Franco Mastroddi
Marco Eugeni, Stefania Gemma, Cristina Riso, Francesco Saltari
Fulvio Stella, Guido De Matteis, Giorgio Riccardi

Research Topics

1. Reduce Order Modeling (R.O.M.): Nonlinear Aeroelasticity
- Perturbation methods and Normal Form analysis
- Analytical and Computational Aeroelasticity

2. R.O.M. 2: Rigid-body v.s. elastic mechanicics for flying vehicles
- Aeroelasticity of a maneuvering vehicle using a F.E. based description

3. R.O.M. 3: Linearized Aeroelasticity around a nonlinear steady solution
- Approach validated for fixed wing.
- Aeroelasticity of a Launch Vehicle

4. Modeling and simulation for (linear) visco-elastic materials
- Frequency and Time domain description (causality issue)
- Spectral representation of viscoelasticity.

5. MDO and MOO for aircraft preliminary design
- Multi-Objective-Optimization (M.O.O.) *v.s.* Single-Objective-Optimization
- The challenge of unconventional optimization problem.

1. ROM 1: Nonlinear Aeroelasticity
- Perturbation methods and Normal Form analysis
- Analytical and Computational Aeroelasticity

In collaborazione con:

Marco Eugeni
Cristina Riso
Giorgio Riccardi

- Eugeni, M., Mastroddi, F., Dessi, D., "Proper Orthogonal Decomposition of an Aeroelastic Piecewise-Linear System," *Aerotecnica Missili e Spazio, Journal of Aerospace Science, Technologies & Systems,* Vol. 90, No. 1, March 2011, pp. 21-32.
- Mastroddi, F., Dessi, Eugeni, M., ``POD analysis for free response of linear and nonlinear marginally stable aeroelastic dynamical systems,'' *Journal of Fluids and Structures, ,* Vol. 33, Aug. 2012, pp. 85-108, http://dx.doi.org/10.1016/j.jfluidstructs.2012.05.001
- Dessi, D., Mastroddi, F., Mancini, S., ``Analytical formulation of 2D aeroelastic model in weak ground effect,'' *Journal of Fluids and Structures,* Vol. 42, 2013, pp. 270-295, http://dx.doi.org/10.1016/j.jfluidstructs.2013.06.004
- Eugeni, M., Dowell, E.H., Mastroddi, F., ``Post-buckling longterm dynamics of a forced nonlinear beam: a perturbation approach,'' *Journal of Sound and Vibration,* 333(7), p. 2617-2631, 2014. http://dx.doi.org/10.1016/j.jsv.2013.12.026
- Riso, C., Riccardi, G., Mastroddi, F., ``Nonlinear aeroelastic modelling via conformal mapping and vortex method for a flat-plate airfoil in arbitrary motion,'' accepted for publication on *Journal of Fluids and Structures,* Vol. 62, 2016, pp. 230-251, http://dx.doi.org/10.1016/j.jfluidstructs.2016.02.002
- Eugeni, M., Mastroddi, F., Dowell, E.H., ``Normal form analysis of a forced aeroelastic plate, *Journal of Sound and Vibration,* 390(3), 2017, p. 141-163, http://dx.doi.org/10.1016/j.jsv.2016.12.001

Aeroelastic Modeling:

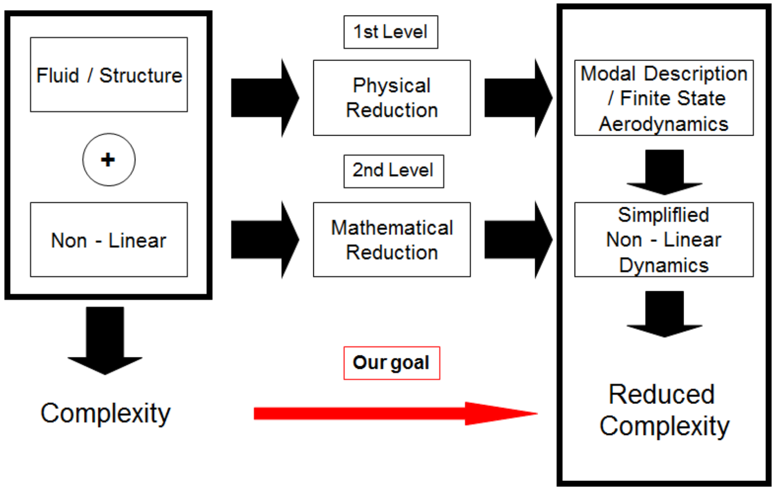
Analitical and num. analysis of nonlinear aeroelastic systems by using ROM

The **increase** of **required performance** in **aeroelastic applications** may require **higher-fidelity models:**

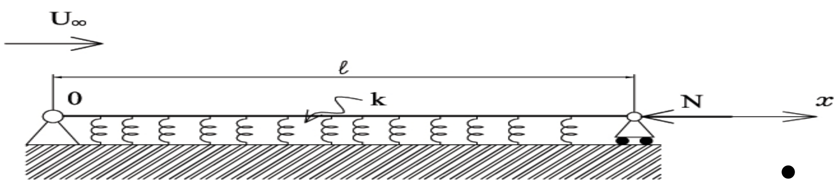
- **Nonlinear phenomena** must be taken into account
- **Large number of degree of freedom** to be considered

Methodologies able to identify the key features of the studied problem:

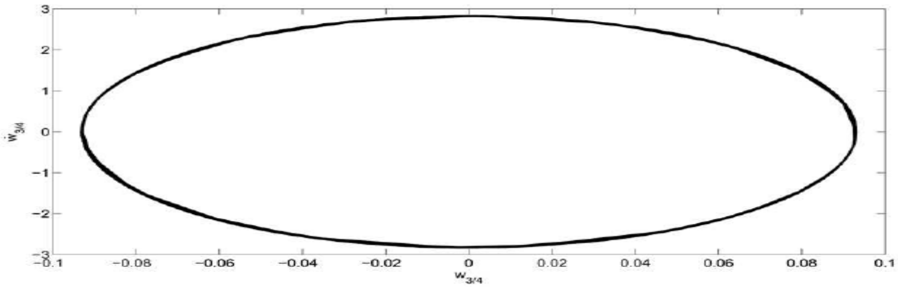
- Analytical methods: **Perturbation Methods based on Normal Form Theory**
- Numerical methods: **Proper Orthogonal Decomposition** (POD)

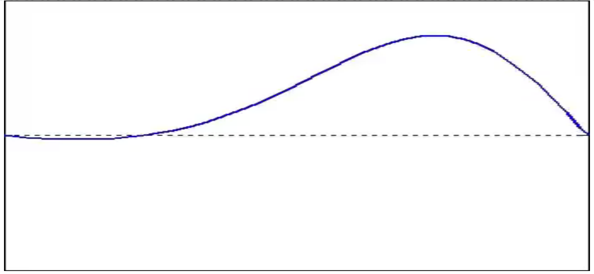


In a neighborhood of a Bifurcation POD modes = invariants manifolds

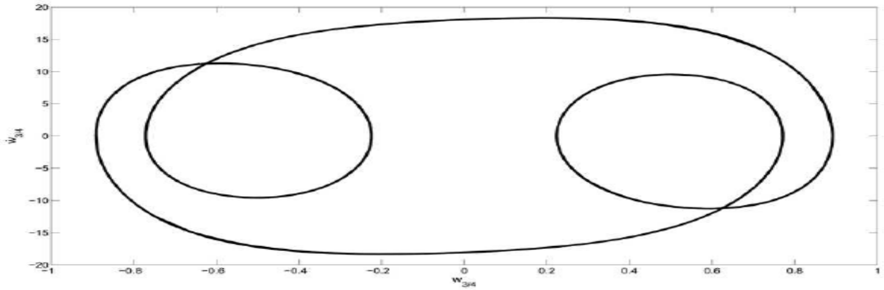


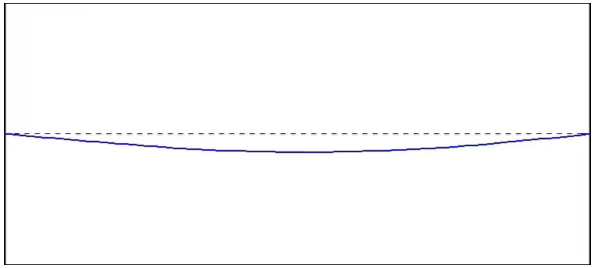
$$N = 0, \quad \theta_1 = 1, \quad \theta_2 = 0, \quad \bar{q} = 344$$



