SAAB Flygtekniskt Seminarium
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POLITECNICO DI MILANO

Application of Fluid-Structure Tight Interaction by Multibody-CFD Simulation to Aircraft Aeroelasticity in Free Flight

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Outline

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- Targets and motivations
- MBDyn multibody code
- New developments in Edge flow-solver for aeroelastic maneuvers
- Test case considered
- MBDyn-Edge coupling: examples of body and deformable analyses
- Conclusions

Targets and motivations

Targets: comprehensive and efficient tool for FSI analysis

to investigate:

- concentrated non-linearities (free-plays, friction)
- non-linear constitutive laws, geometric effects
- flight mechanics and large rotations
- control laws, servo dynamics, aeroservoelasticity
- compressibility effects (shock waves, transonic dip)
- viscous effects (dynamic stall, separations)

A high-fidelity/multi-level solution to the issues consists in coupling:

- <u>MultiBody dynamics</u> (MB)
- <u>Computational Fluid Dynamics</u> (CFD)

The present work shows the <u>first steps</u> towards such a tool

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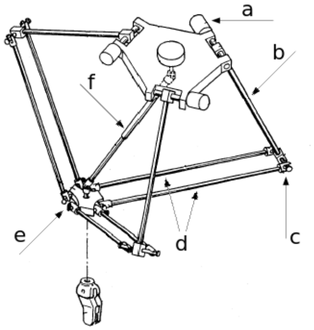
Multibody dynamics

Multibody: a “buzz” word?

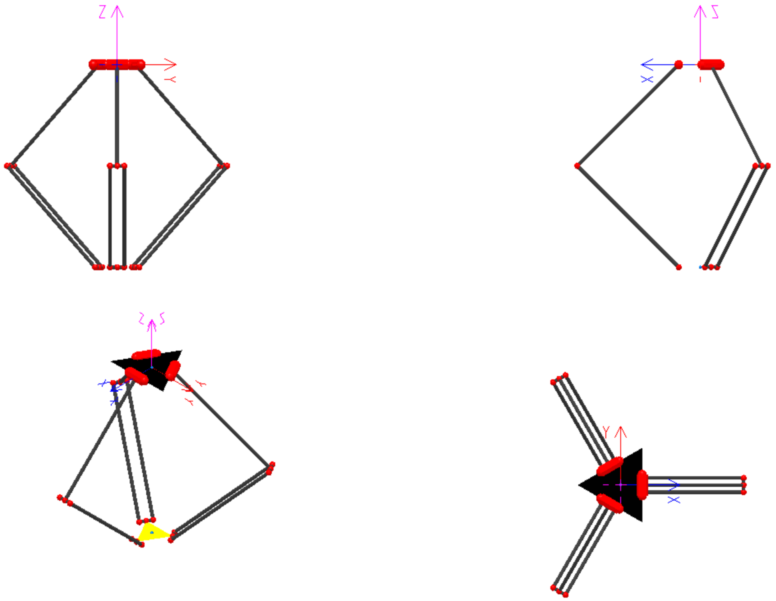
Initial idea:

- automatically write equations of motion of arbitrary mechanisms



Current status:

- efficiently and accurately integrate in time
- exact rigid-body kinematics, plus
- nonlinear finite elements, plus
- natural inclination towards multi-physics & system integration



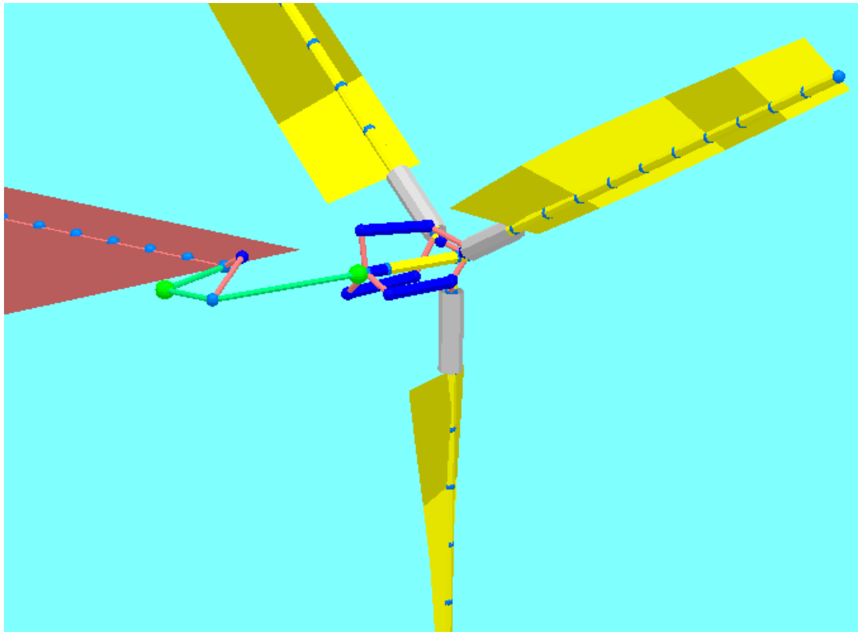
Future:

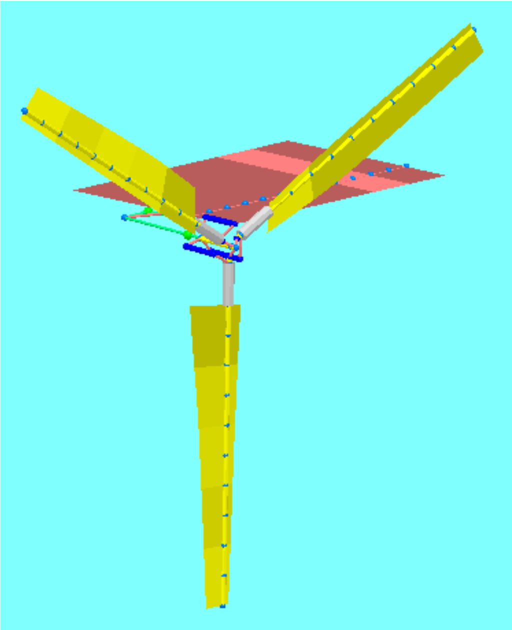
- scale to larger and larger problems, and
- higher performances when solving more complex problems (contacts, friction)

Multibody dynamics

Multibody methods:

- usually are general-purpose: can model a wide variety of mechanical systems;
- should support an arbitrary number of a variety of parts, forces, geometries, constraints, etc.;
- most often use numerical methods to compute solutions;
- often integrated in CAD tools, with Graphical User Interfaces (GUI).



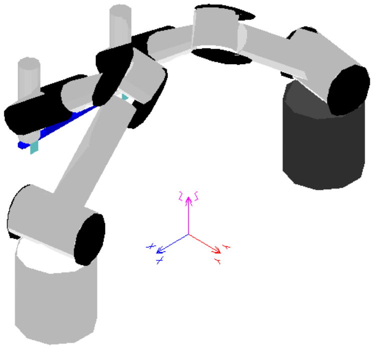


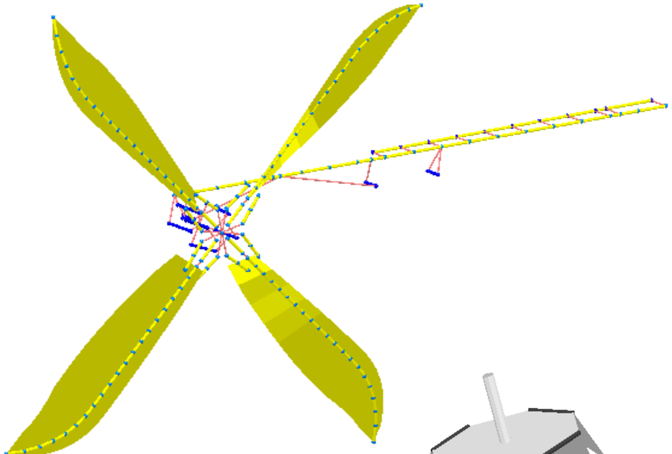
Tilto-rotor multibody model

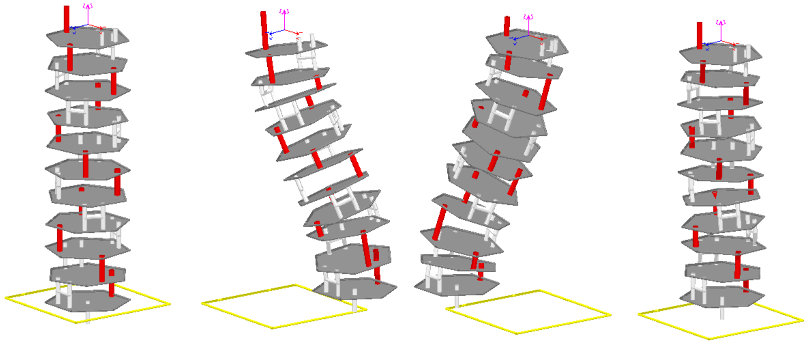
Multibody dynamics

Applications:

- Robotics
- Automotive
- Crashworthiness
- Aerospace engineering
- Industrial automation
- Applied mechanics



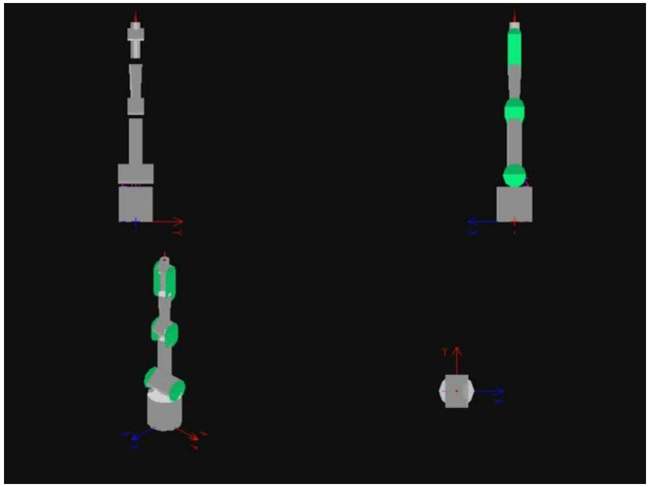




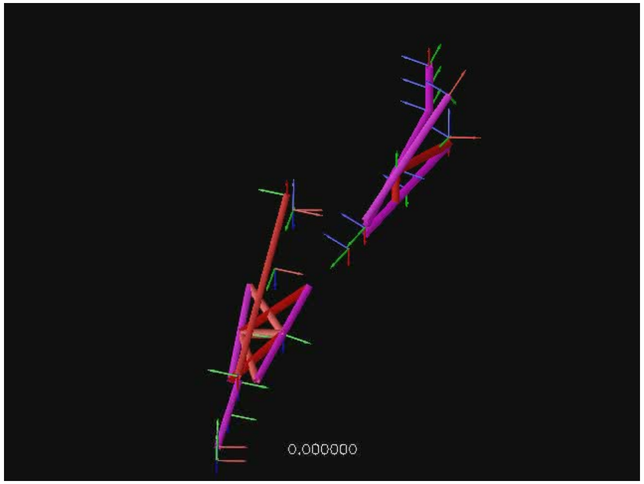
Notice:

- Videogames: revenue higher than engineering software!
- Anywhere realistic motion (or at least that looks realistic) is required, multibody simulation is or can (and will) be used.

