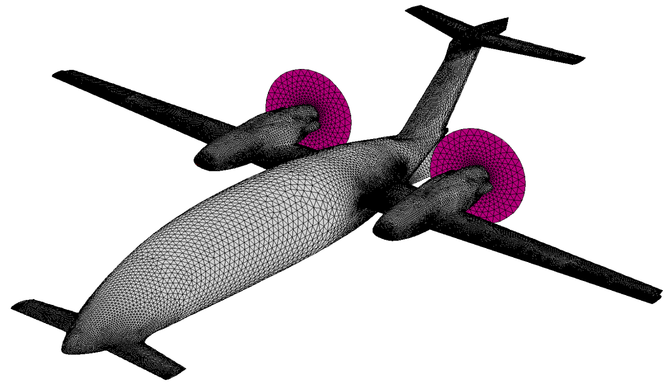
CFD Based Reduced Order Models for T-tail flutter



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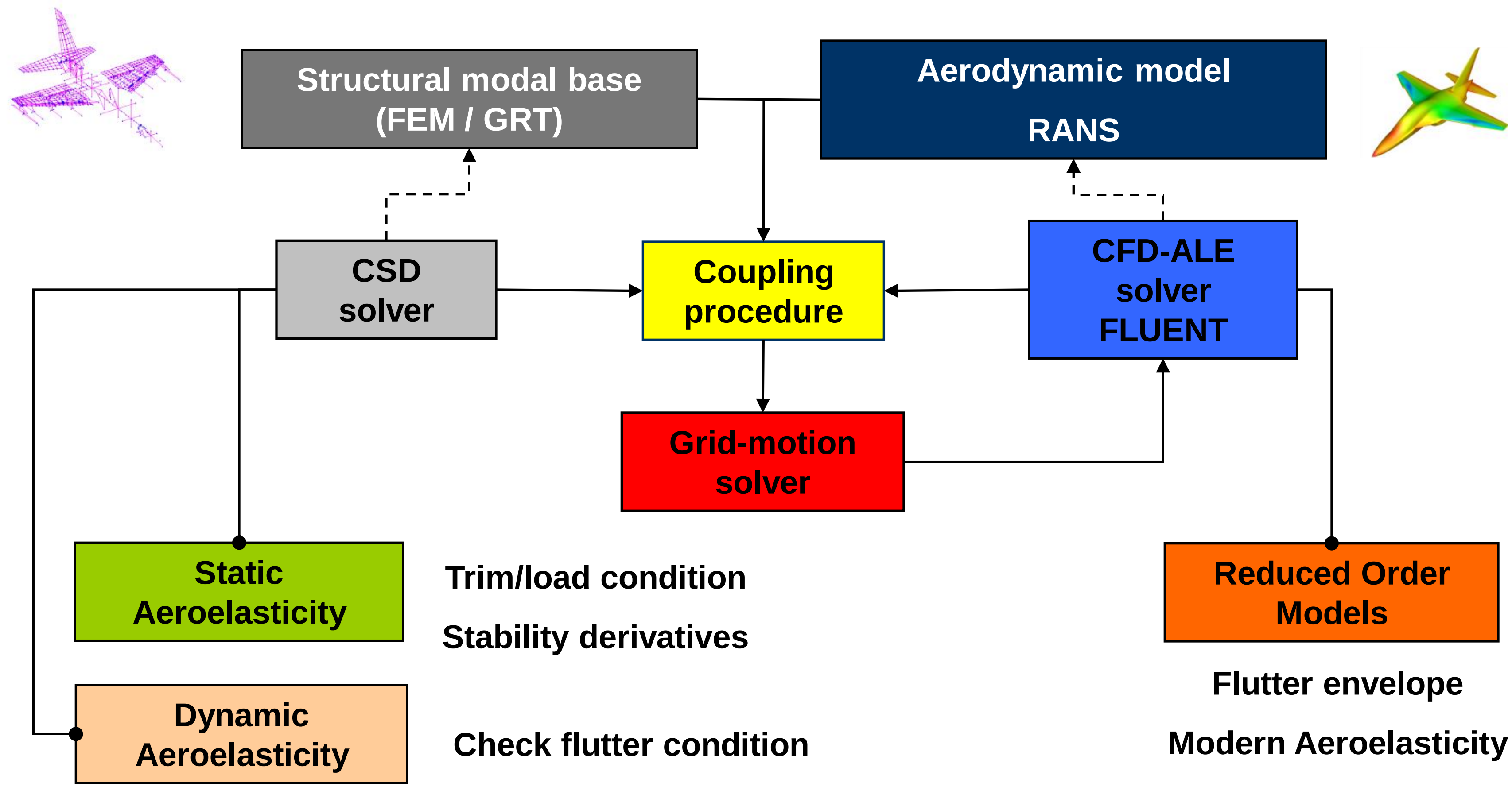
Bifurcation and Model reduction Techniques for Large Multidisciplinary Systems - University of Liverpool
June 26-27, 2008. Liverpool, UK.

Outline

- NAEMO-CFD software
- Test bench: Piaggio Avanti P180
- T-Tail flutter problem
- Spatial coupling algorithm
- Structural model
- Aerodynamic models
- Grid deformations issues
- Control surfaces management
- Trim condition
- Linearized flutter results
- Non-linear coupled simulations
- Conclusions and future developments

NAEMO-CFD Numerical AeroElastic MOdeller based on *CFD*

- Target: aeroservoelastic analysis of aircrafts by means of *RANS* models
- *Plug-in* for the commercial *CFD* solver ***FLUENT*** ®

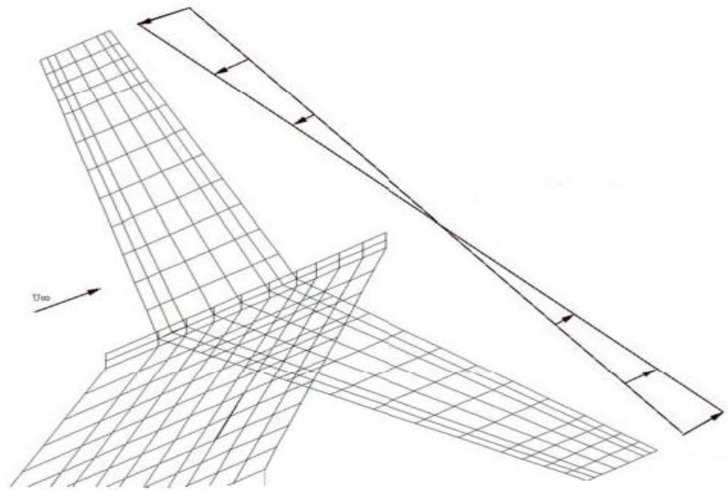


Piaggio P180 aircraft

- Unconventional 3 lifting surfaces, pushing turboprops
- Maximum cruise Mach number: 0.7
- Transonic conditions on the main wing
- Normatives prescribe instabilities assessment up to 1.2 V_D
- Transonic instabilities must be assessed
- T-Tail flutter is the main aeroelastic instability in this case

T-Tail flutter problem

- Fin bending and torsional modes influence HT motion
- Classic small-disturbance theories do not take into account:
  - Static loads effects
  - Inplane contributions



- These effects can lead to flutter speed over estimations
- Classic theories can thus be enhanced with corrections
- CFD methods directly include all these contributions

Spatial coupling

- Need to couple whatever structural/aerodynamic combination
- Meshless approach based on *Weighted Moving Least Squares with RBF functions*

