Numerical analysis of debris containment grid fluid-body interaction

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Numerical Analysis of Debris Containment Grid Fluid-Body Interaction

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Introduction

- Debris containment grids are important part of hydroelectric power plants
- Large amount of logs is the most significant debris in the Madeira River, located in the Amazon rainforest, north of Brazil
  - Logs reach diameters up to 2 m and lengths of 30 m
  - Log booms are a type of debris containment structures developed specifically for containing logs

Log boom line in the Madeira river (left) and a log boom module (right)
Santo Antônio Hydropower Plant

- Hydropower Plant, located in the Madeira River, Amazon rainforest, north of Brazil.

- Fourth largest hydroelectric generator in Brazil
- 3,568 MW of installed capacity
- Spillway flow rate of 84,000 m³/s
- Energy for over 45 million people
Log Boom R & D Project

OMAE2017
- Blockage Effects and Technical Capacitation
  “Analysis of the Blockage Effect on a Cavitation Tunnel Using CFD Tools”

ATTC2017
- Instrumentation Methodology
  “Instrumentation Methodology for a Log Containment Grid Model in Towing Tank Tests”

Model-Scale Log Boom Validation
- “Debris Containment Grid CFD validation with Towing Tank Tests”

COBEM2017
- Model-Scale Log Boom Line Tests
  “Structural Analysis for a Reduced Scale Model of a Hydropower Plant Debris Containment Grid”

Log boom module CFD simulation with Porous Media
- “Hydrodynamic Analysis of Debris Containment Grids in Hydropower Plant Using Porous Media”

OMAE2018
- Model-Scale Log Boom Line with Log Accumulation
  “Structural Investigation of the Log Accumulation Effect in a Debris Containment Grid Through Towing Tank Experiments”

Log boom Line CFD simulation with Porous Media
- “Numerical Analysis of Debris Containment Grid Fluid-Body Interaction”

Force Distribution in the Log Boom Line
- “Nonlinear Truss-Based Quasi-Static Structural Model for Force Distribution prediction on Debris Containment Grid”
Objectives

- Develop a simplified numerical model of a log boom line
  - Truncated version (with fewer modules)
  - Similar to the one in Santo Antonio hydropower plant
- Fluid-Dynamic Interaction
- Hydrodynamic investigation is conducted using CFD software Star-CCM+
- Several conditions: Advance velocity and side-slip angle
- In order to obtain results with accessible computational cost, the numerical model of log boom module must be simplified
  - Main interest in simplification is in macro scale, especially in the module total force
  - Compute the hydrodynamic with an affordable computation cost
Methodology

Complete representation → Simplified representation using porous media approach → Log-boom line with simplified representation
Methodology

Complete representation

Simplified representation using porous media approach

Log-boom line with simplified representation
Domain Geometry and Boundary Conditions

- Two regions: domain region (include the grid) and chassis region

Boundary conditions and dimensions of domain region:
- Pressure outlet
- Periodic interface
- Wall
- Velocity inlet

Dimensions:
- 30.0 m
- 8.0 m
- 25.0 m
- 15.0 m
- 6.2 m

Boundary conditions and dimensions of chassis region:
- Overset boundary
- Wall
- Log boom module: Grid + chassis

Dimensions:
- 2.0 m
- 2.5 m
- 6.4 m
Simulation set-up

- Two DoF: Sinkage of the module and rotation of the chassis
  - The grid are connected to each other, so only sinkage DoF is considered
  - On the other hand, the chassis is connected only to the grid, so the relative rotation is considered

- Evolution of Movements (DoF) and Timesteps

- Simulated Conditions: 6 velocities and 6 side-slip angle
Results

SAf201c01

\( \text{va: } 1.5 \text{ (m/s)} \)
\( \text{beta: } 0 \text{ (deg)} \)
\( \text{Solution Time: } 0.0600154 \text{ (s)} \)
\( \text{Time Step: } 2 \)
\( \text{Sinkage: } 1.1944 \text{ (m)} \)
\( \text{Trim: } 10.06 \text{ (deg)} \)
\( \text{Passo: } 0.0300077 \text{ (s)} \)
\( \text{vz: } 0 \text{ (m/s)} \)
\( \text{angvel: } 0 \text{ (rpm)} \)