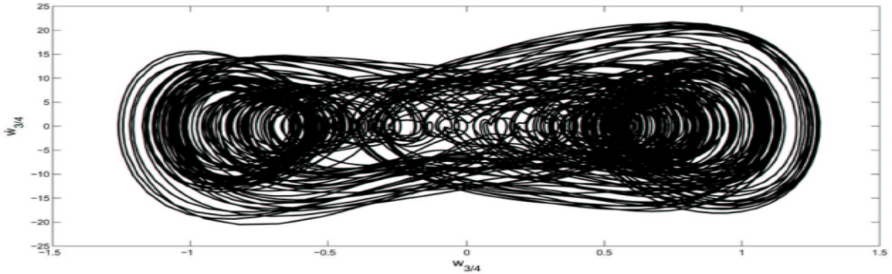


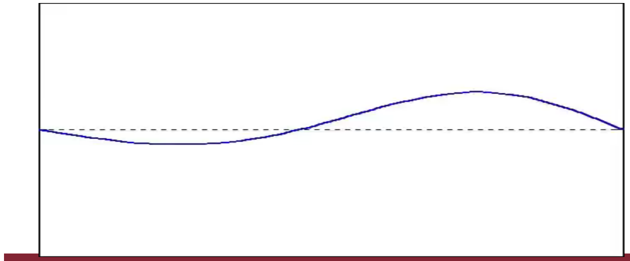
$$N = 3.5, \quad \theta_1 = 1, \quad \theta_2 = 0, \quad \bar{q} = 170.4$$





$$N = 4, \quad \theta_1 = 1, \quad \theta_2 = 0, \quad \bar{q} = 120$$





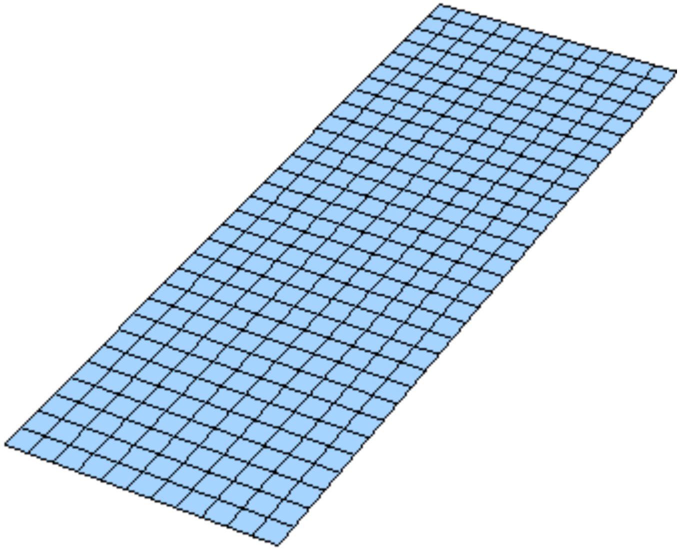
- First two POVs: 99.96 % total energy

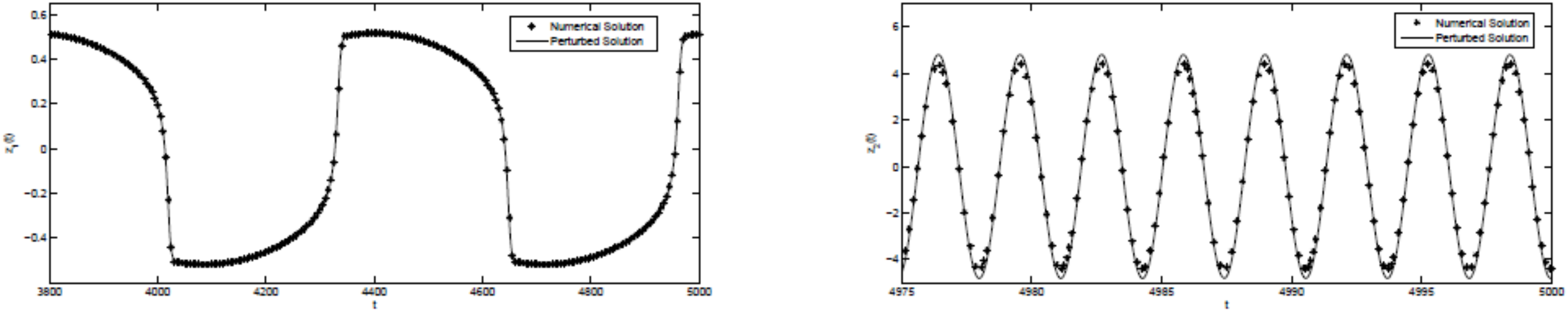
Normal Form capability for Snap-through vibration of VonKarman plate

Buckled VonKarman plate undergone to a harmonic excitation:

Only one dynamic equation is dominant (Normal Form)

$$\varphi = 0.30 \quad \mathrm{S} = 0.68 \quad \mathrm{N_x} = 1.30 \quad \epsilon = 0.11$$





(a) (b)

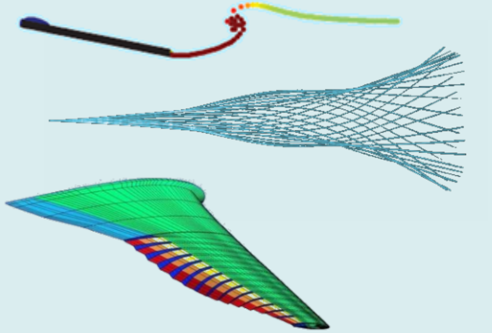
Figure 3: Perturbed vs Numerical solution, $g = 1$ $\Omega_1 = 0.01$, $\Omega_2 = 2$, $f_1 = 1$, $f_2 = 1$

Semi-analytical nonlinear aeroelastic modeling

What?

Nonlinear aeroelastic modeling for (highly) flexible airfoils

Specialized to:
Flat-plate airfoils
Deformable thin airfoils



How?

Conformal mapping

Limitations:
Inviscid incompressible fluids
Attached potential flows

Advantages:
Semi-analytical models
Arbitrary motion
Free-wake effects

Why?

Possible applications

Physical insight:
Thrust generation (MAVs)
Bifurcations and LCOs

Semi-analytical nonlinear aeroelastic modeling

Simulation of a sudden start with free wake

Simulation procedure:

1. **Initial time:** section in configuration of elastic equilibrium and fluid at rest
2. **Input:** sudden start
3. **Transient aeroelastic response**
4. **Aeroelastostatic solution**

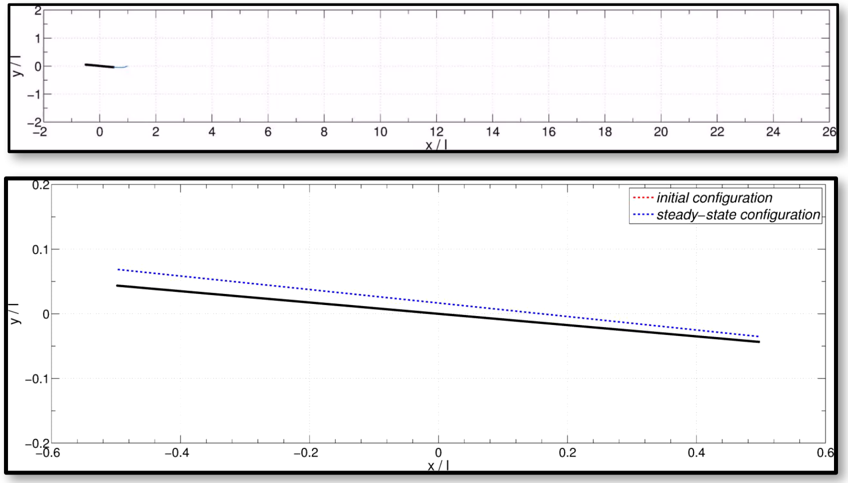
Typical section property	
horizontal spring frequency	12.5 Hz
vertical spring frequency	2.5 Hz
torsional spring frequency	5 Hz
plate length	1 m
added-to-airfoil mass	0.1
added-to-airfoil moment of inertia	0.05
mass center position	half chord
elastic center position	half chord

Case studies:

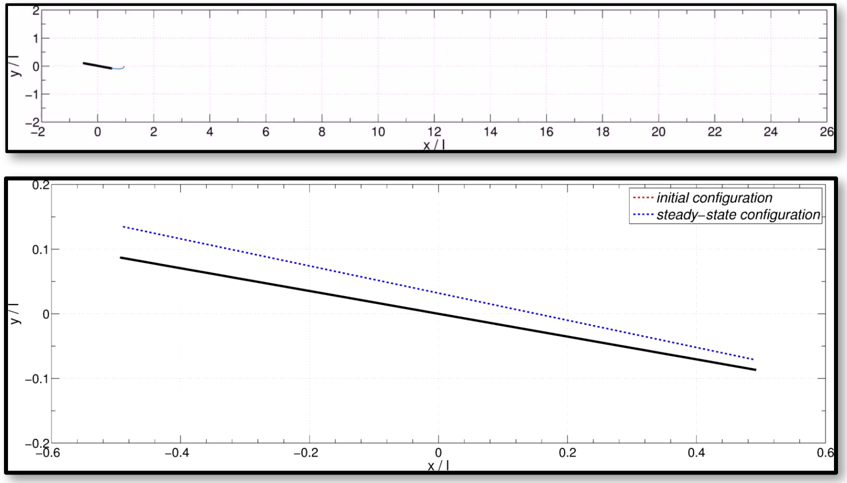
Test	u_∞ (m/s)	α_0 (deg)
1	10	5
2	10	10
3	15	5
4	15	10