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

$$\mathbf{p}^T(\mathbf{x}) = (1, x, y, z, x^2, xy, y^2, yz, z^2, zx)^T$$

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

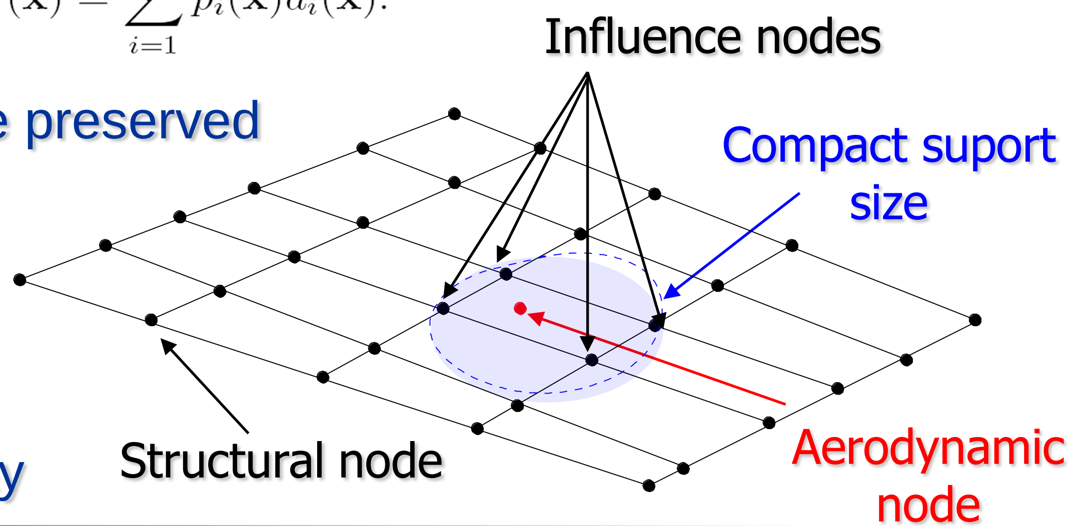
under the linear constraint

$$\hat{f}(\mathbf{x}) = \sum_{i=1}^{m} p_i(\bar{\mathbf{x}}) a_i(\mathbf{x}).$$

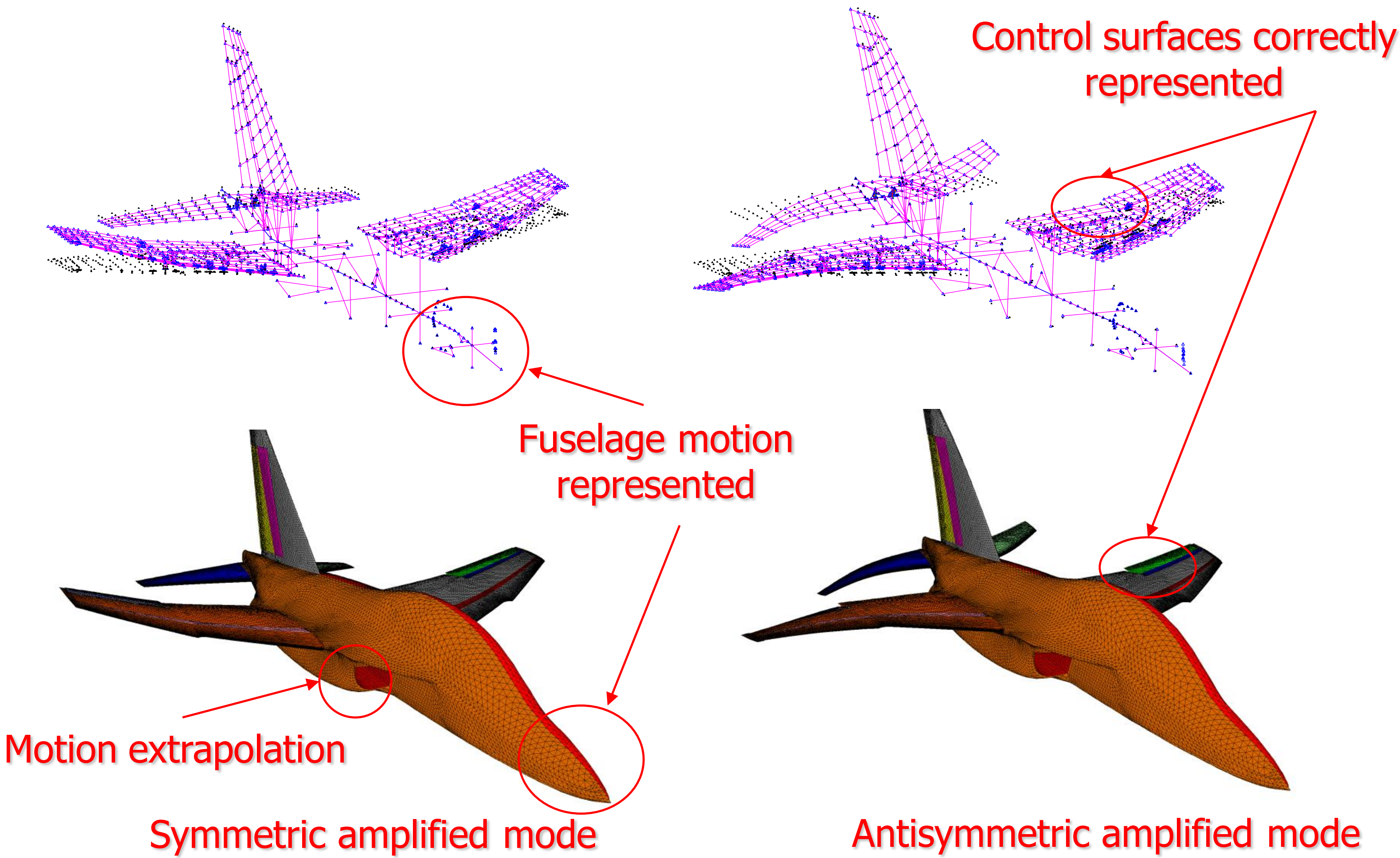
- Energy conservation must be preserved

$$\mathbf{y}_f = \mathbf{H}\,\mathbf{y}_s \qquad \Longrightarrow \qquad \mathbf{F}_s = \mathbf{H}^T\,\mathbf{F}_f$$

- Control of interpolation quality

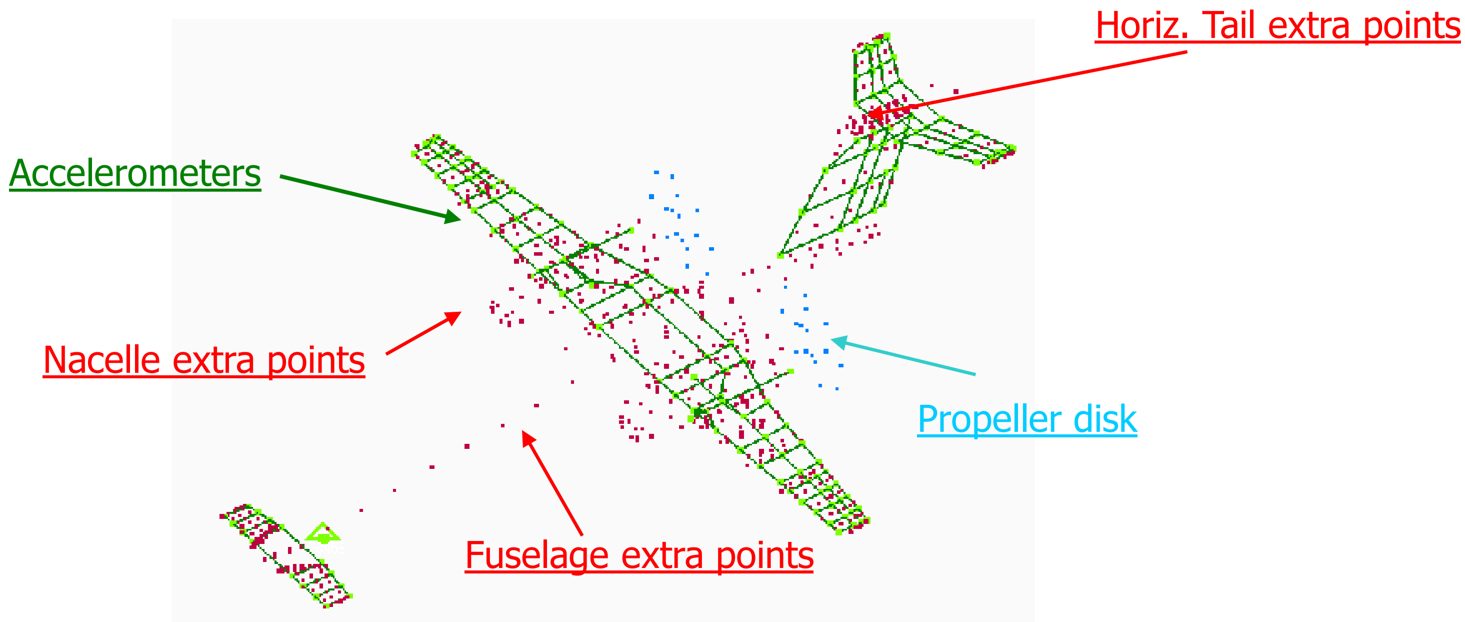


Spatial coupling



Piaggio P180 structural model (I)

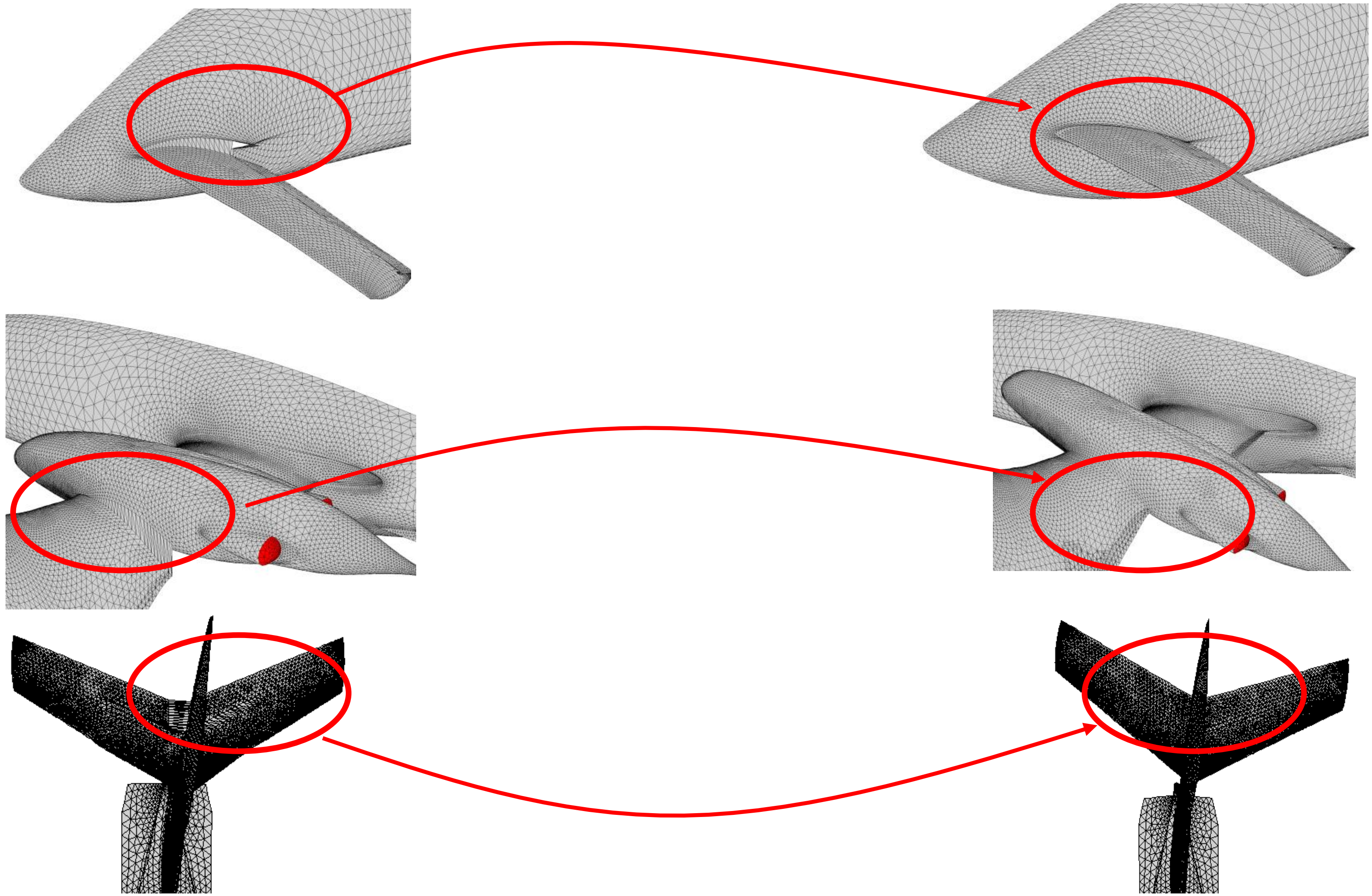
- Ground Resonance Tests (GRT) data by ONERA available
- Modal shapes, frequencies, masses and dampings
- Few accelerometers measured displacements normal to aero surfaces
- A fictitious FEM model is built to replicate GRT data