\( F_x \text{ total: } -180440 \text{ (N)} \)
\( F_y \text{ total: } 206.531 \text{ (N)} \)
\( F_z \text{ total: } 46255.4 \text{ (N)} \)
\( M_y \text{ total: } 113189 \text{ (N-m)} \)
Methodology

Complete representation

Simplified representation using porous media approach

Log-boom line with simplified representation
Simplified representation

- Porous region
  - Volume
  - Momentum sink in each direction
  - Grid and frontal part of chassis
- Floats are represented with Wall Boundary Condition
- DFBI was not used
  - Sinkage and rotation values from complete model
Domain Geometry and Boundary Conditions

- Dimensions are the same as complete representation
- Grid by porous region
  - Grid-exclusive region is required
  - Frontal part of chassis is required

Boundary Conditions of Domain (I), Grid (II), Chassis (III) and Frontal part of Chassis (IV) regions (figures are not in the same scale)
Mesh topology

- Same refining volumes, large element size

Mesh of Domain (I), Grid (II) and Chassis (III) regions (figures are not in the same scale)

Comparative number of elements and faces

<table>
<thead>
<tr>
<th></th>
<th>Elements (Cells)</th>
<th>Interior Faces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complete</td>
<td>Porous</td>
</tr>
<tr>
<td>Chassis (float)</td>
<td>2 209.7 k</td>
<td>78.6 k</td>
</tr>
<tr>
<td></td>
<td>19.1 k</td>
<td>6 622.1 k</td>
</tr>
<tr>
<td>Chassis (front)</td>
<td></td>
<td>227.4 k</td>
</tr>
<tr>
<td>Domain</td>
<td>1 857.3 k</td>
<td>162.2 k</td>
</tr>
<tr>
<td></td>
<td>5 461.5 k</td>
<td>487.6 k</td>
</tr>
<tr>
<td>Grid</td>
<td>6.9 k</td>
<td>18.5 k</td>
</tr>
<tr>
<td>Total</td>
<td>4 067.0 k</td>
<td>266.8 k</td>
</tr>
<tr>
<td></td>
<td>12 083.6 k</td>
<td>781.0 k</td>
</tr>
</tbody>
</table>
Porous Modeling

- Governing equations: Continuity and Momentum equations

\[
\frac{\partial}{\partial t} \int_{\Omega} \rho dV + \oint_{\partial \Omega} \rho \mathbf{v} \cdot d\mathbf{a} = 0
\]

\[
\frac{\partial}{\partial t} \int_{\Omega} \rho \mathbf{v} dV + \oint_{\partial \Omega} \rho \mathbf{v} \otimes \mathbf{v} \cdot d\mathbf{a} = \oint_{\partial \Omega} \rho \mathbf{I} \cdot d\mathbf{a} + \oint_{\partial \Omega} \mathbf{T} \cdot d\mathbf{a} + \int_{\Omega} \mathbf{f}_p dV + \int_{\Omega} \mathbf{f}_b dV
\]

- Porous medium resistance force per volume (porous volume)

\[
f_p = - (\mathbf{P}_v + \mathbf{P}_i |\mathbf{v}_s|) \cdot \mathbf{v}_s
\]

\[
\mathbf{P}_v = \begin{bmatrix}
\rho_{v,xx} & \rho_{v,xy} & 0 \\
0 & \rho_{v,yy} & 0 \\
\rho_{v,xz} & \rho_{v,zy} & 0
\end{bmatrix} ;
\mathbf{P}_i = \begin{bmatrix}
\rho_{i,xx} & \rho_{i,xy} & 0 \\
0 & \rho_{i,yy} & 0 \\
\rho_{i,xz} & \rho_{i,zy} & 0
\end{bmatrix}
\]

\(\mathbf{P}_v\): Viscous resistance tensor (linear)
\(\mathbf{P}_i\): Inertial resistance tensor (quadratic)
Obtaining porosity coefficients

- Reproduce the Forces $F_x$, $F_y$ and $F_z$ in porous model
- Reproduce the Moment $M_y$ of grid in porous model

