Towards a Comprehensive Environment for Aeroservoelastic analysis in Edge flow solver

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November 15, 2007
FOI Swedish Defence Agency, Kista - Stockholm

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 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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Creation of Reduced Order Models (ROM)

Motivations:

- Where can we find flutter instabilities?
- How to study Aeroservoelasticity?

- Create a ROM for discrete reduced freq. jk and Mach M_∞
- Aerodynamic Generalized Forces (GAF) are represented by a transfer matrix: $\mathbf{H}_{am}(jk, M_\infty)$
- Classic aeroelastic system equation:

$$\left(\mathbf{M}\,s^2 + \mathbf{K} - \frac{1}{2}\rho V^2 \mathbf{H}_{am}(p, M_\infty)\right) q = F_{ext} \qquad (1)$$

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Creation of Reduced Order Models (ROM)

Creation of ROM using a CFD code

- A perturbation is given to the system using one modal shape with assigned time-law $q_i(\tau)$
- GAF are postprocessed and contribute to one column of $\mathbf{H}_{am}(jk, M_\infty)_i$
- A numerical linearization process is carried out (to be verified)

Used time-law: blended step

$$q_i(\tau) = \begin{cases} \frac{q_{i\,\infty}}{2}(1 - \cos\Omega_0\tau) & 0 \leq \tau < \tau_{\max}, \\ q_{i\,\infty} & \tau \geq \tau_{\max} \end{cases} \quad (2)$$

with $\tau = \frac{tV_\infty}{L_a}$, $\tau_{max} = \frac{2\pi}{k_{max}}$, $\Omega_0 = \frac{\pi}{\tau_{max}}$

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Creation of Reduced Order Models (ROM)

Creation of ROM using a CFD code

- A FFT of GAF gives the required column for different values of jk:

$$\mathbf{H}_{\mathrm{am}}(jk, M_\infty)_i = \frac{\mathcal{F}\left(\mathbf{f}_a(\tau, M_\infty)_i\right)}{\mathcal{F}\left(q(\tau, M_\infty)_i\right)}. \tag{3}$$

Considerations:

- Fast flutter tracking using classic *p-k* method
- The aerodynamic ROM can be identified into a state space model (Modern Aeroelasticity)
- Servos transfer matrices can be linked to the aeroelastic system
- The starting condition is non-linear and should represent the equilibrium condition to be perturbed

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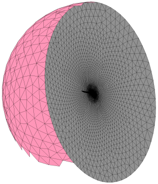
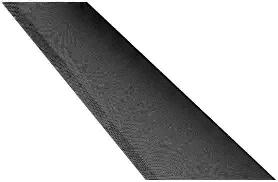
AGARD 445.6 wing: aeroelastic flutter benchmark



Computational domain



Surface mesh

Structural model:

- Structural modal model from GVT
- First 4 vibration modes used ($9 \rightarrow 91 Hz$)
- Tested for different Mach numbers in WT

Aerodynamic model:

- Euler equations
- 227.278 volume points
- 86.371 points on wing boundary

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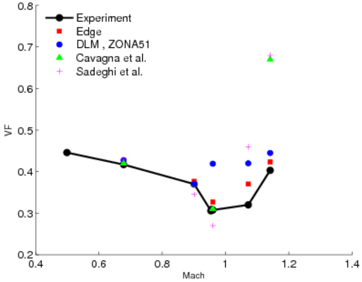
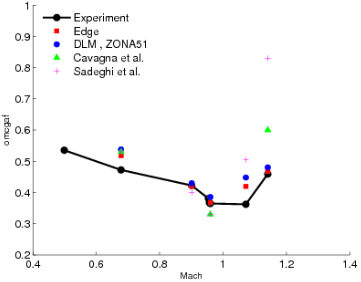


Flutter Speed Index



Flutter Frequency Index

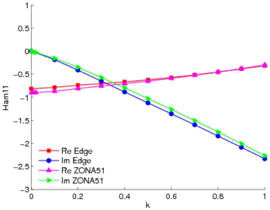
Considerations:

- Very good results using Edge flow solver
- Inviscid model is enough for this simple case

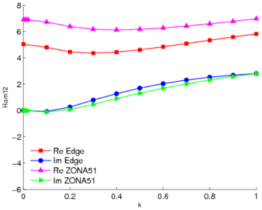
AGARD 445.6 wing: aeroelastic flutter benchmark