- Points added to improve spatial coupling with CFD aerodynamics and reconstruct a compatible displacement field

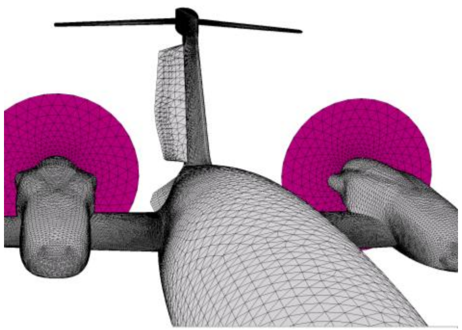
Piaggio P180 structural model (II)

- Compatibility preserved among lifting surfaces

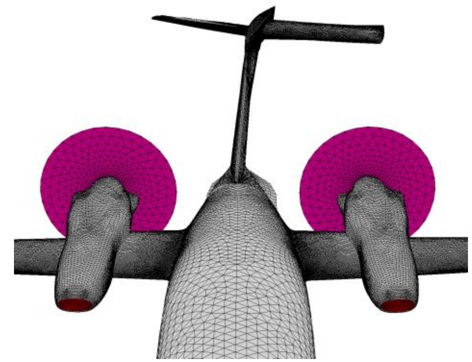


Piaggio P180 structural model (III)

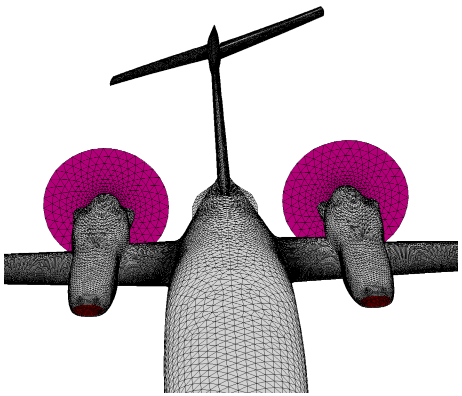
- Modes selected after preliminary DLM analyses



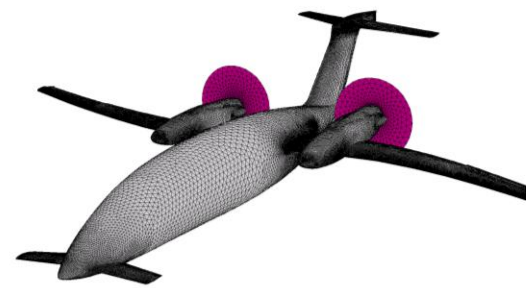
Mode #7
Rigid rudder rotation - 1.73 Hz



Mode #12
Fin bending - 6 Hz

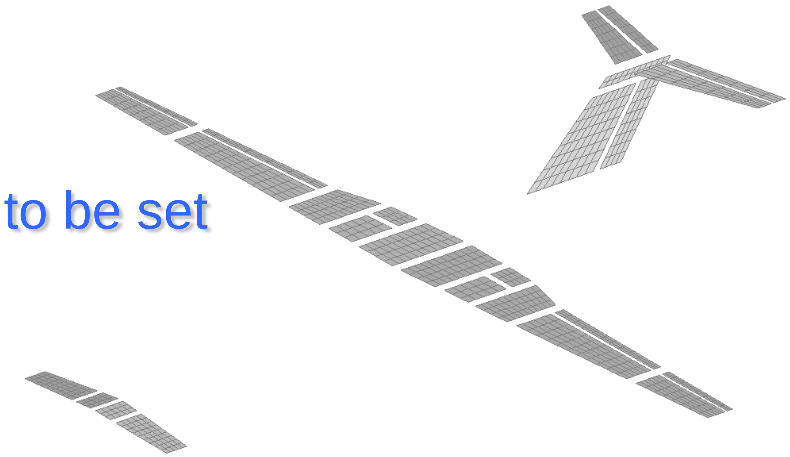


Mode #14
Hor. Tail roll - 6.19 Hz

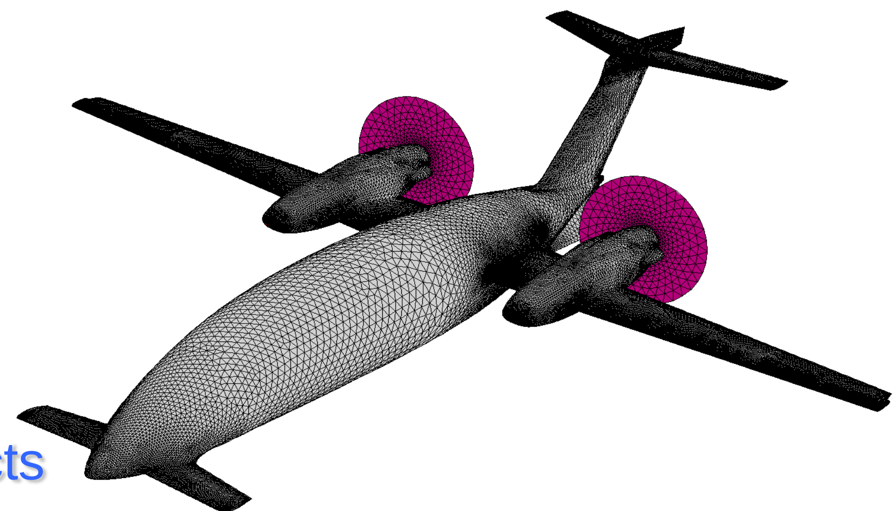


Mode #15
Anti-simmetric engine pitch - 7.31 Hz

Piaggio P180 aerodynamic models

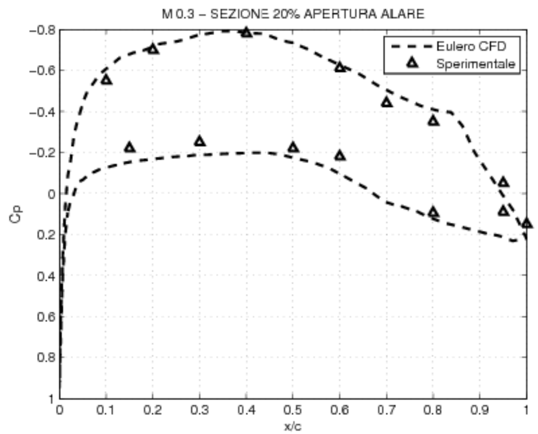


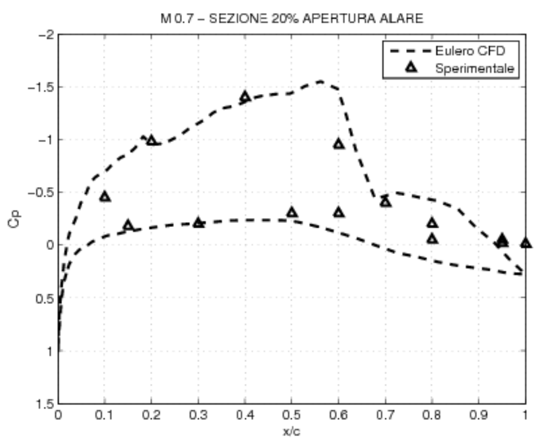
- Classic Doublet Lattice Method (DLM)
  - Very efficient for subsonic regimes
  - Low computational costs and easy to be set



- CFD model (RANS/Euler)
  - High fidelity geometry
  - Interference phenomena
  - Compressibility and viscous effects
  - High computational costs to run and be set

Piaggio P180 CFD model





- Good pressure distribution
- Good agreement in shock wave position on the main wing
- Good agreement in global coefficients

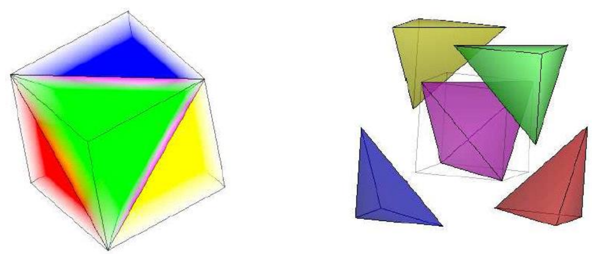
	M_∞	$C_L(\alpha=0°)$	$C_L(\alpha=3°)$	$C_{L/\alpha}$
Wind tunnel	0.3	0.16	0.48	6.112
CFD	0.3	0.156	0.46	5.81
Wind tunnel	0.7	0.197	0.578	7.277
CFD	0.7	0.199	0.56	6.89

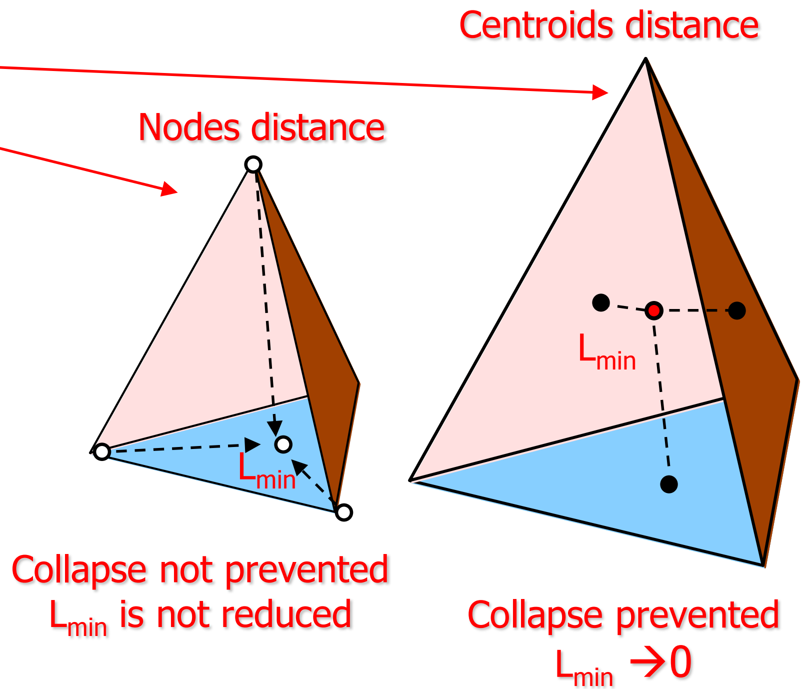
Grid deformation

- Troublesome and time-consuming task (negative cells, millions of cells)
- A robust and efficient method is thus required
- A continuum analogy is exploited
- Each element has a local stiffness given by

$$E_{\mathrm{el}} = \frac{1}{\min\limits_{j,k \in \mathrm{el}} \left\| \mathbf{x}_j - \mathbf{x}_k \right\|^{\beta}} \qquad \nu \in [0; 0.35]$$

