Some issues and challenges on **aeroelastic modeling** and **multi-disciplinary design** of “aero-space” vehicles

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Flexible Engineering
Toward Green Aircraft
CAE tools improvement for sustainability

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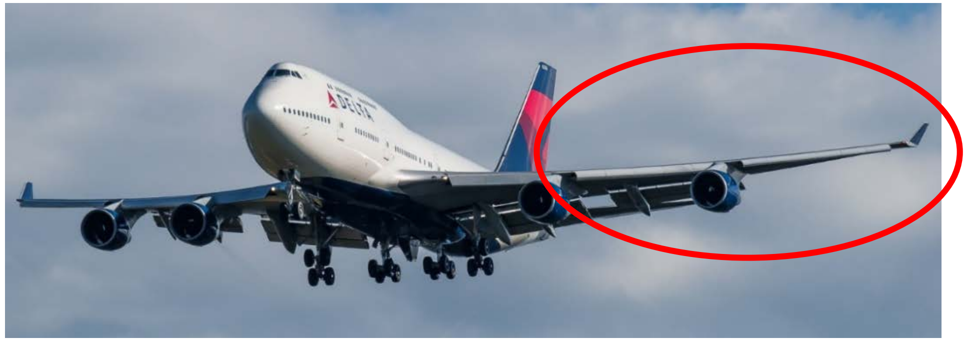
I - MODELLING in AEROELASTICITY: past and present civil aircraft



Relatively **stiff**

Decoupled flight dynamics and aeroelasticity

Linear aeroelastic behavior

Commercial aeroelastic solvers **available**

Increasingly **flexible**

Coupled flight dynamics and aeroelasticity

Nonlinear aeroelastic behavior

Commercial aeroelastic solvers **not available**

Which challenges?

Nonlinear aeroelastic solvers to analyze **complex** very flexible **new configurations**

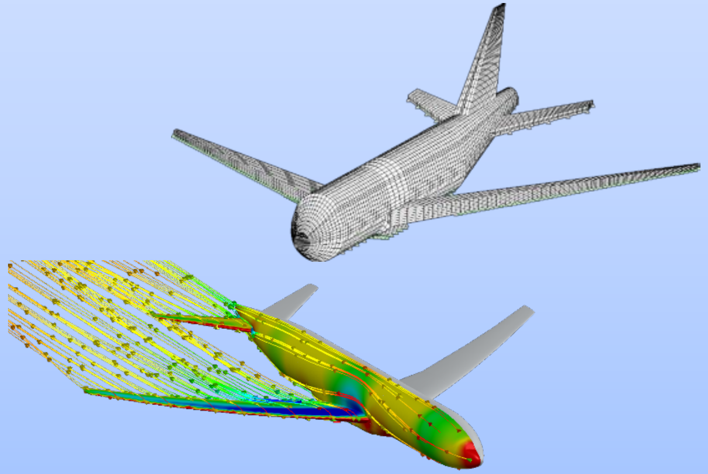
Why?

Commercial solvers **not available**

E.g., **coupled flight dynamics and aeroelasticity** of complex configurations around **nonlinear trim conditions**

How?

Methodology to **couple off-the-shelf solvers** for high-fidelity analysis of fluids and structures → <u>usefull and effective for design</u>

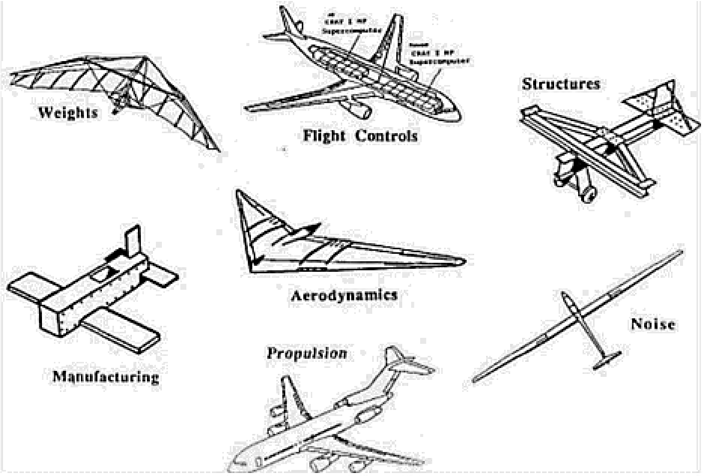


MOTIVATION and SCOPE

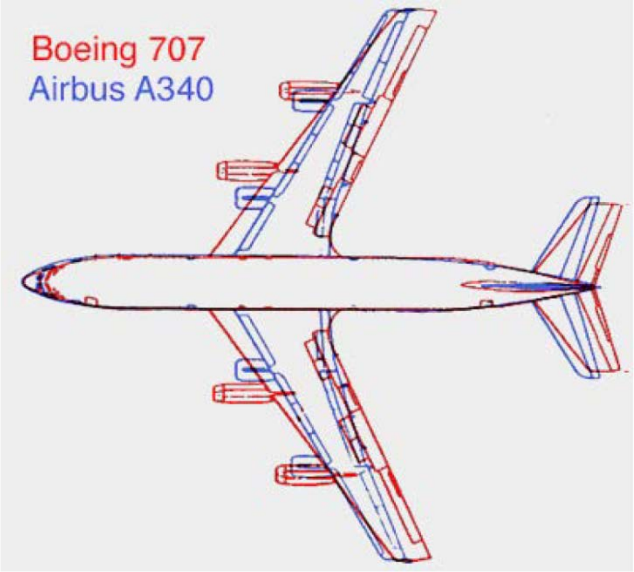
II - MULTIDISCIPLINARY and MULTIOBJECTIVE DESIGN for AIRCRAFT configurations

Aircraft design is a **multidisciplinary** problem having competitive objectives (**multi-objective**)

Compromise design must be achieved

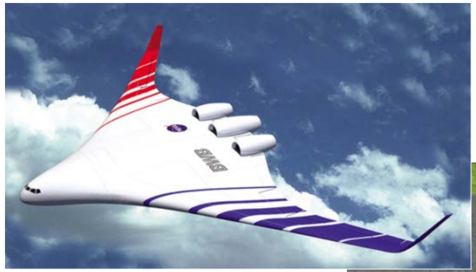


DISCIPLINE	MAIN GOALS	DESIGN REQUIREMENTS
STRUCTURES	Minimum Weight	Reduction of stress (masses placed) in most critical areas Low wing span High wing box thickness
AERODYNAMICS	Maximum L/D	Slender bodies High wing span and aspect ratio Very thin wing box
ENVIRONMENT IMPACT	Minimum Noise Minimum fuel consumption	Very slender design High By-Pass Ratio (high engine diameter)
MANUFACTURING	Minimum costs	Simple components to be assembled and inspectioned
FLIGHT CONTROL	Control surface effectiveness	Minimum structural flexibility



- Traditional approach mostly based on past experience and knowledge
- Conventional configurations are close to their limits
- Environmental goals require new effective designs

To make more than evolutionary improvements requires modeling, simulation and computation-based multidisciplinary design (I. Kroo)



MOTIVATION and SCOPE

II - MULTIDISCIPLINARY and MULTIOBJECTIVE DESIGN for AIRCRAFT configurations

Governed by a number of **coupled disciplines**

Several design variables impact performance of **multiple disciplines**

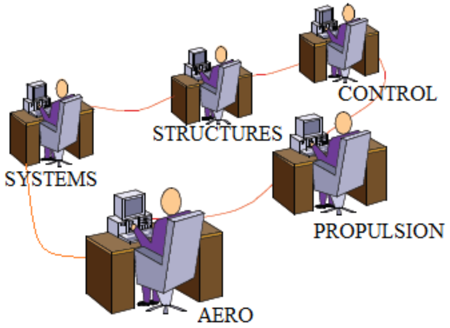
Disciplinary objectives interact and **potentially conflict with each other**

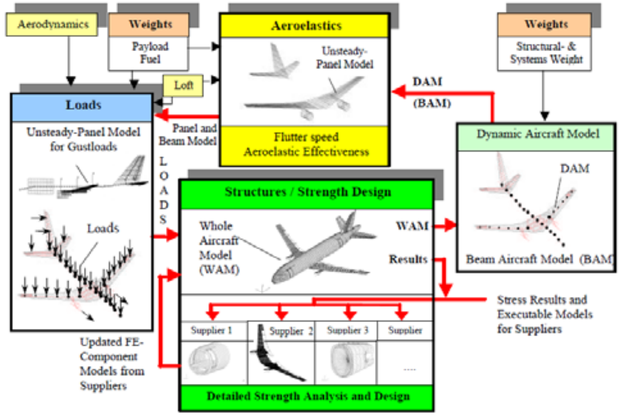
Evaluation of compromise (**multiobjective**) solutions

Design of **new systems** cannot rely on accumulated experience

Traditional approach: *Sequential design*

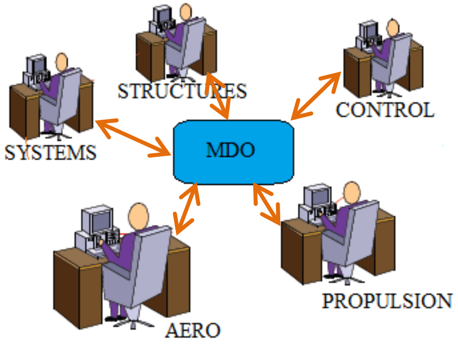
- Cyclic iterative process
- Difficulty in sharing information among work teams
- Premature convergence

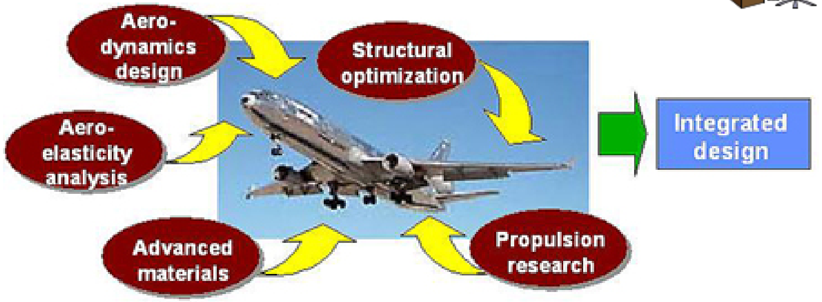




Formal Multidisciplinary Design Optimization (MDO) approach

- Integrated computational environment
- Mutual collaboration among disciplines
- Overall optimum design

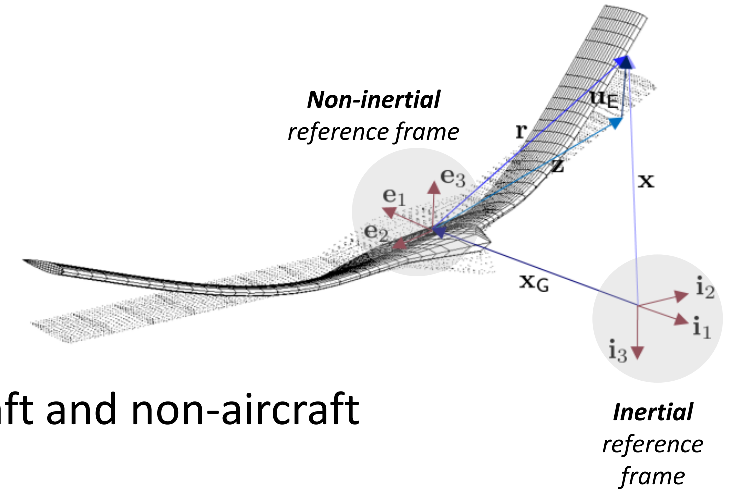




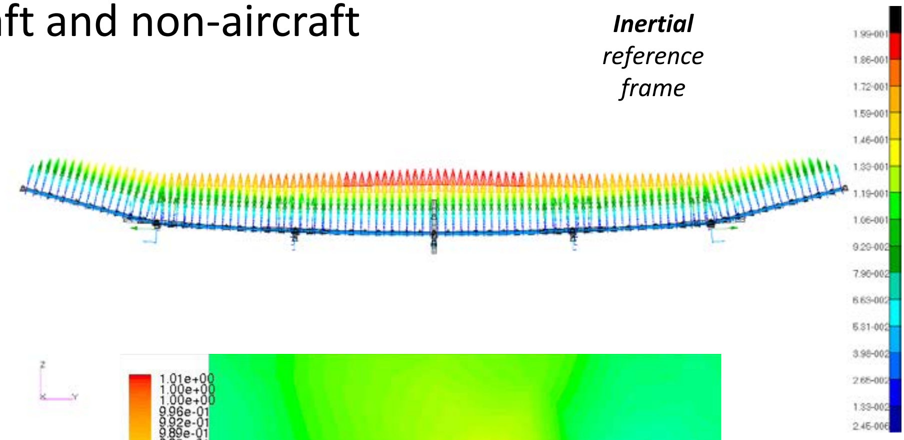
→ Present our research experiences on the trade-off between:

- First-principle-based analysis tools having relatively low computational cost for high fidelity **modeling**

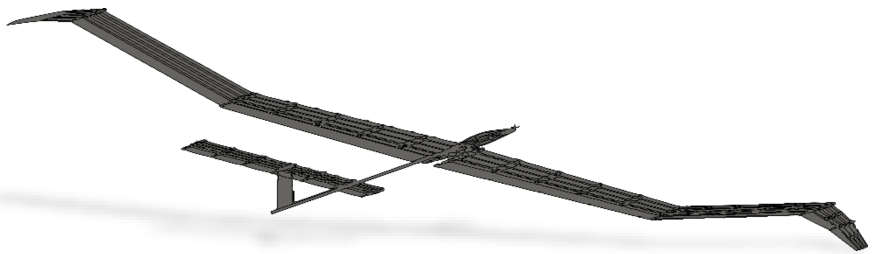
- Computationally fast Integrated Optimal **multi-disciplinary DESIGN** of really new design solutions

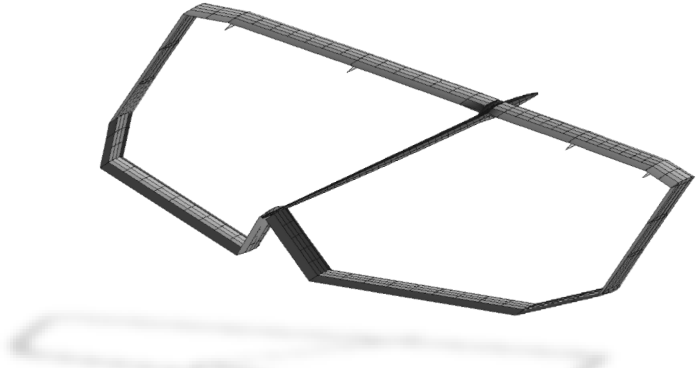


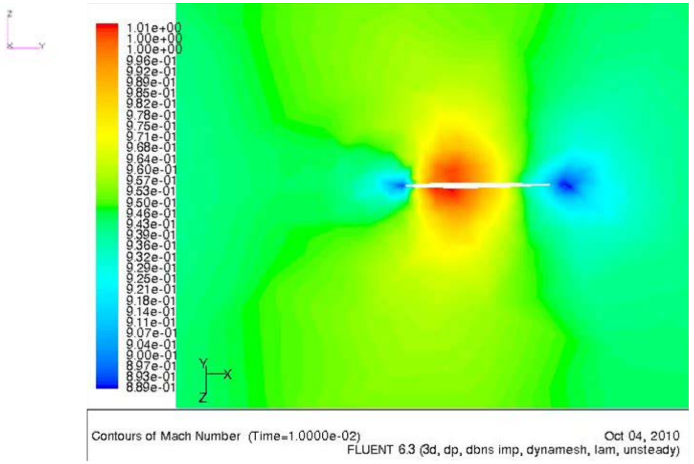
1. **Aeroelastic modeling (from lessons learned by aircraft on …)**
   - Integrated modelling of <u>Aeroelasticity and Flight dynamics</u>
   - Modeling for <u>nonlinear aeroelastic trim solutions</u>
   - Modeling for <u>FSI (unsteady aerodynamics) linearized analysis</u> for aircraft and non-aircraft configurations



2. **Multidisciplinary Design and Multi-Objective optimization of aircraft**
   - Conventional aircraft configuration
   - Unconventional aircraft configuration