Transfer matrix coefficients, $M_\infty = 1.141$

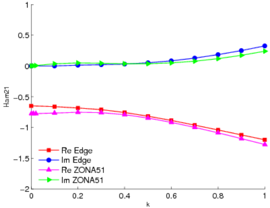
$H_{am}11$



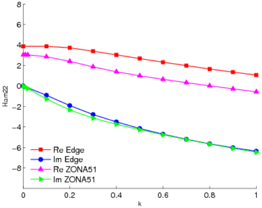
$H_{am}12$



$H_{am}21$

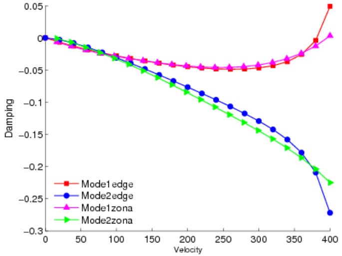


$H_{am}22$

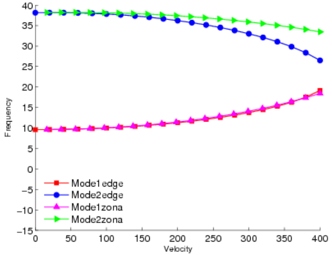


AGARD 445.6 wing: aeroelastic flutter benchmark

Flutter diagrams, $M_\infty = 1.141$



Velocity-damping diagram



Velocity-frequency diagram

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Transpiration method

Advantages:

Simulate domain changes without updating the domain

Applications:

- Classic panel methods to modify thickness by sources
- Boundary layer patching with inviscid models
- Multi Disciplinar Optimization
- Aeroservoelasticity

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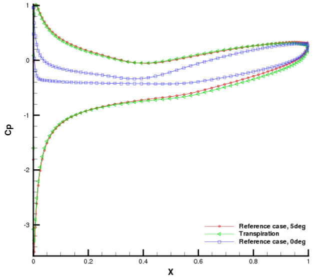
Method principle:

Air suction/blowing through the wall to modify local flow direction

Considerations:

- Many FSI problems depend mostly on mean-flow
- Structural motion represents a small perturbation
- Grid deformation techniques are time-consuming
- Control surfaces deflection is not a trivial task



RAE airfoil, $M_\infty = 0.3$, $\alpha = 5deg$

Transpiration method

Geometric contribution

- Structural deformation/rigid body motion change boundary orientation n_u
- When inviscid flow used the condition on the deformed boundary n_d now reads:

$$V = V - (V \cdot n_d)\, n_d \tag{4}$$

- The flow has a normal component contributing to wall boundary fluxes along n_u now
- The term n_d is always calculated exactly
- Structural displacements cannot be accounted for
- Only normal deflections can be considered

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Transpiration method

Cinematic contribution

- Structural velocity V_B contributes to wall velocity along n_d:

$$V_N = (V_B \cdot n_d) \tag{5}$$

- If a structural model is used, superimposition can be exploited:

$$V_B = \sum_{i=1}^{N} U_i \, \dot{q}_i \,, \; U_i = modal\,shape, \dot{q}_i = modal\,vel. \tag{6}$$

Global boundary condition:

- Thus the transpiration wall boundary condition reads:

$$V = V - (V \cdot n_d - V_B \cdot n_d)\, n_d \quad (also\ on\ MultiGrid) \tag{7}$$

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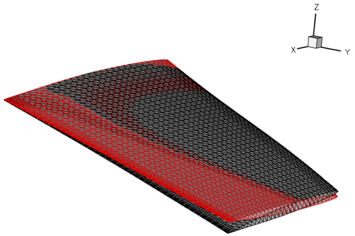
Transpiration method: steady results

Test definition

- AGARD 445.6 deformed along the 1^{st} torsional mode
- Tip twist rotation of 4.5 *deg*
- All the sections are interested to structural deflection

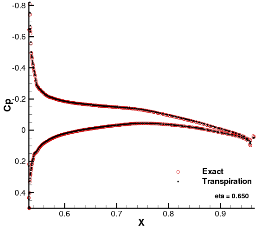
Test presented

- Mach numbers: 0.678, 0.960, 1.141
- *Cp* chordwise compared to deformed grid results
- 4 different stations considered: $\eta = 0.650$, 0.787, 0.853, 0.918



Steady results: $M_\infty = 0.678$

$\eta = 0.650$



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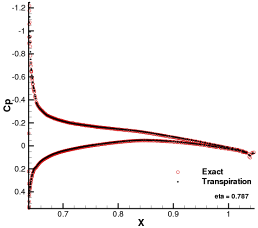
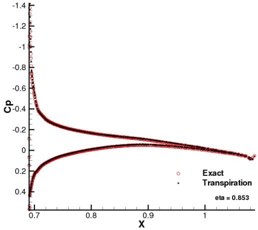
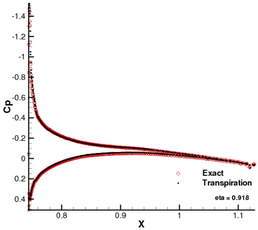