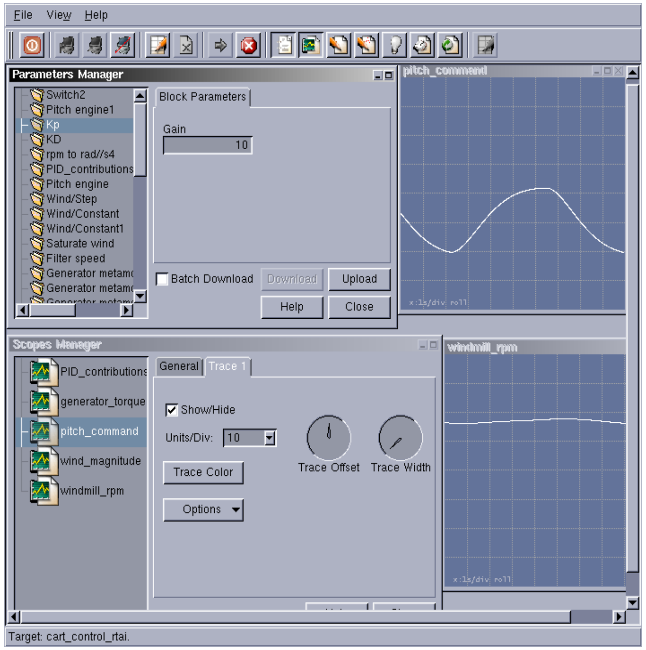
MBDyn project: applications



Control of manipulator



Landing gear walk [1]



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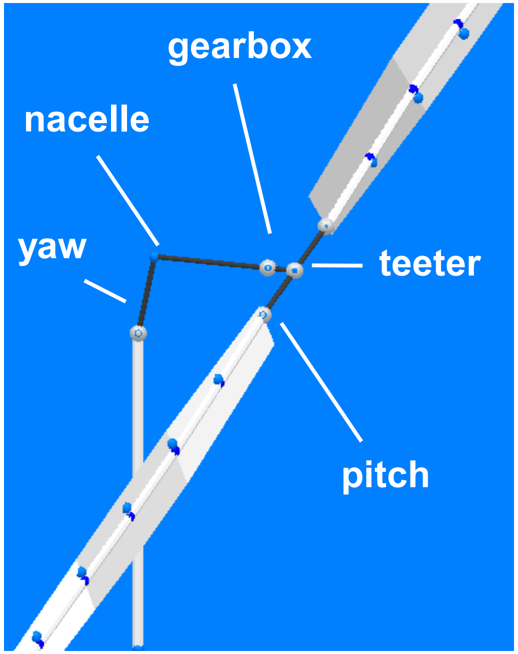
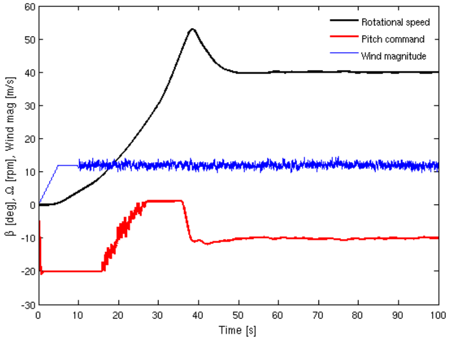
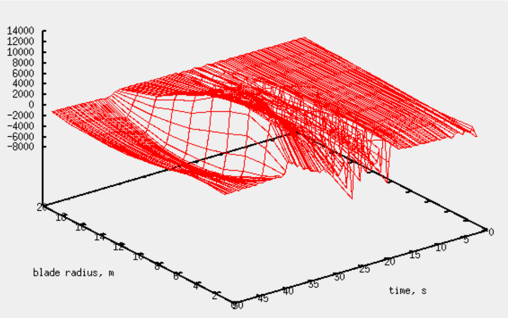
Target: cart_control_rtai.







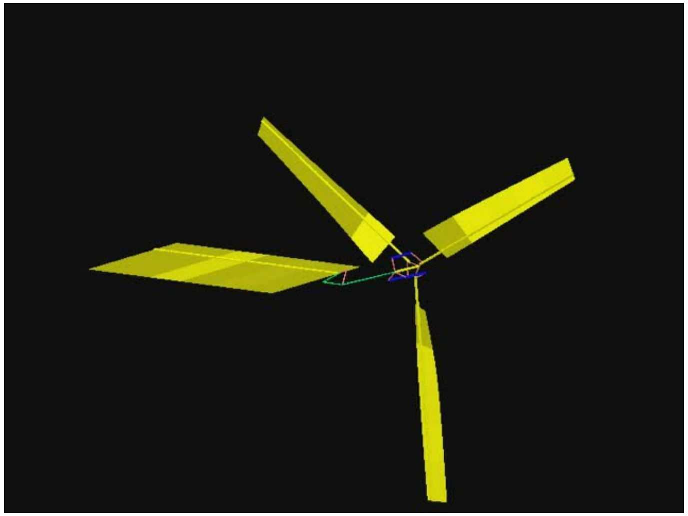
Wind turbine real-time simulation [2]

[1] Gualdi S., Morandini M., Ghiringhelli G.L., Anti-skid induced aircraft landing gear instability,Aerospace Science and Technology
[2] Cavagna L., Masarati P., Morandini M., http://www.aero.polimi.it/~mbdyn/mbdyn-rt/mbrtwind.html

MBDyn project

MBDyn:

- a free-software project under GPL (www.mbdyn.org)
- is a monolithic multibody/multiphysics IVP solver
- has internal deformable components
- lumped components
- nonlinear beams
- Component mode synthesis (CMS)



Tilt-rotor start-up simulation

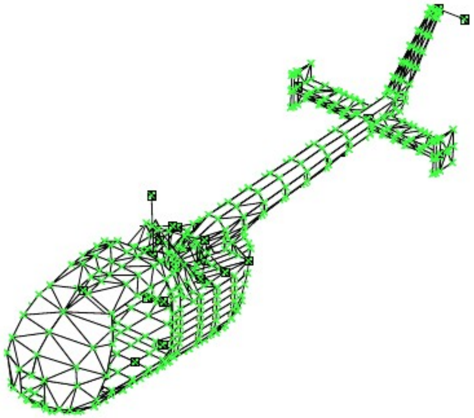
- CMS is common practice in multibody dynamics to synthesize complex deformable components for mechanism dynamics purposes
- an external FEM solver synthesizes data required by the CMS:
  - mode shapes and static shapes from modal/static analysis (Craig-Bampton, Boundary Masses, and similar)
  - corresponding reduced mass and stiffness matrices
  - approximated mass matrix for higher order inertia effects (optional)
- the dynamic analysis is entirely delegated to MBDyn

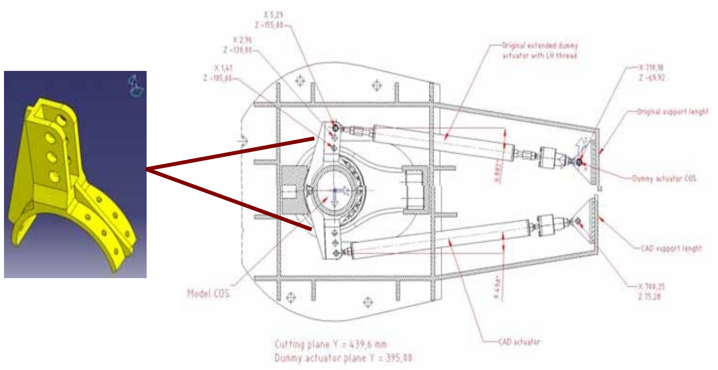
MBDyn

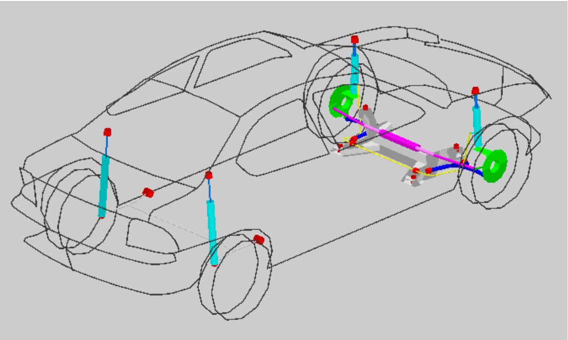
MBDyn project: CSM method

The use of CMS is common practice with MBDyn:

- helicopter airframe dynamics
- tiltrotor wind-tunnel model support
- car chassis in suspension bushings analysis
- …







Detailed stress analysis from dynamic loads:

- coarse dynamic loads from multibody analysis are used to obtain accurate and detailed stress analysis

MBDyn project: CSM method

Sequence:

- prepare a FE model of the deformable component
- extract a reduced order model adopting one of the following approach:
  - use pure normal modes
  - use pure normal modes enhanced by “engineering judgement” static shapes
  - use Craig-Bampton (normal modes of model constrained at interface points, plus interface static shapes)
- format the reduced order model according to MBDyn's format
- run the multibody analysis
- post-process output according to reduced order model coordinates from MBDyn's analysis

Interface parameters:

- pure normal modes: mode selection criteria (mode number, frequency threshold)
- pure normal modes enhanced by static shapes: mode selection criteria (mode number, frequency threshold), load and/or boundary conditions for static shapes
- Craig-Bampton: mode selection criteria (mode number, frequency threshold), interface nodes

MBDyn-FEM interaction

- the multibody model is a reduced order model of a complex structure, capable of sophisticated mechanism dynamics analysis;

- the multibody system dynamics analysis is used to estimate dynamic loads (inertia and other configuration dependent loads);

- dynamic loads are distributed on the detailed FE model of the structure, using a consistent work-preserving scheme *[3]* (also available in Edge now);

- the FE model is used to statically analyze the effects of the dynamic loads (stress analysis, detailed compatibility analysis, ...);

- this procedure has been recently outlined and investigated during a thesis using NASTRAN®; it needs to be further refined.

