Fluid Structure Interactions in OpenFOAM

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Presentation overview

• FSI: Arbitrary Lagrangian Eulerian approach
• implicit scheme with Aitken relaxation factor
• Overview of the FSInterface class
• Lidden flow cavity validation test case
• Note on the convergence criterion and communications issues
• Limitations: singularities arising when folds occur
• Further development and open questions
ALE approach

Fluid equations:
\[
\begin{align*}
\left. \frac{\partial u}{\partial t} \right|_{x_0} + c \cdot \nabla u - 2\nu \nabla^2 u + \nabla p &= b^F \quad \text{in } \Omega^F \times (0, T) \\
\nabla \cdot u &= 0 \quad \text{in } \Omega^F \times (0, T)
\end{align*}
\]

Structural equations:
\[
\rho_s \frac{d^2 d}{dt^2} = \nabla \cdot (F \cdot S) + \rho_s b^s \quad \Omega^s \times (0, T)
\]

Coupling conditions to be met at the F/S interface:
\[
\begin{align*}
u^{n+1}_\Gamma &= \frac{d^{n+1}_\Gamma - d^n_\Gamma}{\Delta t} \quad \text{Continuity of the velocity} \\
f^{F,n+1}_\Gamma &= -f^{S,n+1}_\Gamma \quad \text{Conservation of the forces} \\
d^{G,n+1}_\Gamma &= d^{n+1}_\Gamma \quad \text{Continuity of the displacements}
\end{align*}
\]

The mesh deforms as the structure on the structural interface, it remains undeformed on the rigid boundaries and the movement is arbitrarily (laplacian) spread into the domain.
Implicit coupling

Added mass effects affects the stability of the coupled solution, unless $1^1$:

$$\frac{\rho_s h_s}{\rho_f \mu_{max}} < 1$$

$\rho_s$ density of the structure

$h_s$ thickness of the structure

$\rho_f$ density of the fluid

$\mu_{max} = \frac{L}{\pi h \tan(\frac{\pi R}{L})}$

In the majority of cases the condition is not met, and the algorithm is unstable. The most easy (but computationally expensive) way is to perform fixed point iterations between the fluid and the structure.

Multiple Program Multiple Data type environment, the external solver is “spawned” during the execution time. This generates a communicator we can use for exchanging data (black arrows)
Iteration scheme

\[
\text{if}(k==1) \quad \gamma^\text{Predicted}_{k+1} = 2 \times \gamma_{k+1} - \gamma_{old};
\]

\[
\text{if}(k==2) \quad \omega_k = 0.01;
\]

\[
\gamma_{k+1}^F = \omega_k \tilde{\gamma}_{k+1}^S + (1 - \omega_k) \gamma_{k+1}^F;
\]

\[
\text{if}(k > 2) \quad \text{Calculate } \omega_k;
\]

\[
\gamma_{k+1}^F = \omega_k \tilde{\gamma}_{k+1}^S + (1 - \omega_k) \gamma_{k+1}^F;
\]

Aitken dynamic relaxation factor\(^2\):

\[
\omega_k = \frac{(\gamma_k - \gamma_{k-1}) \cdot (\gamma_k \tilde{\gamma} + 1 - \gamma_k + \gamma_k \tilde{\gamma} + 1 - \gamma_{k-1})}{\|\gamma_k \tilde{\gamma} + 1 - \gamma_k + \gamma_k \tilde{\gamma} + 1 - \gamma_{k-1}\|^2}
\]

Note: linear predicting do not introduce discontinuities of the velocity at the interface

Convergence criterion

Since the fixed point is performed on the pressure, we need a convergence criterion on the pressure. Otherwise, very bad things are likely to happen...

Table 1: Relaxed Dirichlet-Neumann fixed-point iterations

<table>
<thead>
<tr>
<th>normal setting</th>
<th>setting adopted in openFOAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>solve fluid:</td>
<td>solve solid:</td>
</tr>
<tr>
<td>$p_k = S^f(\gamma_k)$</td>
<td>$\tilde{\gamma}_{k+1} = S^s(p_k)$</td>
</tr>
<tr>
<td>solve solid:</td>
<td>apply relaxation:</td>
</tr>
<tr>
<td>$\gamma_{k+1} = S^s(p_k)$</td>
<td>$\gamma_{k+1} = \omega_k \tilde{\gamma}_{k+1} + (1 - \omega_k) \gamma_k$</td>
</tr>
<tr>
<td>apply relaxation:</td>
<td>solve fluid:</td>
</tr>
<tr>
<td>$\gamma_{k+1} = \omega_k \tilde{\gamma}_{k+1} + (1 - \omega_k) \gamma_k$</td>
<td>$p_{k+1} = S^f(\gamma_{k+1})$</td>
</tr>
<tr>
<td>$\gamma_k = S^s(S^f(\gamma_k))$</td>
<td>$p_k = S^f(S^s(p_k))$</td>
</tr>
</tbody>
</table>

Displacement of the mid point - comparison convergence criteria

Pressure probe - comparison convergence criteria
Lidden flow cavity validation

2d Cavity FSI validation test case

Time: 0.00

Displacement of a point in the middle of the cavity F/S interface

Number of fixed point iterations - Aitken dynamic relaxation

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Limitations: parachute canopy

Experiments flying an initially flat membrane held with cables in the cavitation tunnel

During its deformation, large folds are generated on the device

When repeating such experiments with ALE techniques, fall over is experienced due to the inversion of volume cells
Further development and open questions

- How to treat extreme mesh deformations, such as displacements field coming from fabric wrinkling?
- Parallel computing in segregated environment: use of PETSc?
- New validations on external flows (flag test case$^3$)
- How to fix cell regions in the fluid domain