC/Tetra, Rebound, Unsteady Fluid Analysis, Dynamic Structural Analysis*

1. Introduction

1.1 Fluid-Structure Interaction (FSI) analysis

The dynamic interaction between fluid (e.g. air, water, oil) and mechanical structures is increasingly becoming the focus in the development of more compact and high-performance products. In addition, enhancement of computer hardware and analysis software makes it realistic to conduct fluid-structure interaction (FSI) analysis, which analyzes both fluids and structures simultaneously.

CFD software SC/Tetra and FEA software Abaqus/Explicit can be executed concurrently on a co-simulation platform, CSE (SIMULIA Co-Simulation Engine)

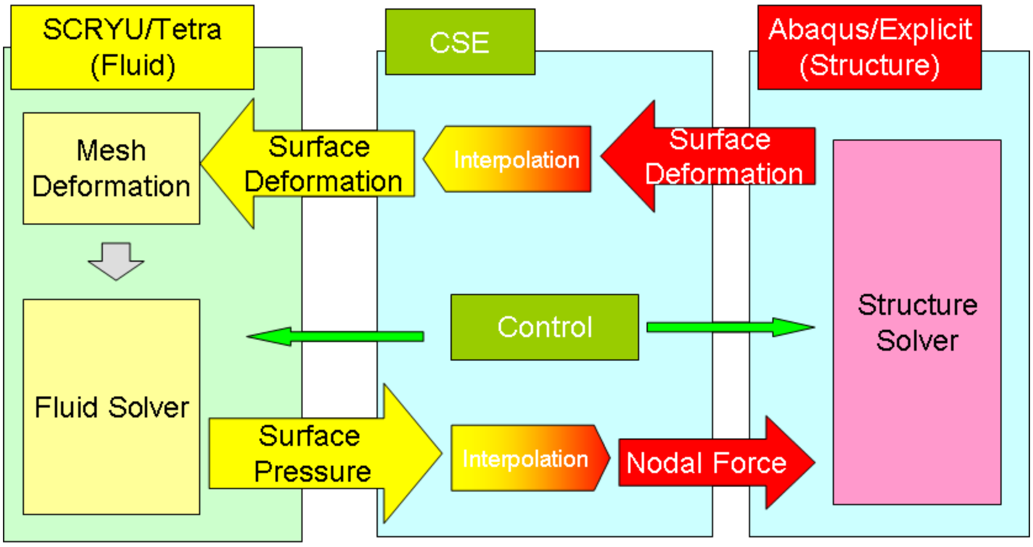

Figure 1. SC/Tetra and Abaqus/Explicit coupled using CSE

1.2 Objective of analyses

The following are critical issues in the development of high speed solenoid valves for hydraulic oil control:

1. Degradation of response time caused by viscous resistance of hydraulic oil
2. Rebound of the valve body caused by elastic deformation when it collides against the valve seat

The first can be analyzed using normal CFD analysis with moving boundaries, but the second includes both fluid and structural dynamics so it cannot be analyzed by ordinary CFD codes.

In this report, one practical case of FSI analysis using Abaqus/Explicit and SC/Tetra to improve our high speed hydraulic solenoid valve, is reported.

2. Analysis model

2.1 Construction of the valve

An analysis was conducted on the solenoid valve shown in Figure 2 which opens while the electromagnet is activated and closes when the electromagnetic force is inactivated and the spring pushes it against the valve seat. All parts are made of steel and the space is filled with hydraulic oil. There is an inlet port on the bottom center and oil flows out the top and side outlet ports. Closing movements were analyzed and the time required for the valve to close and whether the valve rebounds were investigated.

Analysis models for SC/Tetra and Abaqus/Explicit were separately prepared on an identical coordinate system. Both models were executed on the Nabtesco computer cluster using CSE.

