Demonstration of a unified and flexible coupling environment for nonlinear fluid-structure interaction problems

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Motivations

Fluid-structure interaction
- Nonlinear behavior
- Large range of physics
- High fidelity models
- Development of a computational environment for research and design

Primary target application: aeroelasticity
Computational approach

**Monolithic**
- One single framework to solve the coupled problem

**Partitioned**
- Coupling of independent codes
- Each code is optimized for a particular physics
Computational approach

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➡️ Need an interfacing tool

flexible
performant
FSI: governing physics & formulation

\[ \frac{\partial U}{\partial t} + \nabla \cdot F^c - \nabla \cdot F^v = Q \]

\[ U = [\rho, \rho \mathbf{v}, E]^T \]

**Governing equations**

\[ \mathcal{F} \leftrightarrow \text{Fluid operator} \]
\[ \mathcal{S} \leftrightarrow \text{Solid operator} \]

**Coupling conditions**

\[ d_f^\Gamma = d_s^\Gamma = d^\Gamma \]
\[ t_f^\Gamma + t_s^\Gamma = 0 \]

**Fixed-point formulation**

\[ d^\Gamma = \mathcal{S} \left( -\mathcal{F}(d^\Gamma) \right) \]

**Interface loads**

\[ t_f^\Gamma = -p n_f + \bar{t} n_f \]
\[ t_s^\Gamma = \bar{\sigma} n_s \]
Coupling simulations – strong coupling

\[ U_\infty \]

\[ p \]

\[ \tau_w \]

FSI loop

Stresses

Structural loads

New wall BC's

Displacements/velocities

CFD - \( \mathcal{F} \)

\( S - \text{CSD} \)
Multi-codes coupling technology: CUPyDO

- **Multi-languages**
  - C++ for computationally intensive tasks
  - Python for high-level management

Diagram:
- Utility
  - OpenMPI
  - PETSc
- Core
  - CUPyDO C++ kernel
  - MPI functions
  - Interface data
  - Interface matrix
  - Linear solver
- Interface
  - Manager
  - Interpolator
  - Algorithm
    - Generic fluid
    - Generic solid
  - Fluid solver interface
  - Solid solver interface
  - FLUID SOLVER
  - SOLID SOLVER

• Utility
• Core
• Interface
Examples of coupled solver

**Fluid solvers**
- SU2 – FV unstructured (Stanford)
- PFEM – particle FE (ULiège)

**Structural solvers**
- Metafor – NLFEM (ULiège)
- GetDP – LFEM (ULiège)
- RBM integrator (ULiège)

- Ready-to-use interfaces
- No technical restriction for coupling other software, even commercial packages
Isogai wing section

- Determine flutter conditions as a function of $M_\infty$
- Transonic dip is captured
- S-shape curve is well recovered
- Inviscid fluid

$V^* = \frac{U_\infty}{b\omega_\alpha\sqrt{\mu}}$

“K. Isogai. AIAA Journal, 17, 1979”
Isogai wing section

- Moving shock interacting with the motion of the airfoil
- Existence of a LCO due to nonlinear aerodynamics
Stall flutter of a flat plate

- Airfoil motion rapidly turns into stall flutter
- Induced by dynamic flow separation
- Nonlinearities lead to LCO

"X. Amandolese et al., Journal of Fluids and Structures, 43, 2013."
VIV of a flexible cantilever

- Solid motion is generated by vortex shedding
- Large displacement amplitude (nonlinear)
- Laminar flow at Re = 333

“C. Habchi et al., Computer & Fluids, 71, 2013.”
VIV of a flexible cantilever

- From dense to light material
- Low mass ratios = numerical coupling instabilities \(\Rightarrow\) relaxation needed in coupling
- Number of coupling iterations per time step increases

\[
\frac{\rho_s}{\rho_f} \approx 100 \\
\frac{\rho_s}{\rho_f} \approx 10 \\
\frac{\rho_s}{\rho_f} \approx 1
\]

\(\bar{N}_{FSI} = 2.7\) \(f = 3.14\) Hz

\(\bar{N}_{FSI} = 6.9\) \(f = 7.26\) Hz

\(\bar{N}_{FSI} = 31.9\) \(f = 6.2 - 9.8\) Hz

\[\|U\| \text{[m/s]}: 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8\]
• Determine flutter conditions at $M_\infty = 0.96$
• Consider inviscid fluid
• Literature: $V_f^* = 0.243 - 0.327$
• Computed: $V_f^* = 0.281$

\[ V^* = \frac{U_\infty}{b_\tau \omega_2 \sqrt{\mu}} \]
AGARD 445.6 wing

- Post-critical conditions at $M_\infty = 0.96$ and $V^* = 0.300$
- Significant motion of the supersonic region

Bending of a flat plate submitted to cross flow

- Inspired from drag reconfiguration of aquatics plants
- Laminar flow at Re = 1600
- Relatively soft and light solid material:
  \[ \frac{\rho_s}{\rho_f} = 0.678 \]
  ➞ transient response is numerically unstable

“F-B. Tian et al., J. of Computational Physics, 258, 2014.”
Cantilever flat wing

- Material: aluminium | Fluid: air
- High aspect ratio plate with very small thickness
- Very flexible structure

- Two perturbation amplitudes
- Two distinct limit cycles

\[
U_\infty = 17.1 \text{ m/s} \\
T^* = 0.01 \text{ s} \\
f = 6.2 \text{ Hz}
\]

\[
U_\infty = 17.1 \text{ m/s} \\
T^* = 0.1 \text{ s} \\
f = 9.8 \text{ Hz}
\]
Cantilever swept flat wing

\[ ||V|| \text{ [m/s]}: 0.3 \quad 0.6 \quad 0.9 \quad 1.2 \quad 1.5 \quad 1.8 \quad 2.1 \quad 2.4 \quad 2.7 \quad 3 \]

\[ U_\infty = 15 \text{ m/s} \]
\[ t^* = 0.01 \text{ s} \]
\[ f = 4.1 \text{ Hz} \]

Wind tunnel test under the same conditions
Dam break with flexible obstacle

- Incompressible free-surface flow computed with PFEM
- Large structural displacement
Conclusions

• Developed for research and design

• Interfacing tool for strong coupling of independent solvers

• High fidelity models for nonlinear FSI

• Flexible partitioned tool for large range of physics

• Validated on typical benchmarks
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