PROPOSAL OF RESEARCH ACTIVITY

A NOVEL NUMERICAL METHOD FOR FLUID-STRUCTURE INTERACTION PROBLEMS

Scuola di Dottorato in Scienze Tecnologie e Misure Spaziali (STMS)
Curriculum: Sciences and Technologies for Aeronautics and Satellite Applications (STASA)

Ciclo XIII
PhD Student: Federico Dalla Barba
Matricola: 1173676
Fluid-Structure Interaction (FSI) in aeronautics: aeroelastic flutter

- **Aeroelastic flutter of lifting surfaces**: dynamic, **self-sustained instability** that affects flexible aerodynamic surfaces invested by a free stream. It is caused by the **competition between fluid forces and the elastic forces** generated as a response of the deflection of the body. **Can lead to catastrophic failure.**
FSI problems in engineering and sciences

**FSI**: Interaction among a fluid flow and a rigid or deformable solid media.

- The interaction occurs through a **sharp solid-fluid interface**.
- The solid and fluid domains are governed by **different constitutive equations**.

**FSI problems are multidisciplinary, strongly non-linear problems.** To date, a satisfactory comprehension of FSI problems remains a challenge and the capabilities of existing numerical models for applications are still limited.

**Multidisciplinary applications:**

- **Aeroelastic flutter of lifting surfaces.**
- **Aeroelasticity of structural elements in civil engineering.**
- **Erosion of immersed bodies.**
- **Flows in porous media.**
- **Cells in physiological flows.**

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**FSI problems: state of the art**

Possible approaches to FSI problems:

- **Simplified models**
  - **Analytical solutions:**
    - Applicable to simple cases.
    - Limited capabilities of reproducing complex dynamics.
  - **Boundary Element Methods:**
    - Equations are not solved inside fluid domain.
    - Fluid stress and pressure are estimated on solid/fluid interface.
    - Limited capabilities of reproducing complex dynamics.

- **Complex models**
  - **Finite Element Method and CFD solver:**
    - Capabilities of reproducing complex dynamics.
    - High computational cost.
    - Parallelization problems due to non-locality.
    - Usually only mean flow is solved (RANS).

- **Experimental test**
  - Expensive.
  - Scale models are often necessary.

The most part of models and numerical approaches do not resolve turbulent structures in the fluid domain but only mean flow.

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TASK1 - Development of an innovative numerical tool for FSI problems:

- Incompressible Navier-Stokes equations solver equipped with turbulence closure model (Large Eddy Simulation). *Largest turbulent structures are resolved.*
- Peridynamics solver based on massively parallelized particle dynamics engine.
- **Immersed Boundary Method** (IBM) for coupling fluid/solid dynamics.
- **Massive parallelization** to optimize computational efficiency.
- Capabilities of working on computer clusters with **high scalability**.

TASK 2 - Validation of the code and numerical investigation of aeroelastic flutter:

- Validation tests.
- Numerical simulation of the aeroelastic flutter of a scale wing model.
Large Eddy Simulation (LES)

Usually FSI simulations solve only the mean flow (RANS).

**LES: largest turbulent structures** of the fluid flow are directly resolved on the computational fluid grid.

Turbulent structures are non-stationary and affect the dynamics of solid structures driving oscillations over a certain frequency range.

**PROS:**

- Largest turbulent structures are directly resolved.
- Affordable computational cost.

**CONTRAS:**

- Computational cost increases with the Reynolds number.
- The effect of smaller turbulent structures is accounted through turbulence closure models.
Peridynamics

The body is represented by a finite set of **particles interacting among each other through micro-potentials** that generate bond forces.

**Mutual interaction between particles extinguishes after a distance called horizon.**

The body displacements and deformation fields are described by local, integral equations.

**PROS:**

- “Easy-to-implement” and **high efficiency parallelization** due to locality of equations.
- **Crack detection** and **crack propagation** can be easily accounted by the peridynamics formulation: local micro-fracture occurs when the bond force exceeds a limit value.

**CONTRAS:**

- Peridynamics is a novel numerical technique. Few archival literature and know-how are available.
**Coupling: Immersed Boundary Method (IBM)**

**No-slip** and **no-penetration** boundary conditions for fluid flow are not directly imposed. BCs are converted into **equivalent forcing terms** in the right hand side of Navier-Stokes equations:

\[
\rho \left[ \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) \right] = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}
\]

- Fluid and solid grids do not have to conform to the interface.
- IBM force that accounts for the presence of the solid obstacle.

**PROS:**

- Simple, regular Eulerian grid for fluid domain discretization. \(\rightarrow\) Efficient solver.
- No re-meshing is needed for moving bodies. \(\rightarrow\) Low computational cost.

**CONTRAS:**

- Possible effects on accuracy, stability and conservation of properties.
Parallelization

Parallel codes: work on multiple cores or even multiple computers in order to reduce computational time.

The principle of parallelization consists of the domain decomposition: the simulation is performed by more processes each of them advance the solution in one single portion of the domain.

**Fluid domain parallelization**

- Subsets of grid nodes

**Solid domain parallelization**

- Subsets of peridynamic particles
Main advances introduced by the proposed method

- **PERIDYNAMIC APPROACH TO SOLID MECHANICS**
  - Locality of equation.
  - “Easy” to parallelize.
  - High scalability on large clusters.
  - Crack prediction and propagation.
  - Automatic tracking of fragments.
  - Eliminates the need for mesh update strongly reducing computational costs.
  - Simple grid → Efficient solver.
  - Resolve time-evolving largest turbulent structures in the fluid domain.
  - Accounts for the dynamic effects of turbulence on structures.

- **IMMERSED BOUNDARY METHOD**

- **NAVIER-STOKES LES SOLVER**
LES of a scale wing model fluttering

Large Eddy Simulation of a scale wing model:

- Up to $10^8$ points (fluid grid nodes and peridynamics particles).
- Reynolds number up to Re = 500000.
- Computational resources provided by CINECA.
- Analysis of the dataset to study aeroelastic flutter and test the numerical code capabilities.

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Final remarks

During the proposed research activity:

- A highly efficient numerical code able to reproduce general FSI problems working on high performance computer clusters will be developed.

- A novel numerical method for the description of FSI problem will be tested.

- The simulation of a scale wing model will be performed.

- The phenomenon of aeroelastic flutter will be investigated.

- A contribution to the know-how concerning the numerical reproduction of FSI problem will be given.
Thank you for your attention.
GANTT bar chart of the proposed research activity

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