[3] G. Quaranta, P. Masarati, and P. Mantegazza: "A Conservative Mesh-Free Approach for Fluid Structure Interface Problems". Coupled Problems 2005, Santorini, Greece, May 24-27.

MBDyn-FEM interaction

Deformable CMS body kinematics:

$$\mathbf{x}(p) = \underbrace{\mathbf{x}_0 + \mathbf{R}_0}_{\textit{rigid body}} \mathbf{h}_d(p)$$

FEM deformability

$$\boxed{\mathbf{h}_d(p) = \mathbf{h}_{d0}(p) + \mathbf{H}_d(p)\,\mathbf{a}}$$

Deformable CMS body dynamics: added equations

$$\dot{\mathbf{a}} = \mathbf{b}$$

$$\mathbf{M}\dot{\mathbf{b}} = -\mathbf{C}\mathbf{b} - \mathbf{K}\mathbf{a} + \mathbf{f}$$

FEM deformability

Interaction with multibody model: interface nodes

$$\mathbf{x}_j = \mathbf{x}_0 + \mathbf{R}_0\mathbf{h}_d(p_j)$$

$$\mathbf{R}_j = \mathbf{R}_0\mathbf{h}_r(p_j)$$

MBDyn-FEM interaction

Structural dynamics problem (FEM):

$$\mathbf{M}\ddot{\mathbf{x}} = \mathbf{f}\left(\mathbf{x}, \dot{\mathbf{x}}, t\right)$$

Static problem:

$$0 = \mathbf{f}\left(\mathbf{x}, 0, t\right)$$

Rework in terms of structural operator (typically linear):

$$\mathbf{s}\left(\mathbf{x}\right) = \mathbf{f}'\left(\mathbf{x}, 0, t\right)$$

Reduced order dynamics (multibody):

$$\mathbf{M}_r\ddot{\mathbf{x}}_r = \mathbf{f}_r\left(\mathbf{x}_r, \dot{\mathbf{x}}_r, t\right) \qquad \mathbf{x} = \mathbf{h}\left(\mathbf{x}_r\right)$$

Static problem (FEM) with reduced order dynamics loads (multibody):

$$\mathbf{M}\,\ddot{\mathbf{h}}\left(\mathbf{x}_r\right) = \mathbf{f}\left(\mathbf{x}, \dot{\mathbf{h}}\left(\mathbf{x}\right)_r, t\right)$$

$$\mathbf{s}\left(\mathbf{x}\right) = \mathbf{f}'\left(\mathbf{h}\left(\mathbf{x}_r\right), \dot{\mathbf{h}}\left(\mathbf{x}_r\right), t\right) - \mathbf{M}\,\ddot{\mathbf{h}}\left(\mathbf{x}_r\right)$$

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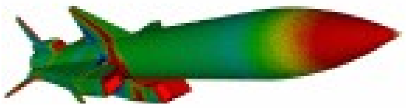
Developments in Edge flow-solver

Features of the solver:

- Edge is a CFD code developed by FOI
- RANS equation (several turbulence models), LES and DES models
- unstructured node-centered finite-volume scheme
- residual smoothing and multi-grid technique
- explicit multi-stage RK scheme for steady analysis
- dual-time stepping (implicit BDF + explicit subiterations) for unsteady analysis



Extra features:

- aeroelastic capabilities mainly based on ALE formulation with deforming grids or basic transpiration bc
- the same technique can then be used to specify rigid body maneuvers and in the most general case to specify the maneuver of a deformable aircraft

  How?

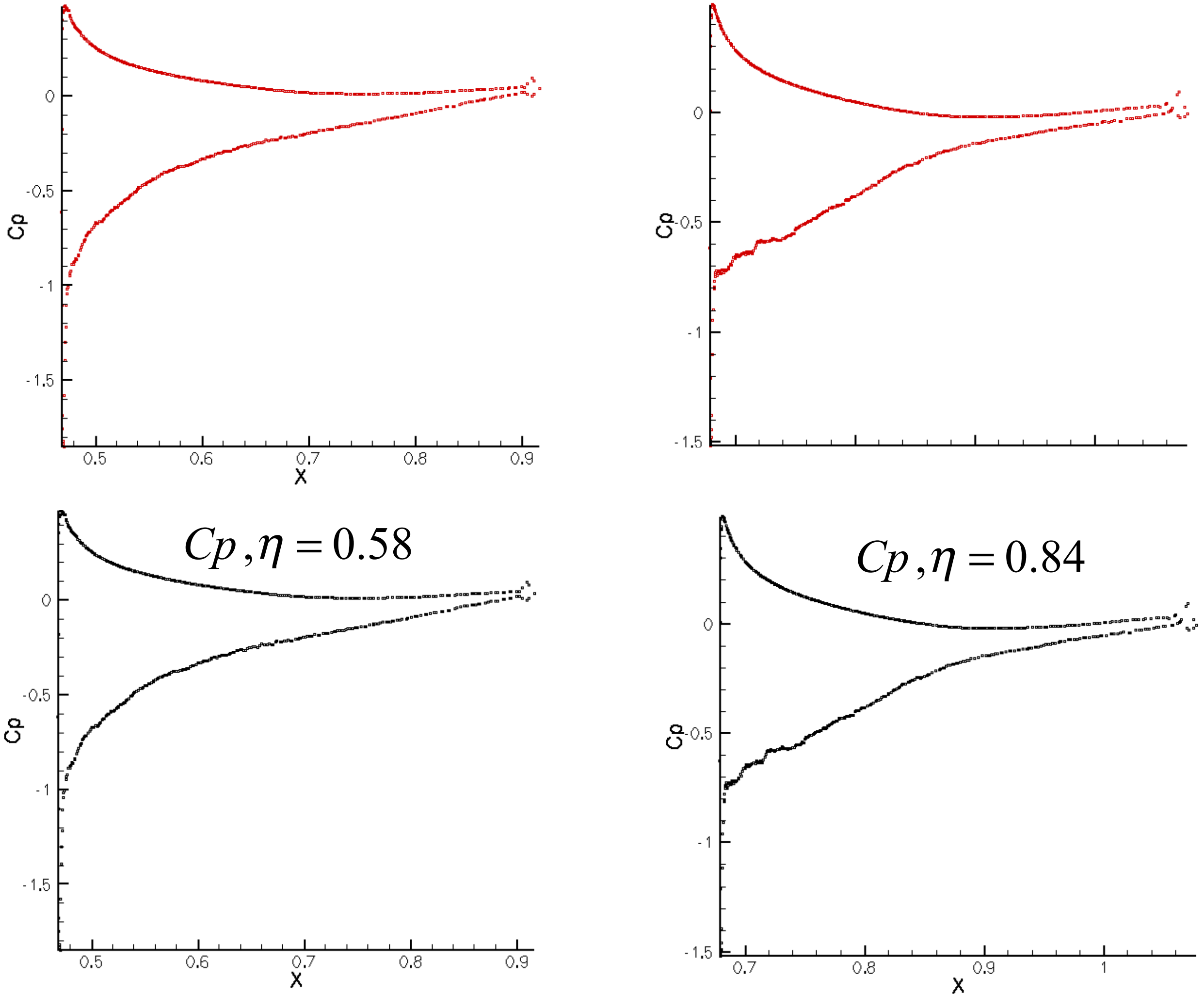
  A general kind of motion can be converted in:

NEW! rigid body attitude nodal velocities + nodal velocities given by structural motion or

NEW! rigid body attitude nodal velocities + transpiration bc for the structural motion

Steady maneuver: AGARD445.6 wing

- Simulate steady horizontal flight using a constant body velocity (unsteady simulation)
- Convert steady analysis data and perform a maneuver to get the same results



Steady analysis

$$\alpha = 5\,\text{deg}$$
$$V_\infty = 231.37\,m/s$$
$$M_\infty = 0.678$$
$$p_\infty = 17.188\,Pa$$
$$T_\infty = 289.4\,K$$

Determine body velocity

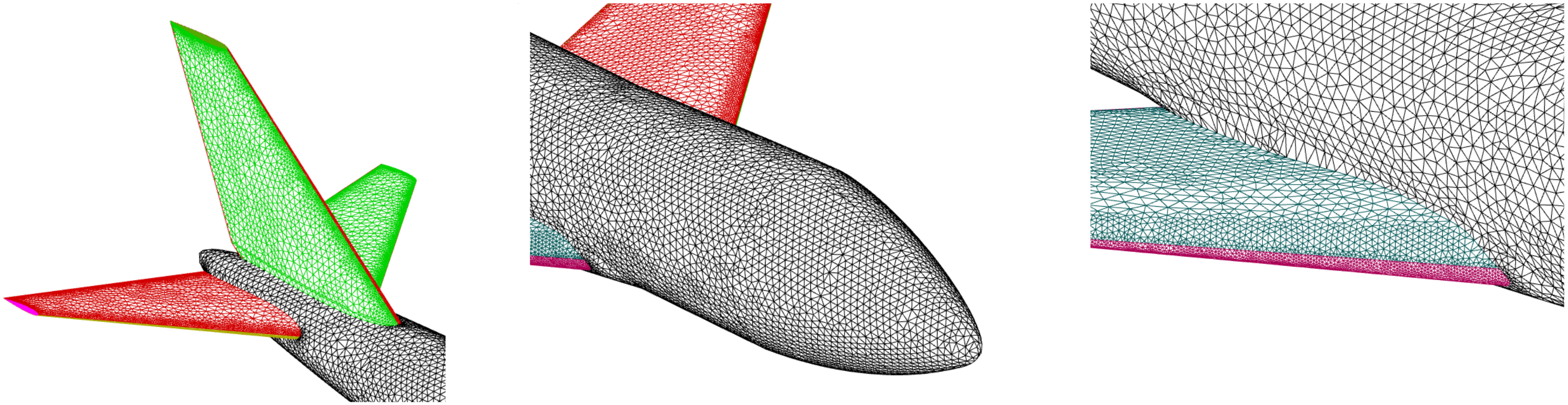
Unsteady analysis

$$V_x = -230.48\,m/s$$
$$V_z = -20.16\,m/s$$

Dynamic derivatives perturbing a maneuver

New functionalities added:

- create a Reduced Order Model for body forces and moments measuring indicial responses after a single perturbation for linear and angular velocities
- extract from this model all the unsteady derivatives adopting a quasi-steady approach (serie-expansion of the aerodynamic ROM matrix around null frequency)
- example considered: “B747-like” aircraft examined in SimSAC EU framework

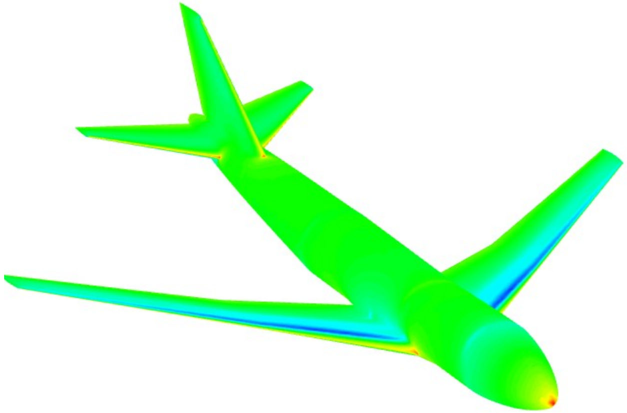


Overview of the CFD mesh

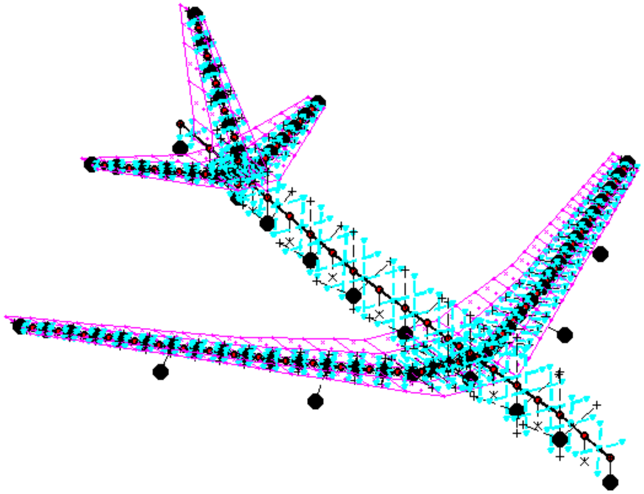
Dynamic derivatives perturbing a maneuver

	$C_z\alpha$	$C_m\alpha$	$C_y\beta$	$C_n\beta$	$C_l\beta$	$C_l p$	$C_m\dot{\alpha}$	$C_z\dot{\alpha}+C_z q$	$C_m\dot{\alpha}+C_m q$
Edge	2.689	-1.813	-0.429	-0.145	0.093	0.211	7.522	-6.881	-24.372
DLM	2.474	-2.272	-0.267	-0.145	0.065	0.205	4.975	-7.067	-23.701

Comparison of dynamic derivatives between Edge and DLM, $M_\infty=0.6$



Pressure contour, Edge, $M_\infty=0.6$



Doublet Lattice model (+beams) used for comparison

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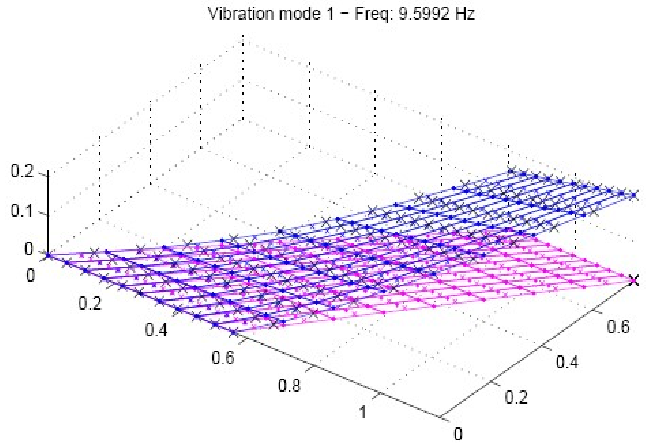
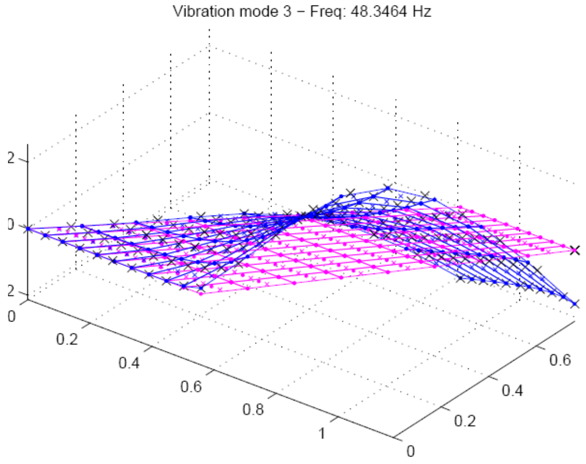
AGARD445.6 wing structural model

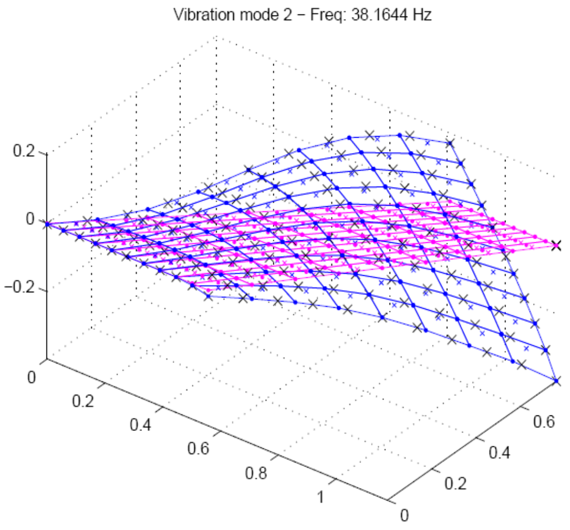


Mode 1

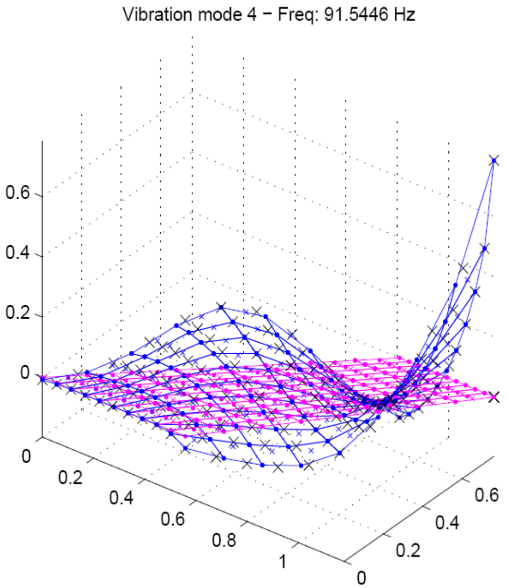


Mode 3

Mode [4]	Freq. [Hz]
1	9.59
2	38.16
3	48.35
4	91.54



Mode 2



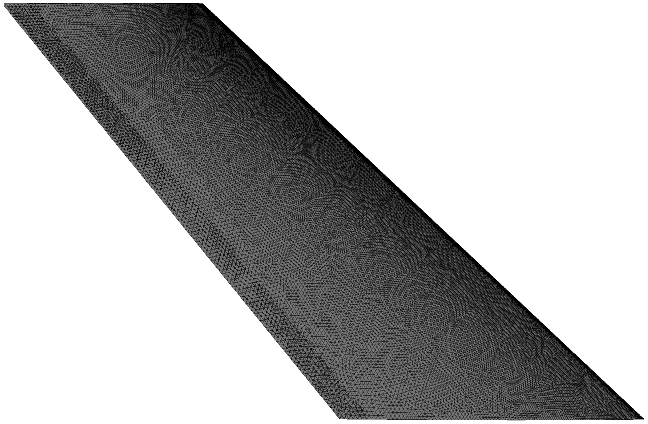
Mode 4

[4] Modal testing results available from E. C. Yates, AGARD standard aeroelastic configurations for dynamic response. I wing 445.6, R765, AGARD, 1985.