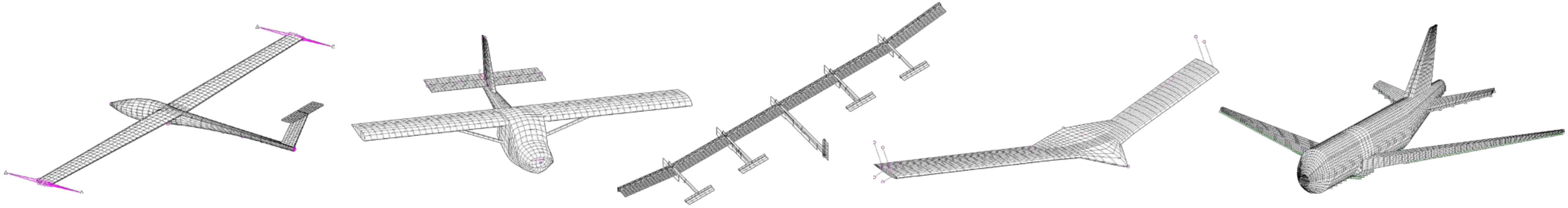






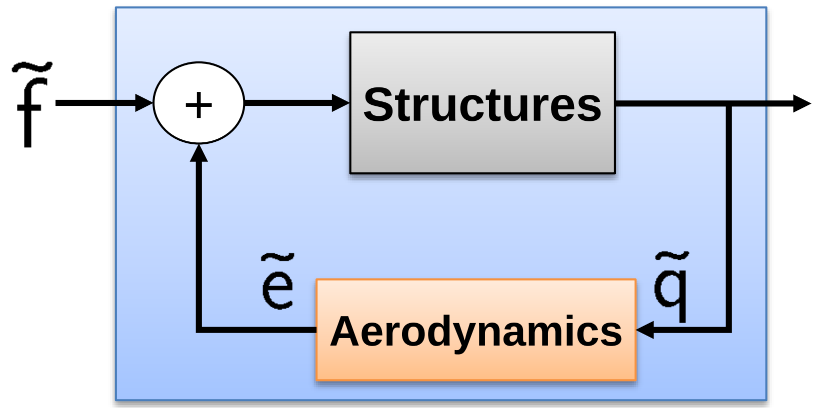
Aeroelastic modeling

From lessons learned by linear fixed-wing aeroelasticity on …



Lesson learned by linear-aeroelastic modeling for aircraft

Fluid-structure description in standard linear theory



PDE Math models

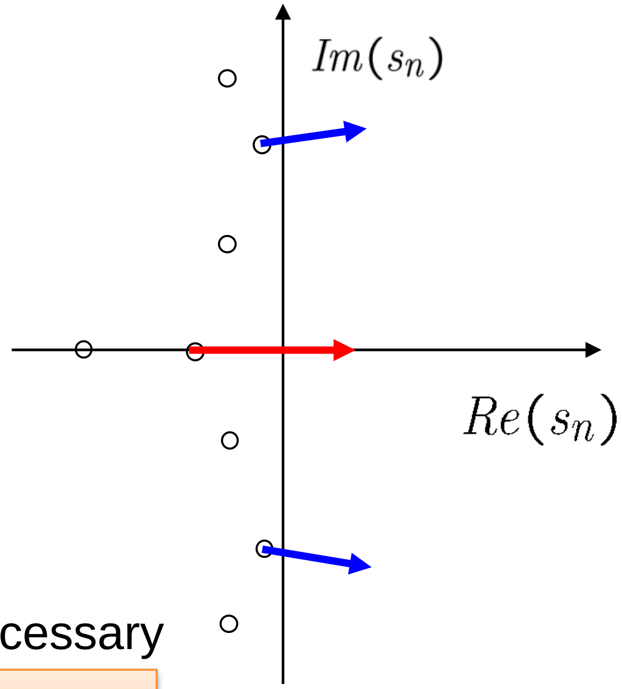
STRUTTURES: linearly-elastic modeling for solids
AERODINAMICS: unviscid attached external flow (ideally-perfect gas)

↓

SPACE DISCRETIZATION (fluid+solids) **FEM**
Lifting Surface (DLM)

↓

Integro-differential Equation in **time domain**
Transcendental system transfer function in **Laplace domain**



Aeroelastic Stability

Flutter: *dynamic instability* characterized by the imaginary axis crossing of a couple of conjugated eigenvalues driven by **flight parameters**

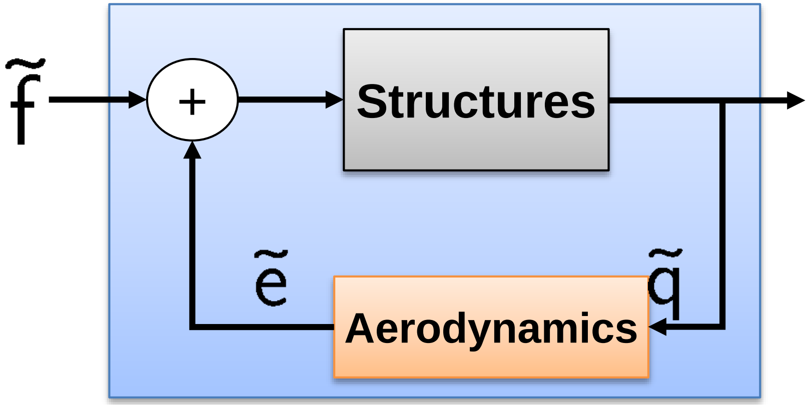
Divergence: static instability characterized by the imaginary axis crossing of a real eigenvalue driven by **flight parameters**

Not standard eigenvalues problem →
iterative procedures (as P-k or k-method in Nastram SOL145) necessary

$$\left[s_n^2 \mathsf{M} + \mathsf{K} - \frac{1}{2}\varrho U_\infty^2 \mathsf{E}(s_n; U_\infty, M_\infty)\right] \mathsf{w}^{(n)} = 0$$

Laplace/Fourier domain

$$s^2\mathsf{M}\tilde{\mathsf{q}} + \mathsf{K}\tilde{\mathsf{q}} = \frac{1}{2}\varrho U_\infty^2 \mathsf{E}(s; U_\infty, M_\infty)\tilde{\mathsf{q}} + \tilde{\mathsf{f}}$$



Aeroelastic Transfer-Function Matrix

$$\mathsf{H}(s) := \left[s^2\mathsf{M} + \mathsf{K} - \frac{1}{2}\varrho U_\infty^2 \mathsf{E}(s; U_\infty, M_\infty)\right]^{-1}$$

NB: Aeroelastic Frequency-Response Matrix for $s = j\omega$

Time domain

$$\mathsf{M}\ddot{\mathsf{q}} + \mathsf{K}\mathsf{q} = q_D \int_0^t \Xi(t-\tau; U_\infty, M_\infty)\, \mathsf{q}(\tau) d\tau + \mathsf{f}$$

where $\Xi(t; U_\infty, M_\infty)$ is the inverse L-transform of $\mathsf{E}(s)$

Note: fractional polynomial approximation

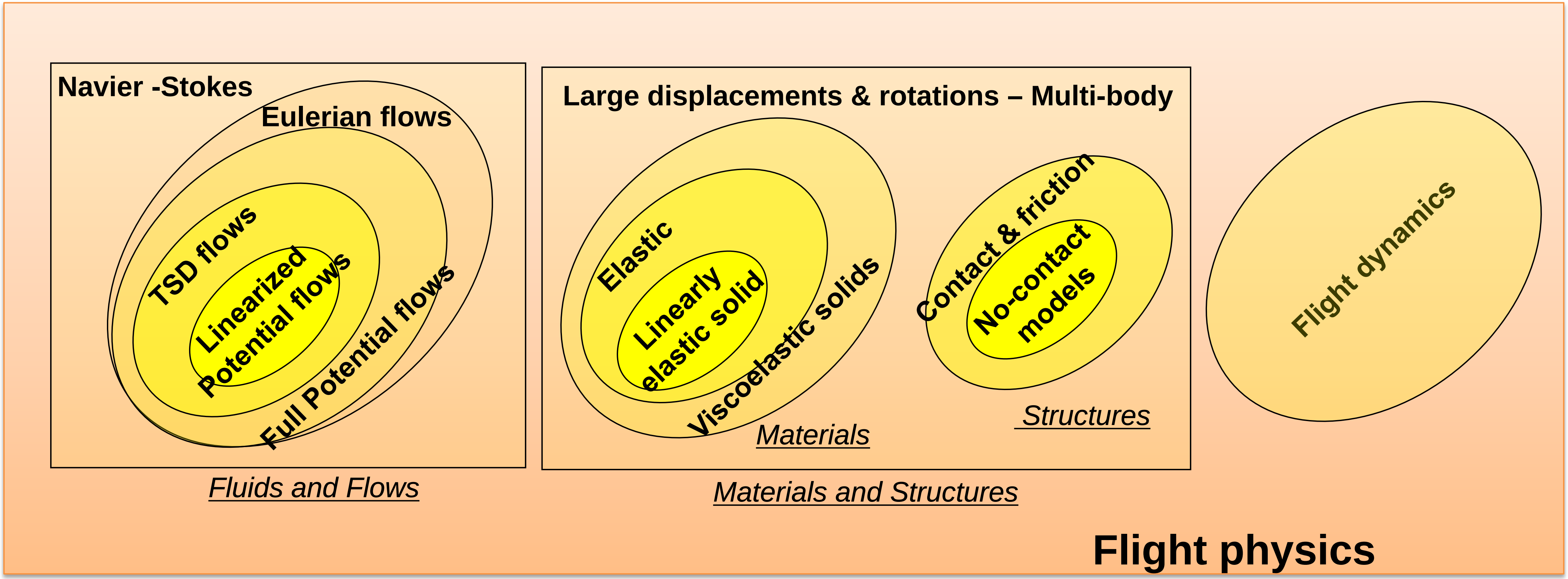
$$\mathsf{E}(k, M_\infty) \Rightarrow \mathsf{E}(s, M_\infty, U_\infty) \approx$$

$$\mathsf{A}_0 + \left(\frac{sb}{U_\infty}\right)\mathsf{A}_1 + \left(\frac{sb}{U_\infty}\right)^2 \mathsf{A}_2 + \mathsf{C}\left(\frac{sb}{U_\infty}\mathsf{I} - \mathsf{A}\right)^{-1} \mathsf{B}$$

allows to obain a standard Ordinary differential Equation problem →
Standard Control Theory applicable

But what about the general nonlinear FSI modeling?

Higher and higher fidelity for physical models (Flows, material & structures, flight dynamics)



Note that, in flight physics, each disciplinary set may have different relationships (intersections or unions) with the others depending on the assumed Interaction Model

General final mathematical model

- **Nonlinear** dynamical system (initial value problem)

$$\dot{x} = f(x)$$
$$x(0) = x_0$$

- ❑ Fully nonlinear

- **Linearized** dynamics around trimmed solution

$$x_e \quad / \quad f(x_e) = 0$$

nonlinear

linearized

$$x = x_e + \Delta x$$
$$\Delta \dot{x} = A\ \Delta x + \cancel{H.O.T.}$$

- ❑ Statically nonlinear & dynamically linear
- ❑ Statically linear & dynamically linear

Model fidelity

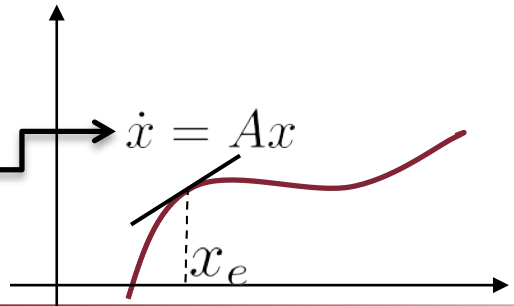
Acceptable level for designing

Computational effectiveness

A geometrical interpretation

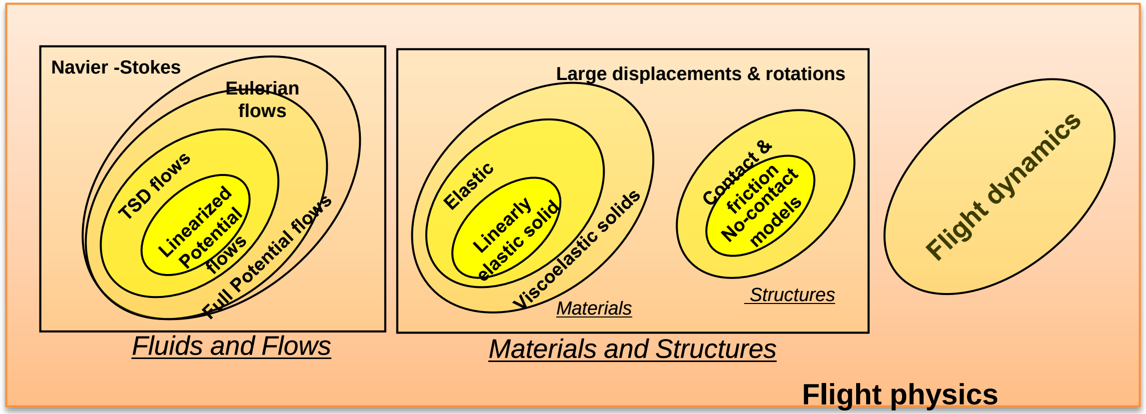
Statically nonlinear

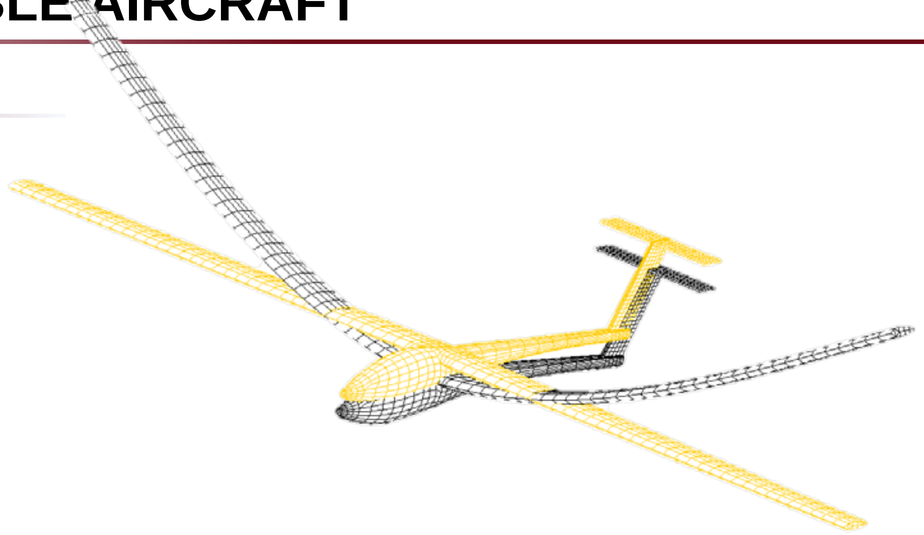
Dynamically linear



Flight physics of FLEXIBLE AIRCRAFT

Integrated Aeroelasticity and Flight Dynamics





Body reference frame

Mean axes

Practical mean axes

Pseudo-body axes

Aerodynamic modeling

Quasi-steady

Fully unsteady (DLM)

Present Approach

Coupling effects

Inertial coupling

Aerodynamic coupling

Structural modeling

Beam Type structures

Any general FE description

Mathematical model

Linear trim + linearized dynamics

Nonlinear trim + linearized dynamics

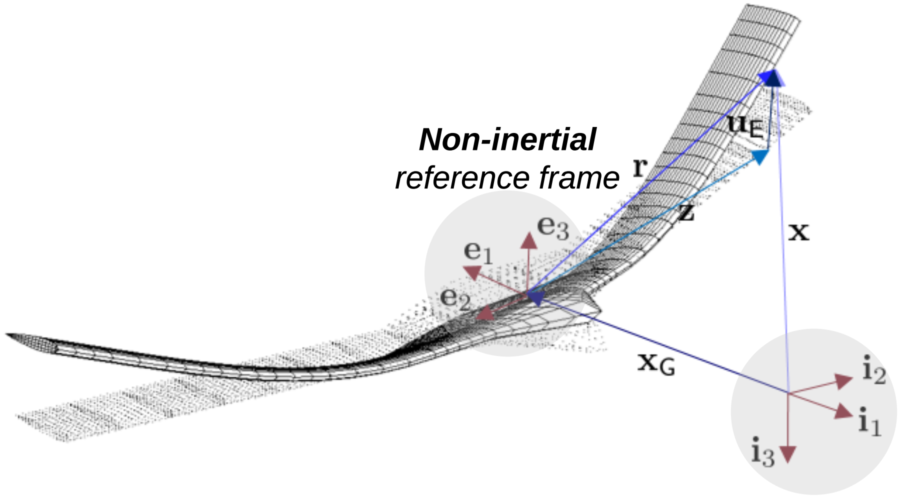
Nonlinear simulation

MSC Nastran solvers

Modal solver 103

Aeroelastostatic solver 144

Flutter solver 145



Motion of unrestrained aircraft

$$\mathbf{x}(\mathbf{z};t) = \mathbf{x}_{\text{G}}(t) + \mathbf{z}(t) + \mathbf{u}_{\text{E}}(\mathbf{z};t)$$