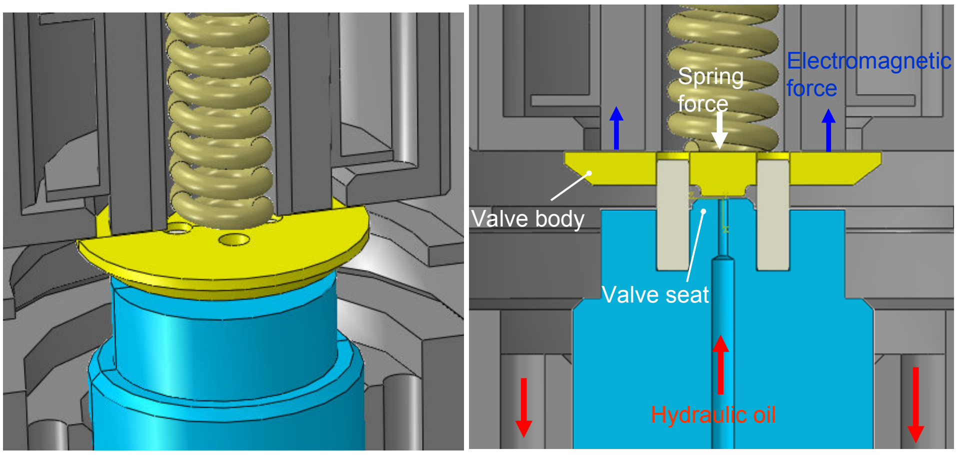

Figure 2. Structure of the solenoid valve

2.2 Structural analysis model

The structure analysis is shown in Figure 3. Abaqus/Explicit 6.12 was used because the target phenomenon was a rapid movement. General contact was used for contacts. The spring was modeled using a connector element with axial elasticity and coupled with the solid model of the spring end.

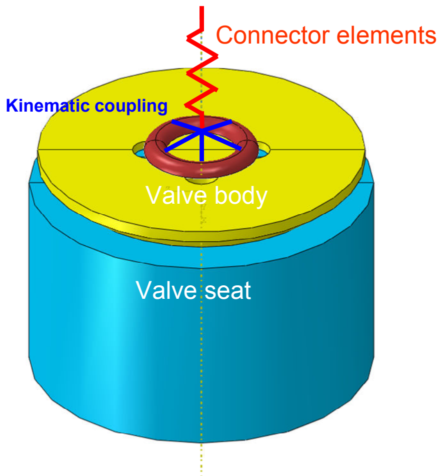

Figure 3. Structure analysis model

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2.3 Fluid analysis model

2.3.1 Overset mesh

Overset mesh is a technique for moving boundaries in CFD. The mesh around the moving object and static space are separately made and the two meshes are combined. The regions where both meshes exist are solved using slave mesh. Variables like velocity and pressure are interpolated on the boundary of the slave mesh (Figure 4).

Generally, it is difficult to analyze a case in which the gap between two walls becomes zero, but the overset mesh implementation in SC/Tetra was able to handle it.

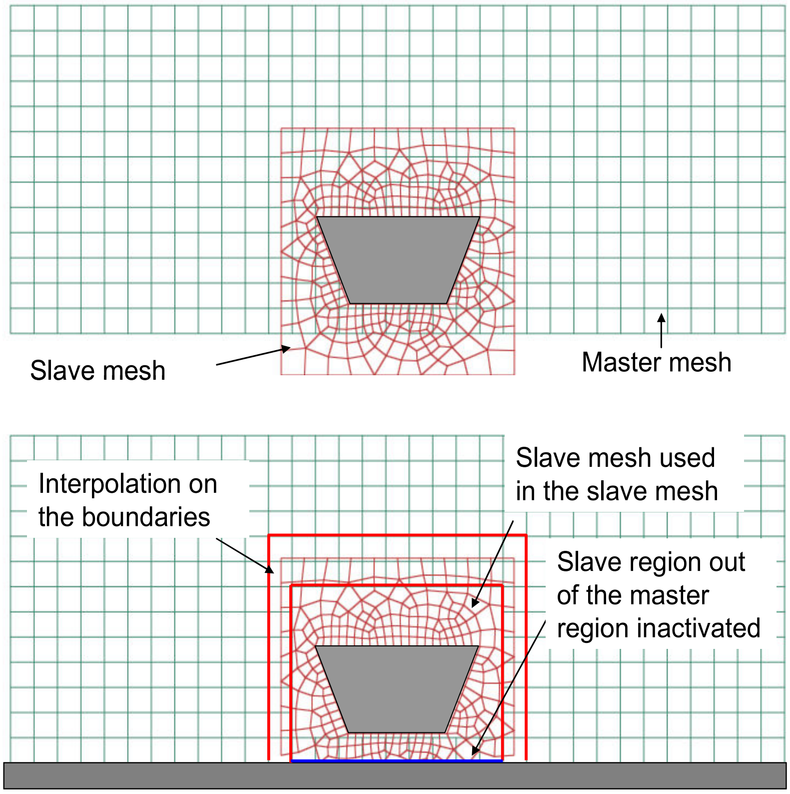
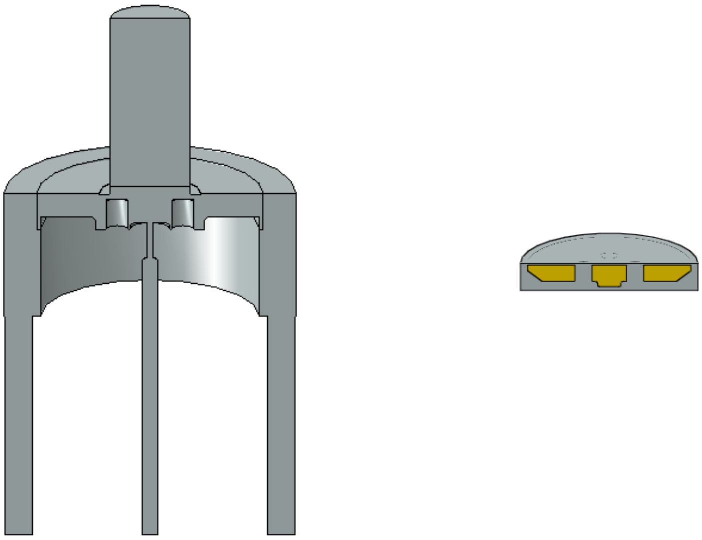