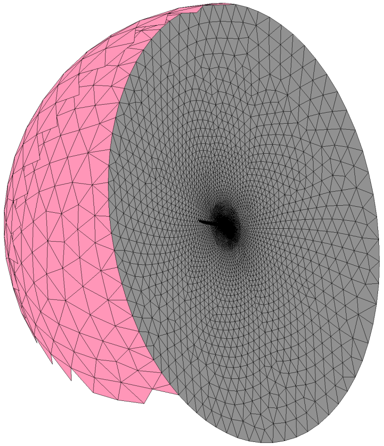
AGARD445.6 wing model

Features:

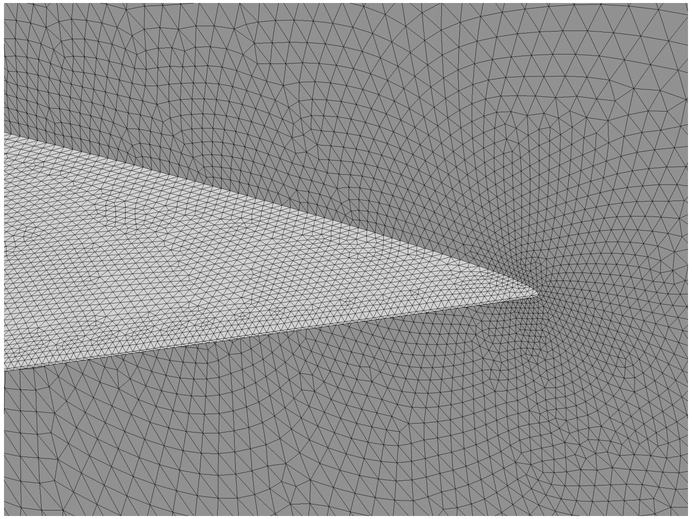
- Euler equations
- 227.278 volume points
- 86.371 points on wing
- 3 experimental conditions considered in wind tunnel



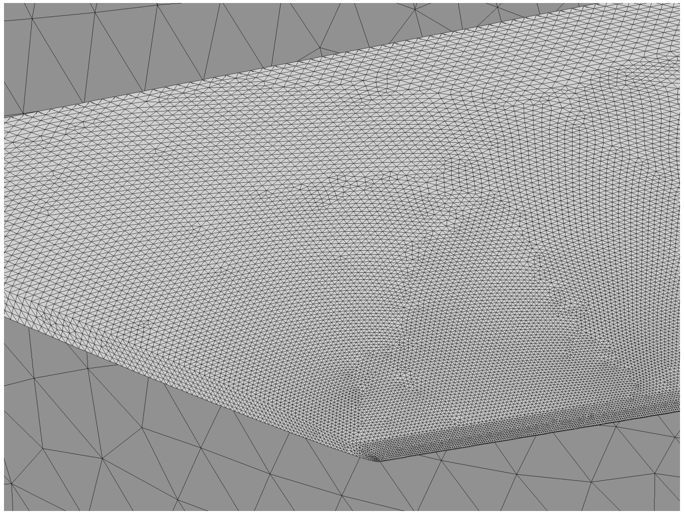
Surface mesh



Computational domain

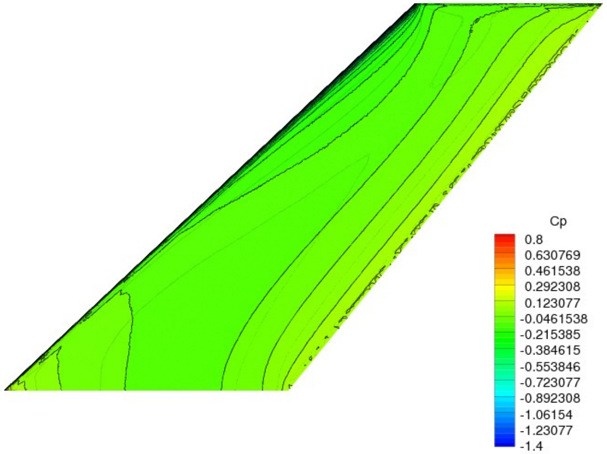


Root detail

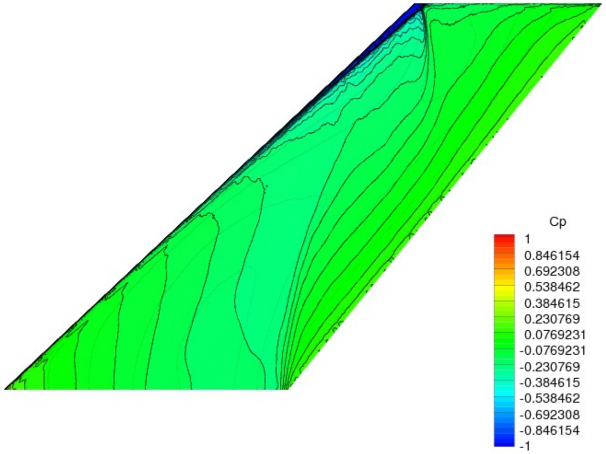


Tip detail

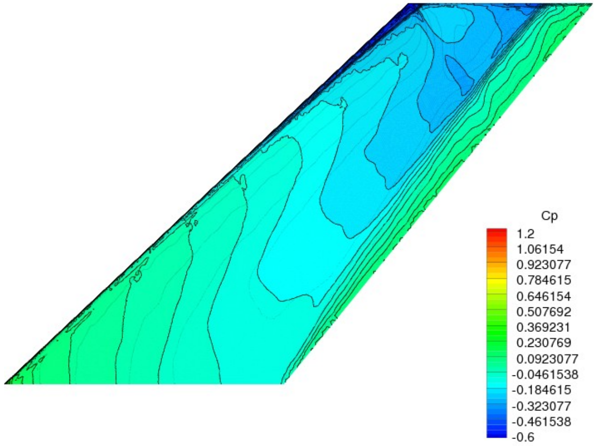
AGARD445.6 wing reference conditions



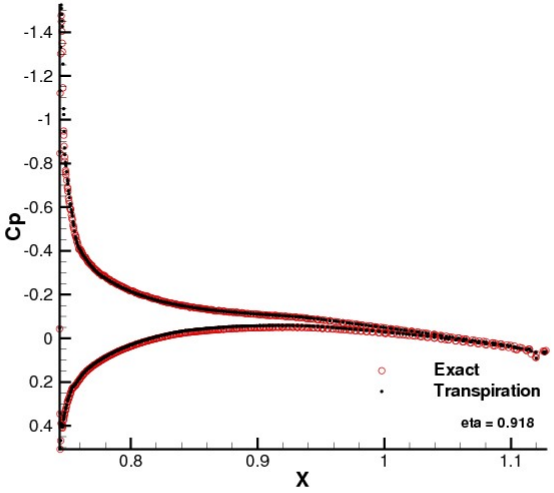
Cp distribution, $M_\infty=0.678$



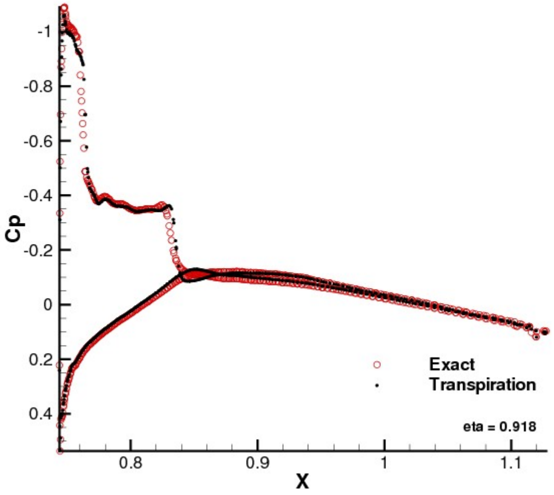
Cp distribution, $M_\infty=0.960$



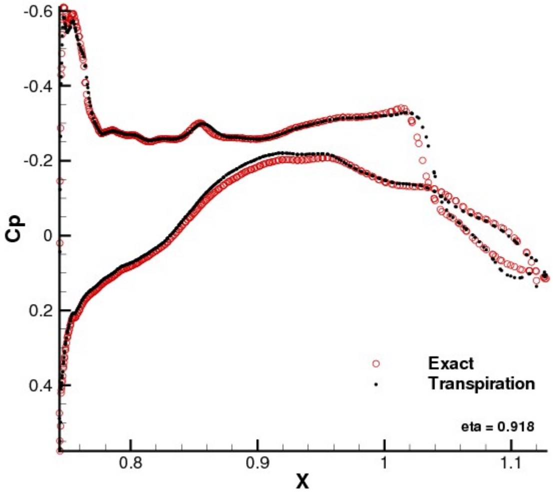
Cp distribution, $M_\infty=1.141$



$$Cp, \eta = 0.65, M_\infty = 0.678$$



$$Cp, \eta = 0.65, M_\infty = 0.960$$



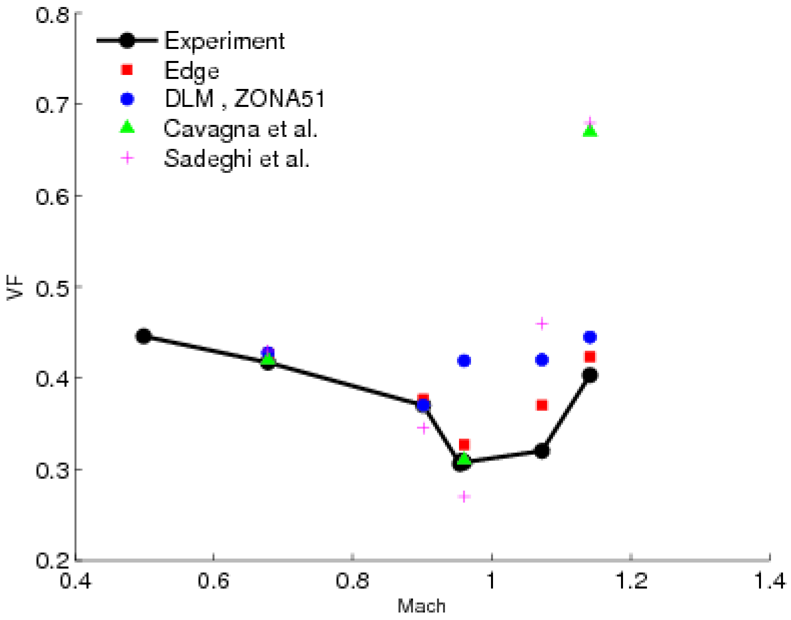
$$Cp, \eta = 0.65, M_\infty = 1.141$$

AGARD445.6 linearized flutter with Edge

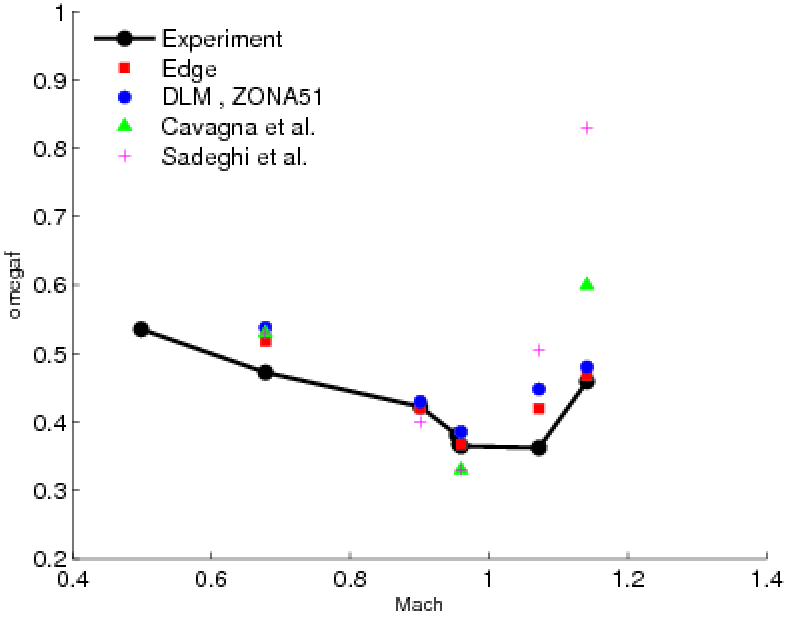
How can we determine efficiently instability points to assess?