- Position of the **instantaneous** center of mass
- Undeformed position with respect to the center of mass
  - $\mathbf{z}$ is expressed in practical mean axes frame, that coincides with FEM reference frame
- Elastic displacement

Small elastic deflections

$$\mathbf{u}_{\text{E}}(\mathbf{z};t) = \sum_{n=1}^{\infty} q_n(t)\boldsymbol{\psi}_n^{\text{E}}(\mathbf{z};t)$$

Nonlinear equations of motion

1. **Translational equations**

$$m\frac{\mathrm{d}\mathbf{v}_{\text{G}}}{\mathrm{d}t} = \mathbf{f}_{\text{T}}$$

2. **Rotational equations**

$$\frac{\mathrm{d}\mathbf{h}_{\text{G}}}{\mathrm{d}t} = \mathbf{m}_{\text{G}}$$

3. **Elastic equations**

$$m_n\ddot{q}_n - \frac{\mathrm{d}\boldsymbol{\omega}}{\mathrm{d}t}\cdot\sum_{m=1}^{\infty}\mathbf{b}_{nm}q_m - \boldsymbol{\omega}\cdot\mathbf{Y}_n\boldsymbol{\omega}$$
$$-2\boldsymbol{\omega}\cdot\sum_{m=1}^{\infty}\mathbf{b}_{nm}\dot{q}_m + k_n q_n = f_n$$

Angular momentum

$$\mathbf{h}_{\text{G}} = \mathbf{J}\boldsymbol{\omega} + \sum_{n,m=1}^{\infty}\mathbf{b}_{nm}q_n\dot{q}_m$$

Inertia tensor

$$\mathbf{J} = \mathbf{J}_0 + 2\sum_{n=1}^{\infty}\mathbf{J}_n q_n + \sum_{n,m=1}^{\infty}\mathbf{J}_{nm}q_n q_m$$

- Mass
- Inertia tensor in undeformed configuration

Directly available from FEM solver

- First order inertia tensors
- Second order inertia tensors
- Inertia tensor sensitivity
- Coupling vectors

Inertial coupling terms: from continuous to FEM discretized structures

Continuous structures

$$m := \iiint_{\mathcal{V}} \rho \mathrm{d}\mathcal{V}$$

$$\mathbf{J}_0 := \langle \mathbf{z} \otimes \mathbf{z} \rangle$$

$$\mathbf{J}_n := \frac{1}{2}\left[\langle \mathbf{z} \otimes \boldsymbol{\phi}_n^{\mathsf{E}} \rangle + \langle \boldsymbol{\phi}_n^{\mathsf{E}} \otimes \mathbf{z} \rangle\right]$$

$$\mathbf{J}_{nm} := \frac{1}{2}\left[\langle \boldsymbol{\phi}_n^{\mathsf{E}} \otimes \boldsymbol{\phi}_m^{\mathsf{E}} \rangle + \langle \boldsymbol{\phi}_m^{\mathsf{E}} \otimes \boldsymbol{\phi}_n^{\mathsf{E}} \rangle\right]$$

$$\mathbf{Y}_n := \mathrm{sym}\,\langle \mathbf{r} \otimes \boldsymbol{\phi}_n^{\mathsf{E}} \rangle = \mathbf{J}_n + \sum_{m=1}^{\infty} \mathbf{J}_{nm} q_m = \frac{1}{2}\frac{\partial \mathbf{J}}{\partial q_n}$$

$$\mathbf{b}_{nm} := \iiint_{\mathcal{V}} \rho \boldsymbol{\phi}_n^{\mathsf{E}} \times \boldsymbol{\phi}_m^{\mathsf{E}} \mathrm{d}\mathcal{V} = -\mathbf{b}_{mn}$$

where

$$\langle \mathbf{a} \otimes \mathbf{b} \rangle := \iiint_{\mathcal{V}} \rho \left[(\mathbf{a} \cdot \mathbf{b})\,\mathbf{I} - \mathbf{a} \otimes \mathbf{b}\right] \mathrm{d}\mathcal{V}$$

Space-discretized structures (FEM)

$$m \simeq \sum_{i=1}^{N_g} m_i$$

$$\mathbf{J}_0 \simeq \sum_{i=1}^{N_g} \{ m_i \left[(\mathbf{z}_i \cdot \mathbf{z}_i)\,\mathbf{I} - \mathbf{z}_i \otimes \mathbf{z}_i\right] + \mathbf{J}_{0_i} \}$$

$$\mathbf{J}_n \simeq \sum_{i=1}^{N_g} \frac{1}{2} \{ m_i \left[2\,(\mathbf{z}_i \cdot \boldsymbol{\phi}_{n_i}^{\mathsf{E}})\,\mathbf{I} - \mathbf{z}_i \otimes \boldsymbol{\phi}_{n_i}^{\mathsf{E}} - \boldsymbol{\phi}_{n_i}^{\mathsf{E}} \otimes \mathbf{z}_i \right] + \mathrm{sk}(\boldsymbol{\varphi}_{n_i}^{\mathsf{E}})\,\mathbf{J}_{0_i}^{\mathsf{D}} - \mathbf{J}_{0_i}^{\mathsf{D}}\,\mathrm{sk}(\boldsymbol{\varphi}_{n_i}^{\mathsf{E}}) \}$$

$$\mathbf{J}_{nm} \simeq \sum_{i=1}^{N_g} \frac{1}{2} \{ m_i \left[2\,(\boldsymbol{\phi}_{n_i}^{\mathsf{E}} \cdot \boldsymbol{\phi}_{m_i}^{\mathsf{E}})\,\mathbf{I} - \boldsymbol{\phi}_{n_i}^{\mathsf{E}} \otimes \boldsymbol{\phi}_{m_i}^{\mathsf{E}} - \boldsymbol{\phi}_{m_i}^{\mathsf{E}} \otimes \boldsymbol{\phi}_{n_i}^{\mathsf{E}} \right] + -2\left[\mathrm{sk}(\boldsymbol{\varphi}_{n_i}^{\mathsf{E}}) : (\mathrm{sk}(\boldsymbol{\varphi}_{m_i}^{\mathsf{E}})\mathbf{J}_{0_i}^{\mathsf{D}})\right]\mathbf{I} - \mathrm{sk}(\boldsymbol{\varphi}_{n_i}^{\mathsf{E}})\,\mathbf{J}_{0_i}^{\mathsf{D}}\,\mathrm{sk}(\boldsymbol{\varphi}_{m_i}^{\mathsf{E}}) - \mathrm{sk}(\boldsymbol{\varphi}_{m_i}^{\mathsf{E}})\,\mathbf{J}_{0_i}^{\mathsf{D}}\,\mathrm{sk}(\boldsymbol{\varphi}_{n_i}^{\mathsf{E}}) \}$$

$$\mathbf{b}_{nm} \simeq \sum_{i=1}^{N_g} \left[m_i\,\boldsymbol{\phi}_{n_i}^{\mathsf{E}} \times \boldsymbol{\phi}_{m_i}^{\mathsf{E}} - \mathbf{J}_{0_i}^{\mathsf{D}} (\boldsymbol{\varphi}_{n_i}^{\mathsf{E}} \times \boldsymbol{\varphi}_{m_i}^{\mathsf{E}}) \right]$$

This coefficients are obtainable by extrapolating the lumped mass matrix **from any off-the-shelf FEM solver**

Space-state model (Aeroelasticity + Flight Mechanics) → STANDARD CONTROL THEORY DESIGN APPLICABLE

$$\mathsf{y} = \begin{Bmatrix} \Delta \mathsf{v}_G \\ \Delta \omega \\ \Delta \dot{\mathsf{q}} \\ \Delta \mathsf{x}_G \\ \Delta \Theta \\ \Delta \mathsf{q} \\ \Delta \mathsf{a} \end{Bmatrix}$$

Translational and rotational velocity

Time derivatives of modal coordinates

Position of CoM and attitude

Modal coordinates

Aerodynamic states

$$\dot{\mathsf{y}} = \mathsf{A}\,\mathsf{y} + \mathsf{B}_g\,\mathsf{u}_g + \mathsf{B}_c\,\mathsf{u}_c$$

$$\mathsf{A} = \begin{bmatrix} -\mathsf{M}^{-1}\mathsf{D} & -\mathsf{M}^{-1}\mathsf{K} & q_D\mathsf{M}^{-1}\mathsf{C} \\ \mathsf{T}_1 & 0 & 0 \\ 0 & \frac{U_\infty}{b}\mathsf{B} & \frac{U_\infty}{b}\mathsf{P} \end{bmatrix}$$

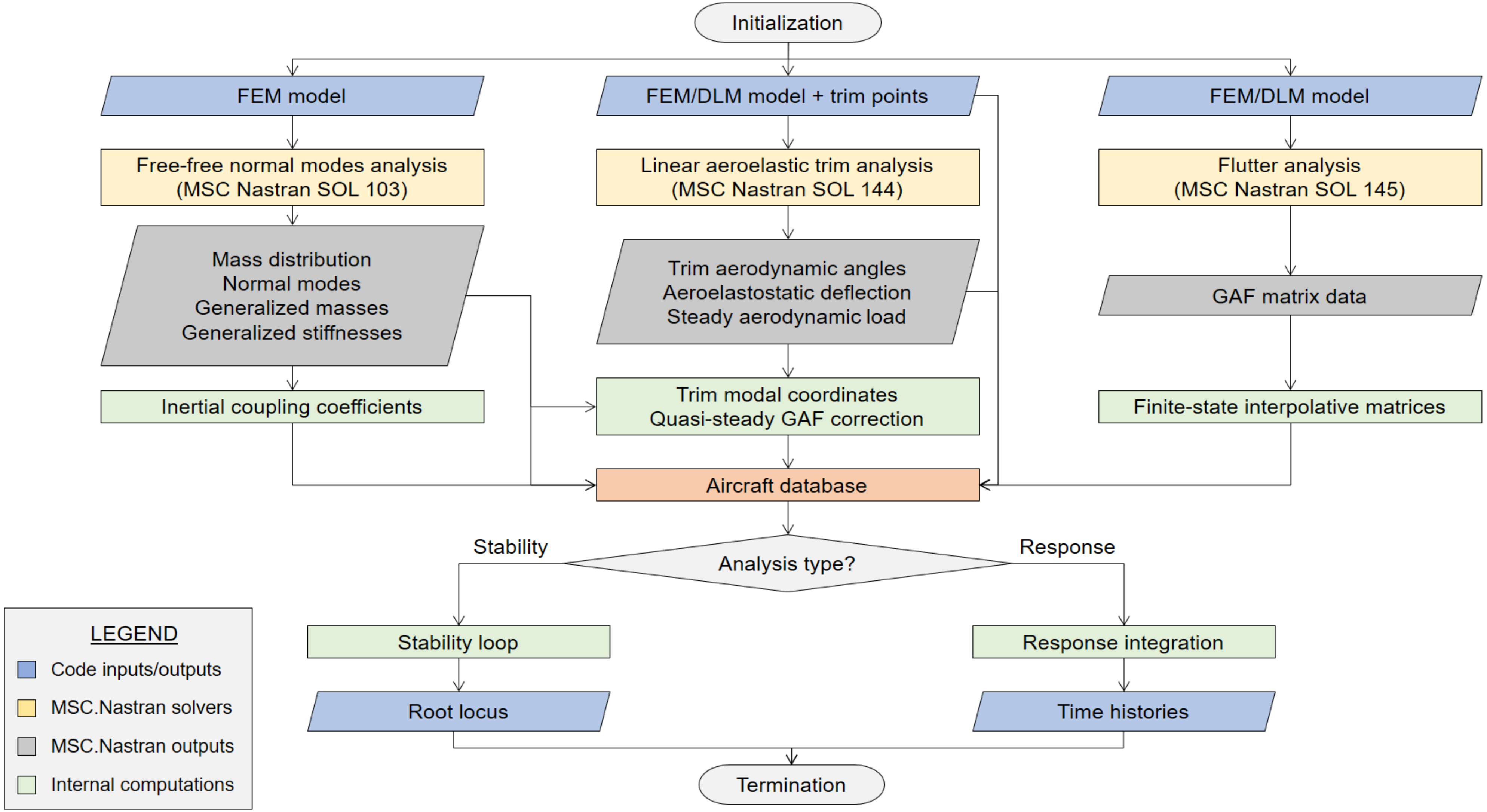
$$\mathsf{M} := \mathsf{M}_I - \frac{1}{2}\,\rho_\infty b^2 \mathsf{A}_2$$

$$\mathsf{D} := \mathsf{D}_I - \frac{1}{2}\,\rho_\infty U_\infty\, b\, \mathsf{A}_1$$

$$\mathsf{K} := \mathsf{K}_I - q_D \mathsf{A}_0 + \mathsf{K}_A$$

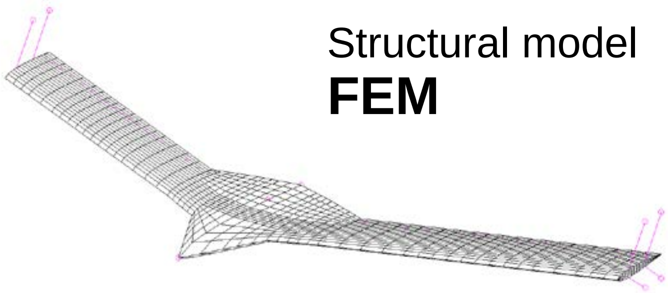
Integrated modeling of aeroelasticity and flight dynamics

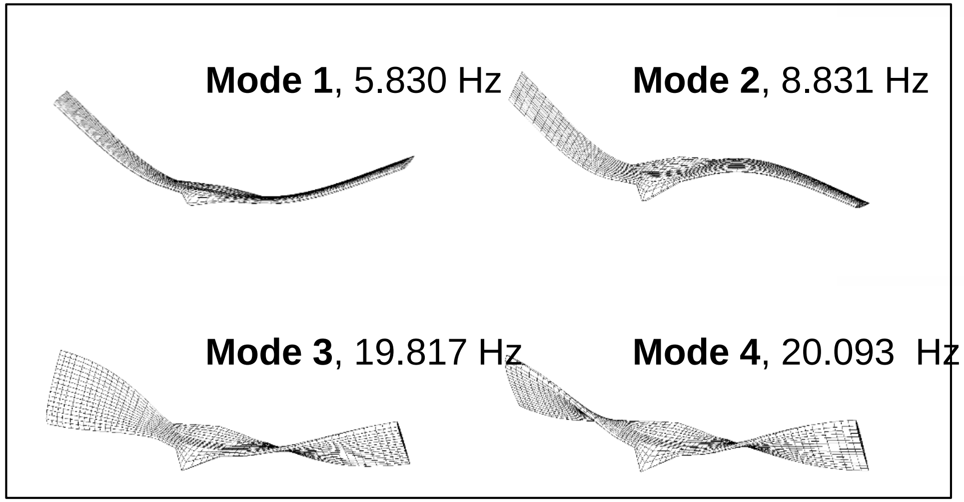
Computational framework for «design level»: Integration of FEM solvers into a home-made code



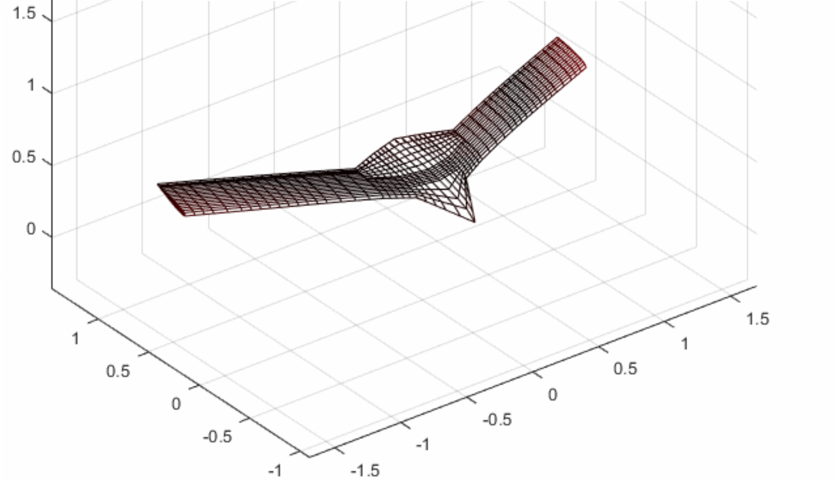
NUMERICAL TEST CASE: Body freedom flutter model