Figure 4. Overset mesh

2.3.2 Fluid analysis model

A CFD analysis model for SC/Tetra V10 is shown in Figure 5. Space in the case is meshed as the master region and space around the valve body and the valve body itself are meshed as the slave region of the overset mesh. Compressible fluid property was applied. Flow was driven by the pressure difference between the inlet port and the outlet ports



Master region Slave region (fluid+ valve body)

Figure 5. CFD model

2.4 FSI

Information is exchanged on the surface of the valve body of both analysis models. SC/Tetra applies pressure on the surface and receives the displacement of nodes on the surface. Abaqus passes node displacements and receives nodal force on the surface. The Gauss-Seidel method, where SC/Tetra explicitly references Abaqus results was used for the time marching method. A section of the input files are shown below. A license for SC/Tetra I/F Option for Abaqus was required in addition to our license for the SC/Tetra solver.

During FSI analysis, the analyses sometimes diverged because of the mesh size of the master and slave meshes and time increments. Numerous trials were made and revealed that the mesh sizes of the master and slave regions had to be close to equal, in addition to considering shape fidelity, CFL conditions and the number of elements.

Abaqus input file(.inp)

```
*CO-SIMULATION, NAME=fsi_01, PROGRAM=MULTIPHYSICS, CONTROLS=control_01
*CO-SIMULATION REGION, TYPE=SURFACE, IMPORT
Surf-FSI, CF                                # Receiving nodal force
*CO-SIMULATION REGION, TYPE=SURFACE, EXPORT
Surf-FSI, U                                  # Passing displacement
*CO-SIMULATION CONTROLS, NAME=control_01, STEP SIZE=IMPORT, COUPLING
SCHEME=GAUSS-SEIDEL, SCHEME MODIFIER=LEAD, TIME INCREMENTATION=SUBCYCLE, TIME
MARKS=YES
```

SC/Tetra S file (.s)

```
CSIM
   1                   # Co-simulation with Abaqus
   2   1   0   0   0   # Passing pressure, receiving displacement
   0  0.001 0          # Time range
wall_fsi               # Region for FSI
/
slave                  # Deforming mesh region
/
wall_master           # Fixed mesh egion
/
```

3. Results and Discussion

3.1 Comparison with Experiments

Deformation is shown in Figure 6. Rebound of the valve body was reproduced and the flow was stopped while the valve body contacted with the valve seat (T=1). Because the valve body elastically deformed into a bowl shape and there is little deformation around the contacting location, rebound of the valve body was caused by elastic deformation of the overall valve body. SC/Tetra can only simulate rebound using the coefficient of rebound, but in this case the coefficient cannot be easily determined so FSI is appropriate.

The position of the valve body is shown in Figure 7. Position was nondimensionalized by the full stroke length and time was nondimensionalized by the time of the first contact in the experiment. The minus-value of the stroke for the experiments, up to T=0.1, was the measurement error caused by the induced current of deactivation of the electromagnet, and did not effect the subsequent measurements.