- No torsional spring required
- All kinds of element can be used
- Every cell is splitted to tetrahedras
- No Gaussian quadrature required

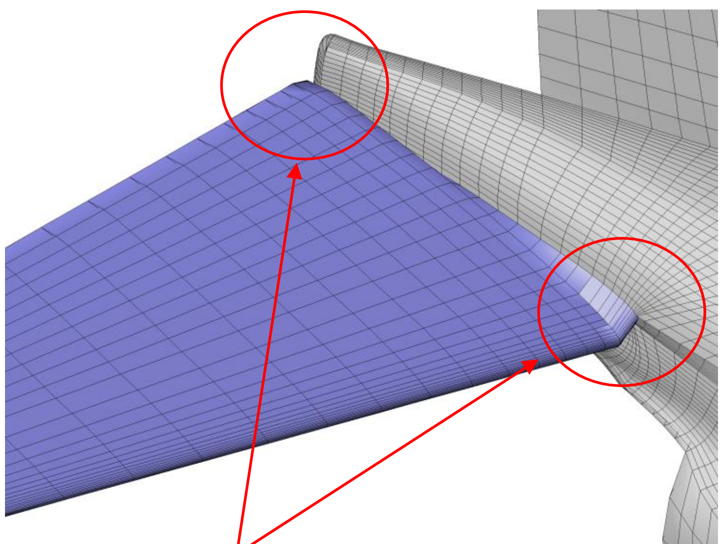




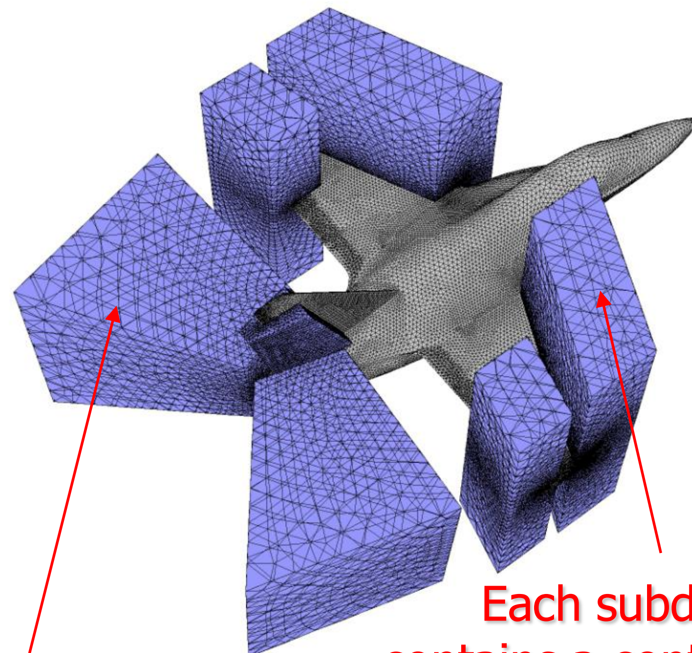
Control surface deflection

- Relatively high rigid rotations may be required for steady trim solution
- Non-trivial task for *CFD* computations
- *Mesh shearing* phenomena lead to ill-conditioned or collapsed cells
- Computational-demanding methods may be applied (overset, remeshing)

- *Non-conformal* mesh technique adopted



Highly distorted cells due to mesh-shearing



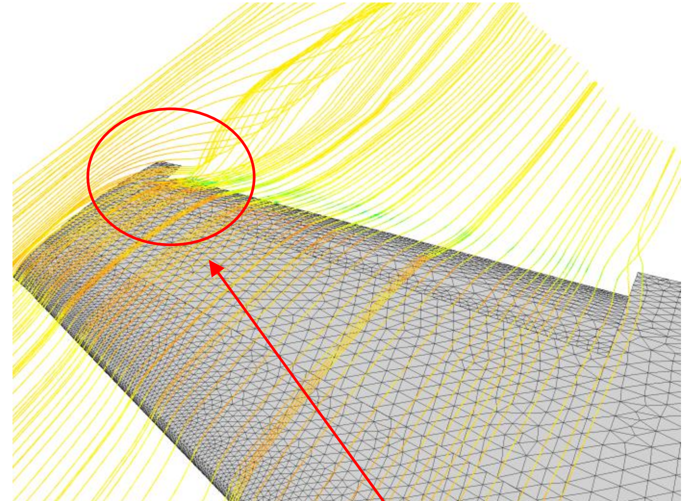
Non-matching sliding surfaces

Each subdomain contains a control surface

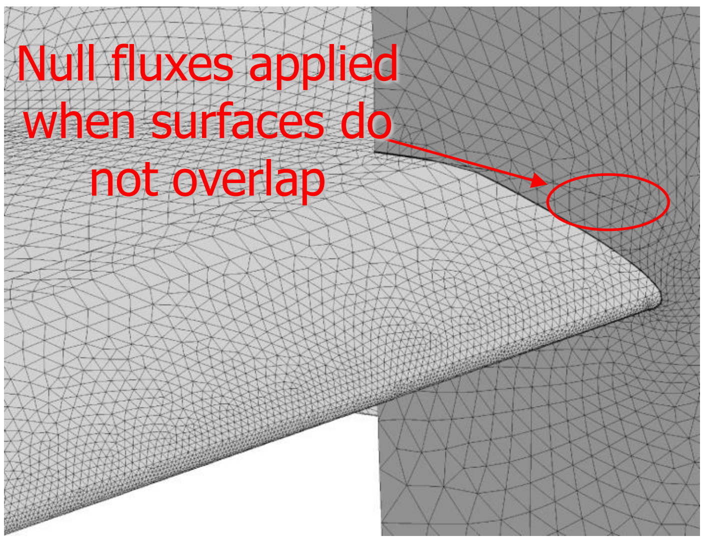
Control surface deflection

- Each sub-domain generated independently (low/high detail level) and then independently internally deformed

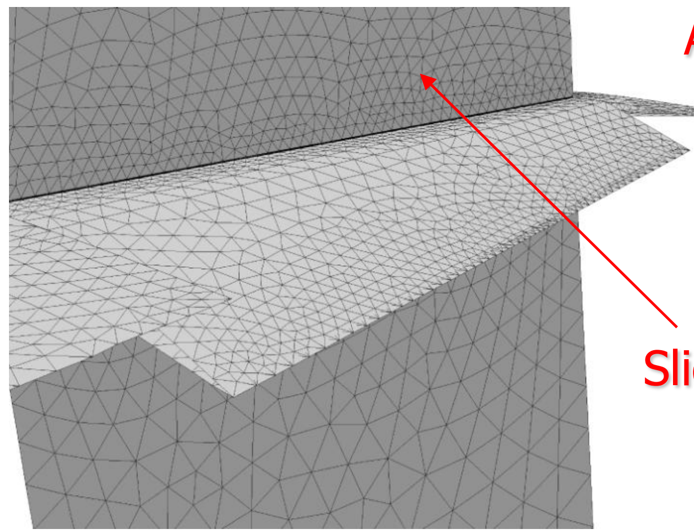
- To better account for structural deformability, each sub-domain can rigidly move inside the master block



Aileron trailing edge vorticies



Nose-droop deflection of 20 deg



Sliding nodes

Aileron deflection of 20 deg

Trim condition for the free-flying aircraft

- A simple task if both structural and aerodynamic models are linear
- With the adoption of *CFD* the aeroelastic system is non-linear
- Flight mechanics and structural equations need to be satisfied

$$\mathcal{F}(\mathcal{P}_F, \mathcal{P}_M) = \begin{cases} \mathcal{F}_R(\mathcal{P}_F, \mathcal{P}_M) \\ \mathcal{F}_E(\mathcal{P}_F, \mathcal{P}_M) \end{cases} = 0.$$

$$\begin{bmatrix} \mathbf{M} & -\mathbf{S} \\ -\mathbf{S}^T & \mathbf{I} \end{bmatrix} \begin{Bmatrix} \mathbf{n}g \\ \dot{\omega} \end{Bmatrix} = q\mathbf{f}_a^R(\mathcal{P}_F, \mathcal{P}_{M_R}, \mathcal{P}_{M_E})$$

Fixed parameters — Configuration parameters

- The non-linear system of equations becomes

$$\mathcal{F}(\underbrace{\rho_\infty, M_\infty, Re_\infty}_{\mathcal{P}_F}, \underbrace{\alpha, \beta, n_x, n_y, n_z, \dot{p}, \dot{q}, \dot{r}, p, q, r, \delta, \mathcal{T}, \mathbf{q}}_{\mathcal{P}_M}) = 0$$

Free-stream conditions always fixed by the user — Flight mechanics and structural parameters

- The configuration parameters exceed the number of equations
- Some of them are fixed a-priori in order to define a specific maneuver
- The remaining parameters are now determined through system solution

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Trim condition for the free-flying aircraft

- Classic Newton method can be adopted
- The Jacobian matrix can come from experiments or numerical tests
- Numerical tests can be very time-consuming
- With the hypothesis of small deformations a staggered solution is adopted

$$\mathbf{J}(\mathcal{P}_M^k)\delta\mathcal{P}_M^k = -\mathcal{F}^C(\mathcal{P}_M^k), \qquad \mathcal{P}_M^{k+1} = \delta\mathcal{P}_M^k + \mathcal{P}_M^k, \qquad k = 0, 1, ..$$