Structural model
FEM

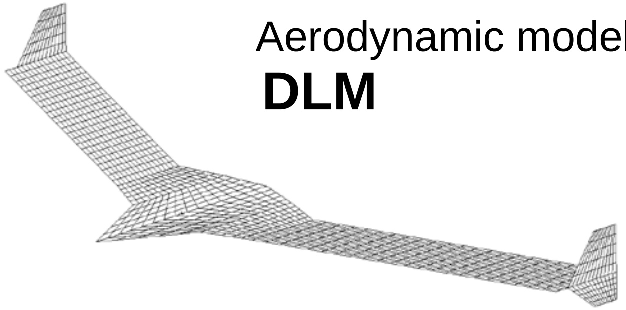


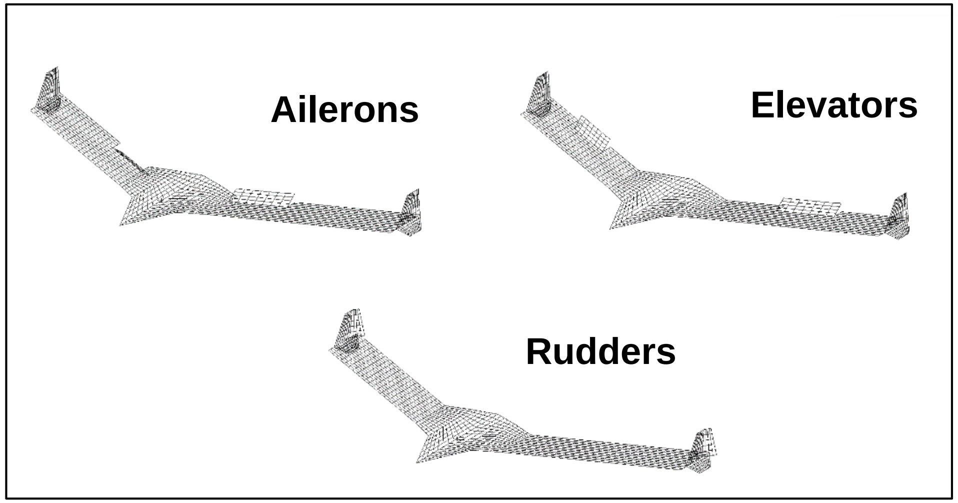


Body freedom flutter instability



Aerodynamic model
DLM

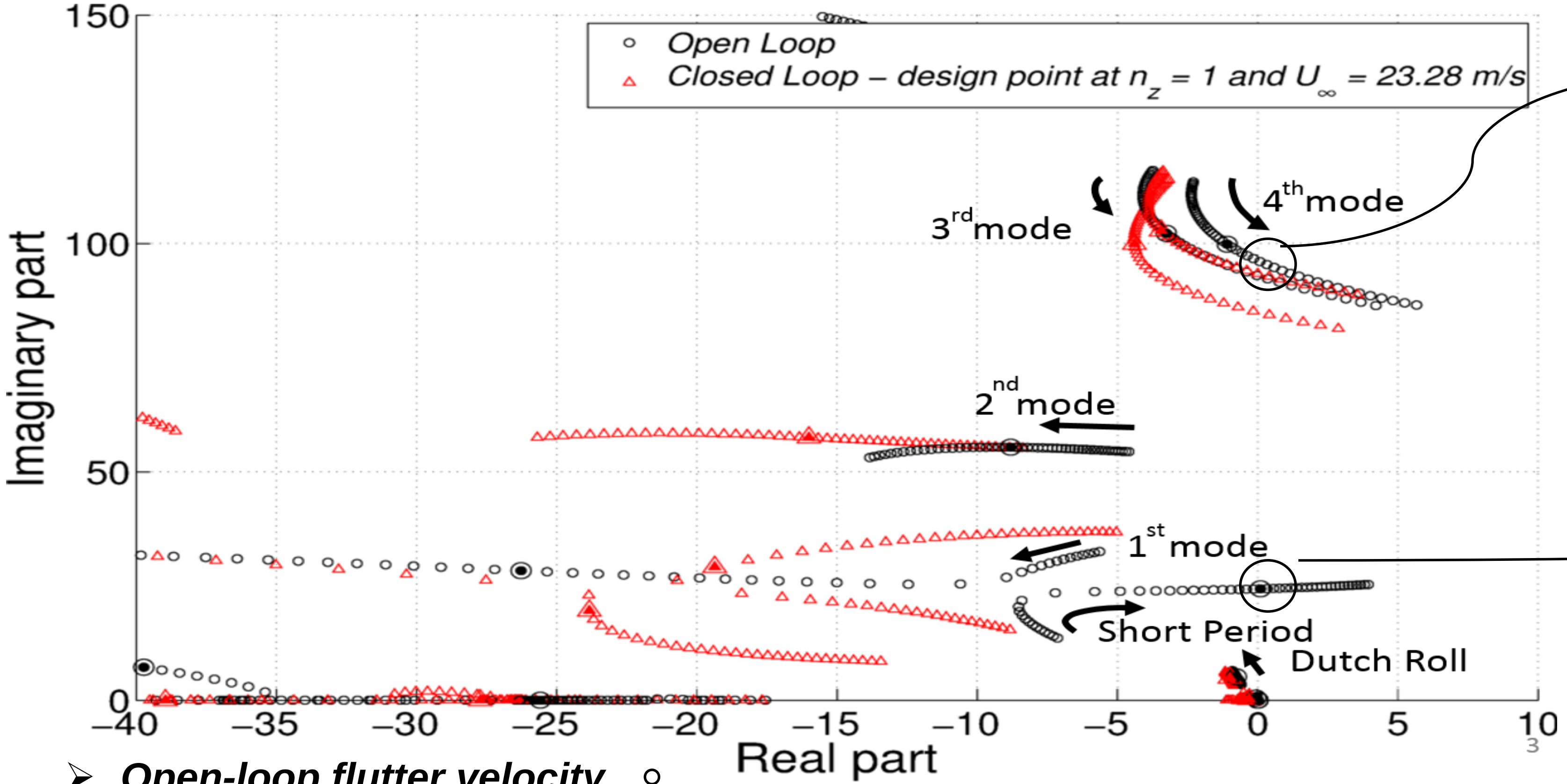




Lockheed-Martin website https://www.lockheedmartin.com/us/products/x-56/body-freedom-flutter.html

Stability: Open-loop and closed-loop (with optimal control) systems

Open-loop versus closed-loop root loci

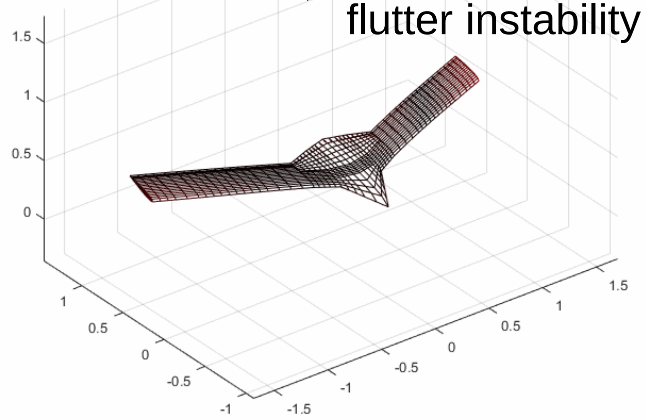


Bending/torsional instability

- ***Root locus parameters***

$$U_\infty = 15 \to 30 \text{ m/s}$$
$$n_{z_e} = 1$$
$$M_\infty = 0$$
$$\rho = 1.225 \text{ kg/m}^3$$

Body freedom flutter instability



- ***Open-loop flutter velocity*** ○

$$U_F^o = 23.28 \text{ m/s}$$

- ***Closed-loop flutter velocity*** △

$$U_F^c = 27.60 \text{ m/s}$$

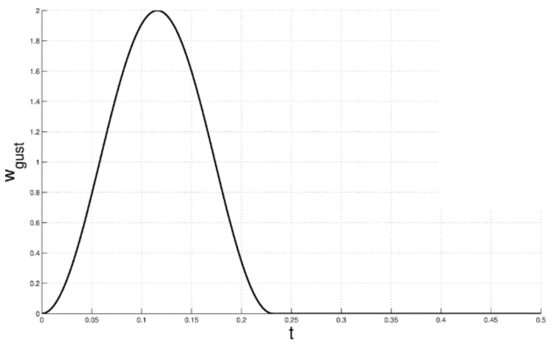
Gust response: comparison controll on v.s. control off cases

Flight parameters

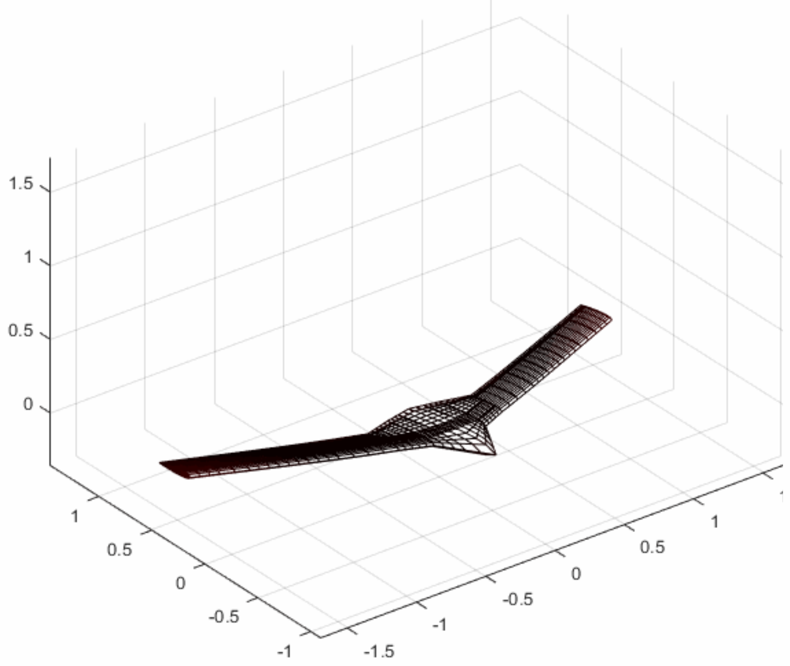
$$U_\infty = 23.28 \text{ m/s}$$
$$M_\infty = 0$$
$$\rho = 1.225 \text{ kg/m}^3$$
$$n_{z_e} = 1$$

Gust parameters

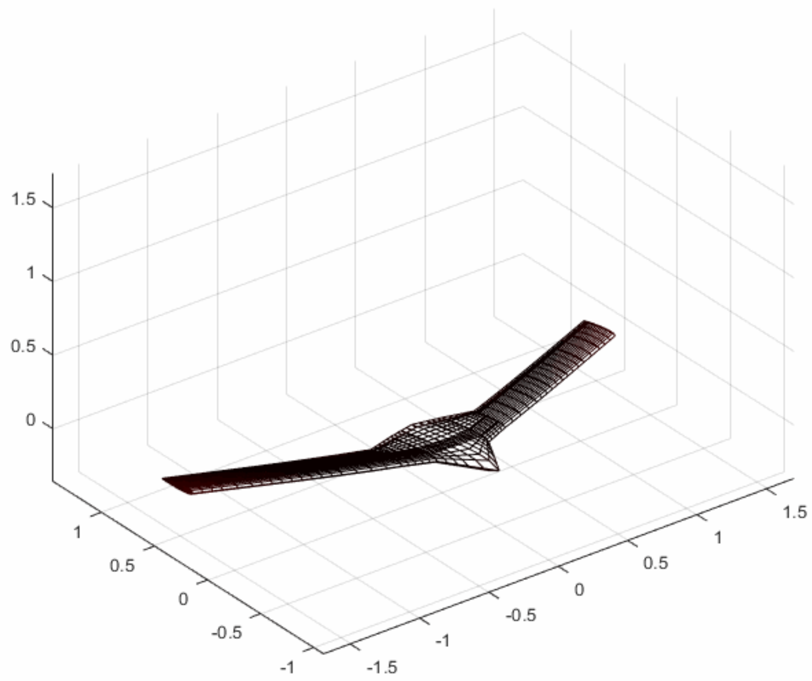
$$f_{gust} = 4.32Hz$$
$$w_{gust} = 2 \text{ m/s}$$



Control **OFF**



Control **ON**



- The controller is also effective for gust alleviation since the critical mode is the most excited one for this kind of gust load

- **Nonlinear aeroelastic trim** solver to analyze **complex** very flexible **configurations**

- Commercial solvers **not available**

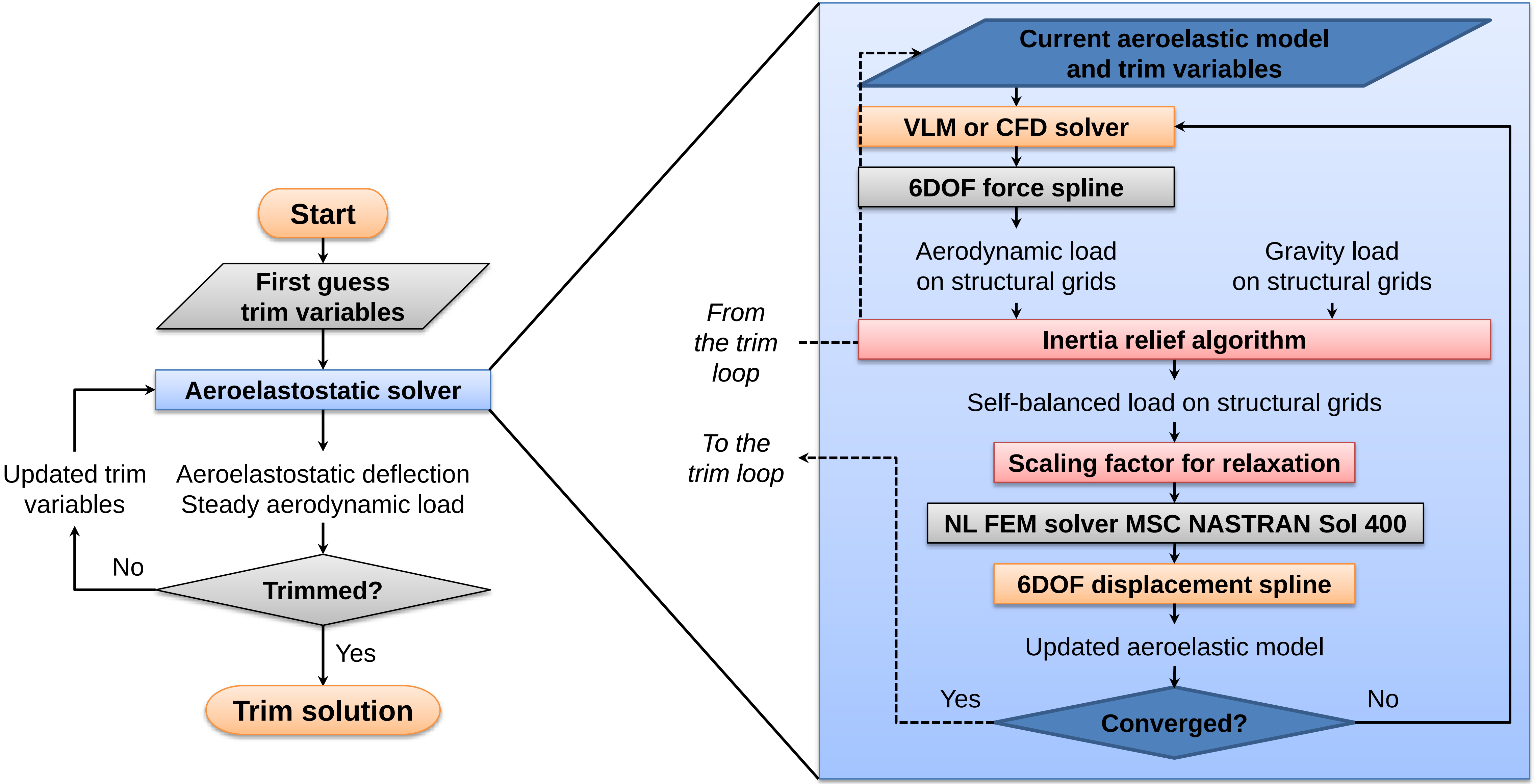
- **Coupled flight dynamics and aeroelasticity** of complex configurations around **nonlinear trim conditions**

- Methodology to **couple off-the-shelf solvers** for high-fidelity analysis of fluids and structures

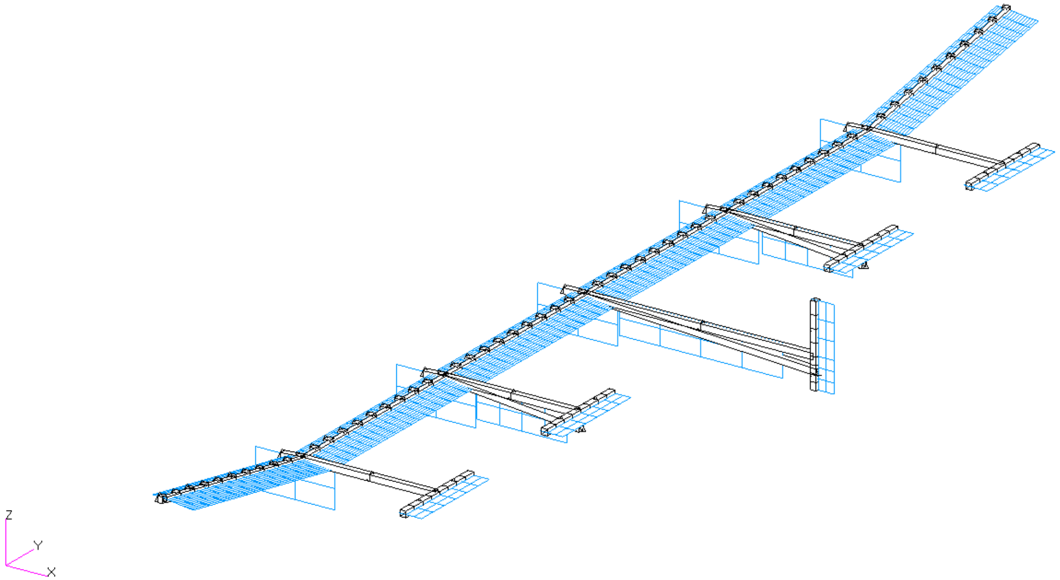
- A **statically nonlinear FSI** flight-physics model

Courtesy of the University of Michigan's Active Aeroelasticity and Structures Research Laboratory (A²SRL)

Algorithm flow-chart



Numerical test case on XHALE: very flexible model



Ritter, M., Jones, J. R., Cesnik, C. E. S., "Enhanced Modal Approach for Free-Flight Nonlinear Aeroelastic Simulation of Very Flexible Aircraft", *15th Dynamics Specialists Conference*, Jan. 2017, San Diego, California, USA.