- by means of a Reduced Order Model (ROM) for generalized forces using a FFT of indicial responses
- flutter equation reads: $(Ms^2 + Cs + K - q_\infty \boxed{H_{am}(p, M_\infty)})q = 0 \quad with\ \ p = \frac{sL_a}{V_\infty}$

NEW! All these capabilities are now available in Edge



Flutter speed index



Flutter frequency index

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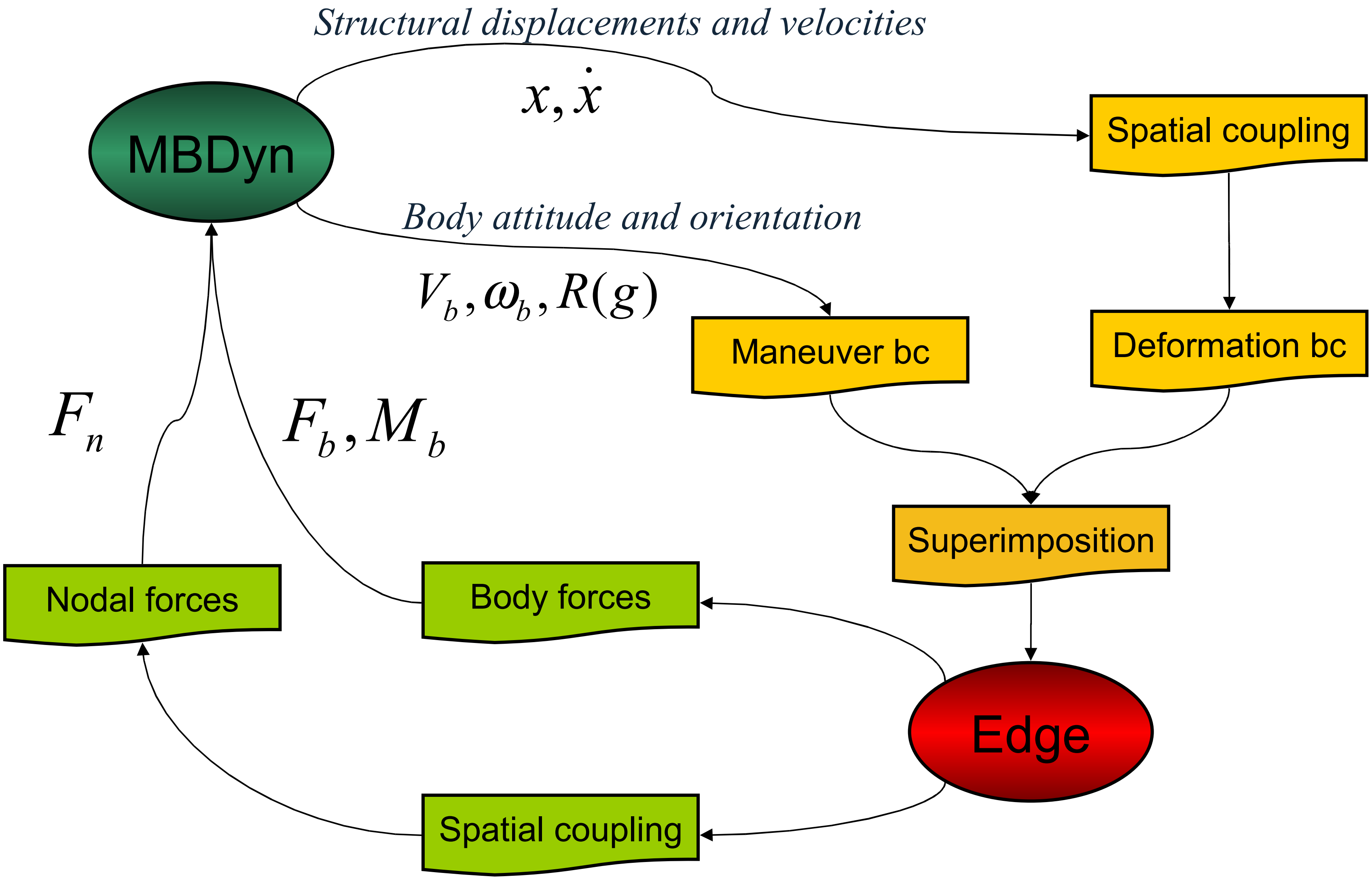
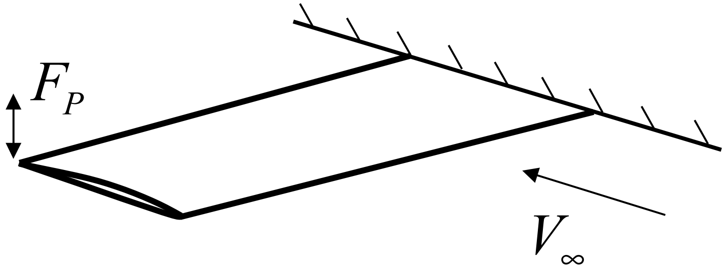
MBDyn-Edge coupling strategy



MBDyn-Edge: AGARD445.6 wing response

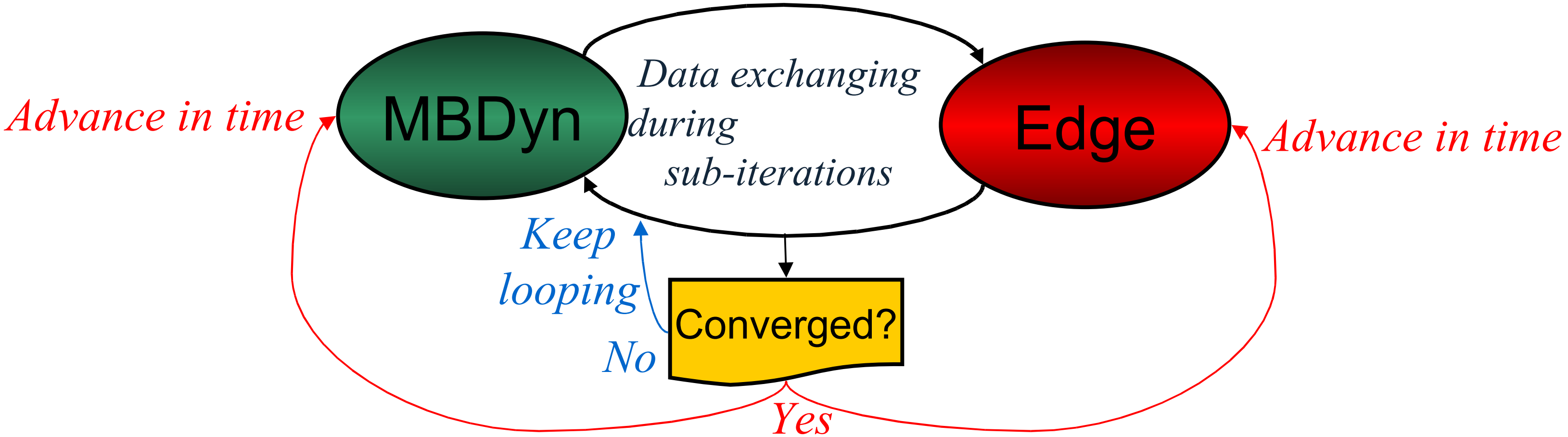
- Coupled simulation to assess instability points and examine post-flutter conditions
- An excitation is given to the wing starting from a reference equilibrium condition

$$F_P = F_0 \sin(\omega t), \quad t < t_0$$
$$F_P = 0, \quad t > t_0$$



Sketch of the direct coupled simulation

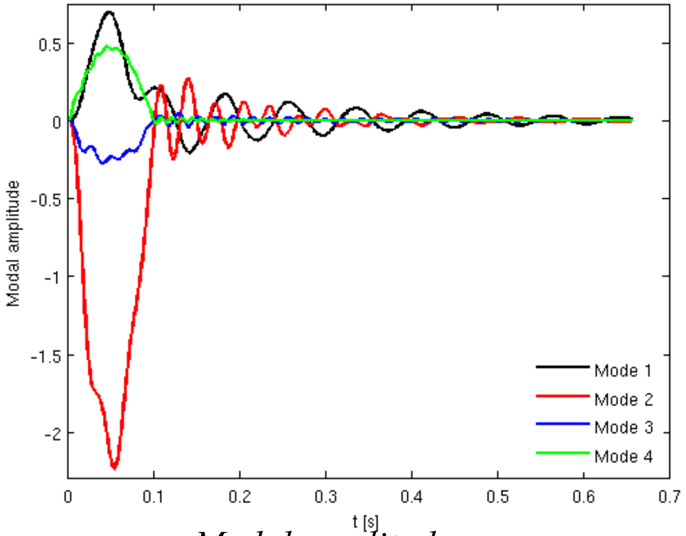
- Stability is determined looking at structural damped/diverging response
- Tightly coupled approach pursued (user-defined parameters)