Reduced Jacobian size

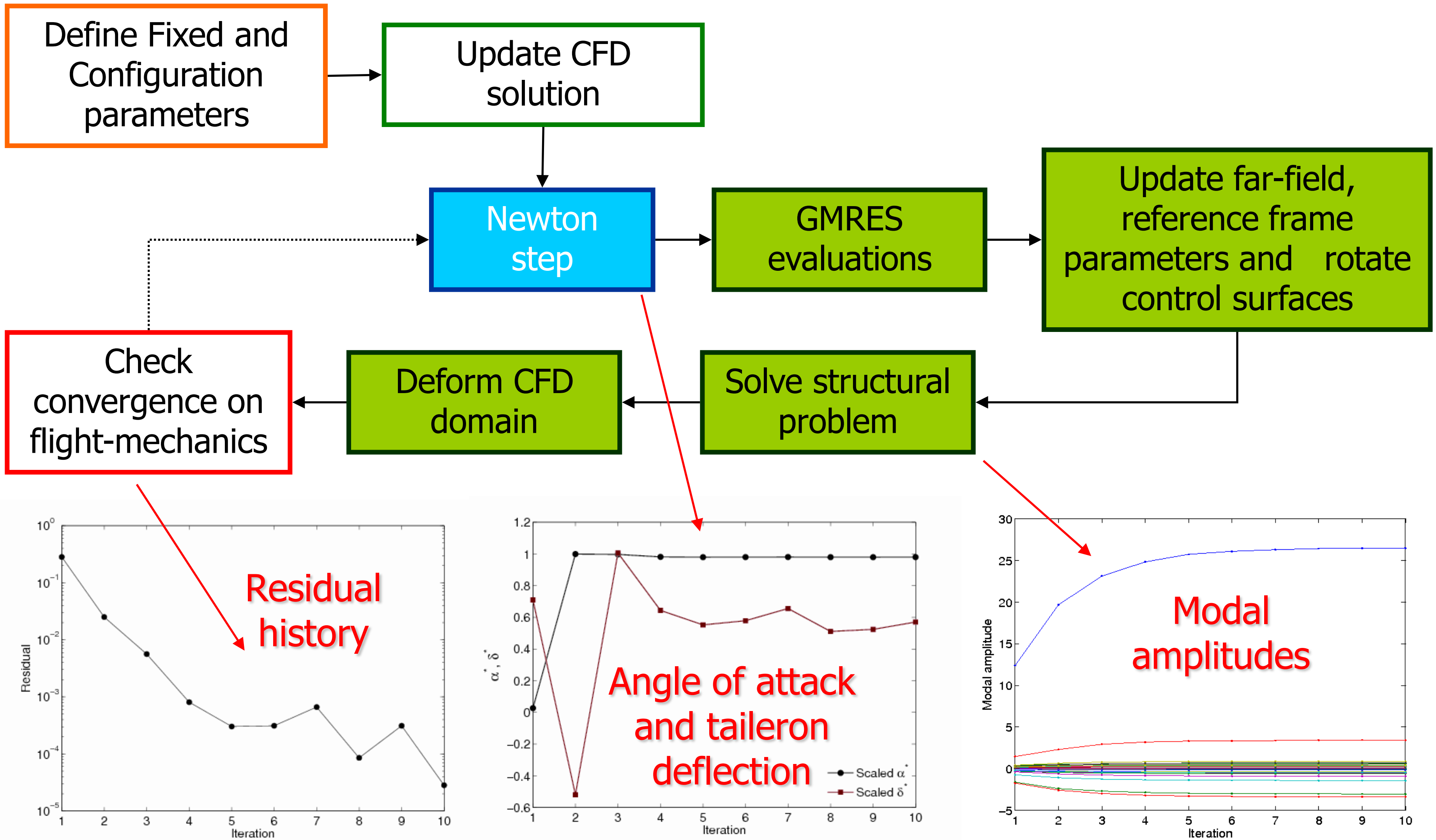
- The Newton method is thus applied only for rigid-dofs (costs-saving)
- *GMRES Newton-Krylov* method is used for linear solution of Newton step

$$\mathbf{J}\mathbf{v} \approx \frac{\mathcal{F}^C(\mathcal{P}_M^k + \varepsilon\mathbf{v}) - \mathcal{F}^C(\mathcal{P}_M^k)}{\varepsilon}$$

The Jacobian is not required and substituted by simple evaluation steps

- Through a trial perturbation $\mathbf{v}$ a sole evaluation of the residual is required
- After one Newton-step, the new-structural configuration is determined

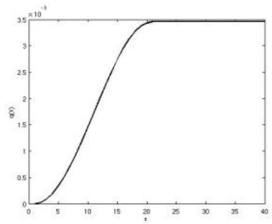
Trim condition for the free-flying aircraft



Generation of Reduced Order Models

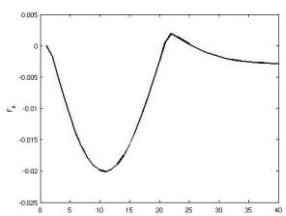
- Where can we find flutter instabilities? How to study aeroservoelasticity?
- A *ROM* is built for discrete values of frequency *jk* and M_∞
- The linear(ized) model is determined through a small perturbation
- The modal shape is given a blended step time-history

k_{max} determines the input signal



$$q(\tau) = \begin{cases} \frac{q_\infty}{2}\left(1 - \cos\Omega_0\tau\right) & 0 \le \tau < \tau_{\max}, \quad \Omega_0 = \pi/\tau_{\max} \\ q_\infty & \tau \ge \tau_{\max} \quad \tau_{\max} = 2\pi/k_{\max} \end{cases}$$

- A *FFT* of the responses gives one column of the *ROM* matrix

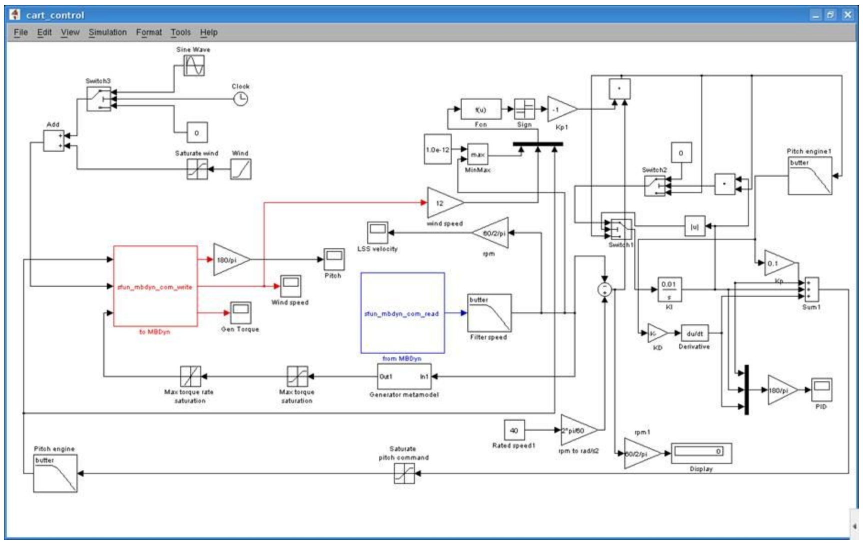


$$\mathbf{H}_{\mathrm{am}}(jk, M_\infty)_i = \frac{\mathbf{w}_\infty + jk\mathcal{F}\left(\mathbf{D}_\mathbf{w}(\tau, M_\infty)_i\right)}{q_{i\infty} + jk\mathcal{F}\left(D_q(\tau, M_\infty)_i\right)}$$

- Flutter tracking is reduced to an eigenvalue problem (*p-k* method,…)
- The linear(ized) model is determined starting from a non-linear condition

Generation of Reduced Order Models

- In real industrial applications several configurations need to be assessed
- Each of them would require a new *ROM* generation (too expensive!!)
- For small structural changes the problem can be re-diagonalized
- If there are not abrupt changes, the aerodynamic *ROM* can still be used



- The *ROM* can be identified into a state-space model

$$\dot{\mathbf{x}}_a = \mathbf{A}\mathbf{x}_a + \mathbf{B}\mathbf{q},$$
$$\mathbf{f}_a = \mathbf{C}\mathbf{x}_a + \mathbf{D}_0\mathbf{q} + \mathbf{D}_1\dot{\mathbf{q}} + \mathbf{D}_2\ddot{\mathbf{q}}$$

Structural modal amplitudes

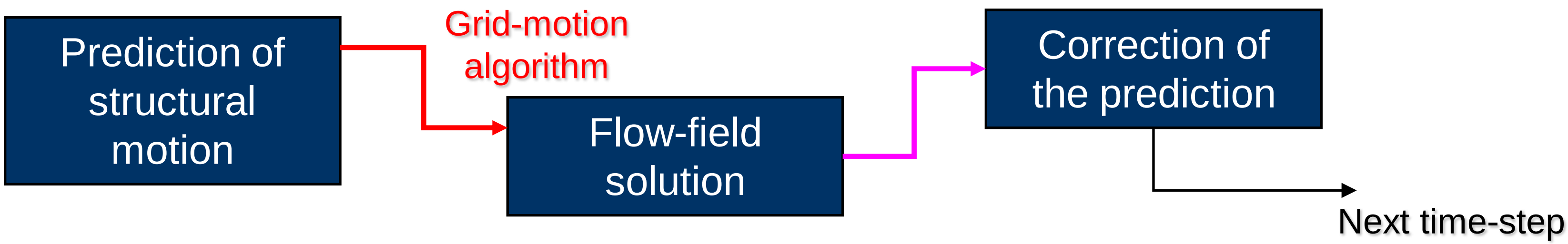
Aerodynamic states

Generalized forces

- Now, all the techniques typical of modern control system can be adopted
- Control laws can be easily verified in a *Simulink/Scicos* model

Non-linear coupled analysis

- What happens nearby flutter points? How does the system evolve?
- This procedure can be used to verify the results of the linearized model
- A partioned *loosely coupled* (only choice available) scheme is adopted



- The method is a predictor-corrector based on *Crank-Nicholson* algorithm

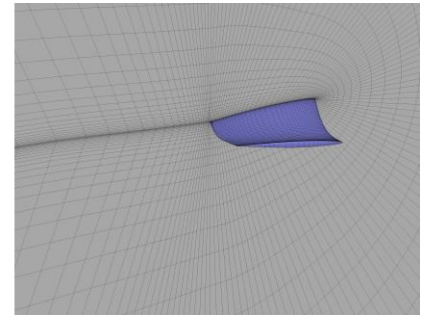
$$\text{Predictor} \quad \mathbf{q}^* = \left(\mathbf{I} + \frac{1}{2}h\mathbf{A}\right)^{-1} \left(\left(\mathbf{I} - \frac{1}{2}h\mathbf{A}\right)\mathbf{q}^{(n)} + h\mathbf{p}^{(n)}\right),$$