Aeroelastic model:

Beam elements with constant stiffness properties and rigid bars

Cambered lifting surface with twist and dihedral and flat plates

6DOF splines

Aeroelastostatic analyses:

Air density	1.22161 kg/m^3
Freestream velocity	16 m/s
Angle of attack	0 deg, 0.5 deg, 1 deg
Gravity	On

Comparison with:

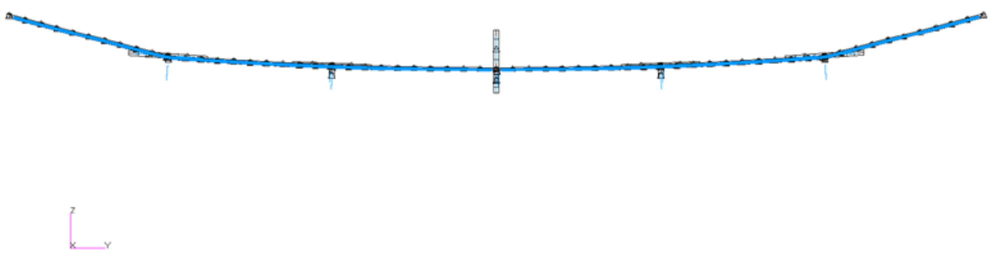
UM/NAST solver with VLM

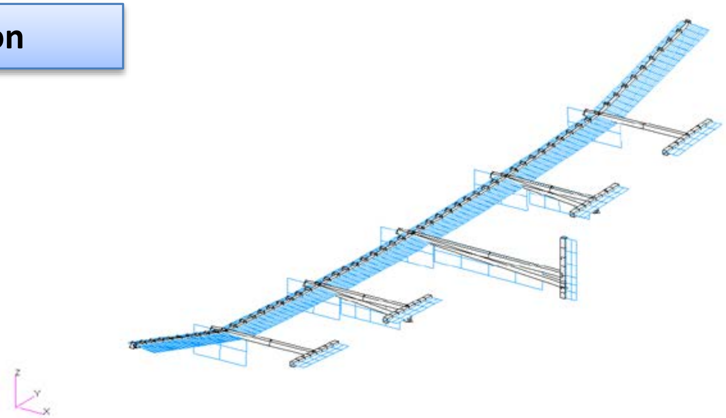
MSC.Nastran SOL 400/VLM solver

Modeling for nonlinear aeroelastic trim solutions

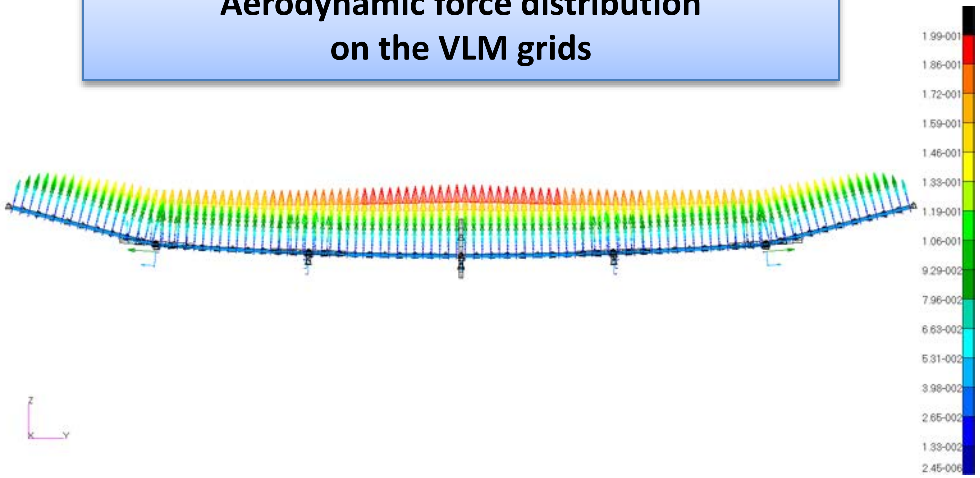
Results: Splined force and displacements

Deformed configuration

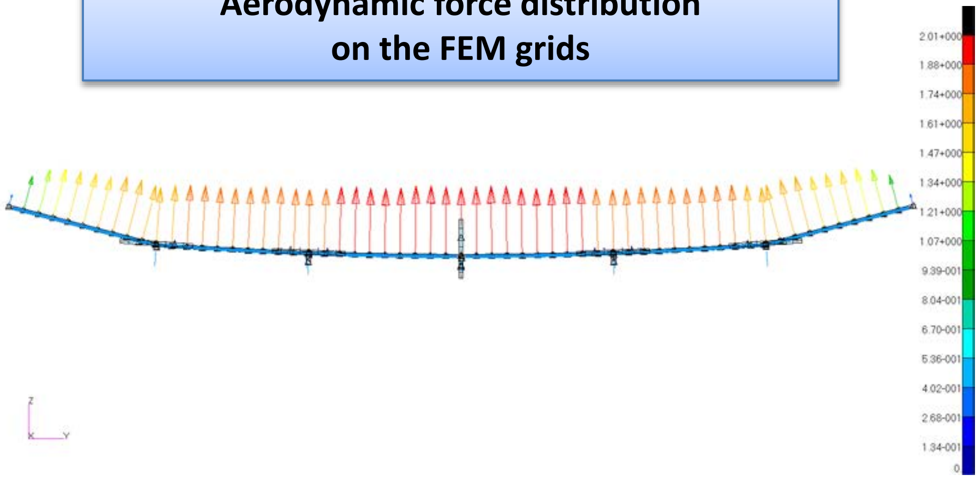




Aerodynamic force distribution on the VLM grids



Aerodynamic force distribution on the FEM grids

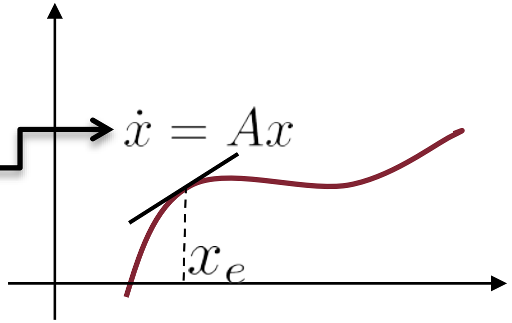


Modeling for FSI (unsteady aerodynamics) linearized analysis (LFD)

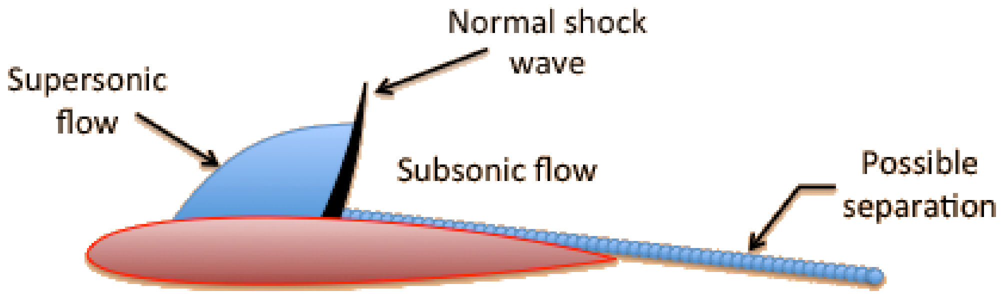
Motivation of statically nonlinear dynamically linear model

A geometrical interpretation

- **Statically nonlinear**
- Dynamically linear



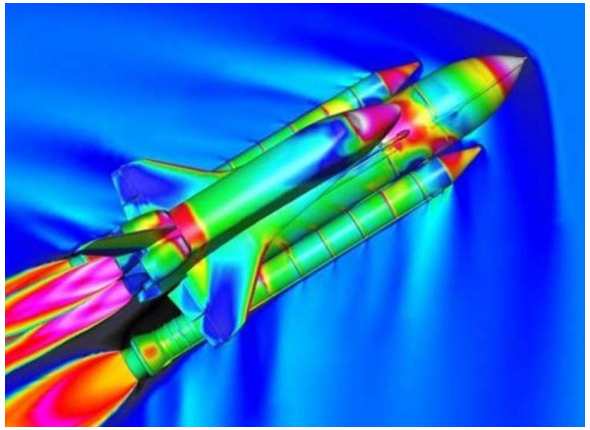
Transonic flows: NL-ties really relevant in static solution



Civil and military aircraft
flight in transonic regime

B787 Dreamliner, A380:
flight tests until Mach 0.97

Complex geometries



Only CFD simulations can assess
the aerodynamics in this case

Modeling for FSI (unsteady aerodynamics) linearized analysis (LFD)

A Linearization procedure in Frequency domain (LFD) for determining the unsteady aerodynamic operator (GAF Matrix)

i) **Apply a motion** to the boundary associated to any *m* mode:

$$\mathbf{x}(\xi^\alpha, t+dt) = \mathbf{x}(\xi^\alpha, t) + \dot{q}^t_m(t)\boldsymbol{\Psi}^{(m)}(\xi^\alpha)dt$$

ii) **Project** the perturbed pressure field ($c_p^{(UNST)}$-$c_P^{(ST)}$) on any *n* mode:

$$e_n^{(m)}(t) = -\frac{1}{2}\rho_\infty V_\infty^2 \oint_S C_p^{(m)}(\xi^\alpha, t)\mathbf{n}(\xi^\alpha)\cdot\boldsymbol{\Psi}^{(n)}(\xi^\alpha)dS$$

modelling

iii) **Apply Fourier transform** on each obtained time generalized aerodynamic force (outputs):

$$\tilde{e}_n^{(m)}(\omega) = \int_0^\infty e_n^{(m)}(t)\ \mathrm{e}^{-j\omega t}\ dt$$

iv) **Divide** (in the Fourier domain) each response by the input to obtain the Generalized Aerodynamic Force (GAF) matrix:

$$E_{nm}(\omega) = \tilde{e}_n^m(\omega)/\tilde{q}_m^t(\omega)q_D$$

Signal processing

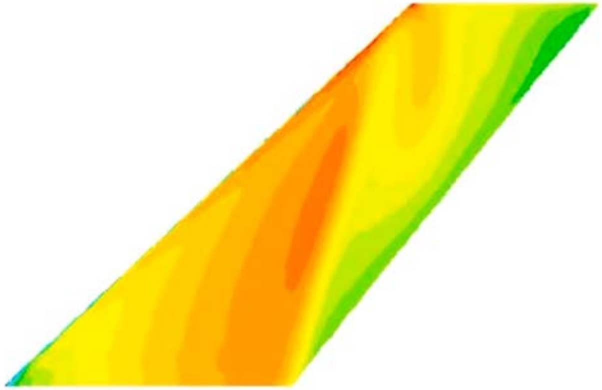
In the Laplace domain the linearized aeroelastic system can be written

$$\sum_m^{M_{modi}} s^2 M_{nm}\tilde{q}_m + \sum_m^{M_{modi}} K_{nm}\tilde{q}_m = \frac{1}{2}\rho_\infty V_\infty^2 \sum_m^{M_{modi}} E_{nm}(s; M_\infty, V_\infty)\tilde{q}_m$$

Reduced Order Model (ROM): LFD for unsteady aerodynamics

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

DOFs: **CFD** $\longrightarrow$ **N Modes**

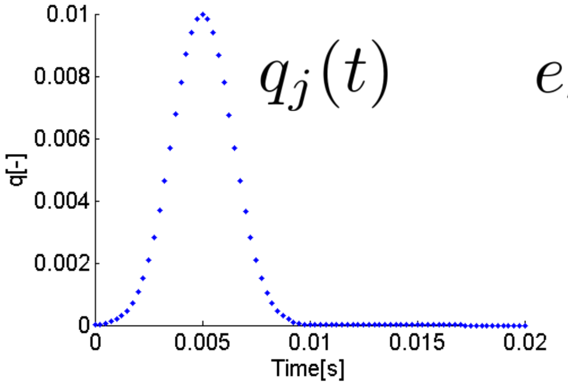


RBF Morph

Developed CFD function

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

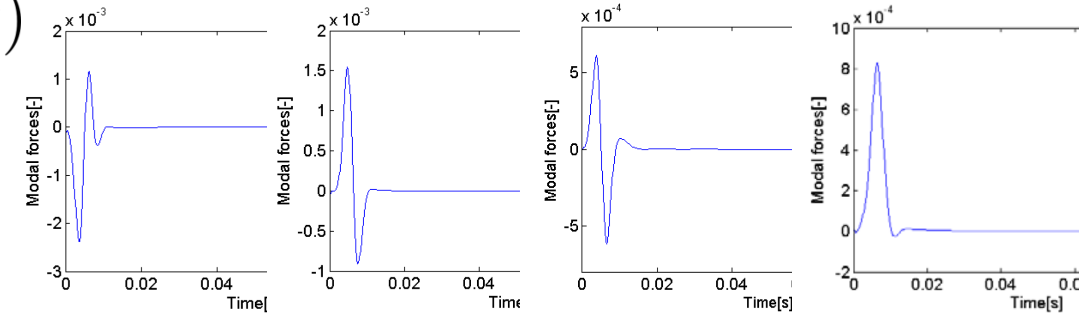
INPUT: n-th mode



$q_j(t)$

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

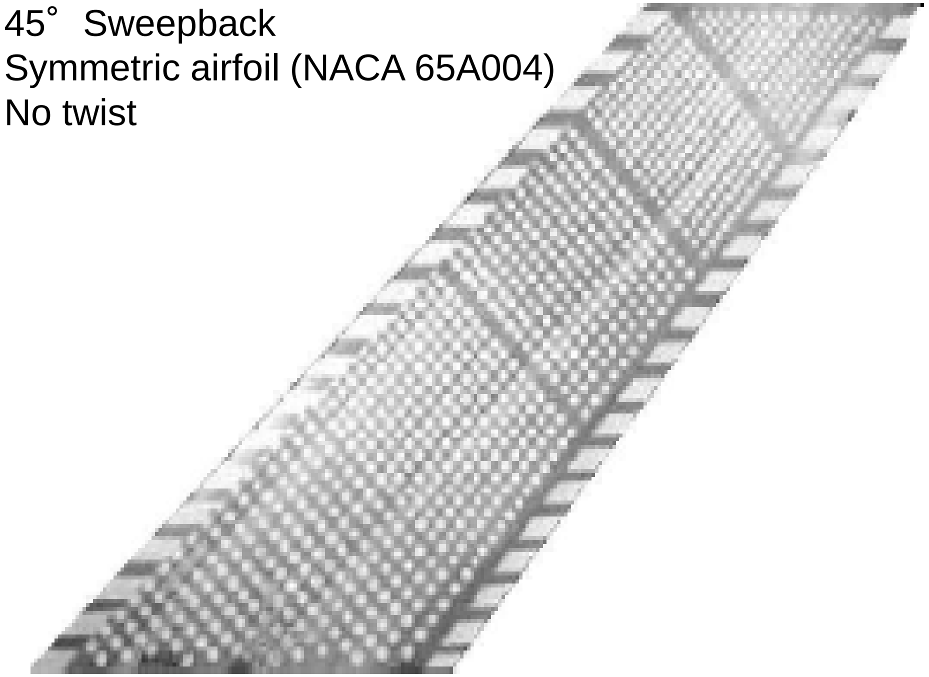
OUTPUT: projected CP



Test case AGARDS 445.6 Wing (AGARD): experimental reference results (wind tunnel tests)