$\eta = 0.853$



$\eta = 0.918$



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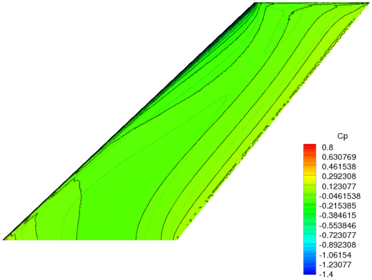
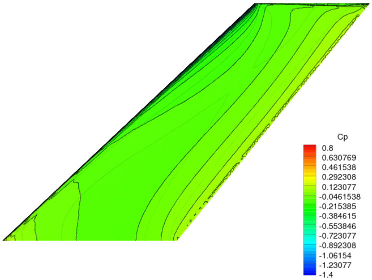


Exact



Transpiration

Steady results: $M_\infty = 0.960$

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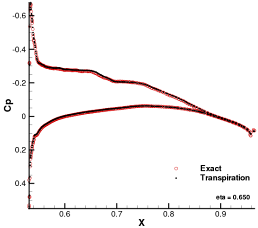

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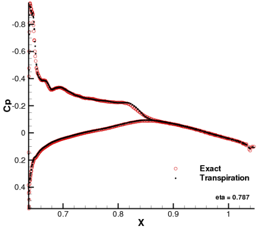

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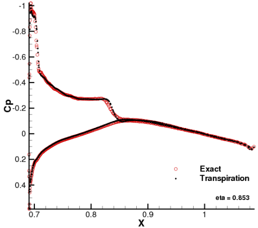

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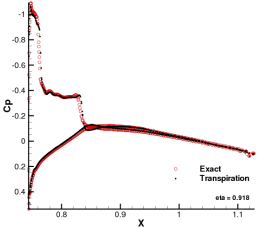

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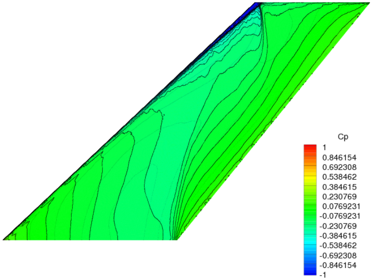

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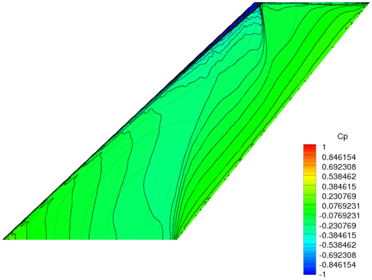

Transpiration

Steady results: $M_\infty = 1.141$

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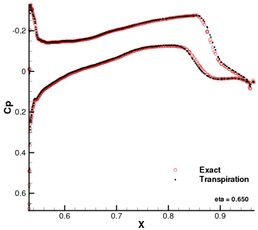

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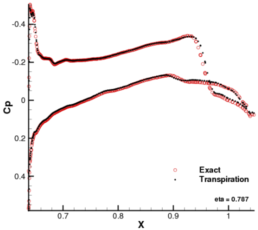

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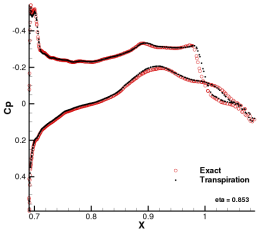

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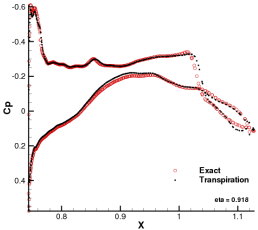
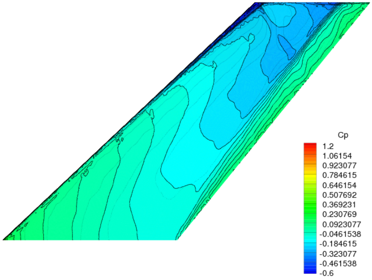
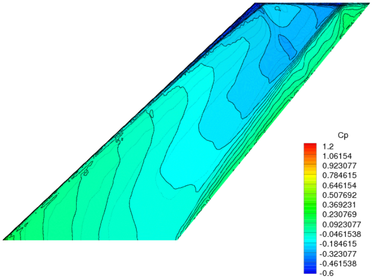


Steady results: $M_\infty = 1.141$



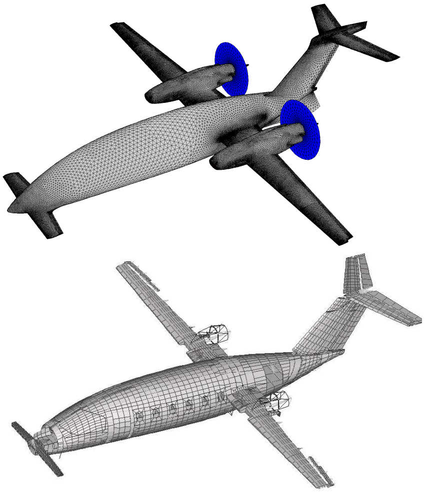
Exact



Transpiration

Outline

Partitioned analysis issues



Modelling differences

- Discretizations
- Refinement
- Topologies
- Element formulation

Constraints

- Interpolation
- Extrapolation
- Mesh independence
- Conservation
- Localization