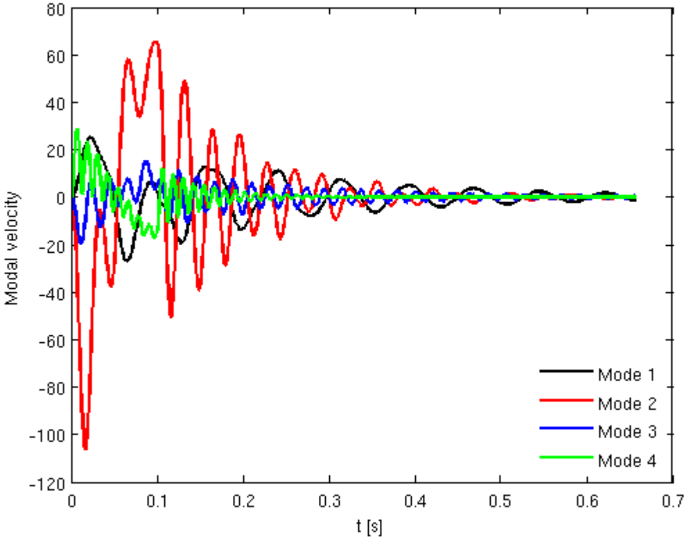
Coupled strategy adopted

MBDyn-Edge: AGARD445.6 wing response

$$V_\infty = 231.37\, m/s$$
$$M_\infty = 0.678$$
$$p_\infty = 10.326\, Pa$$
$$T_\infty = 289.4\, K$$
$$q_\infty = 3.327\ Pa$$

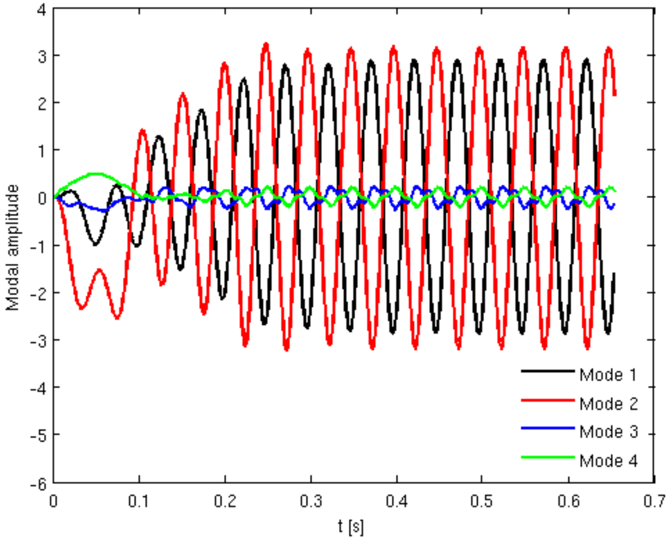


Modal amplitudes

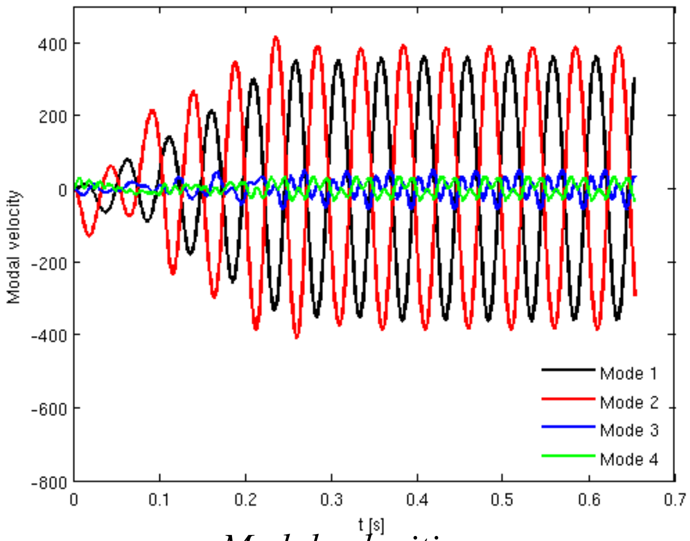


Modal velocities

$$V_\infty = 231.37\, m/s$$
$$M_\infty = 0.678$$
$$p_\infty = 17.188\, Pa$$
$$T_\infty = 289.4\, K$$
$$q_\infty = 4.710\ Pa$$



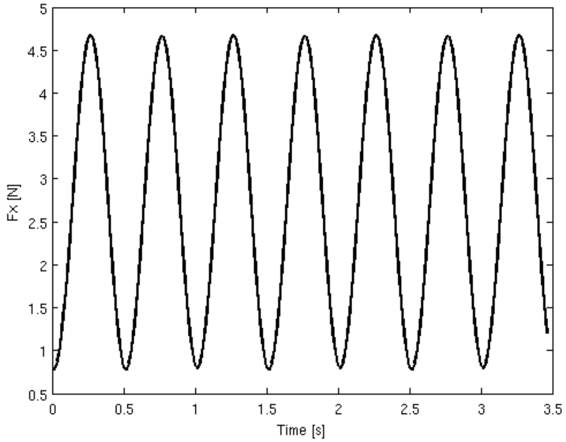
Modal amplitudes



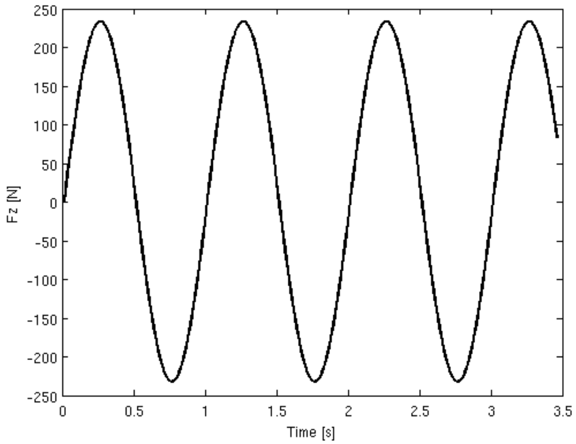
Modal velocities

Unsteady maneuver: AGARD445.6 wing

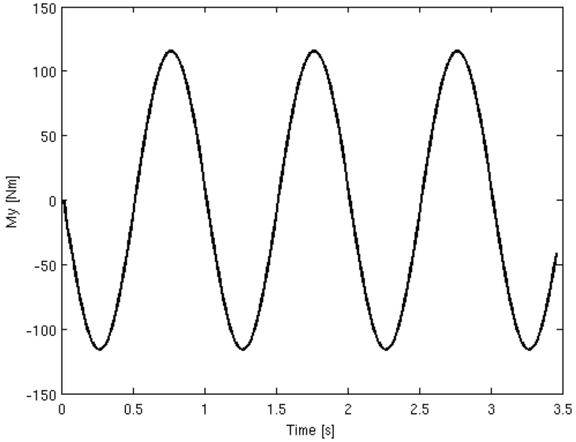
- Simulate a body flying with constant linear velocity and rotating around pitch axis



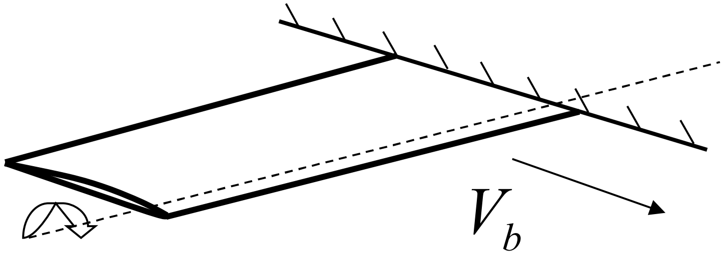
F_x (inertial axes)



F_z (inertial axes)



M_y pitch moment



$$\theta(t) = \theta_0 \sin(\omega t)$$

Sketch of the maneuver

Values	*Edge*
θ_0	2 deg
ω	2π rad/s
V	231.37 m/s
M_∞	0.678

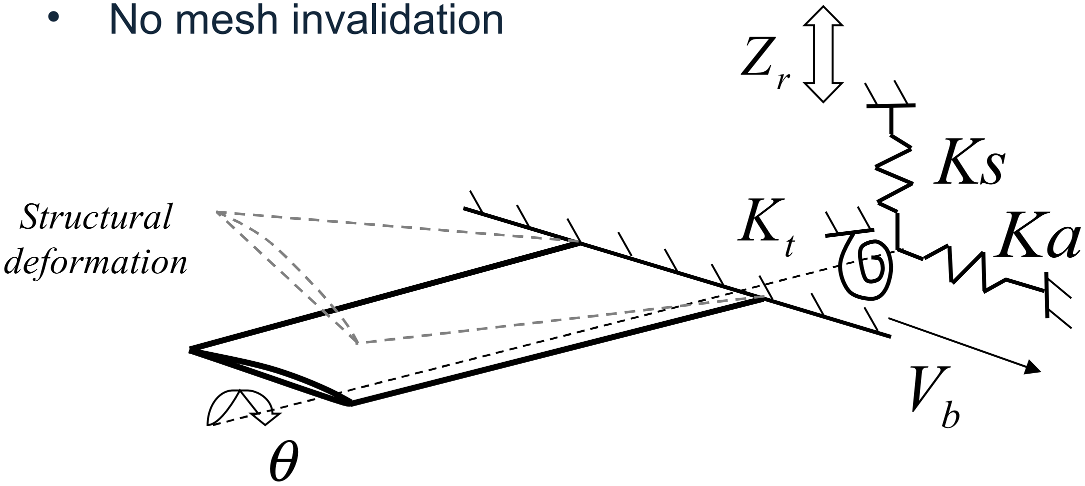
Reference values

Derivative	*Edge*	*DLM*
$C_z\alpha$	3.476	3.274
$C_m\alpha$	3.752	3.655
$C_z\dot{\alpha}+C_zq$	8.643	9.107
$C_m\dot{\alpha}+C_mq$	10.787	11.992

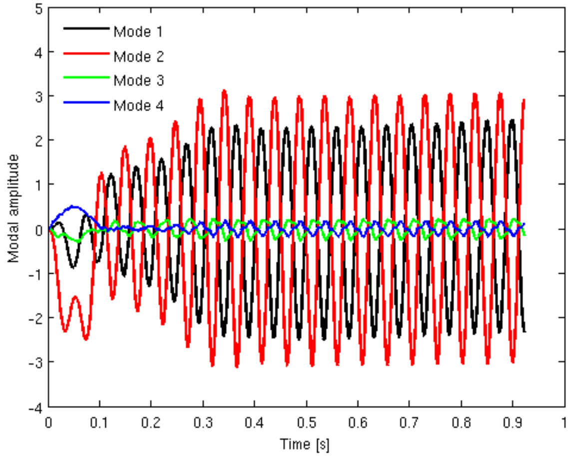
Dynamic derivatives, k=0.006

MBDyn-Edge: rigid and deformable dynamics

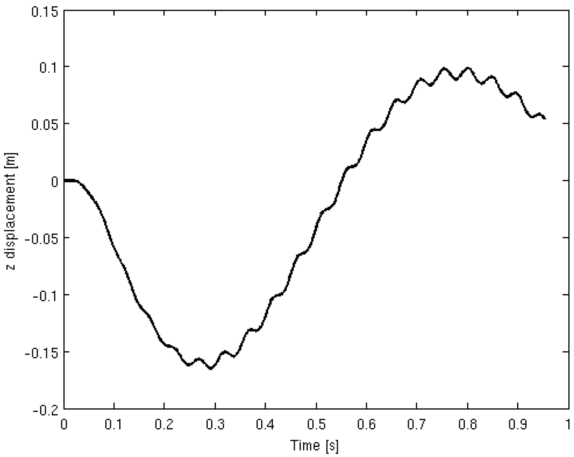
- Rigid and deformable dynamics are combined to analize the most general case
- No mesh invalidation



