A Fluid-Structure Interaction Analysis of the VernaFlo® Flow Control Device

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Abstract: The Vernay VernaFlo® flow controls are custom-designed fluid flow management devices used in a wide range of applications and systems where consistent, reliable operation is essential. Elastomeric rubber components in these devices deform under the influence of upstream variations in fluid pressure. These deformations adjust the orifice diameter and help maintain a constant down-stream flow rate. In this paper we evaluate the performance of a custom VernaFlo® device using the fully coupled fluid structure interaction solution provided by the ABAQUS co-simulation capability. The effects of cavitation on the flow are considered. Finally, we compare the computation results to available experimental data for the device over a pressure range of 0-120 psi.

Keywords: FSI, coupled fluid-structural analysis, co-simulation, axi-symmetric analysis, moving deforming mesh, cavitation, flow control valves

1. Introduction

1.1 Background

Flow control devices are fluid management devices commonly used in a wide range of applications in key industry areas such as automotive, bio-medical and consumer appliances. These devices are designed to maintain constant volume output for varying inlet pressure. These pressure variations may occur due to several factors such as pipe friction loss, downstream restrictions, distance from the water tower, elevation of the water tap. Minimizing the impact of pressure variation on the flow is essential for the reliable and consistent operation of the applications in question.

In this paper we will study the performance of a custom VernaFlo® flow control device design from Vernay Labs, Ohio and benchmark the results to the experimental flow- rate data sheet of the device. Figure 1 shows a typical cross-section of the device. An elastomeric rubber component is housed inside the flow-path. This rubber piece rests on a rigid seat and deforms under the influence of incoming flow. At low operating pressures the rubber device undergoes very little deformation and allows the flow to develop. With increasing upstream pressure the deformation increase and restrict the orifice diameter through which flow can occur, thus limiting the fluid flow. The interaction of fluid flow with the structure deformation and vice versa is critical in accurately predicting the device shape and the subsequent flow behavior and requires a bidirectional fully coupled fluid structure interaction (FSI) analysis. We will study these effects by coupling ABAQUS to FLUENT using the co-simulation technique with MpCCI available since Version 6.5. With this method the fluid and the structural domains are modeled and solved separately with the information exchanged at the fluid structure interface determining the coupled behaviour of the device.

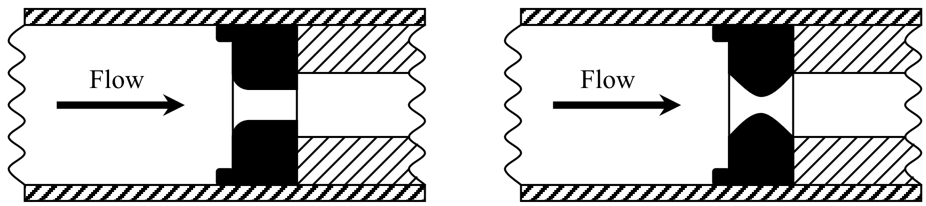

Figure 1 Cross-section of a typical VernaFlo® device

1.2 Outline of paper

In the current paper, we describe the use of ABAQUS in performing the following analysis cases:

1. Fluid-structure interaction analysis capability using co-simulation with MpCCI
2. Range of hyperelastic material models for the simulation of large deformation in elastomeric parts
3. Deformable-to-rigid body contact capability

2. Analysis Approach

2.1 Defining the sub-domain models

We use the inherent symmetry in the VernaFlo® device to perform an axi-symmetric analysis. The ABAQUS sub-domain (Figure 2) includes the rubber component which is modeled using reduced order hybrid axi-symmetric elements. Hyperelastic material behavior for the elastomeric component is determined from uniaxial and biaxial data sheets supplied by the customer. The rubber component presses against a rigid seat which is modeled using a discrete rigid part. A penalty contact with a friction of 0.5 is defined between the rubber and the rigid seat. The model uses ABAQUS/Standard with NLGEOM turned ON to account for non-linearities in the solution.