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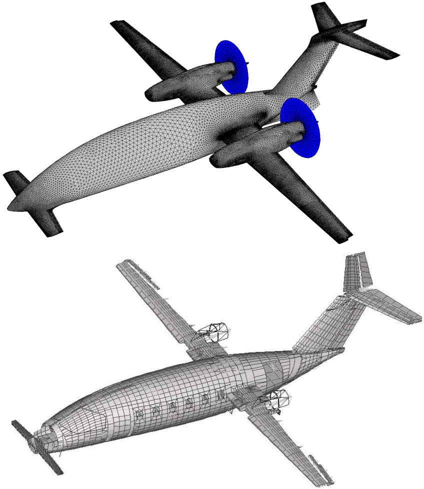

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Moving Least Squares Technique (MLS): definition

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 $f(\bar{\mathrm{x}}_1), \ldots, f(\bar{\mathrm{x}}_N)$ on scattered distinct centres $X = \{\bar{\mathrm{x}}_1, \ldots, \bar{\mathrm{x}}_N\}$

Note

It is not necessary to derive an analitical expression for f

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Moving Least Squares 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 $\mathbf{W}_f, \mathbf{W}_s$:

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

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Moving Least Squares Technique (MLS): approximation

Local approximation

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

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

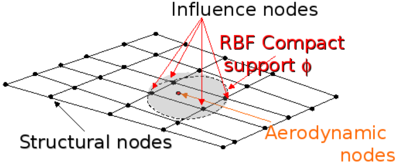
Interface matrix $\mathbf{H}$ construction

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 Squares Technique (MLS): localization



Problem localization

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

Wendland Radial Basis Functions (RBF)

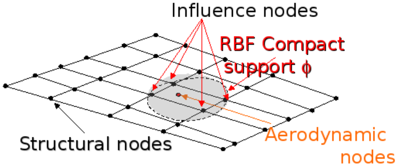
Usually written as function of (r/δ), where δ is the suport size
Example:

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

User control

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

Moving Least Squares Technique (MLS): localization



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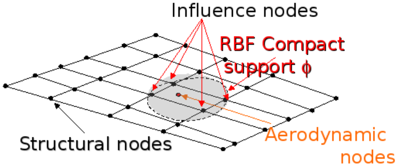

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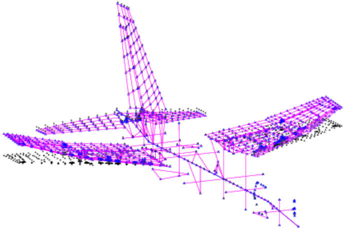
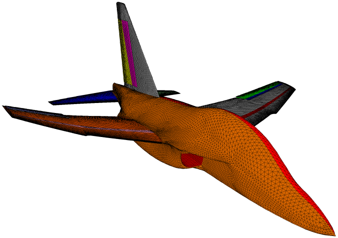
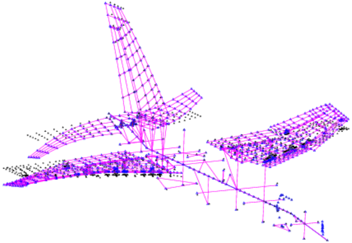
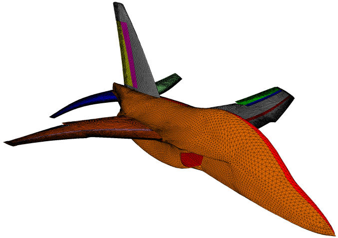
Moving Least Squares Technique (MLS): results









Target:

- Couple Edge and MBDyn (`www.aero.polimi.it/~mbdyn`)
- Investigate free-flying deformable maneuvering aircraft

First required tools:

- General spatial coupling (available soon)
- Transpiration boundary condition (available)
- Moving reference frame (already available)

Multibody features:

- Rigid body dynamics considered and large rotations
- Structural modelled with non-linear or modal elements
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Outline

Conclusion and future developments

Conclusions

- ROM are very useful for fast flutter tracking
- Euler equation represent a good compromise between accuracy and costs
- Transpiration boundary condition can be exploited in many cases
- Spatial coupling needs to be general for whatever model
- Conservation issues to be guaranteed
- Control on coupling smoothness and localization to be guaranteed

Acknowledgments

- Jonathan Smith, FOI
- Peter Eliasson, FOI

References

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November 15, 2007

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