Increasing initial angle of attack →

Test #1



Test #2



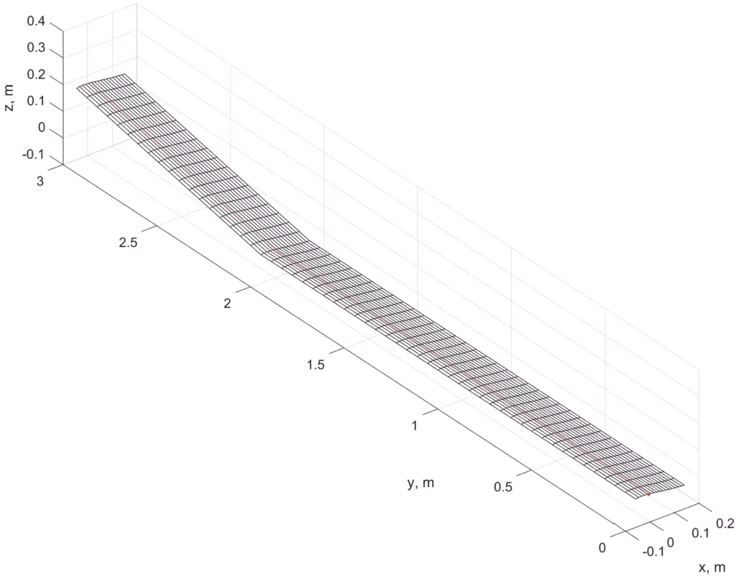
Application to the University of Michigan’s X-HALE: an highly flexible UAV for nonlinear aeroelastic tests

→ **Highly flexible aircraft**

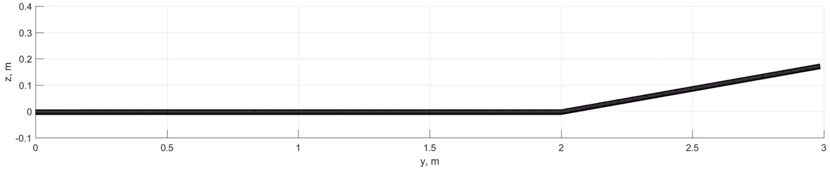
- Integrated formulation of flight dynamics and **nonlinear** aeroelasticity
- Linearization around **nonlinear** trim conditions
- Implementation using off-the-shelf **nonlinear** FEM/VLM (CFD) structural/aerodynamic solvers to**:**
    - Solver nonlinear aeroelastic trim
    - Perform local normal modes analysis
    - Characterize local unsteady aerodynamics

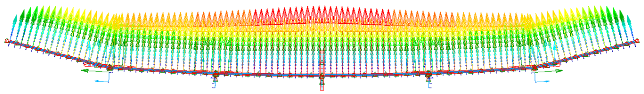
Development of a FEM/VLM environment for nonlinear aeroelastic trim of highly flexible aircraft

X-HALE wing aeroelastostatic deflection in the nonlinear trim loop (isometric view):

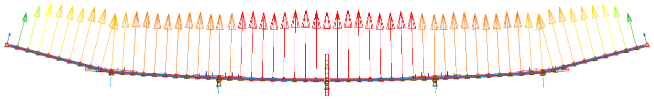


X-HALE wing aeroelastostatic deflection in the nonlinear trim loop (front view):





Trim aerodynamic forces on VLM and FEM grids



2. R.O.M. 2: Rigid-body v.s. elastic mechanics for flying vehicles

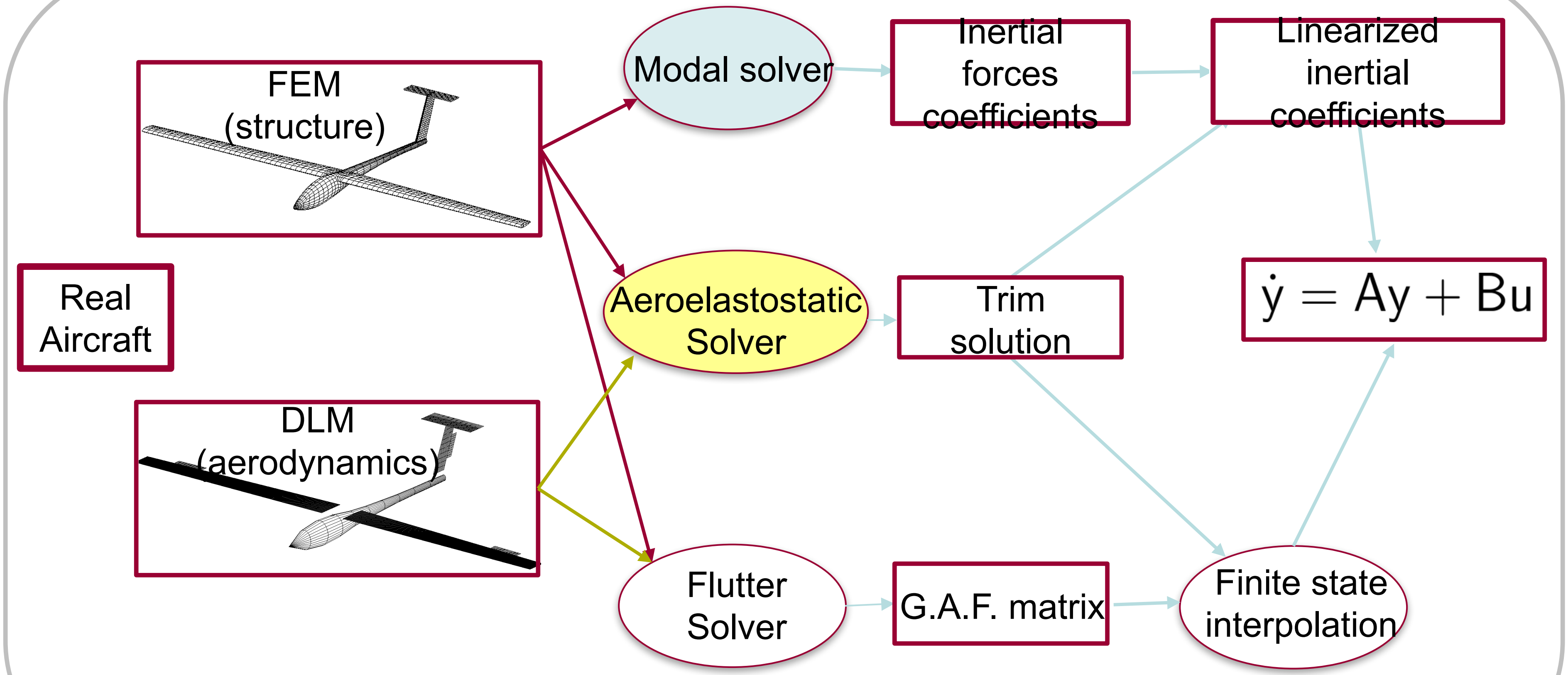
- Aeroelasticity of a maneuvering vehicle using a F.E. based description

In collaborazione con:

Guido De Matteis
Cristina Riso
Francesco Saltari

- Vetrano, F., Mastroddi, F., Ohayon, R., ``POD Approach for Unsteady Aerodynamic Model Updating,'' *CEAS Aeronautical Journal,* Vol. 6, No. 1, March 2015, pp. 121-136. DOI: 10.1007/s13272-014-0133-0
- Saltari, F., Riso, C., De Matteis, G., Mastroddi,F.,``Finite-Element Based Modeling for Flight Dynamics and Aeroelasticity of Flexible Aircraft," accepted for publication on ," *AIAA Journal of Aircraft*, 2016.