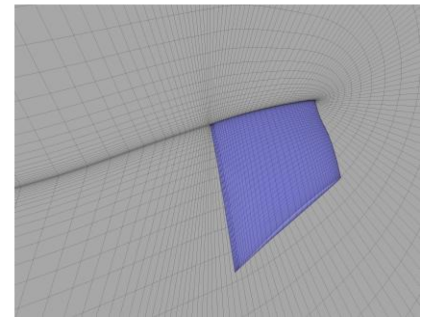
$$\text{Corrector} \quad \mathbf{q}^{(n+1)} = \left(\mathbf{I} + \frac{1}{2}h\mathbf{A}\right)^{-1} \left(\left(\mathbf{I} - \frac{1}{2}h\mathbf{A}\right)\mathbf{q}^{(n)} + \frac{1}{2}h\left(\mathbf{p}^{(n+1)} + \mathbf{p}^{(n)}\right)\right)$$

- The time-step is chosen only for accuracy (well known frequency content)

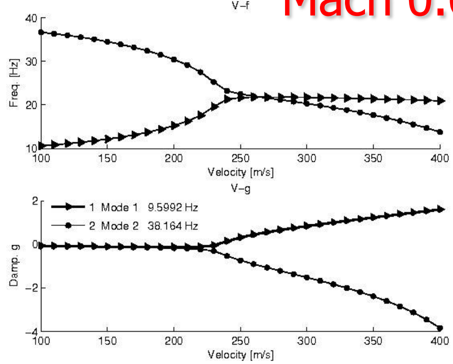
AGARD 445.6 Wing

- Subsonic, transonic and supersonic regimes tested
- Classic bending-torsional flutter
- Less than 1% error in subsonic and transonic
- 20% error in supersonic regime (we're not alone!)

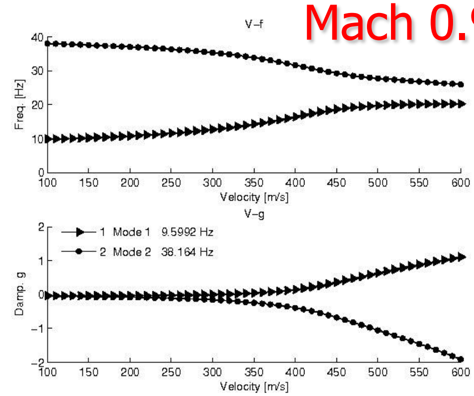


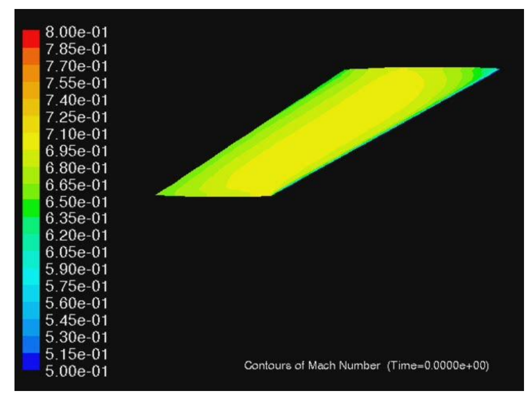


Mach 0.678

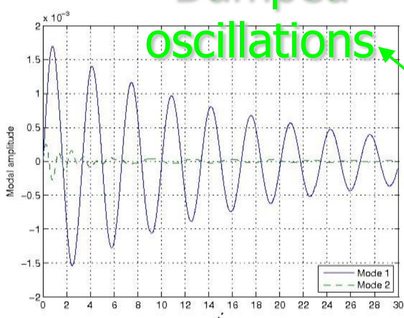


Mach 0.960

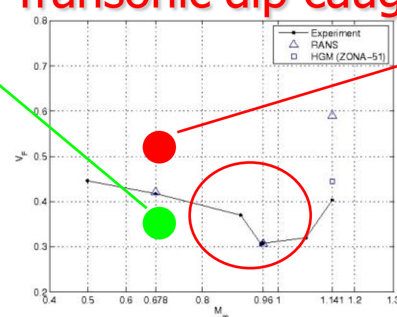




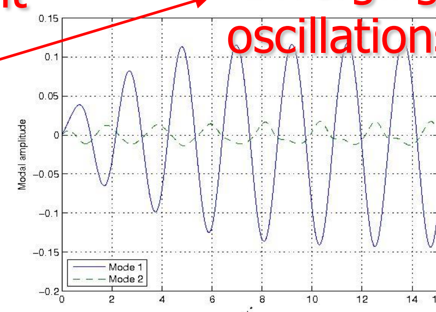
Damped oscillations



Transonic dip caught

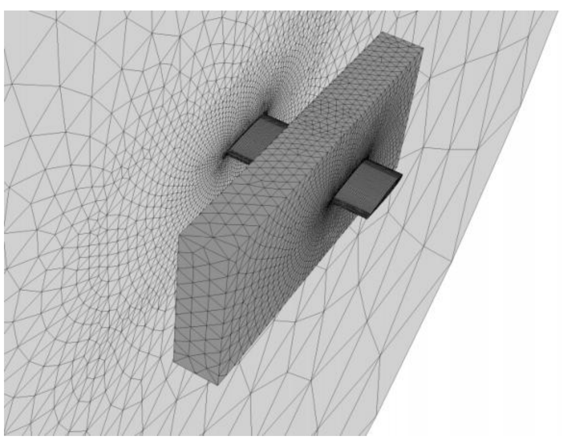


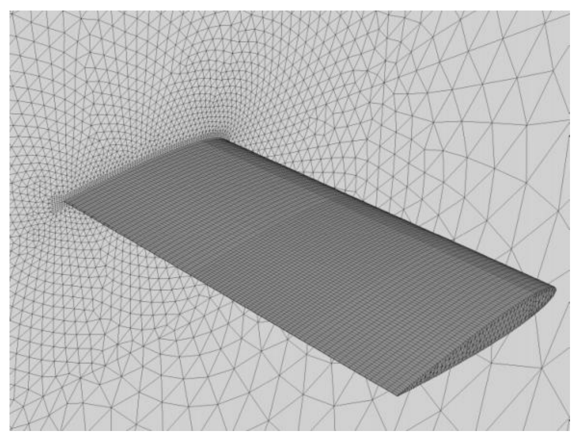
Diverging oscillations

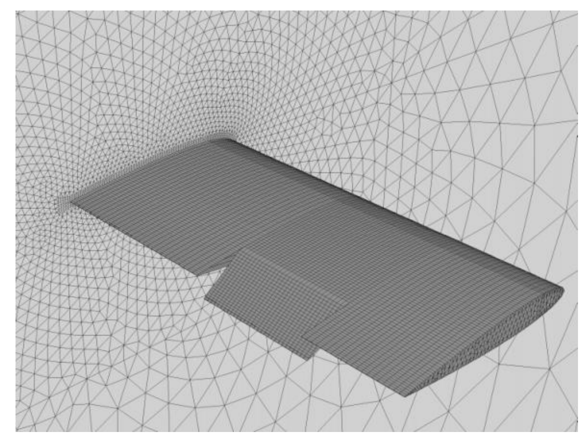


BACT aeroservoelastic benchmark

- Benchmark for active flutter suppression by means of control surfaces
- Many measurements are available
- The wing is limited only to pitch and plunge motion
- Experimental flutter results agree with other research codes
- Many uncertainties can be discussed (Mach, turbulence intensity, transition strips, wind tunnel conditions)