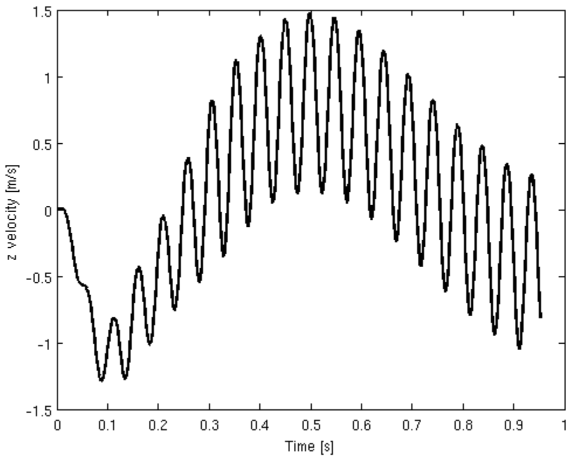
Sketch of the maneuver



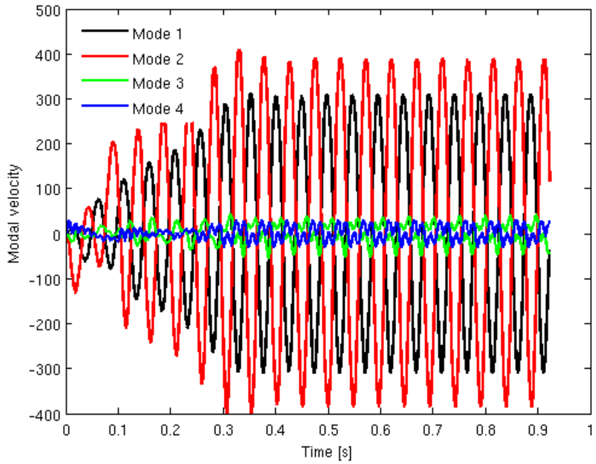
Modal amplitudes



Vertical displacement

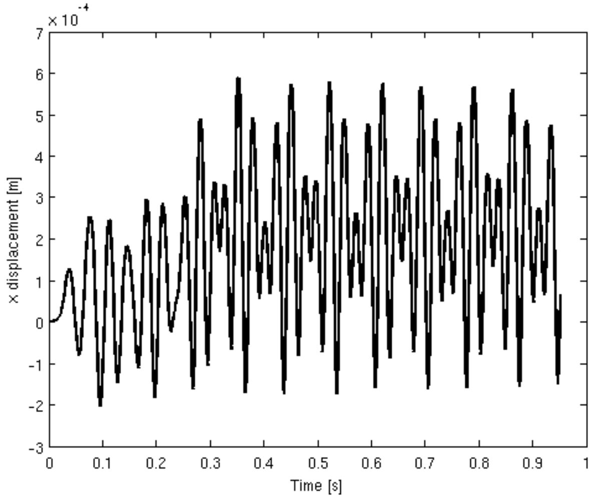


Vertical velocity

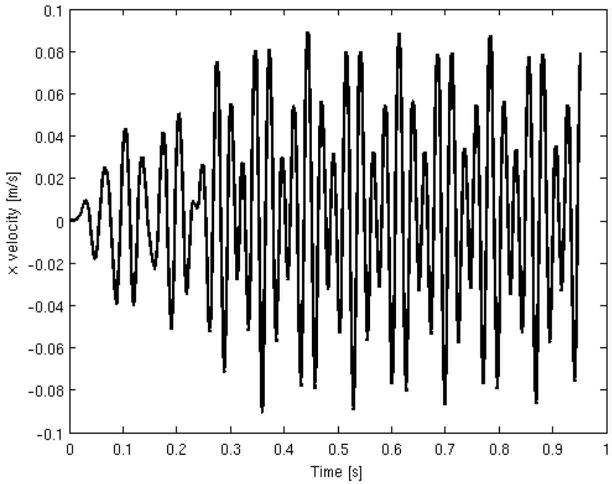


Modal velocities

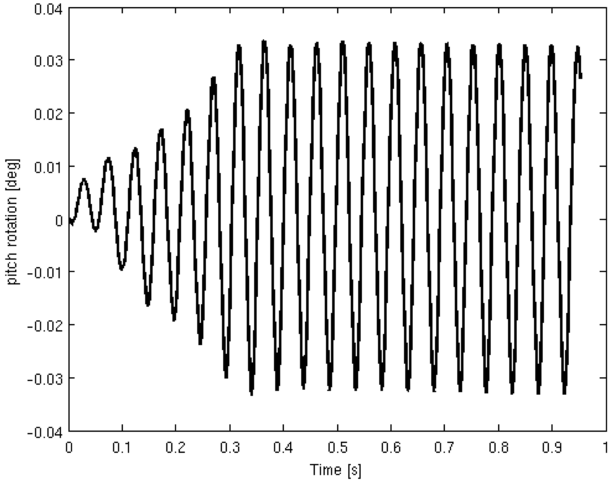
MBDyn-Edge: rigid and deformable dynamics



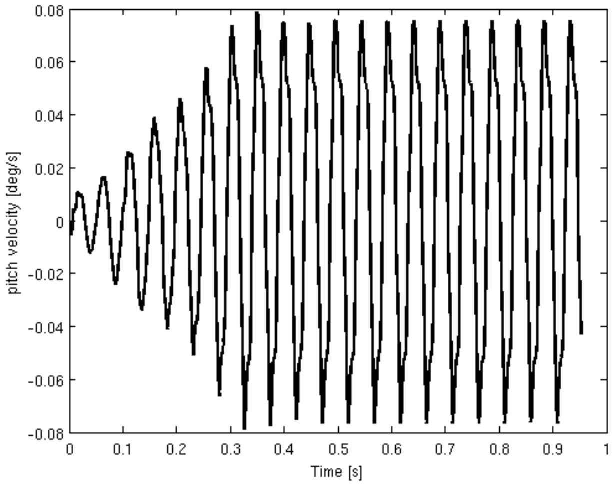
Axial displacement



Axial velocity



Angular displacement



Angular velocity

Outline

- Targets and motivations
- MBDyn multibody code
- New developments in Edge flow-solver for aeroelastic maneuvers
- Test case considered
- Examples of body and deformable analyses
- Conclusions

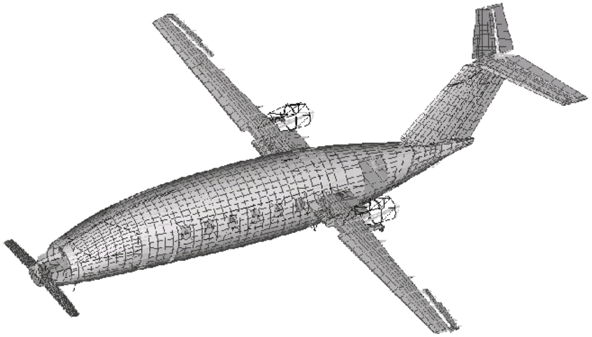
Conclusions

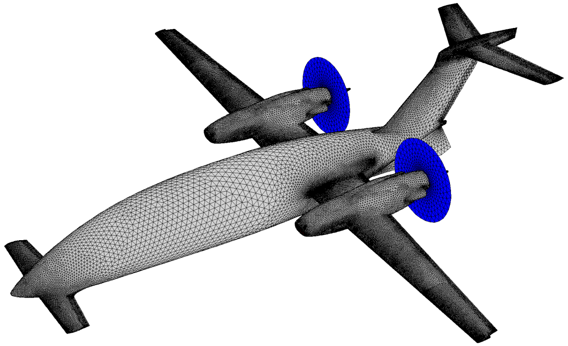
- the first step towards the creation of a high-fidelity tool for FSI has been presented
- several kinds of non-linearities from both structure and flow can be considered
- the coupling of multibody and CFD has been successfully applied to a very simple case up to the case of a deformable maneuver
- the results are encouraging but…

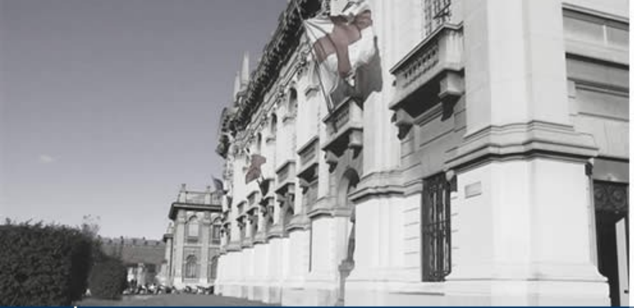
several developments/improvements are being considered!

Future works:

- aeroelastic maneuver of the Piaggio P-180 using FE model or modal testing results
- improve control surfaces deflection in Edge







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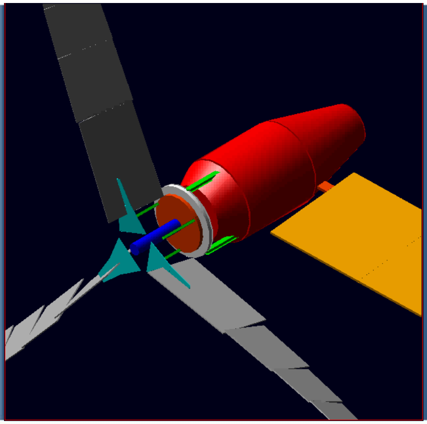

Application of Fluid-Structure Tight Interaction by Multibody-CFD Simulation to Aircraft Aeroelasticity in Free Flight

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