Schema piattaforma numerica



Real Aircraft

FEM (structure)

DLM (aerodynamics)

Modal solver

Aeroelastostatic Solver

Flutter Solver

Inertial forces coefficients

Trim solution

G.A.F. matrix

Linearized inertial coefficients

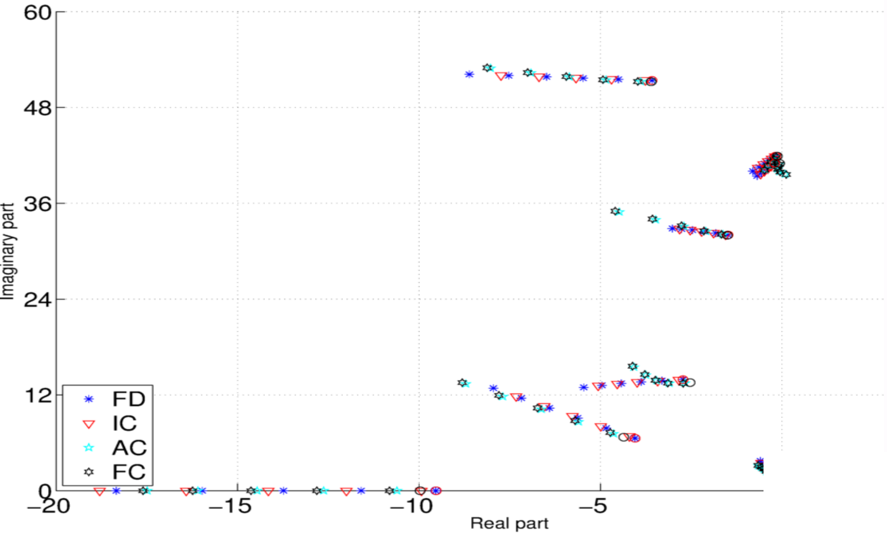
$$\dot{y} = Ay + Bu$$

Finite state interpolation

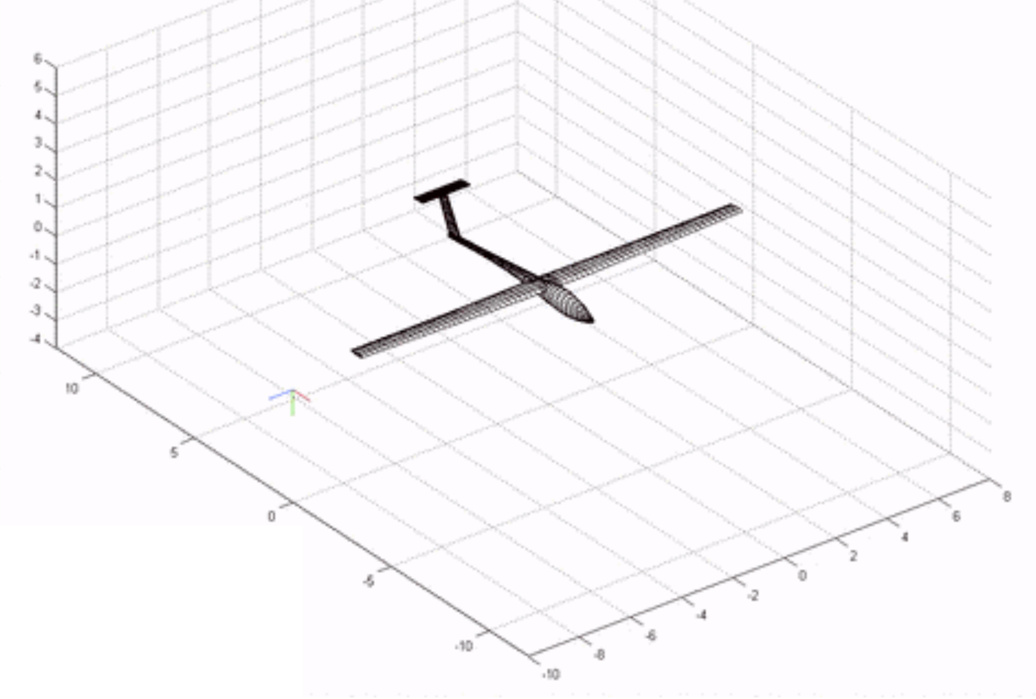
Integrated Flight Dynamics-Aeroelasticity Tool

Modellazione integrata di dinamica del volo e aeroelasticità (III)

Studio della **stabilità**



Studio della **risposta alla raffica**



3. ROM 3: Linearized Aeroelasticity around a nonlinear steady solution

- Approach validated for fixed wing.
- Aeroelasticity of a Launch Vehicle

In collaborazione con:

Fulvio Stella

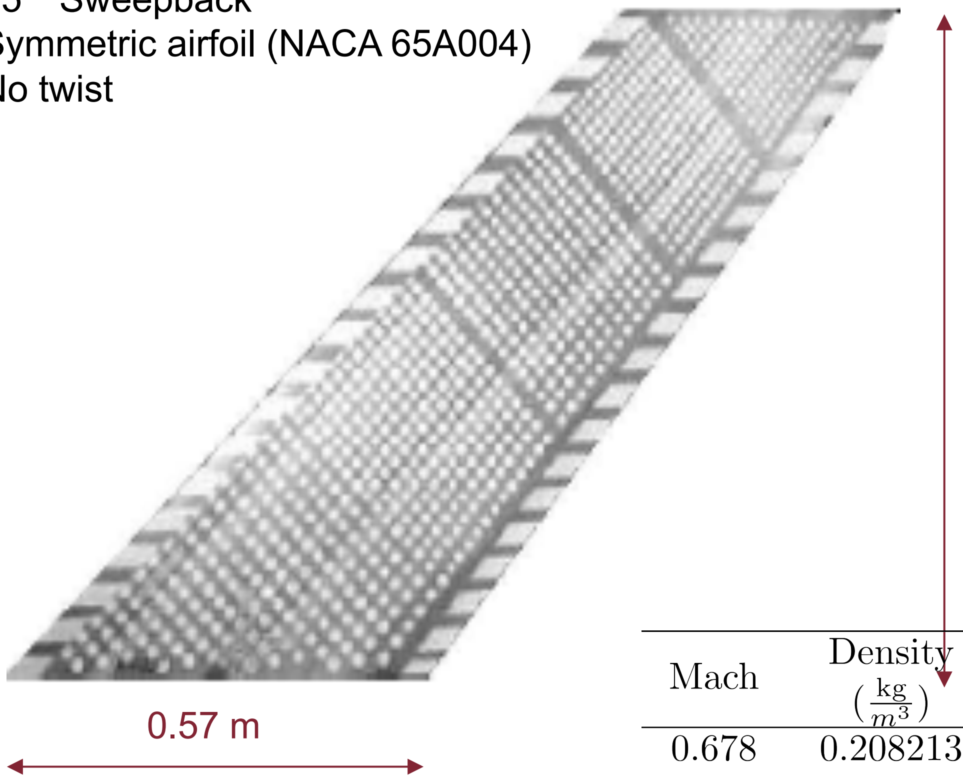
- Mastroddi, F., Stella, F., Cantiani, D., Vetrano, F., ``Linearized Aeroelastic Gust Response Analysis of a Launch Vehicle,'' *AIAA - Journal of Spacecraft and Rockets,* Vol. 48, No. 3, May-June 2011, pp. 196-206. DOI: 10.2514/1.47268
- Mastroddi, F., Linari, M., Coppola, F., ``Un ambiente computazionale integrato per l’analisi interazionale fluido struttura di sistemi non-lineari di interesse aeronautico,” *A & C. Analisi e Calcolo, Anno XII,* No. 44, maggio 2011, pp. 13-16.
- Vetrano, F., Mastroddi, F., Ohayon, R., ``POD Approach for Unsteady Aerodynamic Model Updating,'' *CEAS Aeronautical Journal,* Vol. 6, No. 1, March 2015, pp. 121-136. DOI: 10.1007/s13272-014-0133-0
- Castronovo, P., Mastroddi, F., Stella, F., Biancolini, M.E., ``Assessment and Development of a ROM for Linearized Aeroelastic Analyses of Aerospace Vehicles,” submitted and under revision on *CEAS Aeronautical Journal*, 2016.

Test case AGARD 445.6

Langley Transonic Dynamic tunnel (AGARD)

[Yates E.C., "AGARD Standard Aeroelastic Configurations for Dynamic Response I.-Wing 445.6", AGARD report No 765, 1985.]

- 45° Sweepback
- Symmetric airfoil (NACA 65A004)
- No twist



Experimental Data

- Modal Parameters
- Wing Tunnel set-up
- **Flutter** points

Configuration **Weakened 3**

- Laminated Mahogany
- Uniformly Drilled

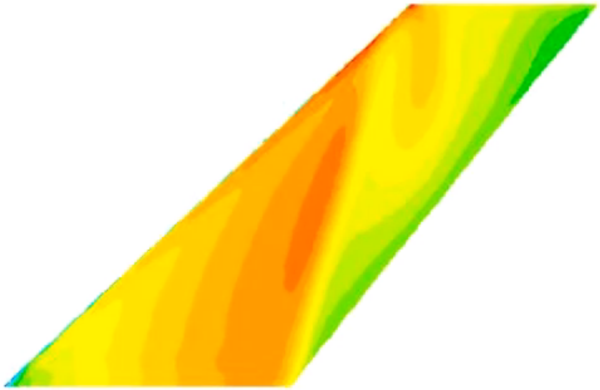
Experimental Flutter points

Mach	Density $(\frac{kg}{m^3})$	Velocity $(\frac{m}{s})$	Dynamic pressure (Pa)	Frequency (Hz)
0.678	0.208213	231.37	5573.21	18.0
0.960	0.063392	309.01	3026.47	13.9
1.141	0.078338	364.33	5199.05	17.5

ROM for Unsteady Aerodynamics

ROM: technique for reducing the computational complexity of mathematical models in numerical simulations. The physical model is unchanged.