[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



0.76 m

0.57 m

Experimental Data

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

Configuration **Weakened 3**

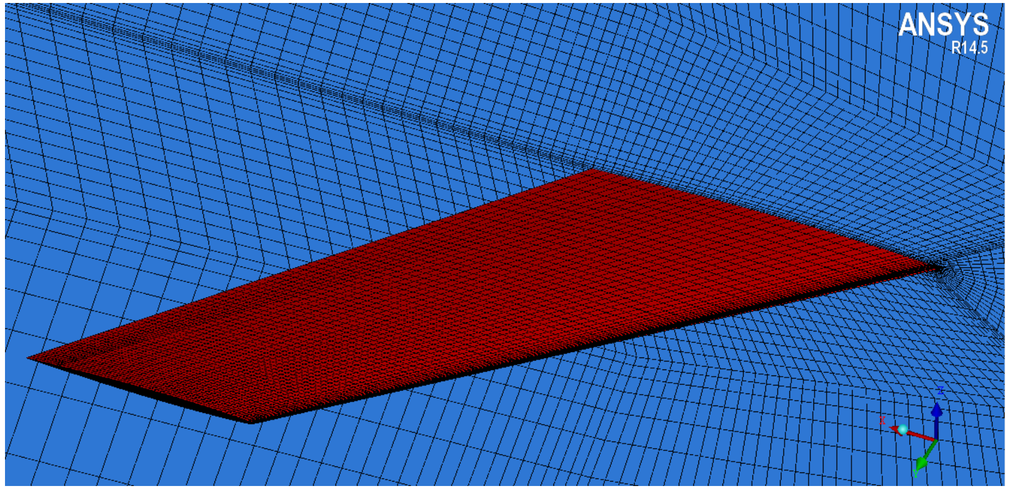
- Laminated Mahogany
- Uniformly Drilled

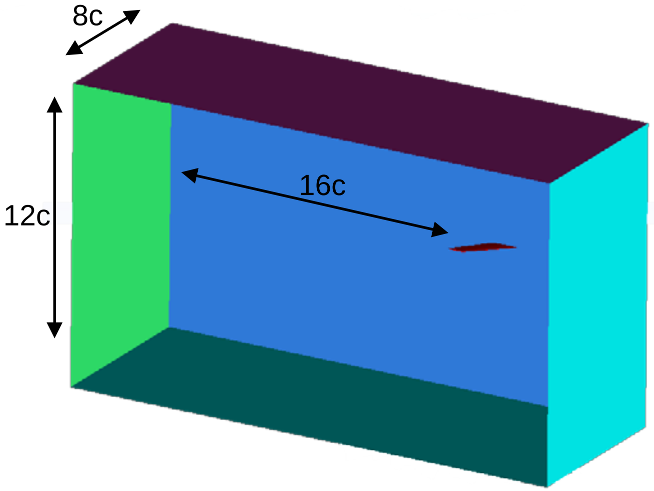
Experimental Flutter points

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

Test case AGARDS 445.6 Wing (AGARD): reated CFD simulation

Structured hexa mesh



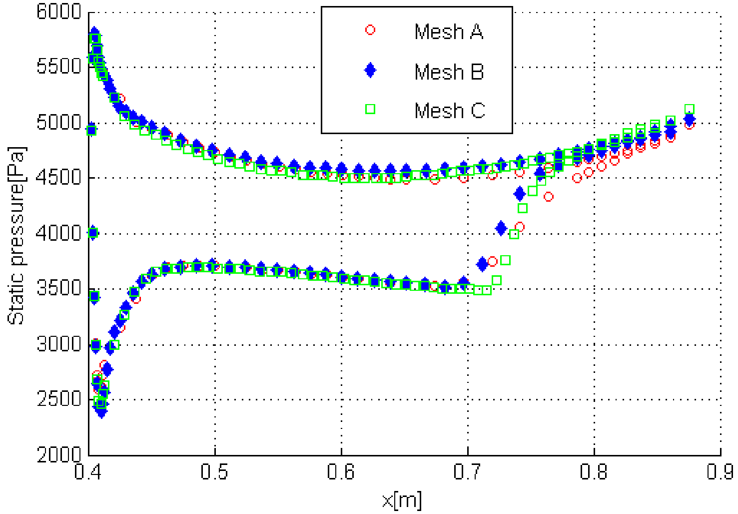


Euler model

Mesh Sensitivity

Steady case: α=3

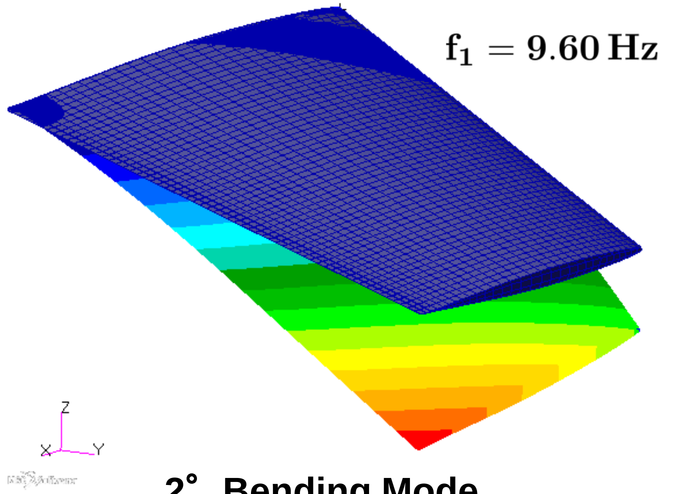
Mesh	A	**B**	C
Nodes	372000	**761000**	3039000
Time	10 min	**20 min**	3 h



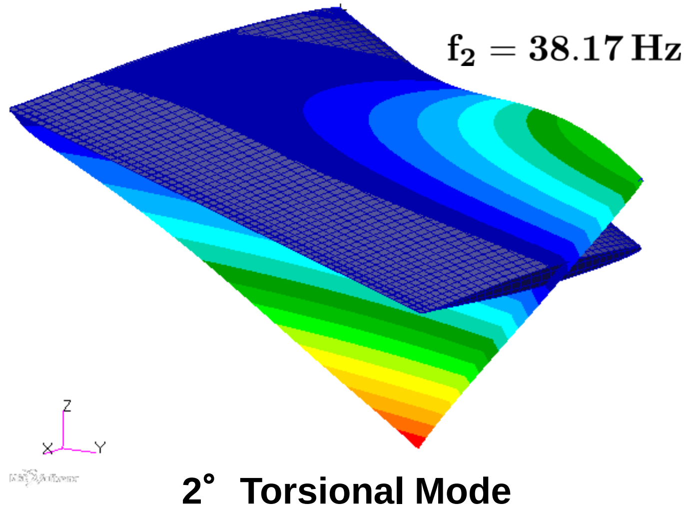
Modeling for FSI (unsteady aerodynamics) linearized analysis (LFD)

Updated modes (via structural optimization in FE framework)

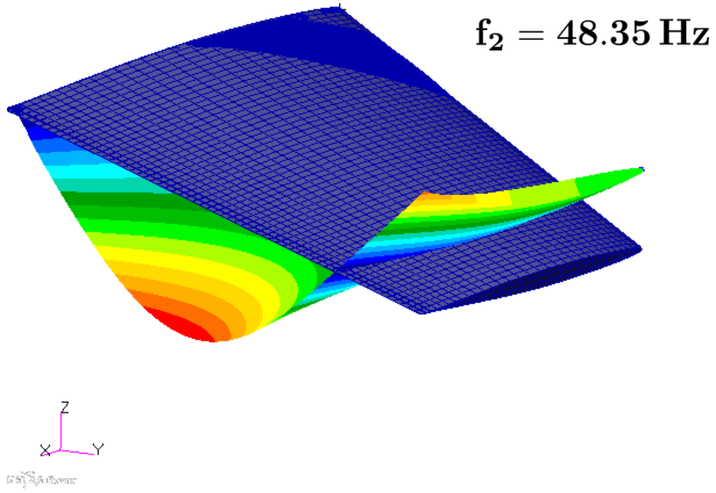
1° Bending Mode



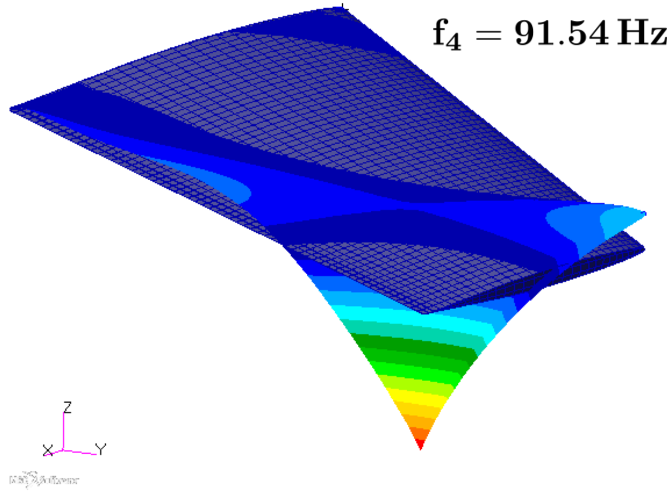
1° Torsional Mode



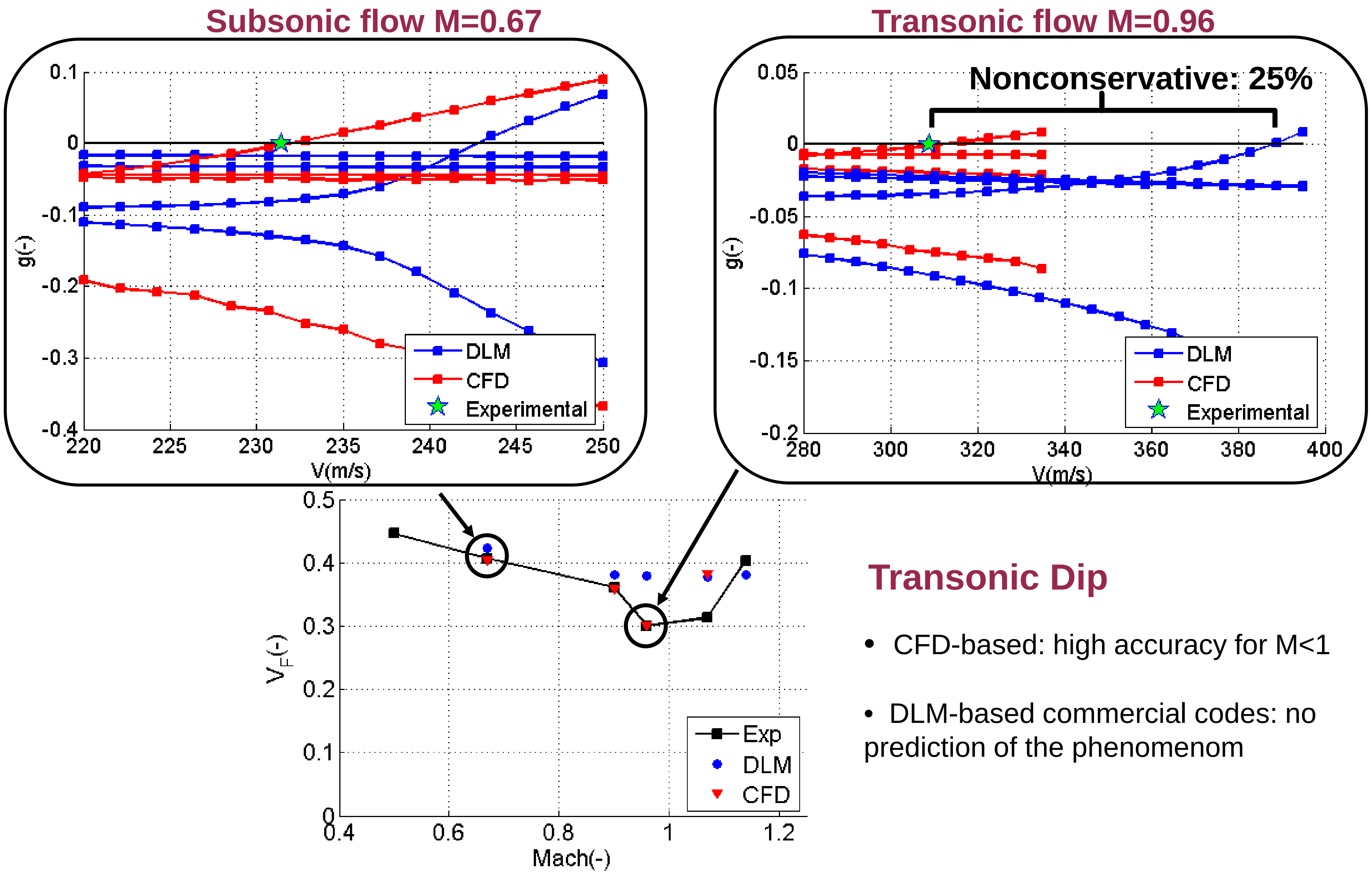
2° Bending Mode



2° Torsional Mode



Flutter prediction and comparison with experimental results



Transonic Dip

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

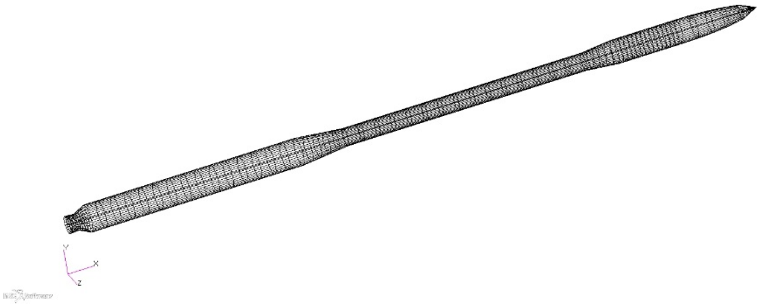
No commercial codes exist in this case

Technical data:
- Diameter: 1 m
- Length: 25.8 m
- Total mass: 17850 Kg
- Thrust: 513 kN
- 4 stages

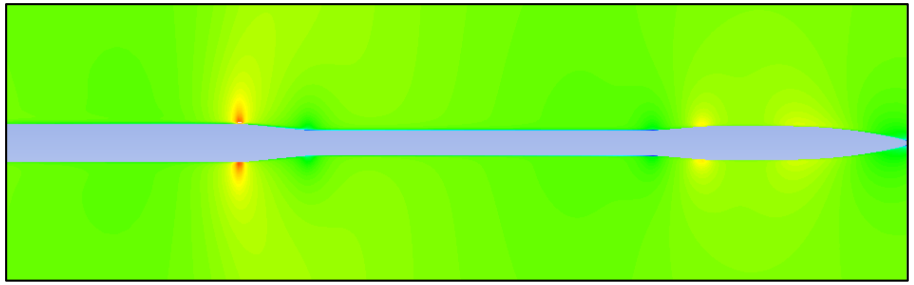
Transonic Flight

- M = 0.88
- $\alpha = 1^{\circ}$
- V = 293.6 m/s
- p = 65057 Pa
- ρ = 0.80 kg/m^3