Figure 2 Axi-symmetric model of the rubber seat

The CFD domain shown in Figure 3 models the flow path. The flow path includes a short upstream section, followed by the section around the rubber component and a long downstream section. The upstream variation in pressure is accounted for using the pressure-inlet boundary condition while the outlet is set to a pressure outlet boundary condition with ZERO gage pressure. To enable local remeshing, the flow path is modeled using triangular elements. Water is modeled as an incompressible fluid and the turbulence and multi-phase models (to enable cavitation) to solve for the flow equations using the steady-state implicit segregated solvers.

Figure 3 Axi-symmetric model of the flow path

After the ABAQUS and the Fluent sub-domains have been created we proceed to defining the fluid structure interface using MpCCI. The interaction definitions which include the interaction surface and the desired solution quantities are shown in Figure 4. ABAQUS receives the fluid pressures from Fluent and sends the resultant deformation to Fluent. In addition, MpCCI automatically handles the transformations to account for the difference in axi-symmetric conventions used by ABAQUS and Fluent.

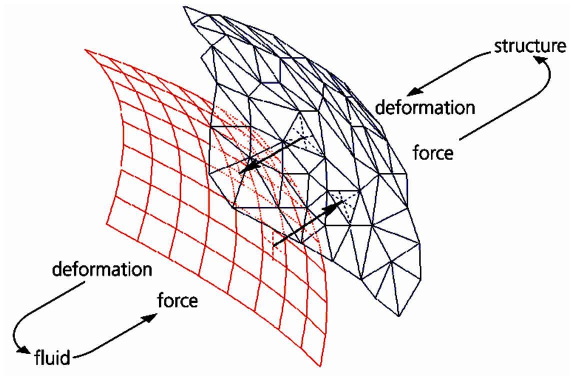

Figure 4 MpCCI interface definitions

2.2 Address domain pinching issues

During the analysis, a constant fluid topology is required in FLUENT. As the rubber component deforms in response to the upstream fluid pressure, it will come into contact with its rigid seat, thus "pinching" the fluid domain completely. Since pinching terminates the coupled analysis, a special modeling technique has been used to prevent such an occurrence.

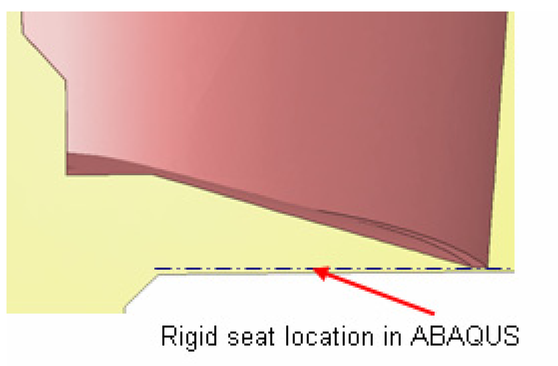

Figure 5 Contact offset to avoid domain pinching

As shown in Figure 5, the rigid contact surface in ABAQUS (dashed line) represents the true location of the rigid seat; however, the FLUENT wall zone that corresponds to the rigid seat has been slightly offset. The offset helps maintain a small, finite clearance at all times during contact between the rubber insert and the rigid seat. While this clearance leads to some localized flow behavior, the overall impact of this gap on the constriction path and the corresponding bulk flow behavior was found to be relatively small.

2.3 Solution Methodology

The analysis is driven by an applied boundary condition on the fluid inlet pressure; specifically, this quantity is ramped up from 0 to 120 psi. During the simulation, the pressures acting on the rubber insert in the fluid sub-domain are mapped and transferred to the structural sub-domain in ABAQUS via MpCCI. ABAQUS then computes the deformations and the resulting stress state in the structure. The interface deformation quantities are then mapped and transferred from the structural sub-domain to the fluid sub-domain via MpCCI. This process of exchanging solution quantities continues incrementally until the analysis completes.

3. Results and Discussions

The main objective of the FSI analysis is to determine the effect of the variation of inlet pressure on the bulk fluid flow rate through the device. After presenting these results, the effect that each sub-domain has on the coupled results will be examined.

3.1 Global Convergence

The fluid inlet pressure boundary condition is applied in an incremental fashion; specifically, the pressure is increased in fixed increments during the analysis. Global convergence between the two sub-domain solvers is obtained by iterating the exchange process several times at the given pressure level.