- Flowchart of iterative method to determinate the porosity coefficients
Obtaining porosity coefficients: Initial condition

- Initial guess of porosity coefficients is such that it satisfy the linear equation
  \[ f_{c\bullet} = \mathbf{v}_p \cdot \mathbf{p}_{i\nu} \]
- 35 conditions: 35 points of velocity and resulting force
- Linear Least Squares to obtain the initial porosity coefficients

\[
\text{Min}_{\mathbf{p}_{i\nu}} \quad \frac{1}{2} \left\| [\mathbf{v}_p] \cdot \mathbf{p}_{i\nu} - [f_{c\bullet}] \right\|_2^2
\]

such that \( \mathbf{p}_{i\nu} \geq 0 \)
Obtaining porosity coefficients: CFD simulation

- **Input of simulation**: porosity coefficients.
- **Output of simulation**: force divided in components of surface-integral and volume-integral surfaces

\[
sim\left(p_{iv}^{[i]}\right) = f_{\Omega}^{[i]}\]
Obtaining porosity coefficients: Correct porous

- Model of porous forces

\[ f^{[i]}_{\Omega} = p_{i_{_h}}^{[i]} \circ v_p \cdot k^{[i]} \]

- **k**: correcting the local velocity – using the far field velocity
  - Ratio between local and far-field velocities
  - Linear Least Squares is used to obtain correction k
Obtaining porosity coefficients: Get new porosities

- Model of porous forces with correction

\[
\dot{f}_c = v_p \circ k^{[i]} \cdot P_{iv}^{[i+1]}
\]

- Term of surface-force must be discounted. Obtain only the volume-integral force

- Linear Least Squares is used to obtain new porosity coefficients
Obtaining porosity coefficients: Get new $z_m$

- Bi-linear (triangle) porosity distribution
- $Z_m$: largest porosity position
  - Largest force
- Reproduce the torque generated by the porous grid

\[
p_{X*} = \frac{hm_*}{2}
\]

\[
m_{c*} = v_p \cdot k^{[i]} \cdot \frac{1}{3} \left( h + 3z_0 + z_m^{[i+1]} \right) p_{iv}^{[i+1]}
\]
Results

Comparative of complete and porous model in grid force magnitude (x and y directions) (left); and in moment (right)
Methodology

Complete representation

Simplified representation using porous media approach

Log boom line with simplified representation
Mesh Topology

- Same previous refining volumes from the simplified module representation

- Extra refining volumes between each module
  - New volume around the grid
  - Bigger volume around the chassis
  - Refinement due to the module’s movement, mainly, in the direction of the fluid and vertically.
Final line’s shape with 5 modules

\[ v_a = 1.0 \text{ m/s} \]

\[ v_a = 1.5 \text{ m/s} \]

\[ v_a = 2.0 \text{ m/s} \]

\[ v_a = 2.5 \text{ m/s} \]
Conclusions

- Porous media approach were satisfactorily achieved
  - Simulation time noticeably lower
- Some weaknesses of the porous model in the previous work were improved
  - Moment generated by the grid
  - Implementation of a porous volume to represent the front of the chassis.
- Several connected log boom modules were simulated, showing their feasibility, even without the fully defined values of porosity.
  - Results were satisfactory, especially at the required computational cost
- Porous region in grid: almost identical to those obtained with the complete model
- Some issues still persist, such as representing the chassis, which has a fraction outside the water, using the porous approach
Next Steps

- Use a nonlinear approach of the porosity force as a function of velocity, manually introducing the expression in the momentum equations.

\[
F_x = \frac{1}{2} \rho v_a^2 S_{grid} [1.6327 \cos(1.0403 \beta)]^{1.5126}
\]

\[
F_y = \frac{1}{2} \rho v_a^2 S_{grid} [0.1363 \sin(1.6898 \beta)]^{1.3835}
\]
Next Steps

- DFBI model to simplified model
  - Sinkage and rotation DoF
  - Verify if porous model simulation reaches the same equilibrium point
- Asymmetric line conditions, in which one edge of line is ahead.
- Compare results with experimental values obtained in IPT’s Towing Tank
Thank you

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