Computational Aeroelasticity with CFD Models: Required Tools

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Outline

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Motivations and Targets

Why adopting CFD Models in Computational Aeroelasticity (CA)

- Enhance the modelling of the aerodynamics with non-linear effects
- Overcome the lacks provided by classic linear(ized) theories

Applications:

- Phenomena related to compressibility (Transonic Dip)
- Phenomena related to viscosity (separations, stall flutter, buffeting)
- Investigate Limit Cycle Oscillations (LCO)
- Consider interference effects (under-wing stores, innovative configurations, joined wings)

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Few considerations

- Apply Computational Aeroelasticity (CA) CFD in real life applications
  - Unsteady CFD is now a research succesfull research field
  - Computational costs precluded it so far from extensive industrial applications
  - Aircraft is designed by different dedicated departments
  - Large number of configuration needs to be assessed

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Times are mature to apply fast CA in real industrial applications

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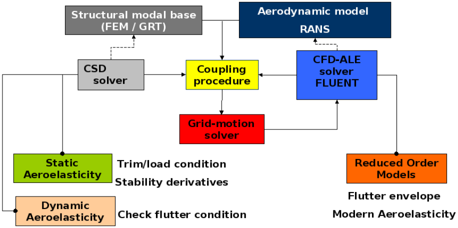

Features

- Partitioned Approach
- Plug-in for FLUENT© solver
- Modal structure
- Different discretizations
- Spatial coupling
- Grid motion solvers
- Static Aeroelasticity
- Reduced Order Models
- Dynamic Aeroelasticity

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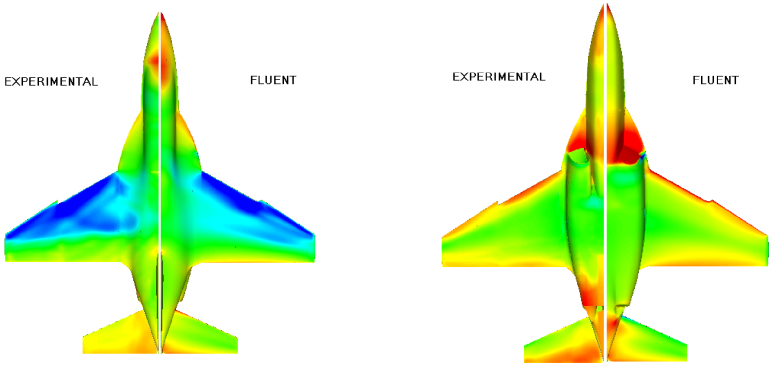
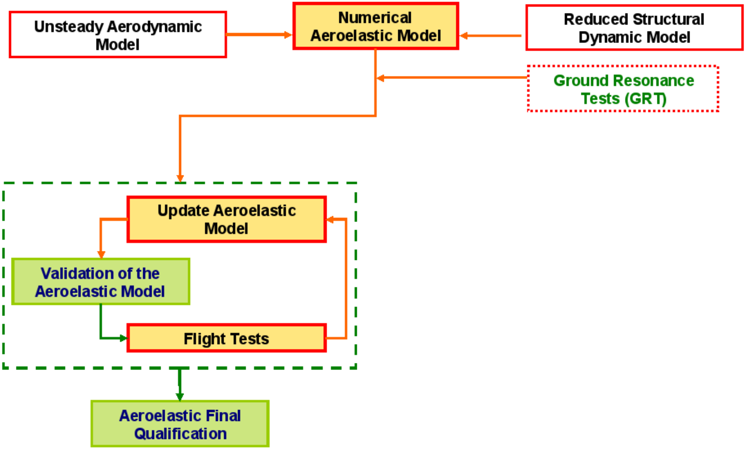