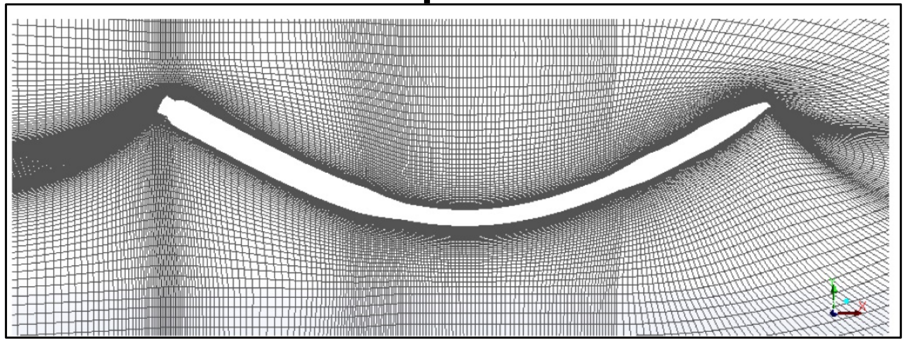
Structural model



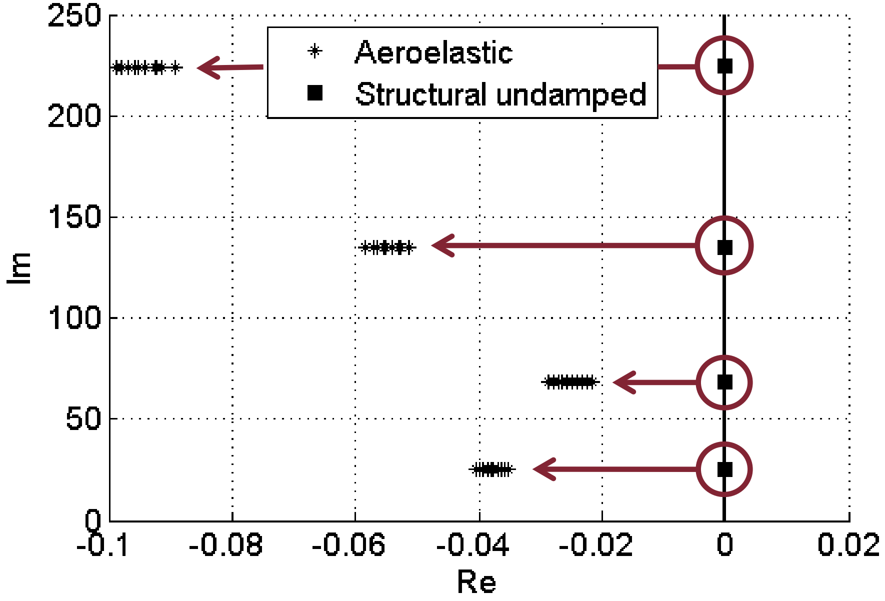
CFD model



Unstedy BC and pressure field projection via RBF morph



Flight **Speed** range**:** 260 – 300 m/s



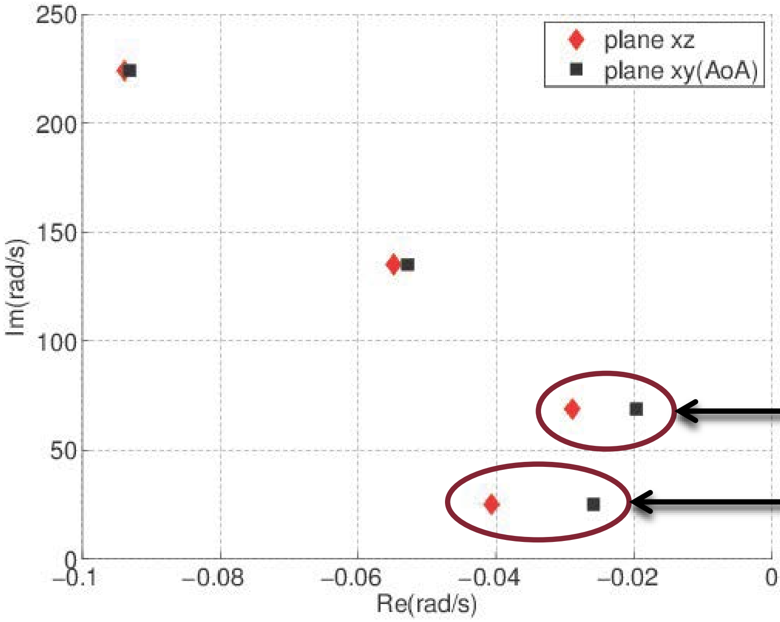
No dynamic instabilities occur in transonic flight

↓

Damped Aeroelastic poles for all flight speeds investigated

Modes both **in-plane** and **out-of-plane** are used

The presence of an **angle of attack** in the static solution causes **decoupling** of the aeroelastic poles of the system

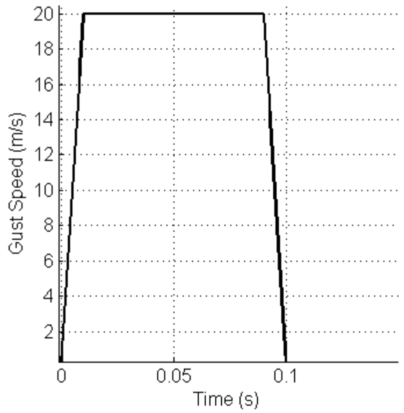


The importance of a **linearization** taking into account the **static solution** is confirmed

Modeling for FSI (unsteady aerodynamics) linearized analysis (LFD)

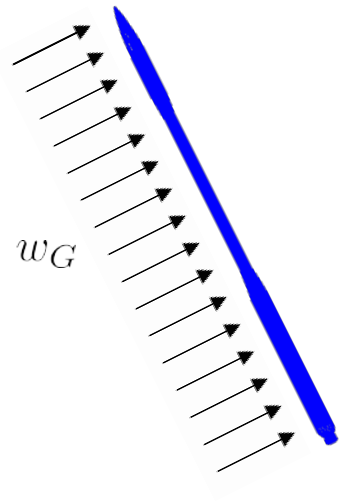
Linearized gust response for a LV

Gust profile



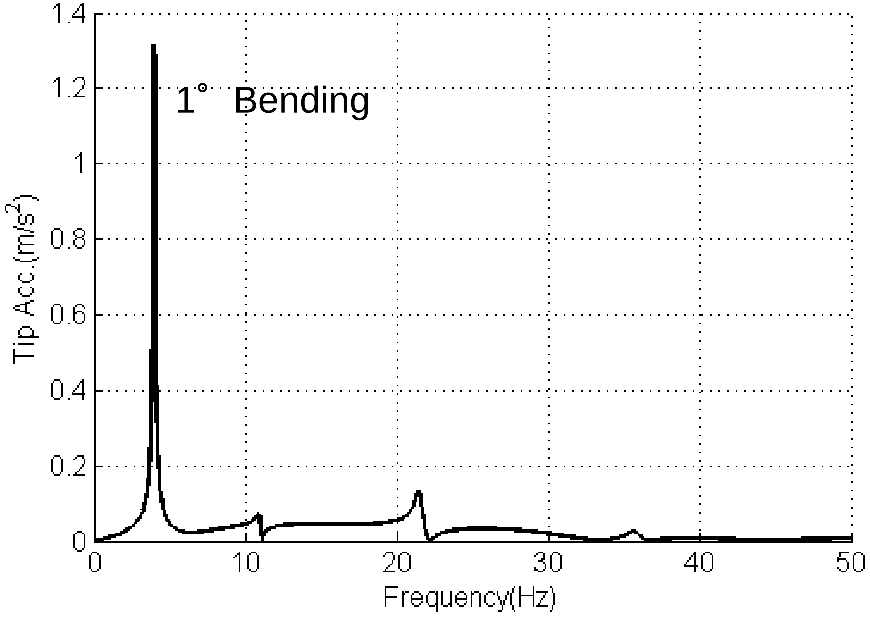
Transonic flight

ROM developed for **lateral** gust

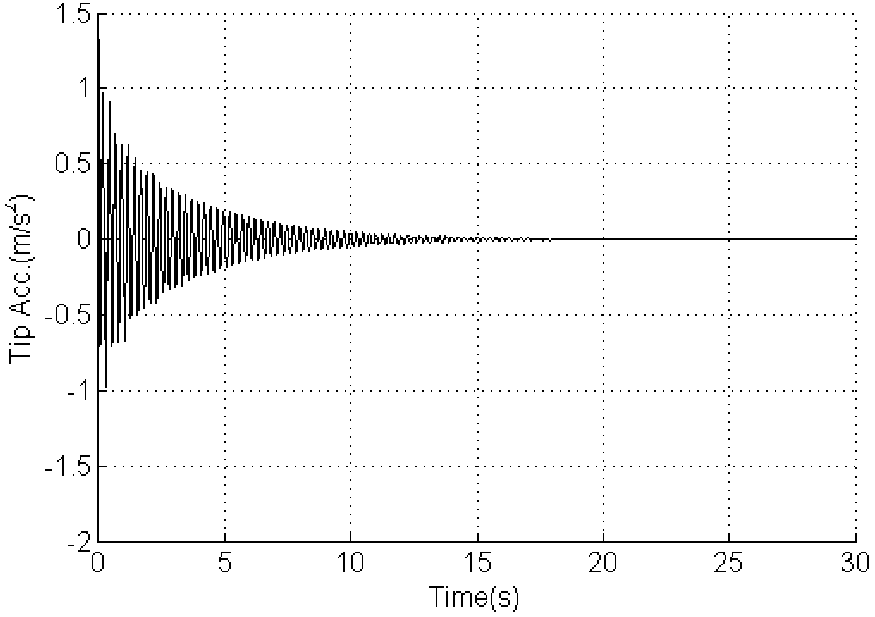


Acceleration induced at **payload fairing**

Frequency domain



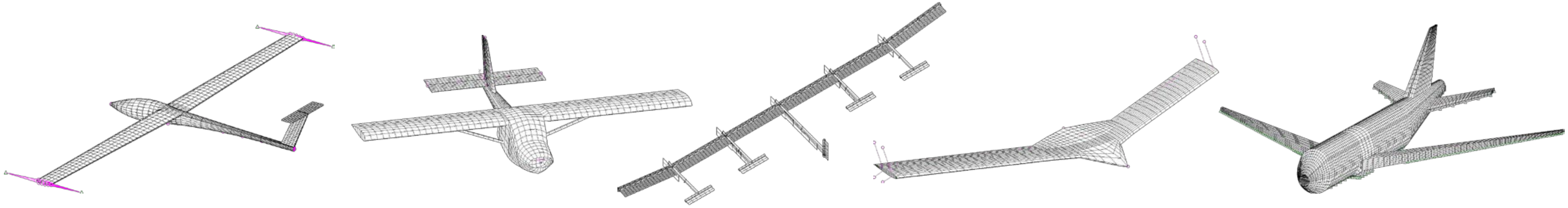
Time domain



Multidisciplinary-Design and

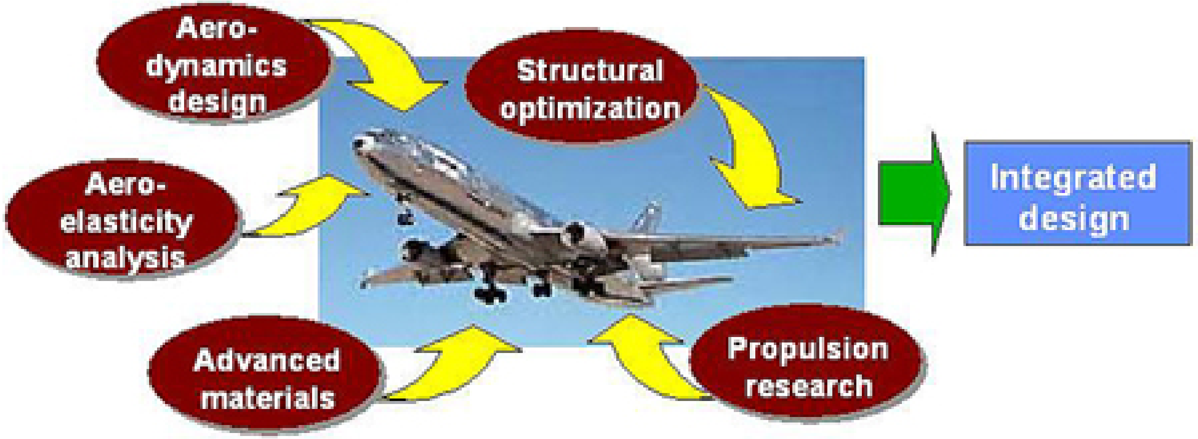
Multi-Objective Optimization of aircraft

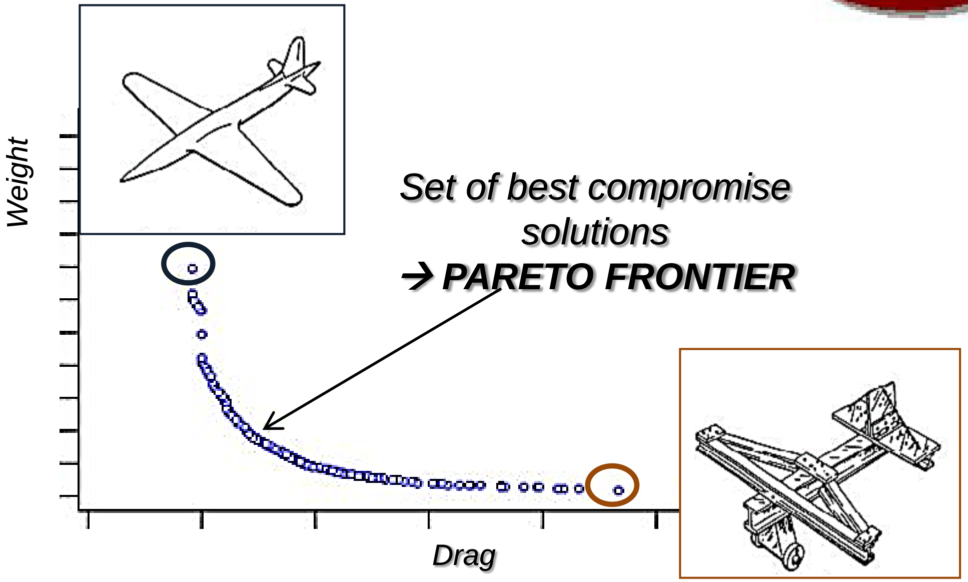
….. How to use the learned lessons on modeling?



MDO – MOO combination

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



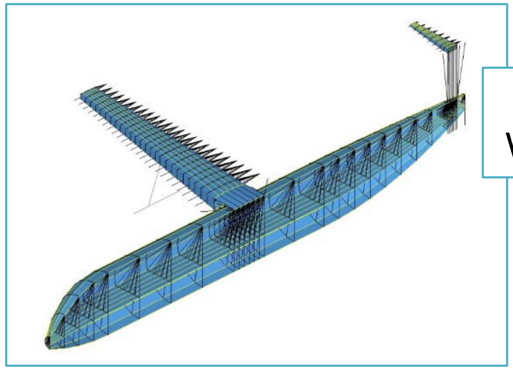


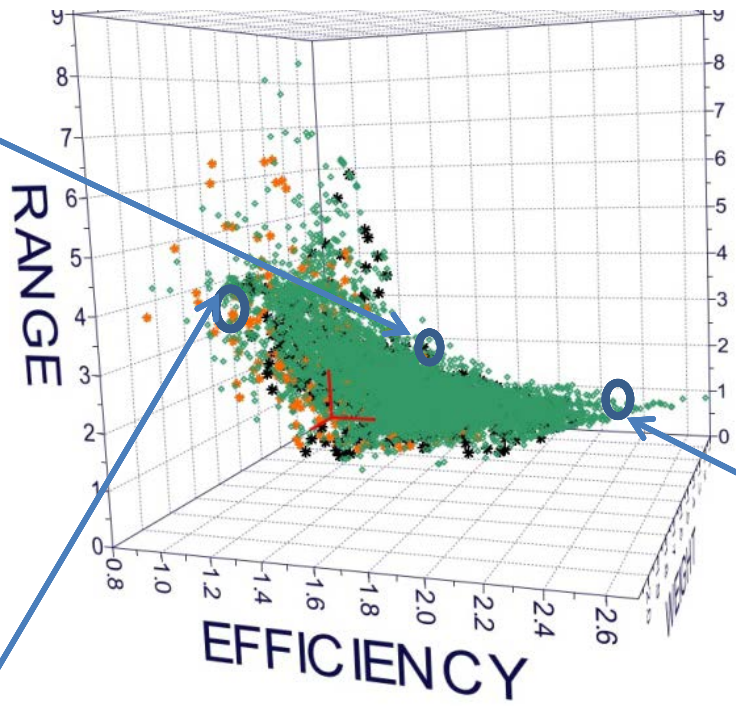
THE BEST DESIGN SOLUTION:
Multi-Objective Optimization (MOO) for a MDO problem allows to keep homogeneus relevance for each discipline:

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

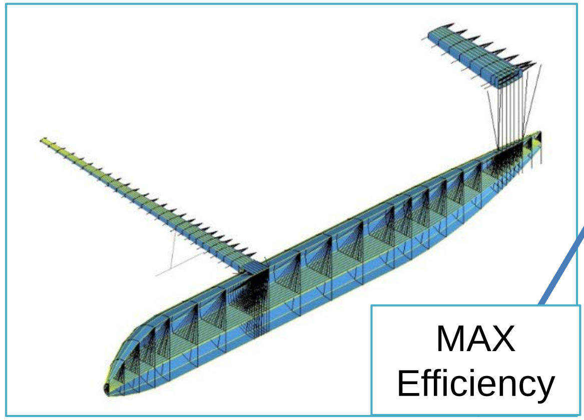
MDO and MOO for a conventional aircraft configuration