DOFs: CFD → N Modes

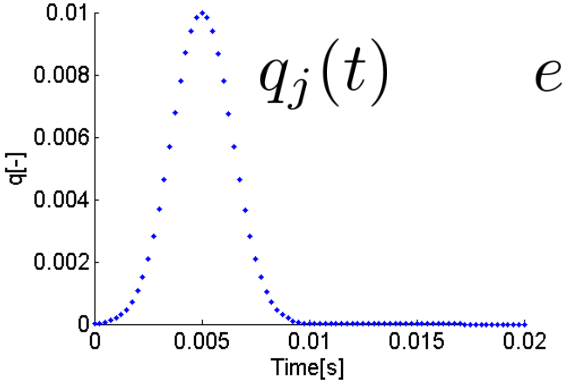


Developed CFD function

$$\oiint_{\mathcal{S}} \tilde{C}_p \, \mathbf{n} \cdot \boldsymbol{\psi}_n(\mathbf{x}) \, d\mathcal{S}$$

Mode interpolation

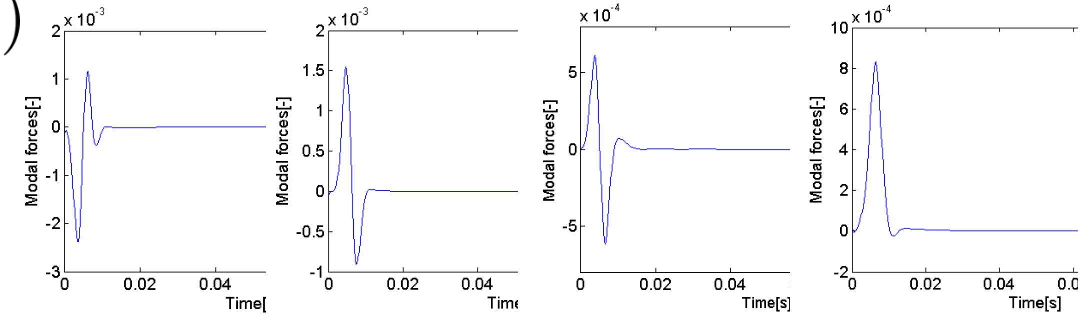
INPUT: n-th mode



$q_j(t)$

$e_i^{(j)}(t)$

OUTPUT: projected C_P



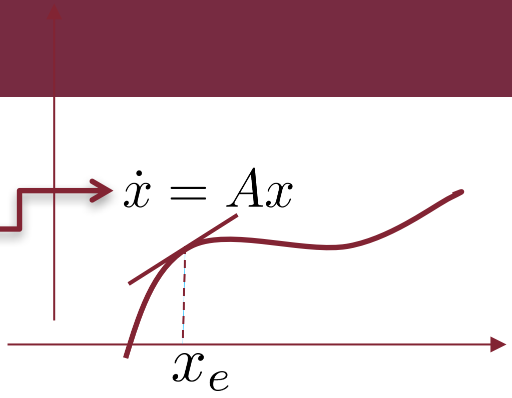
Generalized Aerodynamic Force Matrix

Linearization around x_e

Statically nonlinear

Dynamically linear

$\dot{x} = Ax$



Input

$q_j(t)$

$e_i^{(j)}(t)$

Output

FFT

$$\boxed{E_{ij}(f, U_\infty, M_\infty)} = \frac{e_i^{(j)}(f, U_\infty, M_\infty)}{q_j(f)}$$

$$(s^2 M + sD + K)\tilde{q} = q_D \boxed{E(s; U_\infty, M_\infty)} \tilde{q} + \tilde{f}$$

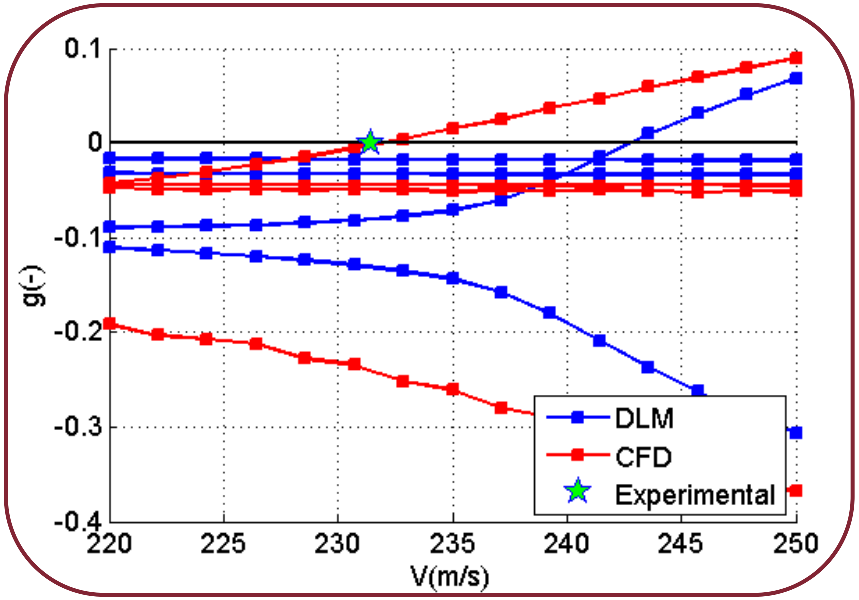
Numerical continuation method on s

Find **aeroelastic poles** iteratively for a combination of:

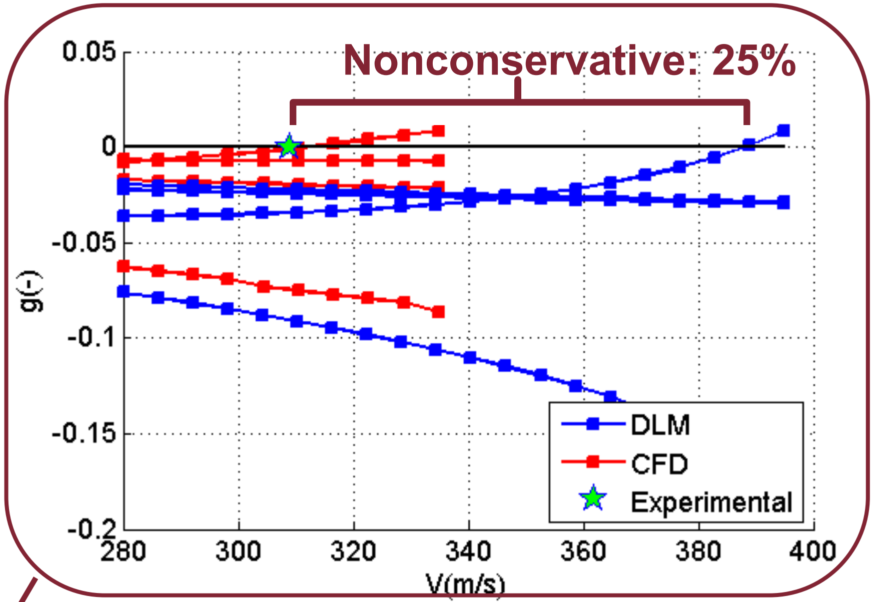
$U_\infty \quad M_\infty \quad \varrho_\infty$

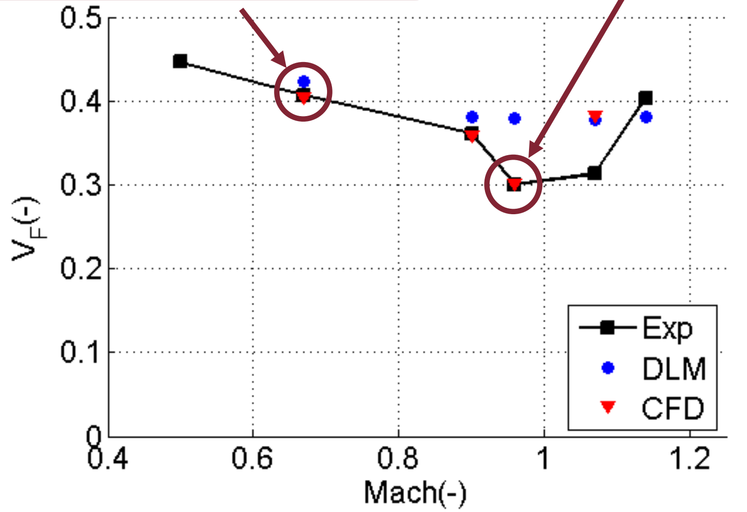
Flutter prediction

Subsonic flow M=0.67



Transonic flow M=0.96





Transonic Dip

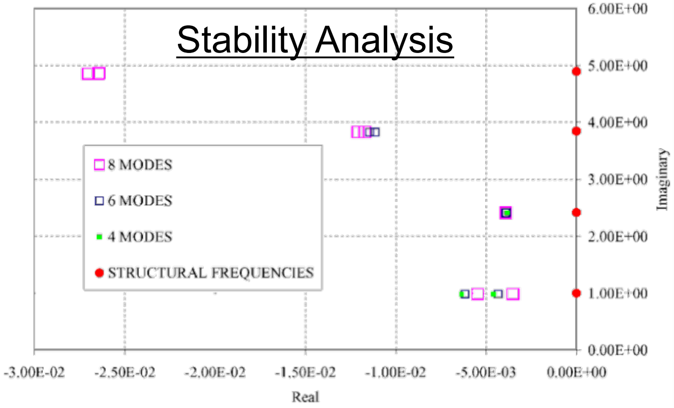
- CFD-based: high accuracy for M<1
- DLM-based commercial codes: no prediction of the phenomenom