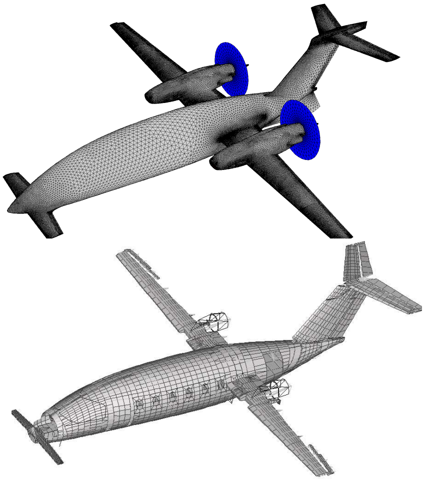
Aerodynamic model qualification

- RANS comparison to wind tunnel data
- Prediction of shock waves position


Unsteady Aerodynamic Model
Numerical Aeroelastic Model
Reduced Structural Dynamic Model
Ground Resonance Tests (GRT)
Update Aeroelastic Model
Validation of the Aeroelastic Model
Flight Tests
Aeroelastic Final Qualification

Outline

Partitioned analysis issues



Modelling differences

- Discretizations
- Refinement
- Topologies
- Element formulation

Constraints

- Interpolation
- Extrapolation
- Mesh independence
- Conservation
- Localization

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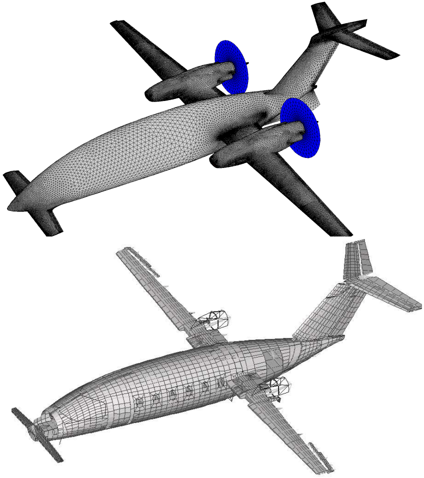

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Moving Least Square Technique (MLS): definition

Features

- Meshless approach
- Energy conservation
- Suitable for complex geometries and incompatible meshes
- Freedom to rule the quality/smoothness of the interpolation

Problem formulation

Reconstruction of a generic function $f \in C^d(\Omega)$, on a compact space $\Omega \subseteq \mathbb{R}^n$, from its values $f(\bar{x}_1), \ldots, f(\bar{x}_N)$ on scattered distinct centres $X = \{\bar{x}_1, \ldots, \bar{x}_N\}$

Note

It is not necessary to derive an analitical expression for f

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Moving Least Square Technique (MLS): conservation

Conservation issues

- Coupling conditions are enforced in a weak sense through a variational principle

Application of the Virtual Works Principle

Given two admissible virtual displacements $\delta \mathbf{y}_f$, $\delta \mathbf{y}_s$ for each field and matrix $\mathbf{H}$

$$\delta \mathbf{y}_f = \mathbf{H}\, \delta \mathbf{y}_s; \mathbf{F}_f = \mathbf{H}\, \mathbf{F}_s$$

then by equating the virtual works $\mathbf{W}_f, \mathbf{W}_s$:

$$\mathbf{W}_f = \delta \mathbf{y}_f^T \mathbf{F}_f = \delta \mathbf{y}_s^T \mathbf{H}^T \mathbf{F}_f = \delta \mathbf{y}_s^T \mathbf{F}_s$$

follows: $\mathbf{F}_s = \mathbf{H}^T\ \mathbf{F}_f$

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Moving Least Square Technique (MLS): approximation

Local approximation

f is usually expressed as sum of monomial basis functions $p_i(\mathbf{x})$

$$\hat{f}(\mathbf{x}) = \sum_{i=1}^{m} p_i(\mathbf{x}) a_i(\mathbf{x}) \equiv \mathbf{p}^T(\mathbf{x})\, \mathbf{a}(\mathbf{x}),$$

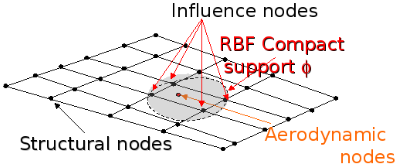
Interface matrix H construction

The coefficients $\mathbf{a}_i(\mathbf{x})$ are obtained by performing a weighted least square fit for the approximation $\hat{f}$

$$\text{Minimise } J(\mathbf{x}) = \int_\Omega \phi(\mathbf{x} - \bar{\mathbf{x}}) \left(\hat{f}(\mathbf{x}, \bar{\mathbf{x}}) - f(\bar{\mathbf{x}}) \right)^2 \, d\Omega(\bar{\mathbf{x}}),$$

with the constraint: $\hat{f}(\mathbf{x}, \bar{\mathbf{x}}) = \sum_{i=1}^{m} p_i(\bar{\mathbf{x}}) a_i(\mathbf{x})$

