Fluid-Structure Interaction of Thin Structures in Turbulent Flows

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1 Motivation / Objectives

2 Computational Methodology

3 Validation
   - Definition of the Test Cases
   - Simulations and Comparison with Experiments (FSI-PfS-2a)

4 Conclusions
Motivation / Objectives

Computational Methodology

Validation
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- Simulations and Comparison with Experiments (FSI-PfS-2a)

Conclusions
Tents / Sun Shades / Mobile Umbrellas

Motivation / Long-term Objectives
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FSI in Turbulent Flows

\[ \Delta x \]

**CFD**

Partitioned Approach

\[ F_p, F_\tau \]

**CSD**

Publication

Computational Methodology: FSI with LES and Thin Structures
Computational Methodology:
FSI with LES and Thin Structures
Forces on the Estimation of structural displacements

Momentum Eq.
Runge–Kutta

Poisson Eq.

Grid adaptation

Predictor

Corrector

FASTEST–3D
FVM (2\textsuperscript{nd} order)
Predict.–Correct.
LES
Block–struct. grids
ALE

Grid adaptation

Parton ailed Approach

Computational Methodology:
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Estimation of structural displacements

FASTEST−3D
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Predict.−Correct.
LES
Block−struct. grids
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Momentum Eq.
Runge−Kutta
$u_i^*$

Predictor

Corrector

Poisson Eq.
$u_i, p$

Forces on the structure

Grid adaptation

FSI−Subiteration Loop
(ensure dynamic equilibrium)

CoMA

Grid−to−Grid
Displacement Interpolation
(bilinear)

MPI

Underrelax. of Displacements

Grid−to−Grid
Fluid Force Interpolation
(conservative)

Index: n

FSI convergence?

yes

no

Index: k

Partitioned Approach

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4 Conclusions
FSI Test Cases for Turbulent Flows

- **FSI-PfS-1a**
  - Fixed cylinder (rigid)
  - EPDM-rubber (flexible)
  - $E = 16 \text{ MPa}$
  - $\nu = 0.48$
  - $Re = 30,470$
  - Quasi 2D-deformations
  - Small deformations
  - First swiveling mode

- **FSI-PfS-2a**
  - Fixed cylinder (rigid)
  - Para-rubber (flexible)
  - $E = 4.10 \text{ MPa}$
  - $\nu = 0.48$
  - $Re = 30,470$
  - 2D-deformations
  - Large deformations
  - Second swiveling mode

**Parameters**
- $u_\infty$
- $\phi 22 \text{ mm}$
- $60 \text{ mm}$
- $2 \text{ mm}$
- $50 \text{ mm}$
- $10 \text{ mm}$
## Publications for FSI-PfS-1a


## Publications for FSI-PfS-2a


- [http://qnet-ercoftac.cfms.org.uk/w/index.php/UFR_2-14](http://qnet-ercoftac.cfms.org.uk/w/index.php/UFR_2-14)
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4 Conclusions
Axial pump with motor
Flow straightener
Test section

Water Channel

Flow measurement methods (PIV / V3V)
Laser displacement sensor

⇓

Experimental Data

High-speed video (real frequency 11.25 Hz)

FSI-PfS-2a: Experiments
Fluid/CFD:
- wall–resolved LES
- 13.5 million CVs
- 72 CVs in spanwise direction
- periodic boundary conditions

Structure/CSD:
- 7–parameter shell elements
- $30 \times 10$ quadrilateral four-node elements
- zero $z$–deformation vs. periodic b.c.
- (Rayleigh damping)

FSI-PfS-2a: Computational Setup
<table>
<thead>
<tr>
<th>93 cores needed for each simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 13.5 million CVs on 91 blocks → 91 processes for CFD</td>
</tr>
<tr>
<td>• 1 process for CSD</td>
</tr>
<tr>
<td>• 1 process for coupling program</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>2 seconds physical time computed for each simulation</th>
</tr>
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<tr>
<td>• CPU: 1000 hours wall-clock</td>
</tr>
<tr>
<td>• RAM: 242 Mbytes per core → 22 Gbytes for the entire simulation</td>
</tr>
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</table>

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<tr>
<th>Sensitivity study on FSI-PfS-2a</th>
</tr>
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<tr>
<td>• about 30 simulations with different parameters conducted</td>
</tr>
</tbody>
</table>
EXP: Raw Signal

CFD: Raw Signal

Monitoring Point (mid plane)

FSI-PfS-2a: Deflection of the Structure
FSI-PfS-2a: Deflection of the Structure
<table>
<thead>
<tr>
<th></th>
<th>St</th>
<th>$f_{FSI}$</th>
<th>Error</th>
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<tbody>
<tr>
<td>EXP</td>
<td>0.177</td>
<td>11.25</td>
<td>-</td>
</tr>
<tr>
<td>CFD</td>
<td>0.183</td>
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## Frequency

<table>
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## Displacements

|       | \( \frac{U_y}{D} \big|_{max} \) | Error | \( \frac{U_y}{D} \big|_{min} \) | Error |
|-------|-------------------------------|-------|-------------------------------|-------|
| EXP   | 0.667                         | -     | -0.629                        | -     |
| CFD   | 0.670                         | 0.5   | -0.674                        | 7.2   |
Streamwise velocity in the midplane
FSI-PfS-2a: Comparison of Phase-averaged Data
$(t \approx 1/24 \ T)$
Streamwise velocity

Transverse velocity

FSI-PfS-2a: Comparison of Phase-averaged Data
(t \approx \frac{5}{24} \, T)
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Computational Methodology for FSI and Thin Structures

- Each program **specialized** in its task
- Each program **parallelized** (MPI, OpenMP)
- **New** FSI coupling scheme developed
  - based on **explicit** time-marching scheme (predictor-corrector), but nevertheless **stable and strong** FSI algorithm
  - corrector step and structural computation directly connected in a FSI subiteration loop to achieve dynamic equilibrium
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Validation

- Methodology validated for **laminar flows** (not presented here)
- Methodology validated for **turbulent flows** (FSI-PfS-2a,...)
- Generation of FSI test cases for the community with **experimental and numerical data available online** (ERCOFTAC/QNET wiki)

Conclusions
Outlook

- New coupling program (EMPIRE) → more flexibility in the coupling
- Reduce the CPU costs with the help of special wall models

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