Aeroelastic Modeling:

- stability and response linearized analyses for Launch Vehicles (VEGA LV)

OBJECTIVE:
Study of interaction between *structures/esternal flow* to determine possible critical flight conditions

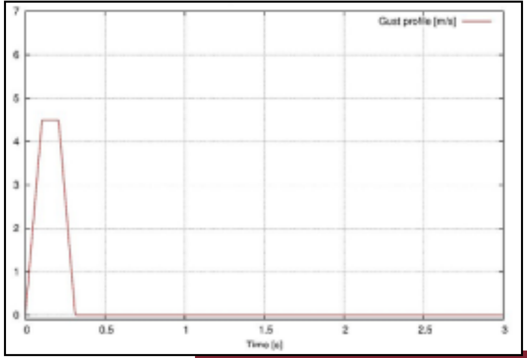
- **N.B.: Linearization process based on lessons learned on fixed-wing linear aeroelasticity**
- Structure described by means of a modal basis, the aerodynamics by a CFD Euler-based solver.


Stability Analysis

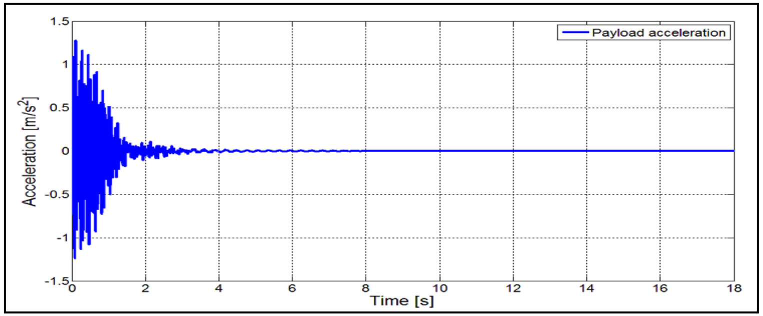

eroelastic Gust Response for VEGA LV: first input type, time simulation for 7s, displacements multiplied by 100

Gust Response in Transonic Flight Condition

Gust input



Gust output: payload acceleration



4. Modeling and simulation for (linear) visco-elastic materials

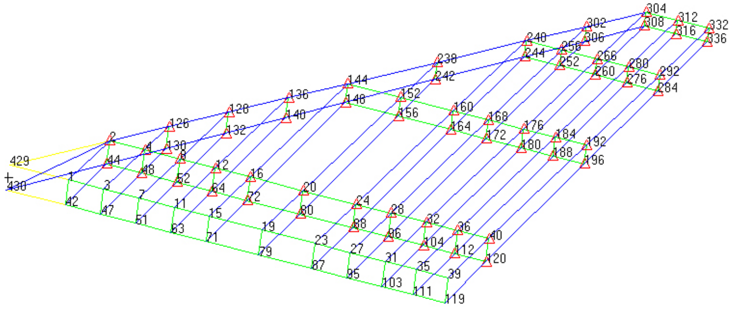
- Spectral representation of structures viscoelasticity.
- Frequency and Time domain description (causality issue)

In collaborazione con:

Marco Eugeni
Giuliano Coppotelli

- Mastroddi, F., Calore, P., ``On the Modal Decoupling of Linear Mechanical Systems with Frequency-Dependent Viscoelastic Behavior,'' *Mechanical Systems and Signal Processing*, Vol. 70-71, 2016, pp. 769-787, DOI: 10.1016/j.ymssp.2015.09.024 2014.
- Mastroddi, F., Eugeni, M., Erba, F., ``On the Modal Diagonalization of Viscoelastic Mechanical Systems, " submitted and under revision on *Mechanical Systems and Signal Processing*, 2016.

Spectral decomposition of the of a structure Frequency-Response with a high level of damping

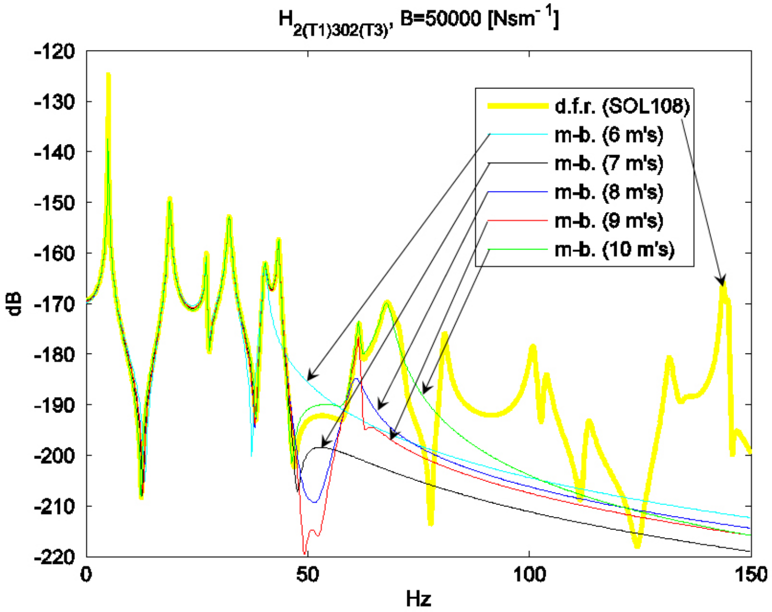


Cassone velivolo ad ala corta

Wing span	7.00 [m]
Root	2.49 [m]
Tip	0.35 [m]
E	72.5 [GPa]
v	0.33
ρ	2810[kg m^{-3}]
Nodi	86
g.d.l	186 (3 × 86-3 × 24)

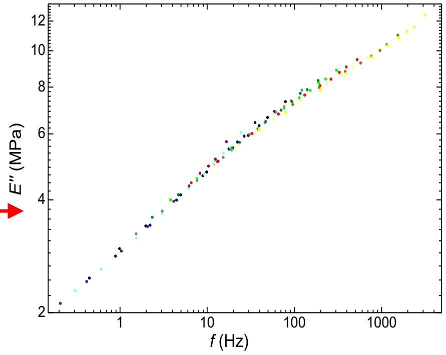
BASE MODALE COMPLETA:

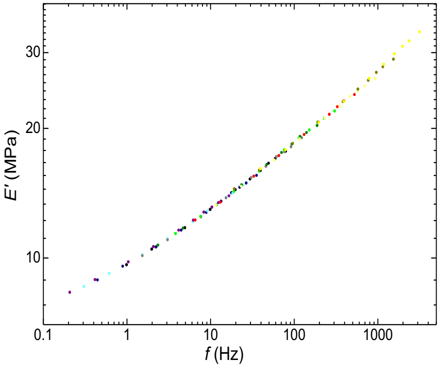
186 modi *reali*

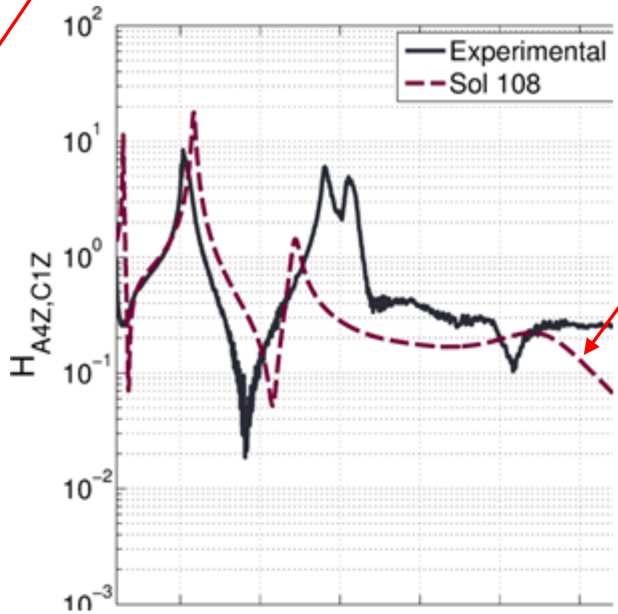


Elementi smorzanti del tipo ***dashpot dampers*** sono posti **lungo il t.e e l.e.** superiormente e inferiormente.

Spectral decomposition of the of a structure Frequency-Response with a high level of damping







Some *causality* problems to be fixed if the model is used in Time domain taking a Inverse Fourier Transform

5. MDO and MOO for aircraft preliminary design

- MOO v.s. S.O.O.

- The challenge of unconventional optimization problem.