Moving Least Square Technique (MLS): localization



Problem localization

Function W can be chosen as a smooth non-negative compact suport Radial Basis Function

Wendland Radial Basis Functions (RBF)

Usually written as function of (r/δ), where δ is the suport size

Example:

- $W(r/\delta) = (1 - r/\delta)^2 \quad (C^0 \;\; Wendland \;\; Function)$

User control

The smoothness is ruled by changing the suport size δ and the number of source points through optimized searching algorithms

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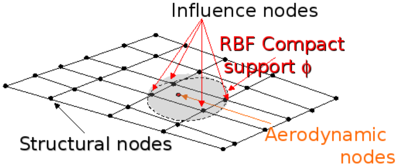

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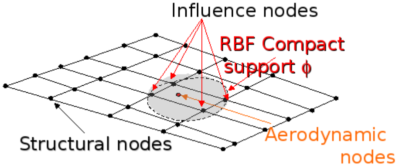

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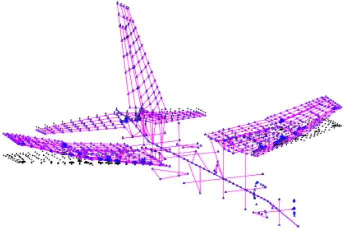
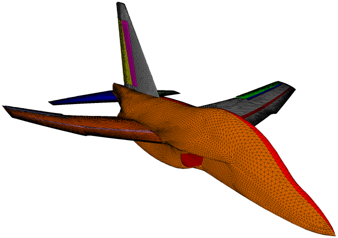
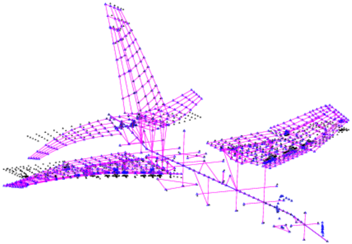
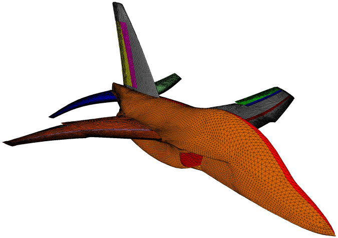

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Grid Motion: overview

Target

- Account for structural motion in a general way
- Avoiding complex methods like CHIMERA or re-meshing

Issues

- Troublesome (negative volumes, element distorsions)
- Time-consuming (several thousands of cells, parallelization)
- Correct management of sliding/fixed nodes

Note

- No physical accuracy is required to solve this problem
- Several methods are thus based on structural analogies

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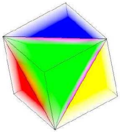
Grid Motion: continuum analogy method

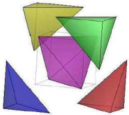
Features

- CFD mesh is translated into an FEM continuum model
- Moving boundaries nodes contribute to system rhs
- Sliding nodes along generally oriented planes easily accounted
- Avoid expensive torsional springs (no rotational dof required)
- Cell distorsions are automatically prevented
- Non-linearity can be introduced if stiffness matrix is updated

Assumption

- Every element can be split into basic tetrahedra
- No gaussian quadrature is required





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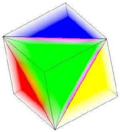

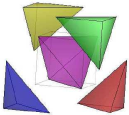

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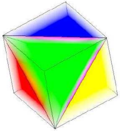

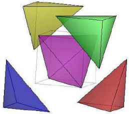

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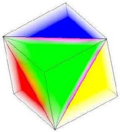

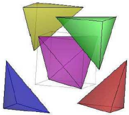

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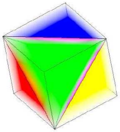

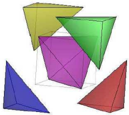

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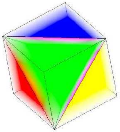