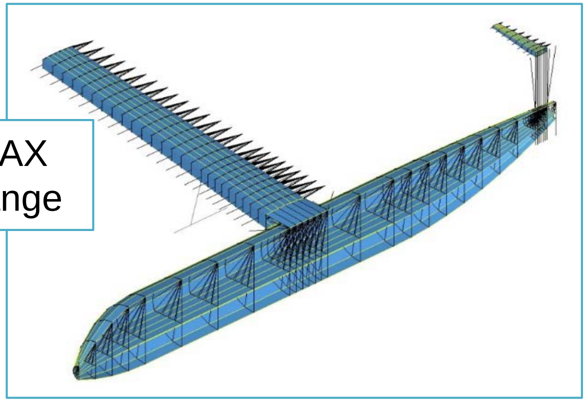
Application on standard civil-aircraft configuration





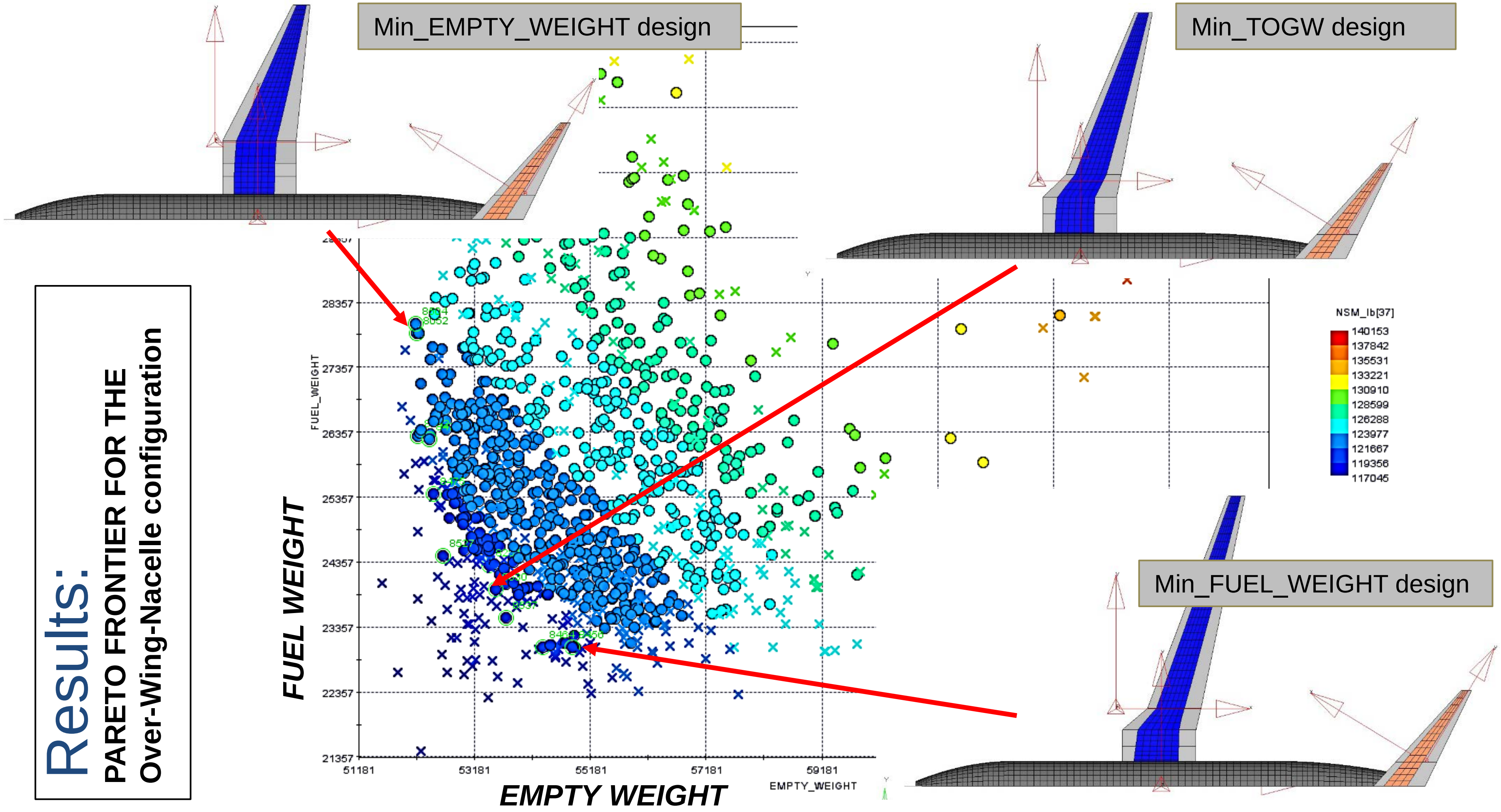
Design	W [kg]	E	R [km]
Initial design	16047	12.25	4209
W_{opt}	16041	13.180	3792
E_{opt}	17359	25.549	1531
R_{opt}	16338	9.266	5307
min d_{ut} design	17054	14.14	3991
min d_{Gcr} design	16077	14.75	3201
Final design	**16073**	**14.11**	**3438**





- OWN is a middle step between conventional transport aircraft designs and more unusual configurations
- OWN concept is promising to be a very efficient solution for improving transonic performance thanks to shock location control in the inboard section of the wing
- Several benefits due to the over wing engine installation (Noise reduction, larger engine diameter, thrust reversal spoilers, etc..)

Results:
PARETO FRONTIER FOR THE Over-Wing-Nacelle configuration



Results of the MDO-MOO on **unconventional** High Altitude Long Endurance (HALE) or High Altitude Pseudo Satellite (HAPS)

HALE

High-Altitude
Long-Endurance
unmanned aerial vehicles

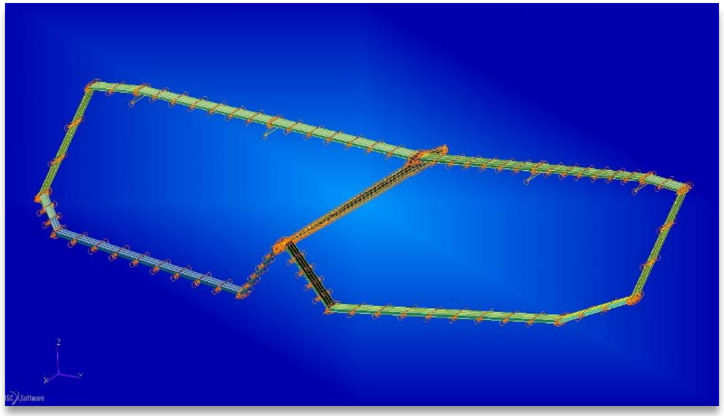
HALEs are able to perform most of the **LEO** satellites AKA **HAPS, High Altitude Pseudo Satellites**

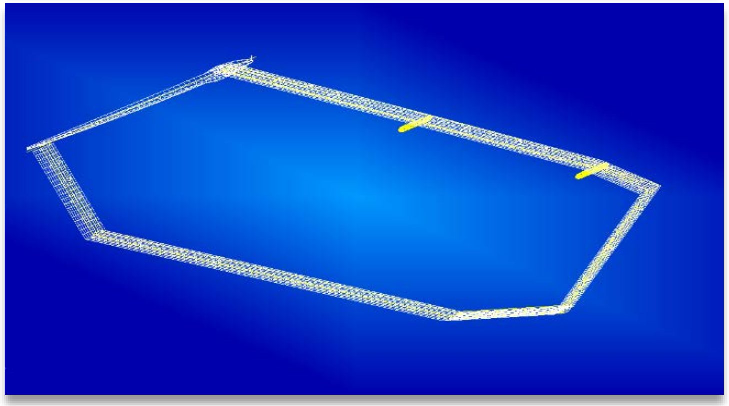
This is possible thanks to the capability of flying aloft for long periods of time (a fortnight is the record) thanks to a ***green*** energy source: **SUN Energy**

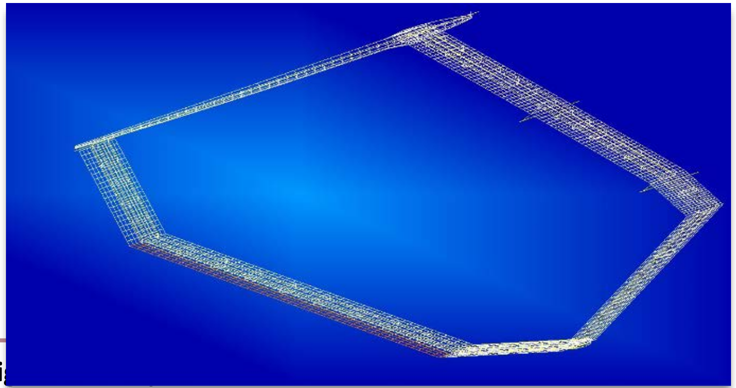
Multi-disciplinary analyses

After the model generation, some preliminary analyses have been done.

- **Linear static analysis** (gravity and landing): no failure and acceptable displacements (MSC Nastran SOL 101);
- **Modal analysis**: very low frequencies (SOL 103);
- **Aeroelastostatic analysis**: trim is possible (SOL 144);
- **Flutter analysis**: no flutter occurs (SOL 145);
- **Gust response analysis**: high flexibility (SOL 146).







Results of the MDO-MOO on unconventional High Altitude Long Endurance (HALE) or .. High Altitude Pseudo Satellite (HAPS)

HALE unconventional geometries and the particular tasks involve **different engineering branches**

The Multidisciplinary Design Optimization (MDO)
A genetic algorithm has been applied

Multi-Objectives Optimization

MOO analysis:
1) **Max. lift to drag ratio**;
2) **Max. caught Sun power**;
3) **Min. mass**.
All the objectives **are in opposition**!!!

A Process Integration and Design Optimization software ESTECO ModeFrontier

FemWing
the FEM models generator

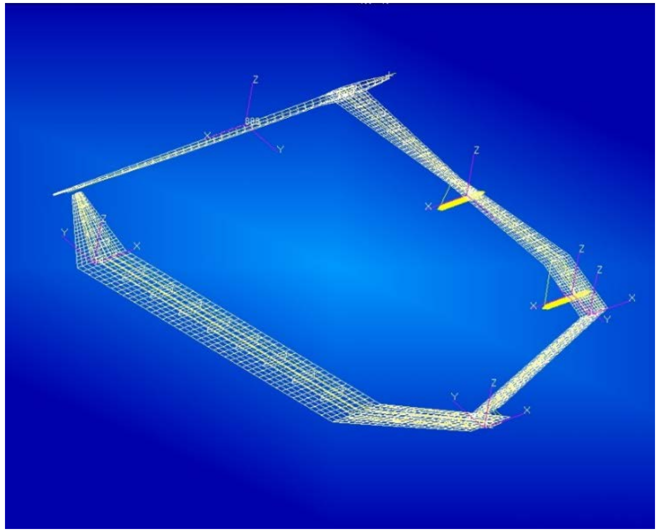
A Computational Structural Mechanic solver MSC Nastran

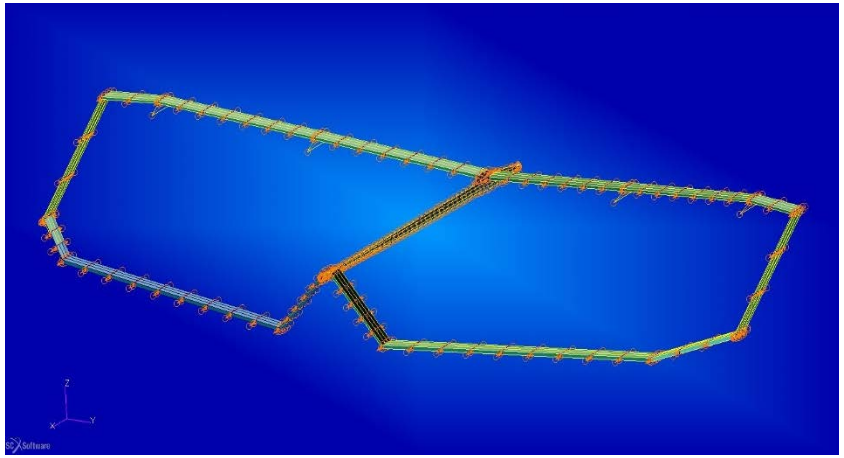
SunWing
the Sun flow estimator

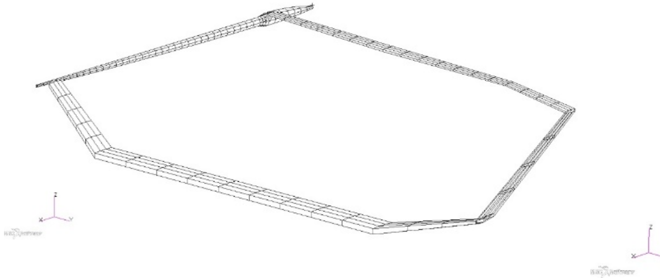
MDO and MOO for an unconventional aircraft configuration

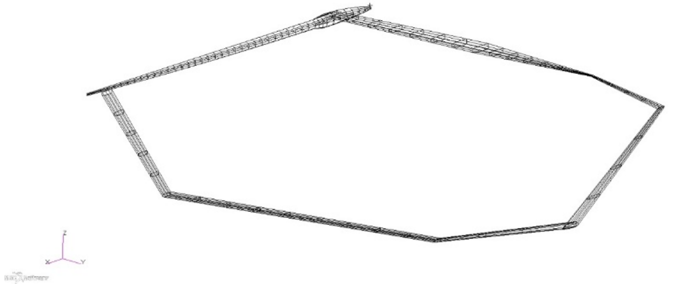
Results of the MDO-MOO on unconventional High Altitude Long Endurance (HALE) or .. Hight Altitude Pseudo Satellite (HAPS)

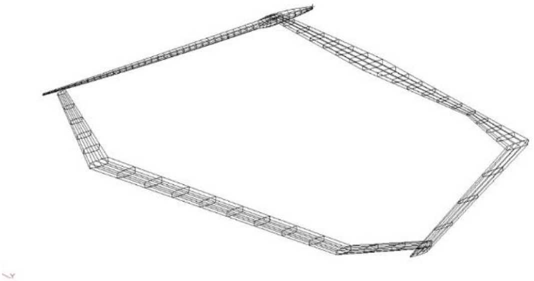
Multi-OBJECTIVE optimizarion











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

Maximize L/D ratio ONLY

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

Minimize structural weight ONLY

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

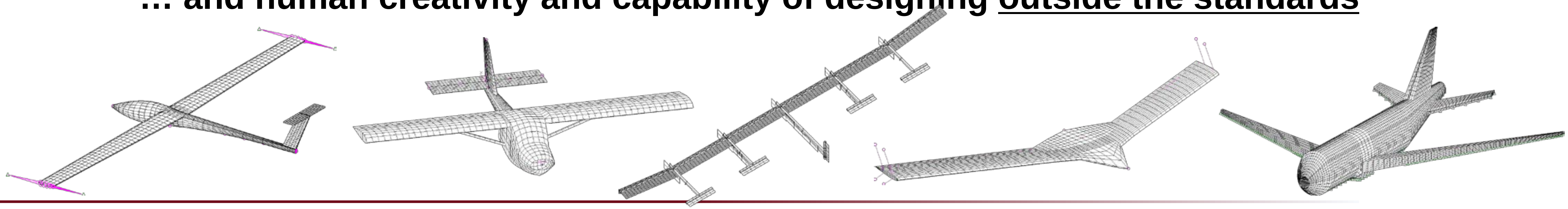
Maximize captured sun energy ONLY

Some final remarks

Old/New challenges for aircraft modelling and design:

1. **More and more <u>integrated multidisciplinary modelling and optimization</u>**
   Cross-fertilization between different scientific communities is mandatory to significantly improve future designs
2. **More and more <u>physical fidelity</u> of modelling**
   Models based on first principles (not surrogates) and capturing the relevant physics are necessary to guide design optimization
3. **More and more <u>computational efficiency</u>**
   First-principle-based and possibly high-fidelity models must be at the same time computationally efficient if to be used for design (reduced-order modeling)

… and human creativity and capability of designing <u>outside the standards</u>



Related publications

- Morino, L., Mastroddi,F., De Troia, R., Ghiringhelli,G.L., Mantegazza, P., "Matrix Fraction Approach for Finite-State Aerodynamic Modeling", *AIAA Journal*, Vol.33. No 4 April 1995, pp. 703-711.
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Thank you for your attention