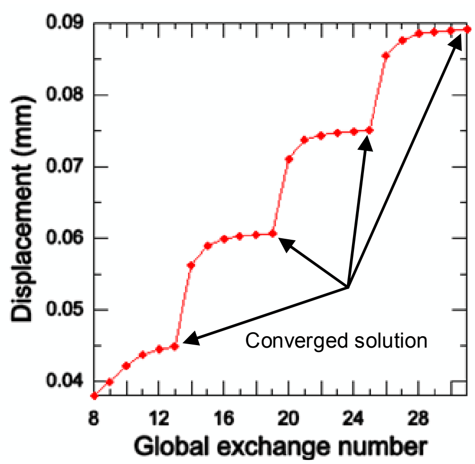

Figure 6 Displacement solution at trailing edge of rubber insert

The nature of the convergence for this analysis is apparent from Figure 6, in which the displacement magnitude of the trailing edge of the rubber insert is plotted versus the global exchange number. This plot considers the increase in pressure from 2 psi to 5 psi. During each pressure increment, the converged solution was obtained after five global exchanges.

3.2 Bulk flow rate vs Inlet pressure

The computed flow rate as a function of inlet pressure is shown in Figure 7. Initially, as the pressure is ramped from zero the flow rate increases. As the inlet pressure approaches 20 psi the flow is found to stabilize at approximately 2.1 liters/min. Further changes in the inlet pressure do not affect the flow rate significantly.

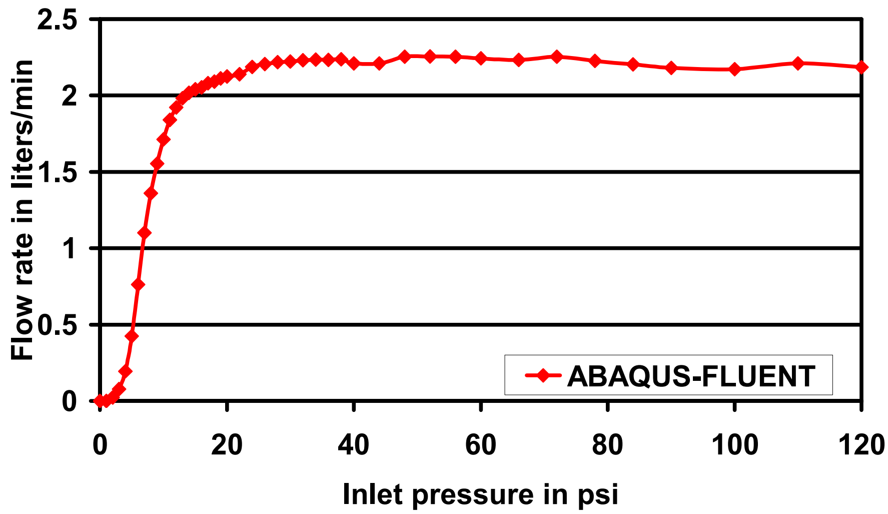

Figure 7 Computed bulk flow rate vs. inlet pressure

3.3 Effect of fluid flow over deformation

At any given inlet pressure level, the upstream surface of the rubber device is subject to a fairly uniform pressure distribution. These forces acting on the leading surface are largely responsible for compressing the device and forcing it down on the rigid seat. The pressure drop in the constriction region contributes to further narrowing of the flow path and results in a region of very high stresses as shown in Figure 8.