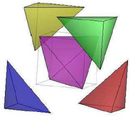

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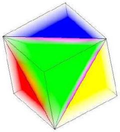
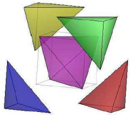




Grid Motion: continuum analogy method

Negative volumes preventing

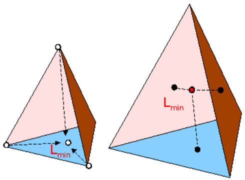
- Large cells far from moving faces are intentionally softened
- Each cell has a local *Young* modulus **E**:

$$E_{\mathrm{el}} = \frac{1}{\min\limits_{j,k \in \mathrm{el}} \|x_j - x_k\|^{\beta}} \quad , \quad \nu \in [0.3 : 0.45]$$

- Additional stiffness introduced according to wall distance

Characteristic length choice

A well chosen length further prevents cell-collapsing



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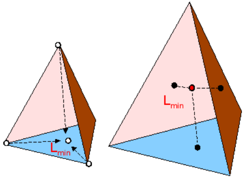


Grid Motion: solution method

Solver

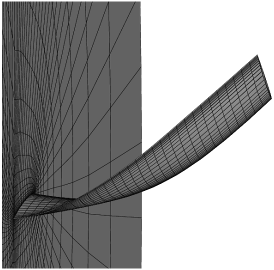
- Simple *smoothers* adopted (Jacobi, SOR)
- High frequency error is rapidly lowered
- Easy parallelization (good scalability)
- Each node deforms its CFD partitions
- Interface data exchanged

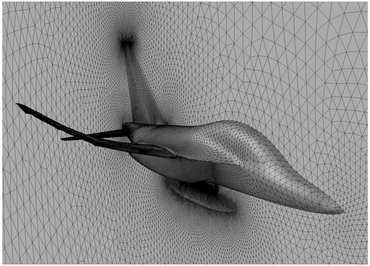
Negative volumes preventing

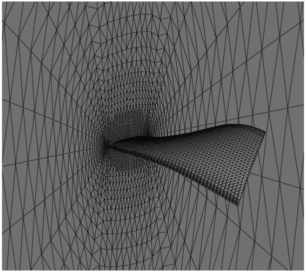
Displacement field can be subdivided into multiple tasks and stiffness updated

Grid Motion: results

Different results on structured and unstructured mixed grids







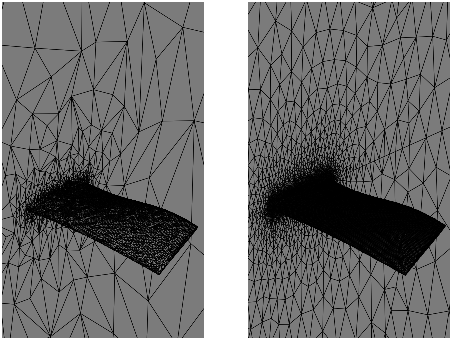
Grid Motion: further methods

Simplified strategies

- Store perturbation grids
- Thermal solver (three 1D runs)

Multigrid method

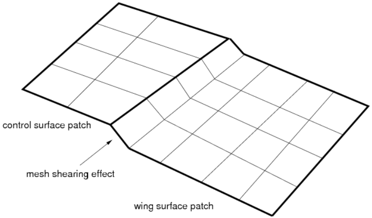
- A valid coarse grid is created
- Coarse deformation
- MLS interpolation for discarded nodes

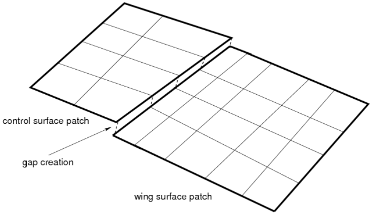


Grid Motion: control surfaces

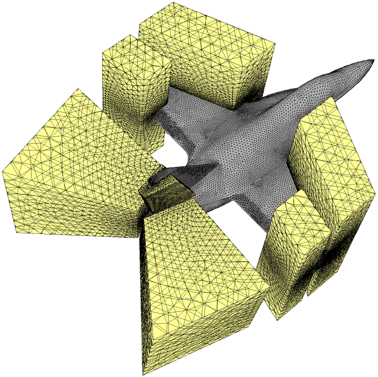
Issues

- Control surfaces rotations locally lead to large displacements
- Gaps are created when a surface is deflected
- Gap meshing is not trivial and raise cell number
- Mesh shearing easiliy leads to ill-conditioned cells