The velocity of the valve body and the rebound in the FSI analysis were in good agreement with the experimental data. The CFD analysis was nearly identical to the FSI analysis until the valve body touched the valve seat at around T=1. Rebounds were reproduced successfully with the FSI technique described here.

3.2 Shape improvement using FSI

Countermeasures for rebounds were explored using this method. Two of the results are shown in Figure 8. Holes and slits were added to reduce viscous resistance in Improvement 1. One of the gaps was adjusted to suppress rebounds in Improvement 2. It was revealed that the response time of the valve could be improved by modifying the shape of the valve body and the valve case.

4. Conclusion

FSI analyses combining Abaqus/Explicit for structure and SC/Tetra for fluid were conducted to simulate the high-speed motion of an electromagnetic valve.

Although the analyses were effective, we have concluded that further improvements need to be implemented to solve the problem of calculation time and divergence caused by mesh settings.

5. References

1. Abaqus Users Manual, Version 6.12, Dassault Systémes Simulia Corp., Providence, RI.
2. SC/TetraVersion 10 User's Guide Fluid-Structure Interface Analysis (Abaqus®), Software Cradle Co., Ltd.

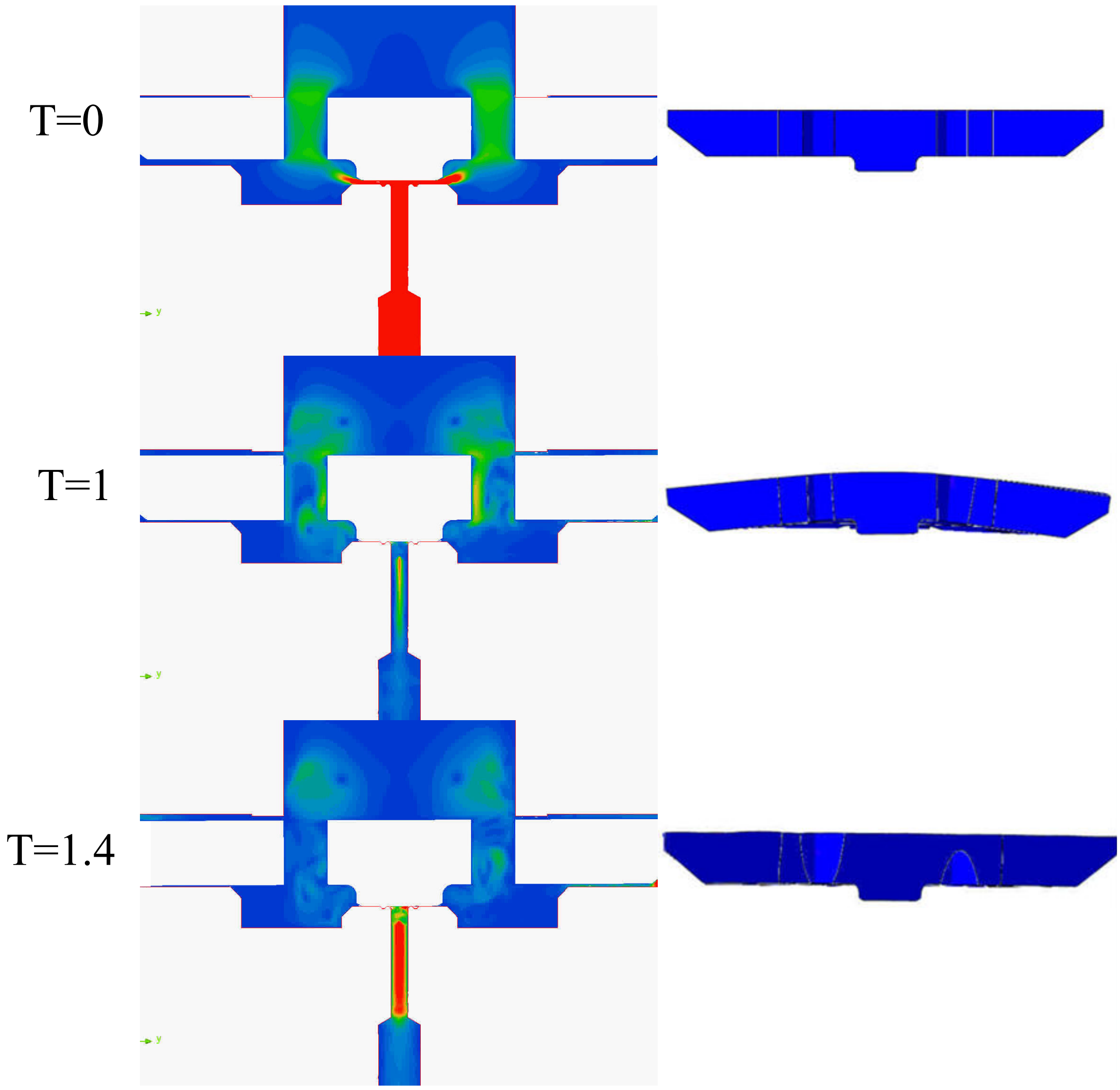


Figure 6. Results: Snapshot

(Left: SC/Tetra flow velocity magnitude, Right: Abaqus deformation x100)

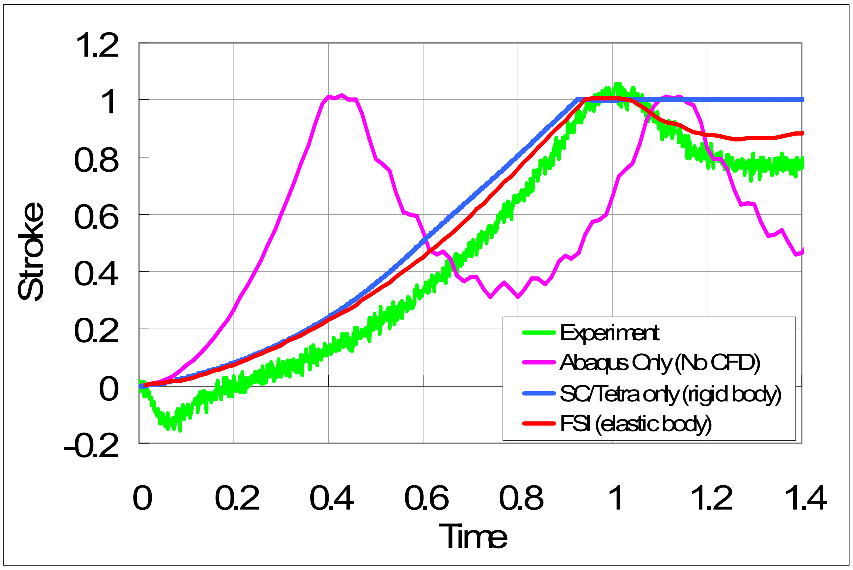


Figure 6. Valve stroke (validation with the experiment)

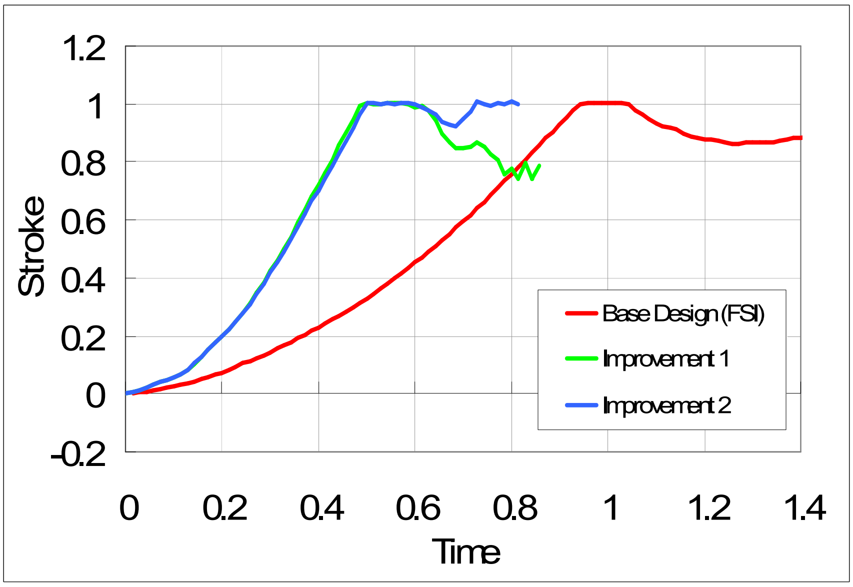


Figure 7. Valve stroke (shape improvement)