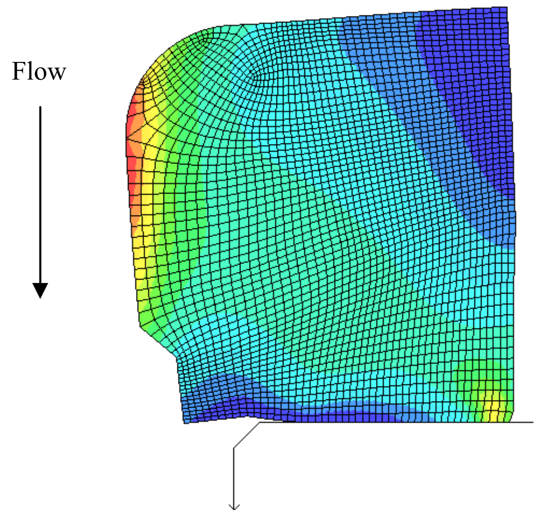

Figure 8 Mises stress in rubber insert at 40 psi inlet pressure

3.4 Fluid structure coupling effects on the flow rate

At a given deformation state, as shown in Figure 9, the cross-section through the constriction path governs the flow behavior. As the flow quickens through the narrow constriction region the fluid pressure drops significantly, resulting in a dramatic drop in the absolute pressure of the liquid; this may lead to cavitation in the fluid.

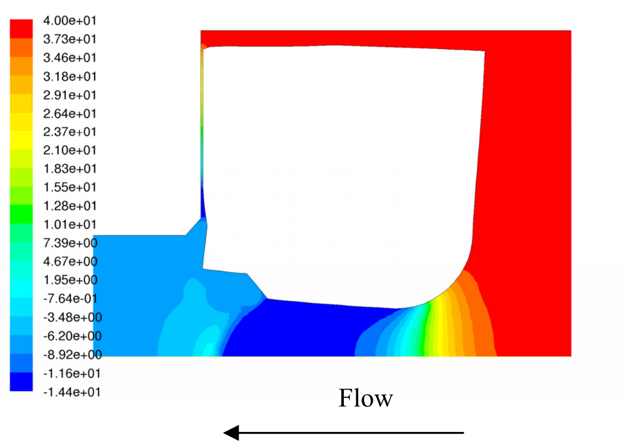

Figure 9 Static flow pressure at 40 psi inlet pressure

3.5 Fluid structure coupling effects on the flow rate

Figure 10 shows contour plots of the fluid pressures at inlet pressure levels of 20, 60 and 90 psi. The corresponding deformed shapes are shown in Figure 11 with contour plots of Mises stress.