Grid Motion: control surfaces deflection strategy



Adopted method

- Non-conformal mesh
- Sliding interfaces
- Fluxes calculation on intersecting faces
- Moving or fixed boxes

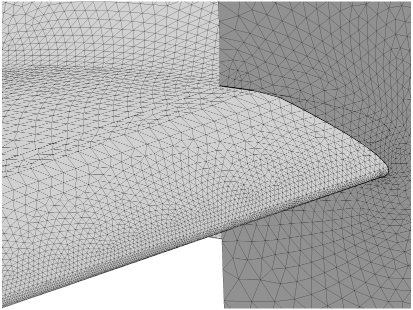
Note

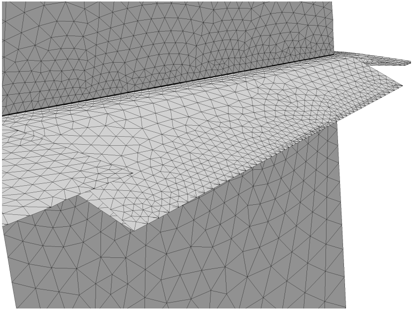
Each box independently meshed and substituted if local refinement required

Grid Motion: control surfaces deflection strategy

Gap modelling

If one of the interface zones extends beyond the other, additional wall zones for the portion(s) of the non-overlapping boundary are created





Grid Motion: control surfaces deflection strategy

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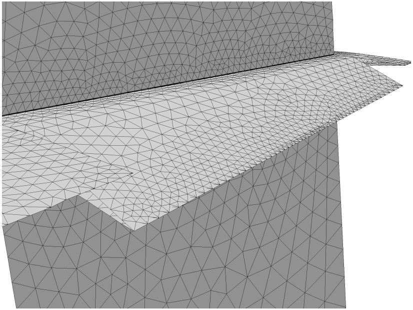
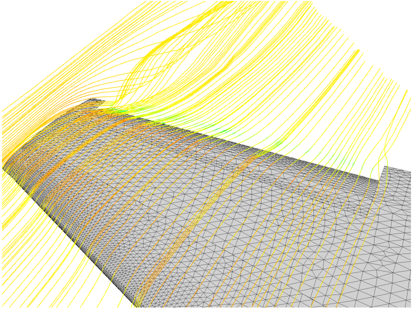
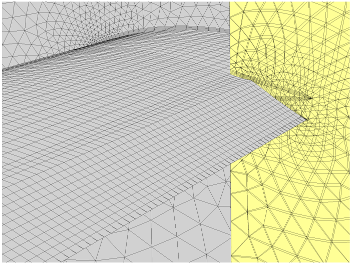
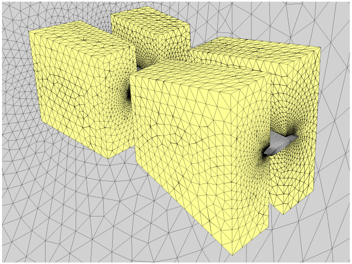
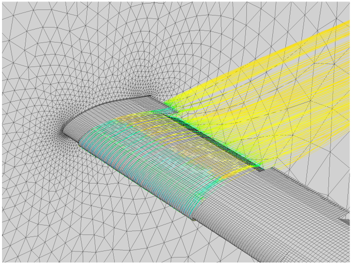




Grid Motion: control application







Outline

Conclusion and future developments

Conclusion

- Spatial coupling needs to be general for whatever model
- Conservation issues must be guaranteed
- Control on coupling smoothness and localization
- On line mesh deformation may be important
- Transpiration boundary condition can be exploited
- Control task is not trivial and requires dedicated techniques

Future developments

- Maneuvering deformable aircraft in transonic regime
- Coupling to Multibody dynamic solver MBDyn (`www.aero.polimi.it/~mbdyn`)

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References

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