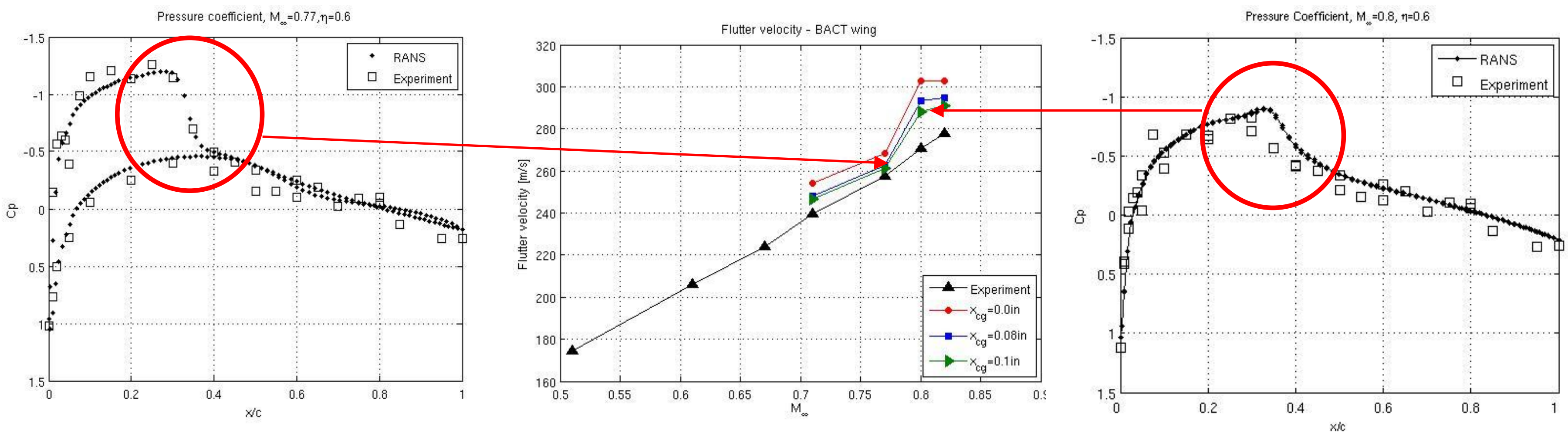




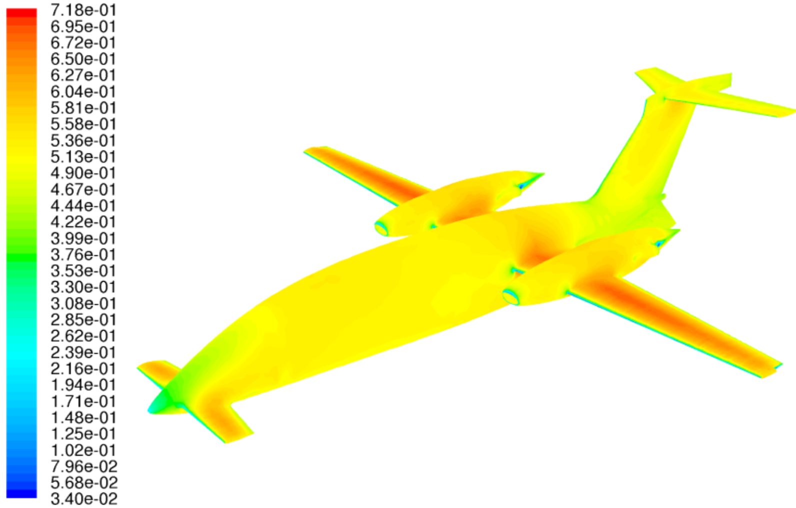


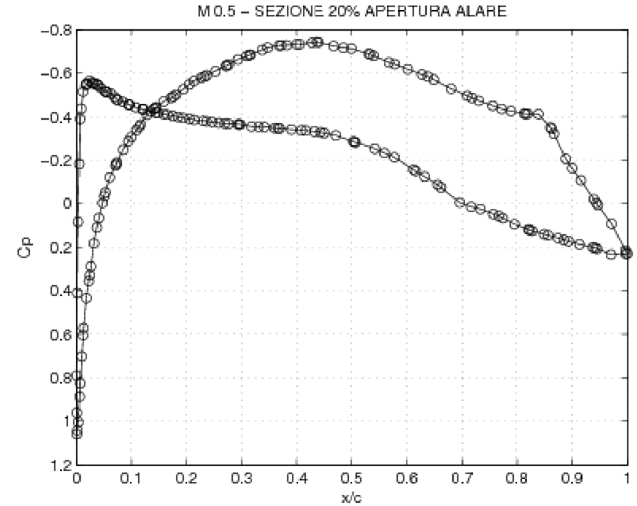
BACT aeroservoelastic benchmark

- Possible dependences of mass unbalance have been pointed out
- A *ROM* enables to study structural parameters variation easily
- A small variation of mass unbalance leads to a substantial variation on flutter but…
- A possible alternative reason could be the shock-wave position which is different from the experiment
- The predicted aerodynamic moments are thus smaller
- The consequence is the same as having a different mass unbalance



T-tail flutter results – Mach 0.5, α = 0°





Equivalent flutter speed VEAS

Modal base	DLM Nastran	CFD1 only normal displ.	CFD2 complete displ.	Piaggio DLM Onera
12-14	--	--	225 m/s	--
12-15	--	--	261 m/s	--
12-14-15	187 m/s	217 m/s	156 m/s	150 m/s
7-12-14-15	--	222 m/s	221 m/s	--

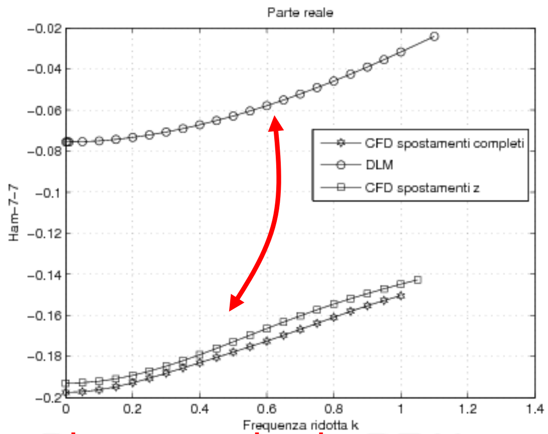
Displacement effects

Inplane corrections (?)

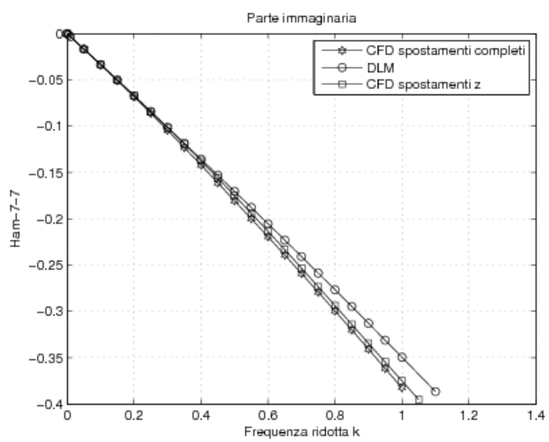
Control surface effectiveness

T-tail flutter results – Mach 0.5, α = 0°

- Aerodynamic transfer matrix, coeff. 7-7 – rudder rigid rotation

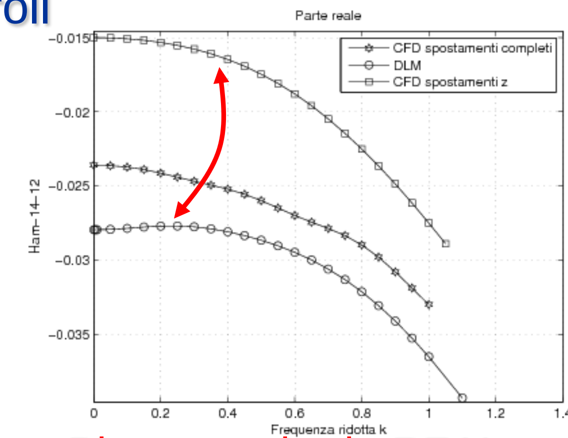


Discrepancies in REAL part

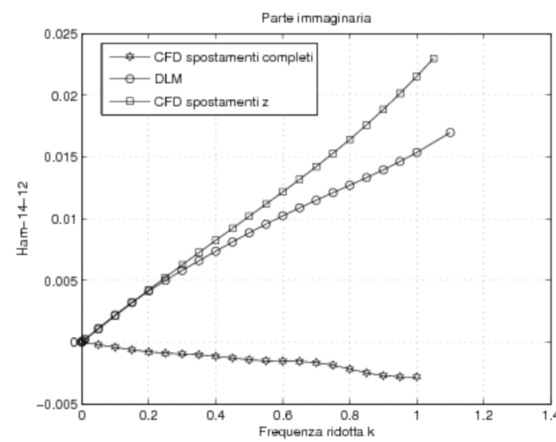


Good agreement in IMAG part

- Aerodynamic transfer matrix, coeff. 14-12 – fin bend. on HT roll

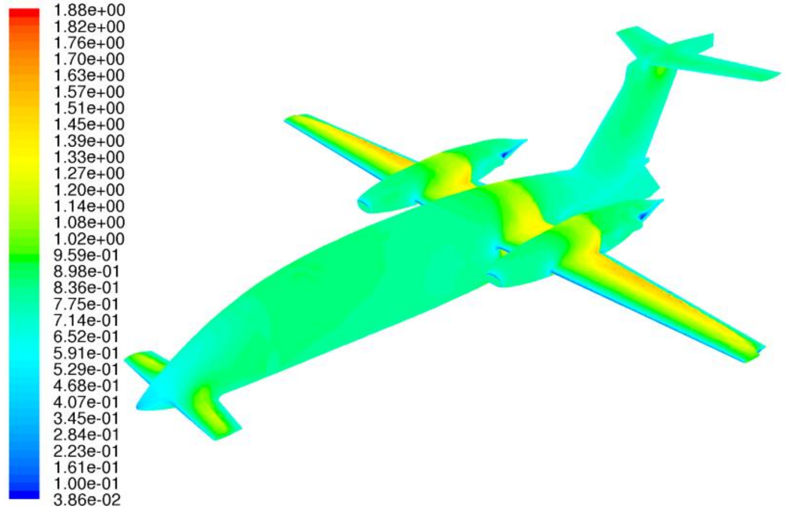


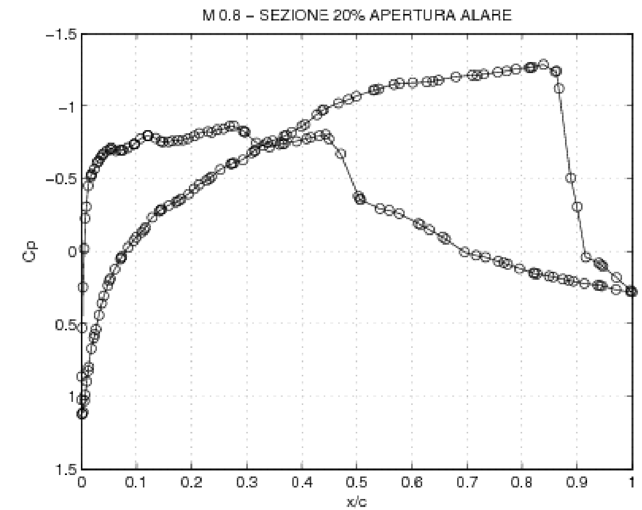
Discrepancies in REAL part



Opposite IMAG part due to inplane contrib.

T-tail flutter results – Mach 0.8, α = 0° (I)





