A Co-Simulation Approach to Modeling the Solenoid Valve Multiphysics

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Problem Description

Solenoid Valves

- Electromechanical (EM) valves that are used to control the flow of liquids and gasses
  - Complex mechanisms of operation requiring interaction between electromagnetic, fluid and structural domains
  - From a design perspective, the time required to open or shut off the valve is of significant interest
Problem Description

Solenoid Valve Multiphysics

- Coupled multiphysics simulation using Abaqus and STAR-CCM+
  - Accurate evaluation of electromagnetic and fluid dynamic forces
  - Understanding their interaction with the valve’s structural components
  - Leverage best-in-class solvers for respective physics

- Benefits
  - Computationally study the solenoid valve’s response times
  - Evaluate the effect of design variables
    - Material properties
    - Spring constants
    - Spring damping
    - Coil properties
    - Fluid properties
    - Geometry
Problem Description

Solenoid Valve Model

EM Analysis

FSI Analysis
Solution Workflow

Multiphysics Approach

Electromagnetic Analysis
- Obtain EM force as a function of electric current and plunger location
- A parametric study is performed to generate the data
- Python scripting and Isight facilitates the parametric study
- EM analysis in Abaqus/Standard

FSI Analysis
- Co-simulation between fluid and structural domains
- Co-simulation engine in Abaqus performs a conservative physics-based mapping between dissimilar fluid and structural meshes

CFD Analysis
- STAR-CCM+
- Viscous incompressible fluid dynamics
- Laminar/Turbulent flows
- Moving deforming mesh

Abaqus/Standard
- Sensor output on plunger displacement
- EM force applied through user subroutine UAMP
EM Analysis

Methodology

- Plunger and core
  - Soft magnetic materials with magnetic properties similar to that of an ASME 1010-grade steel
  - BH curve to account for the magnetic saturation at high field intensities

- Compute magnetostatic response of the valve in **Abaqus/Standard**
  - Magnetic vector potential-based formulation
  - Compute at a given current and plunger position
  - Current is assumed to be quasi-static
  - Ignore eddy currents arising from the motion of the plunger in the magnetic field

Nonlinear BH curve of the plunger and the core
EM Analysis

Methodology

▸ Obtain total force on the plunger
▸ Integrate Maxwell’s stress tensor over the surface of the plunger

Magnetic flux density at plunger displacements various plunger displacements (1 A current)

Force vs. plunger displacement

Increasing current
FSI Analysis

Structural Model

- **Abaqus/Standard**
  - EM force is applied as a CLOAD through user subroutine UAMP
  - Sensor history output of current plunger position is obtained
  - Force for a given current and position is calculated through linear interpolation

![Electric circuit time constant = 10 ms](image)

![Applied current vs. time in UAMP](image)
FSI Analysis

CFD Model

- **STAR-CCM+**
  - Transient incompressible flow analysis
  - Boundary condition
    - Inlet mass flow rate = 0.5 kg/s
    - *Laminar flow: Reynolds number ~ 169*
    - Outlet pressure is atmospheric
    - Mesh motion is constrained at inlet, outlet and walls
    - FSI coupling dictates the mesh motion and velocities at the plunger interface

**Fluid:** Viscous Oil
- Oil density = 998 kg/m$^3$
- Viscosity = 0.15 Pa.s
FSI Analysis

CFD Model

- STAR-CCM+
  - Mesh:
    - Polyhedral mesh with prism layers
    - Total number of cells: 649646
    - Volumetric refinement near valve seat
    - Volumetric coarsening in inlet region and far outlet region
FSI Analysis

CFD Model

- STAR-CCM+
  - Solver settings
    - Segregated solver,
      - Transient SIMPLE algorithm
      - 100 inner iterations ensuring residuals reduce 3 orders of magnitude in each of the time step
      - Under-relaxation: Pressure – 0.2, Momentum – 0.8
  - Mesh morpher
  - Total physical time of simulation: 0.2 s

Total physical time of simulation: 0.2 s
FSI Analysis

Coupling between Abaqus/Standard and STAR-CCM+

- Coupling is driven through STAR-CCM+ GUI
  - Easy-to-use

- Coupling methodology
  - Carried out using the Abaqus Co-Simulation Engine (CSE)
  - Runs in background without user-intervention
  - Physics-based conservative mapping of solution quantities (such as forces and heat fluxes)
  - Does not require matching meshes between solid and fluid domains

- Explicit coupling
  - Implicit coupling for tightly coupled physics

- Rendezvous scheme between solvers employing either a min-min or constant coupling time strategy
  - Min-Min strategy: Minimum of the time increment sizes determined by the automatic time incrementation schemes of the individual analyses
  - Constant coupling time strategy: Exchange at constant coupling time
Results

- Coupled EM/FSI simulation demonstrated steady-state operating condition for the plunger after the electric current is activated.
  - The valve reaches a steady-state operating condition at $t = 60 \text{ ms}$ after the electric current is activated (the electric current circuit time constant is 10 ms).

Plunger displacement vs. time

Plunger steady-state configuration

Steady-state
Results

- Flow velocity in steady-state operating condition
Results

Pressure in the flow field

Flow streamlines (colored by pressure)

Initial and deformed mesh
Conclusions

- Methodology for simulating the coupled electromagnetic (EM) and fluid-structure interaction (FSI) analysis of a solenoid valve
- Study solenoid valve’s response times
- Design variations can be studied
  - Study effect of geometry, fluid properties, coil properties and material properties etc.
- Coupled or follow-up structural analysis can be performed
- Leverage EM and structural capabilities of Abaqus and CFD capabilities of STAR-CCM+
  - Seamless integration between Abaqus and STAR-CCM+
  - Superior STAR-CCM+ user interface
- Future work:
  - Valve closure modeling, that requires CFD volume mesh pinching capability, will be modeled with the over-set mesh technology in future version of STAR-CCM+
Questions?
THANK YOU