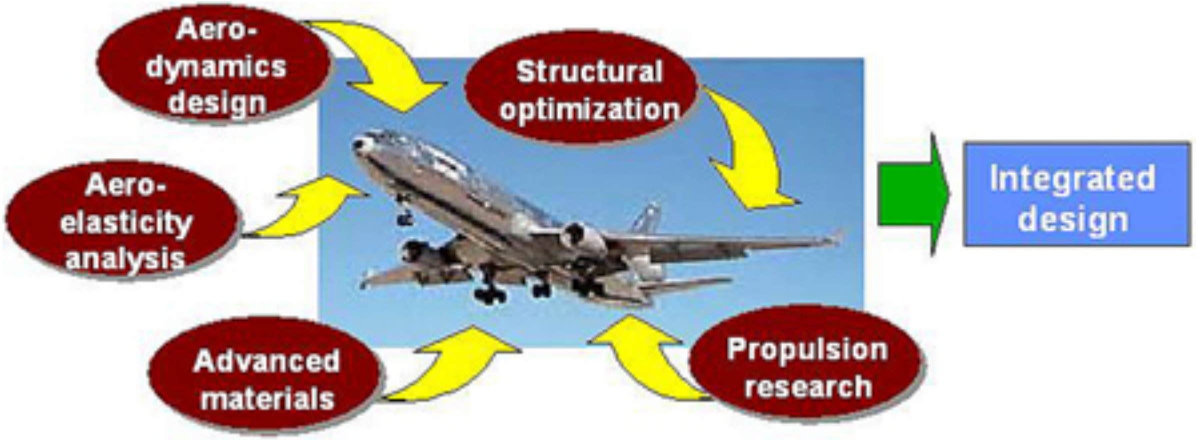
In collaborazione con:

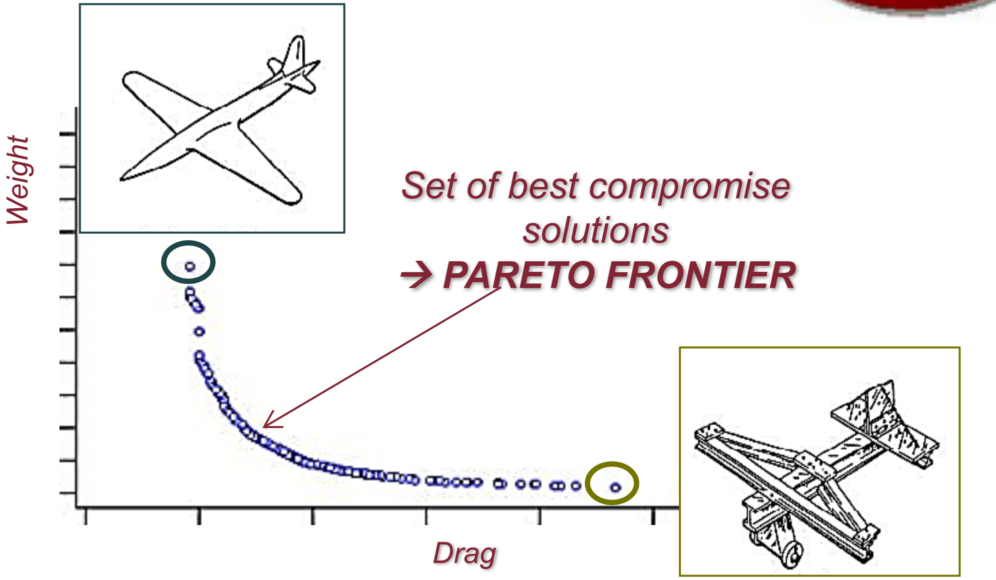
Stefania Gemma
Guido De Matteis

- Mastroddi, F., Tozzi, M., Capannolo, V., ``On the use of geometry design variables in the MDO analysis of wing structures with aeroelastic constraints on stability and response", *Aerospace Science and Technology*," Vol. 15, N. 3, 2011, pp. 196-206. DOI: 10.1016/j.ast.2010.11.003.
- Mastroddi, F., Gemma, S., ``Analysis of Pareto Frontiers for Multidisciplinary Design Optimization of Aircraft,'' *Aerospace Science and Technology*, Vol. 28, pp. 40-55, 2013, DOI 10.1016/j.ast.2012.10.003, 2012.
- Gemma, S., Mastroddi, F., ``Nonlinear modelling for Multi-Disciplinary and Multi-Objective Optimization of a complete aircraft,'' *Aerotecnica Missili e Spazio, Journal of Aerospace Science, Technologies & Systems,* Vol. 92, No. 1-2, March-June 2013, pp. 61-68
- Mastroddi, F., Travaglini, L.M., Gemma, S., De Matteis, G., `` Multi-objective Optimization for the Design of an Unconventional Sun-Powered High-Altitude-Long-Endurance Unmanned Vehicle," submitted and under revision on *Structural and Multidisciplinary Optimization,* 2017.

Multidisciplinary-Design Optimization (MDO) and Multi-Objective Optimization (MOO) for Aircraft Preliminary Design

THE BEST PHYSICAL MODELING:
Multi-Disciplinary Analysis and Optimization (MDAO) allows designers to <u>integrate simultaneously</u> all the disciplines into a multidisciplinary computational environment → *coupling interactions*



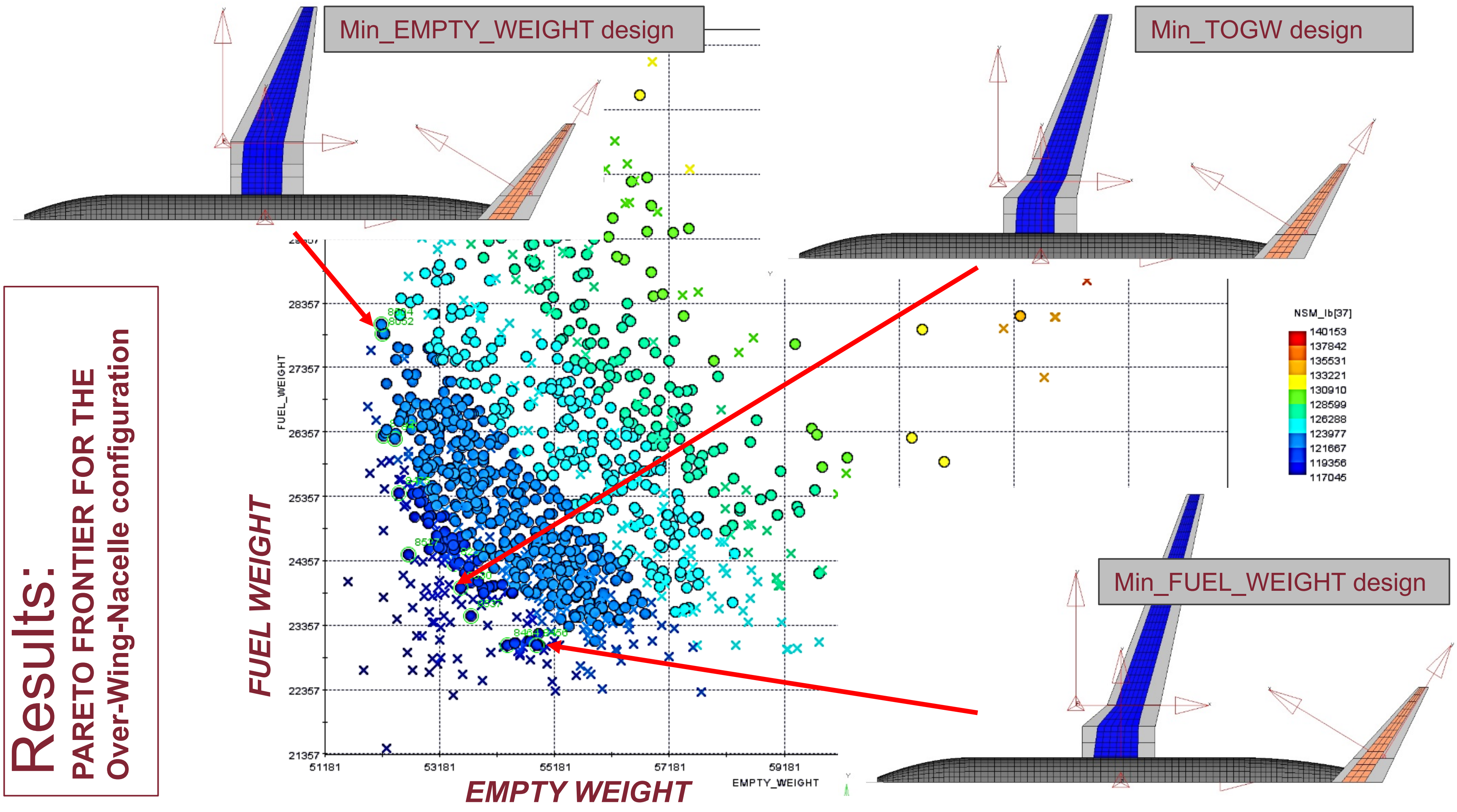


Set of best compromise solutions
→ PARETO FRONTIER

THE BEST MATHEMATICAL FORMULATION:
Multi-Objective Optimization (MOO) for a MDO problem allows to keep homogeneus relevance for each discipline:

- *No artificial constraints are introduced in the optimization problem*
- ***Pareto Frontier** describes the compromise among contrasting objectives*

MDO and MOO for Aircraft Preliminary Design: application on OverWingNacell NASA concept



Min_EMPTY_WEIGHT design

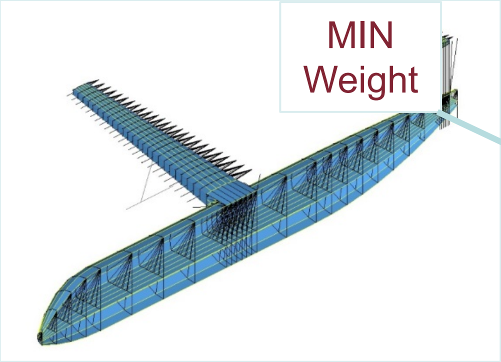
Min_TOGW design

Min_FUEL_WEIGHT design

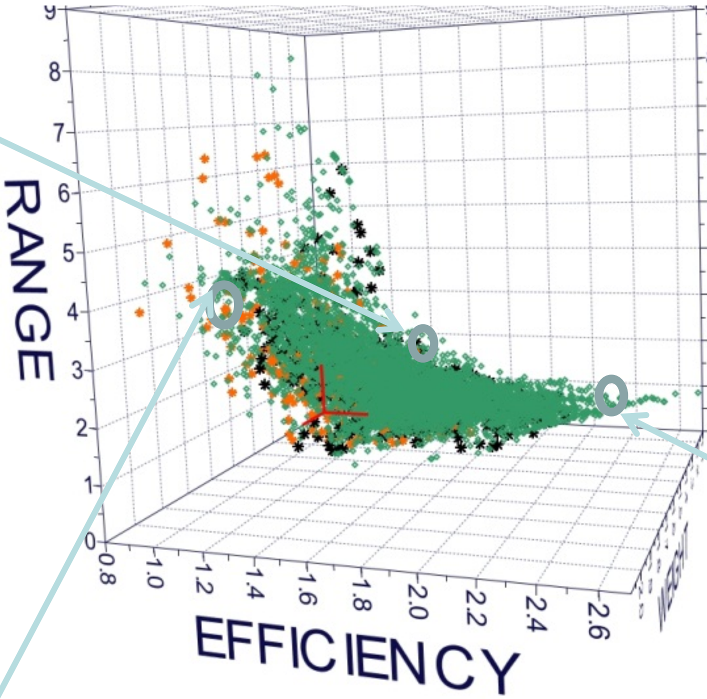
Results:

PARETO FRONTIER FOR THE Over-Wing-Nacelle configuration

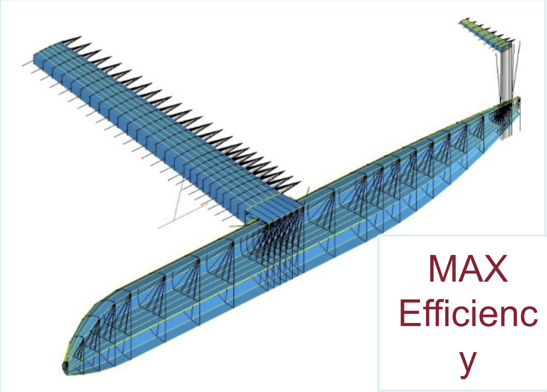
MDO OF A CONVENTIONAL TRANSPORT AIRCRAFT
Results of the MDO-MOO: significant designs



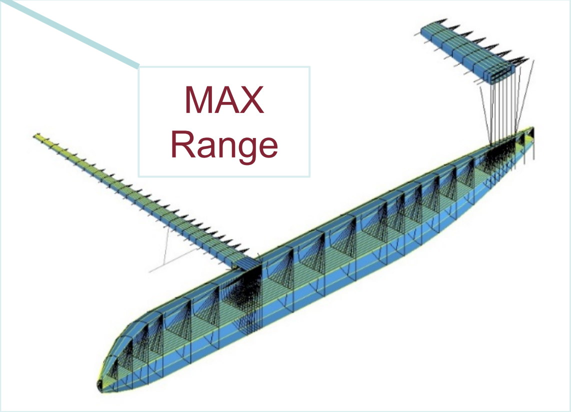
MIN Weight



Design	W [kg]	E	R [km]
Initial design	16047	12.25	4209
W_{opt}	16041	13.180	3792
E_{opt}	17359	25.549	1531
R_{opt}	16338	9.266	5307
min d_{ut} design	17054	14.14	3991
min d_{Gcr} design	16077	14.75	3201
Final design	**16073**	**14.11**	**3438**



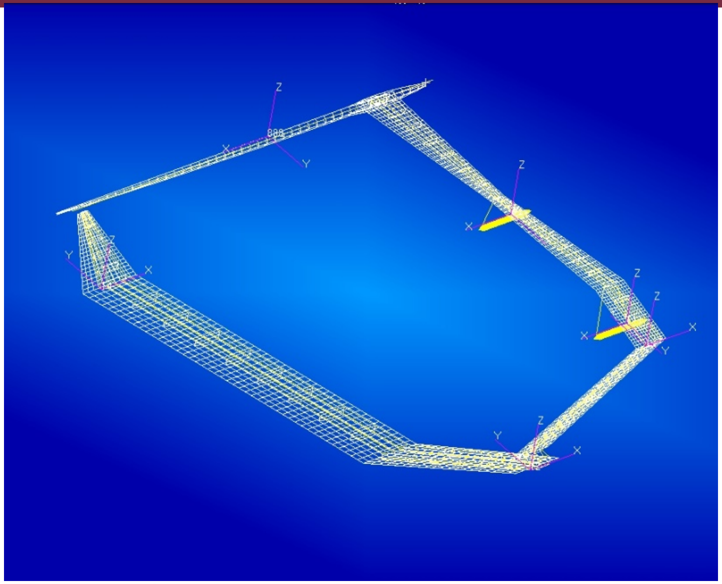
MAX Efficiency

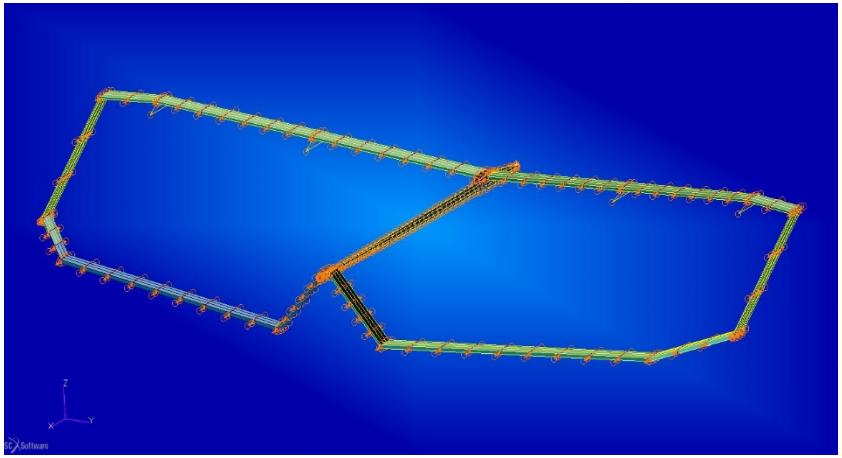


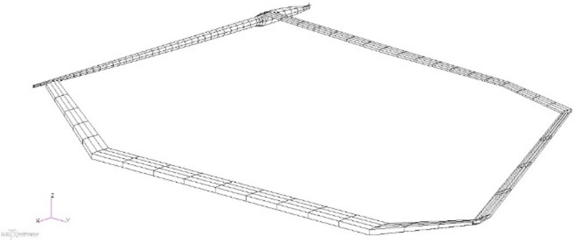
MAX Range

MDO OF AN UNCONVENTIONAL High Altitude Long Endurance (HALE)
Results of the MDO-MOO: significant designs

MOO optimizarion





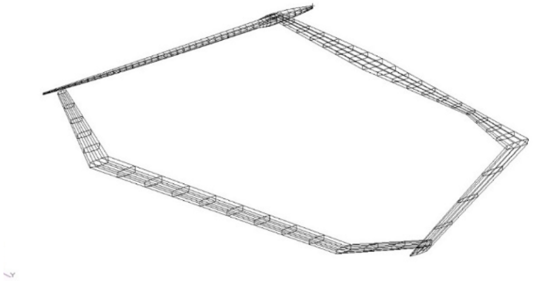


Run	Efficiency(L/D)	ϕ_{tot} $[Jm^2]$	W [kg]
I	**30.8**	9209.96	487.0

Maximize L/D ratio

Run	Efficiency(L/D)	ϕ_{tot} $[Jm^2]$	W [kg]
I	21.2	5845.249	**301.0**

Minimize structural weight



Run	Efficiency(L/D)	ϕ_{tot} $[Jm^2]$	W [kg]
I	22.1	**11259.81**	598.0

Maximize captured sun energy