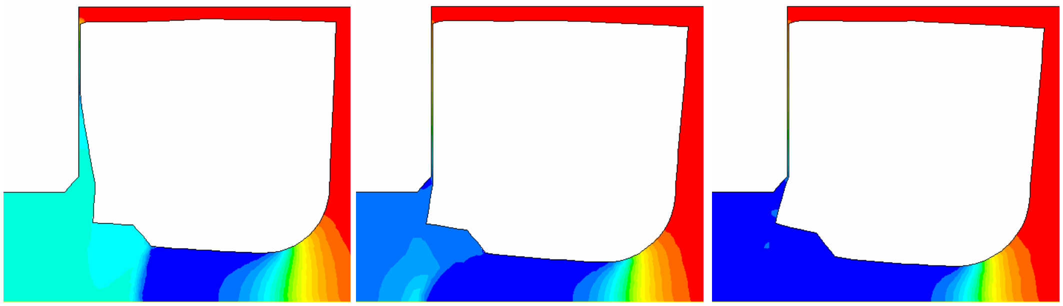

Figure 10 Static flow pressure at 40 psi inlet pressure

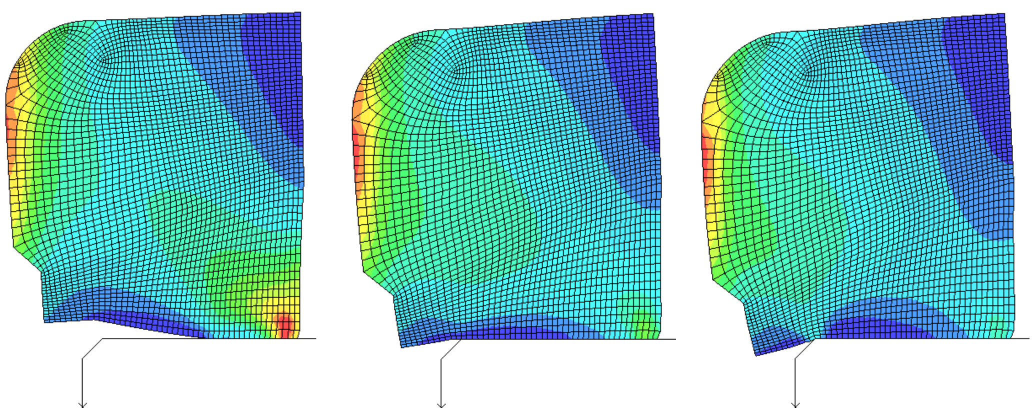

Figure 11 Mises stress at 20, 60 and 90 psi inlet pressure

With an increase in the inlet pressure the rubber device deforms and experiences increased contact with the rigid seat. Partial contact is observed at 20 psi, with full contact being established at the higher pressure of 60 psi. The constriction path narrows during the inlet pressure rise resulting in an increased resistance to the fluid flow. However, the increased material stiffness helps maintain the bulk flow rate at a fairly constant level

3.6 Cavitation

As discussed earlier, cavitation effects are observed at higher upstream pressures. Figure 12 shows the vapor region in the flow at an inlet pressure of 40 psi. The phase change is prominent in the downstream region right after the narrowest flow path. As the inlet pressure increases the vapor envelope stretches further downstream but the vapor region collapses before reaching the outlet.

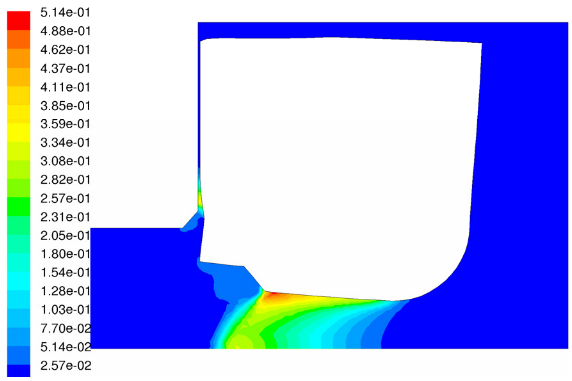

Figure 12: Volume fraction of vapor at 40 psi inlet pressure

3.7 Experimental Validation

Finally, the results from the analysis are compared to experimental results. Figure 13 shows a close match of the computational flow rate results to the experimental data. The flow rate increases from 0 to 2.1 liters/min during the initial pressure ramp-up from 0 to 20 psi and has near constant flow in the operating pressure range of 20 to 120 psi.

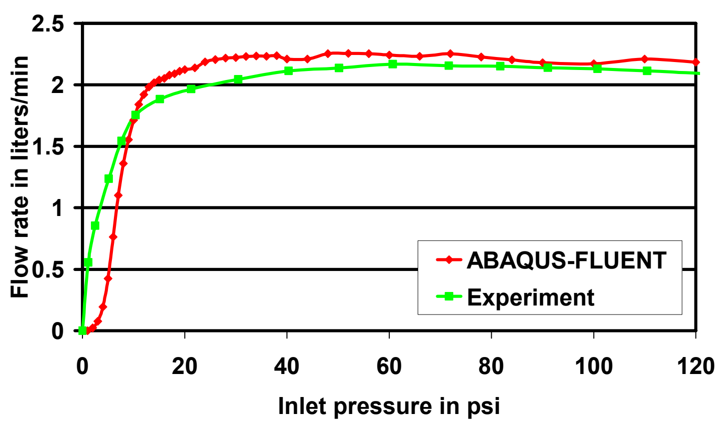

Figure 13: Experimental validation of computation results

4. Conclusions

In this paper, a fluid structure interaction analysis of the VernaFlo® flow control device using the ABAQUS co-simulation technique for FSI is presented. The results obtained are in good agreement with experimental results. This study highlights the importance of FSI in this class of problems and successfully demonstrates the capability of ABAQUS to perform such advanced coupled physics simulations.

5. Acknowledgements

The authors would like to thank David Schowalter at Fluent, Inc. for assisting with the cavitation modeling.

6. References

1. ABAQUS Users' Guide on Fluid Structure Interaction Using ABAQUS and FLUENT.
2. ABAQUS Analysis User's Manual: Co-simulation
3. Vernay VernaFlo® flow devices and related product information from www.vernay.com.
4. Fluent Users' Guide