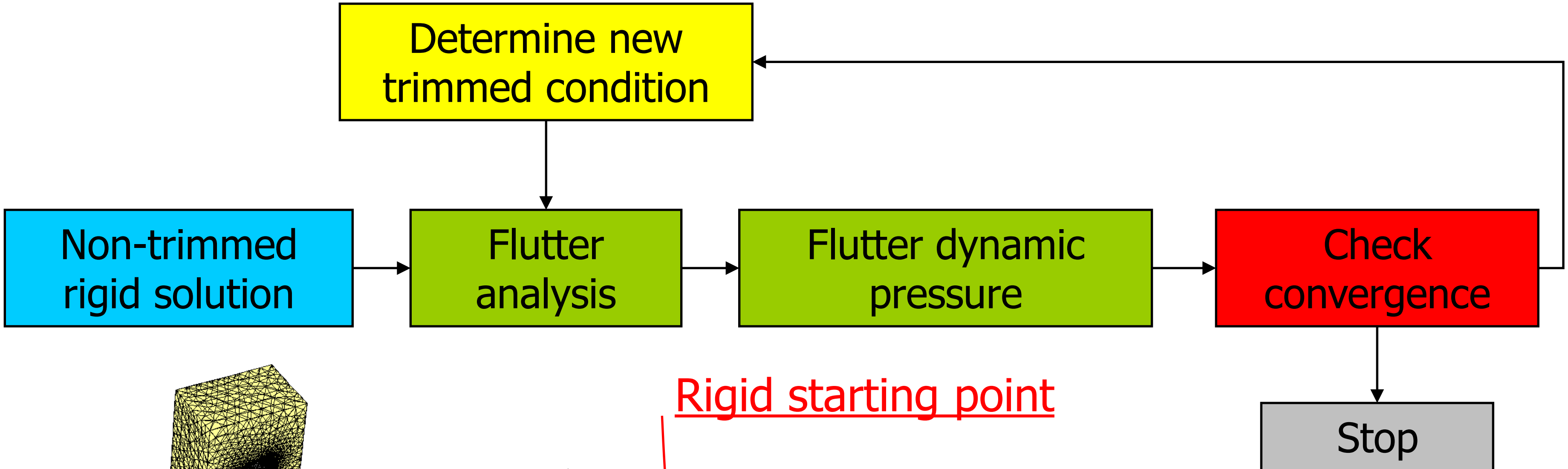
Equivalent flutter speed VEAS

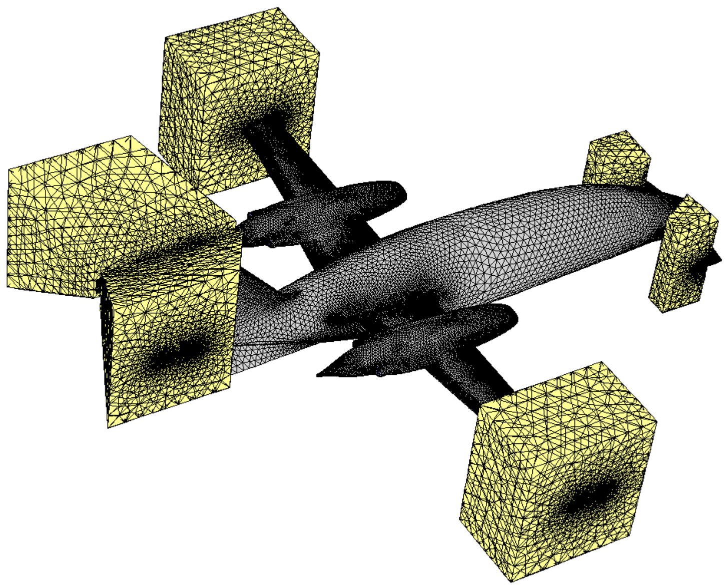
Modal base	DLM Nastran	CFD2 complete displ.	Piaggio DLM Onera
12-14	193 m/s	116 m/s	90 m/s
12-15	217 m/s	259 m/s	180 m/s
12-14-15	112 m/s	89 m/s	90 m/s
7-12-14-15	--	130 m/s	160 m/s

Control surface effectiveness

T-tail flutter results – Mach 0.8, α = 0° (II)

- Flutter condition is alligned and depens on equilibrium point





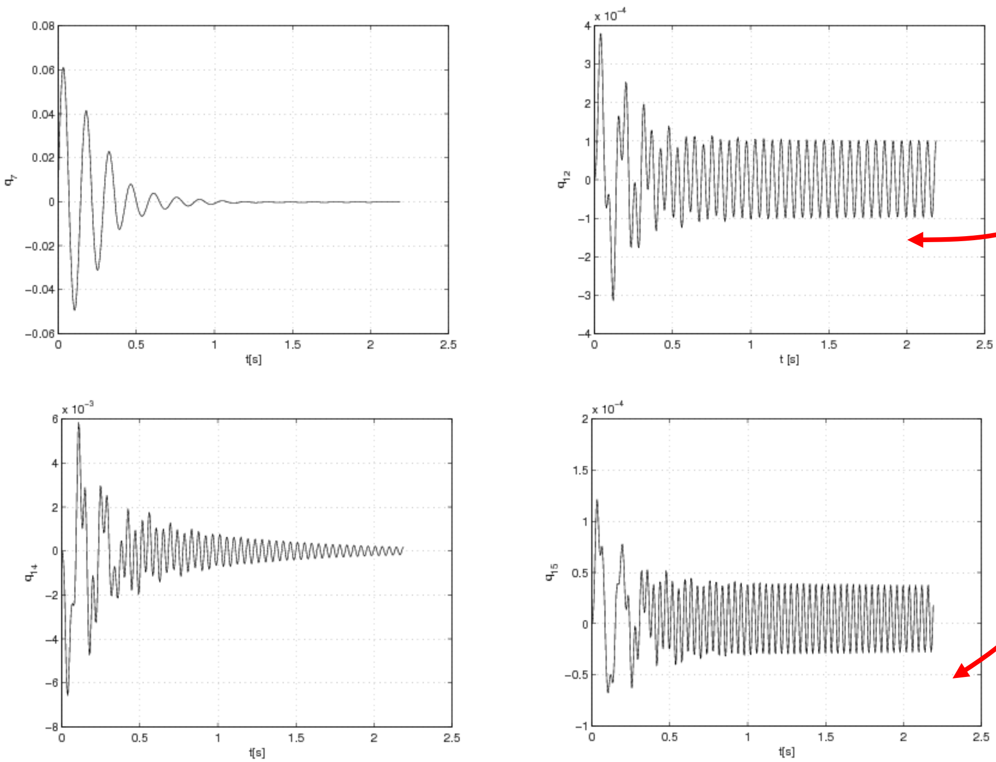
Rigid starting point

Altitude m	δ_e deg	α deg	V_f m/s	q_∞ Pa
0	0	0	130	19406
7400	0.87	-0.40	165	17330

Final converged solution after 4 steps

Non-linear coupled simulation – Mach 0.8

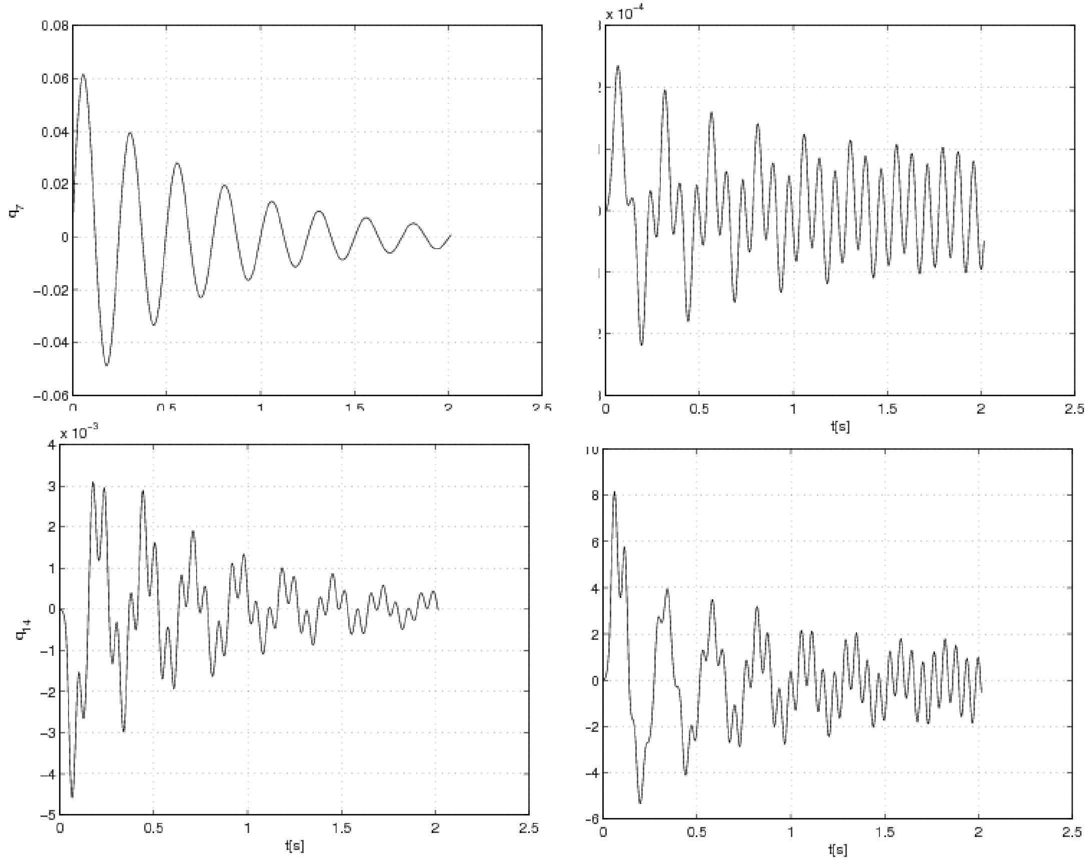
- The stability of the system is inferred from its response
- Higher dynamic pressure than the one predicted by linear method
- Altitude = 6000 m, q_∞= 21100 Pa



- LCO with small amplitude and high frequency
- Modal base enlargement does not affect the result

Non-linear coupled simulation – Mach 0.8

- Lower dynamic pressure than the one predicted by linear method
- Altitude = 9000 m, q_∞= 13730 Pa
- Damped modal responses confirm the stability



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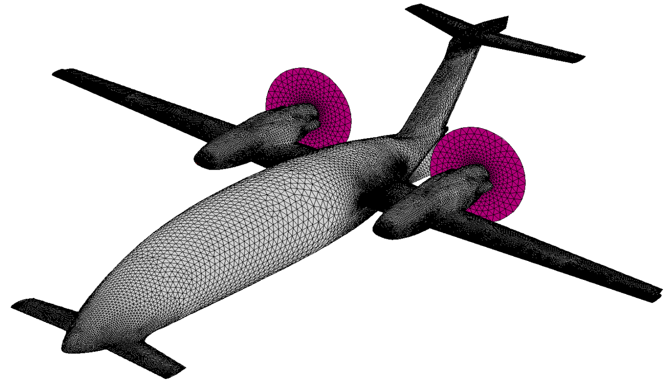
Conclusions and future developments

- Different tools are required:
  - Conservative spatial coupling
  - Grid deformation
  - Control surface management
- A ROM for generalized forces definitely lowers computational costs
- Correct allignement with trimmed condition and flutter
- Complex CFD models require high computational costs and set-up time
- The whole aircraft is considered even for tail flutter investigations
- Ready to investigate transonic regimes for tail as well

Next developments

- High angles of attack (Navier-Stokes)
- Include propeller effects

CFD Based Reduced Order Models for T-tail flutter



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Bifurcation and Model reduction Techniques for Large Multidisciplinary Systems - University of Liverpool
June 26-27, 2008. Liverpool, UK.