UNIVERSIDAD CARLOS III DE MADRID DEUTSCHES ZENTRUM FÜR LUFT UND RAUMFAHRT

VALIDATION AND EXTENSION OF AN MDO FRAMEWORK INCLUDING DYNAMIC AEROELASTIC ANALYSIS

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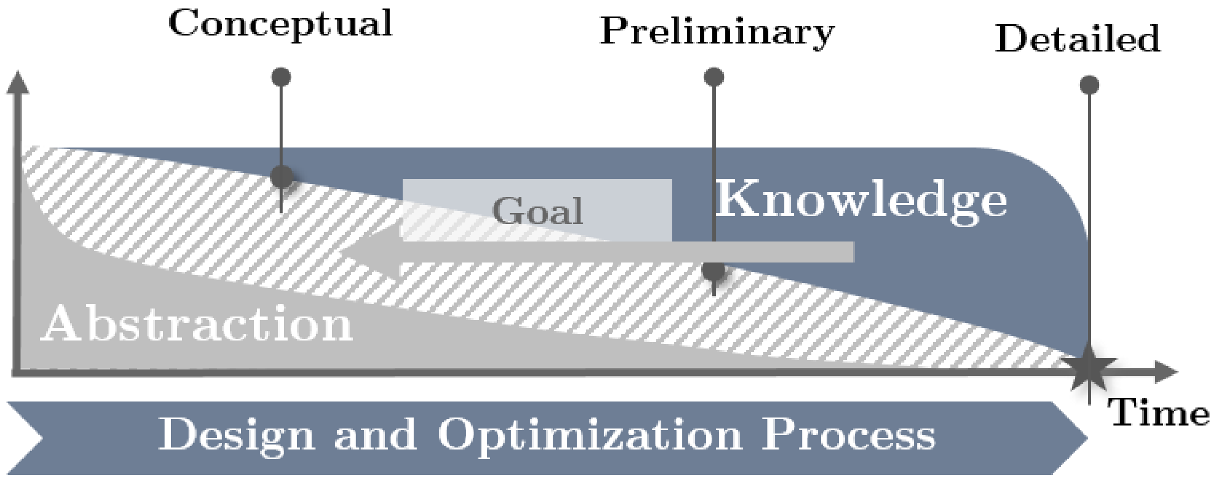
THE AIRCRAFT DESIGN PROCESS

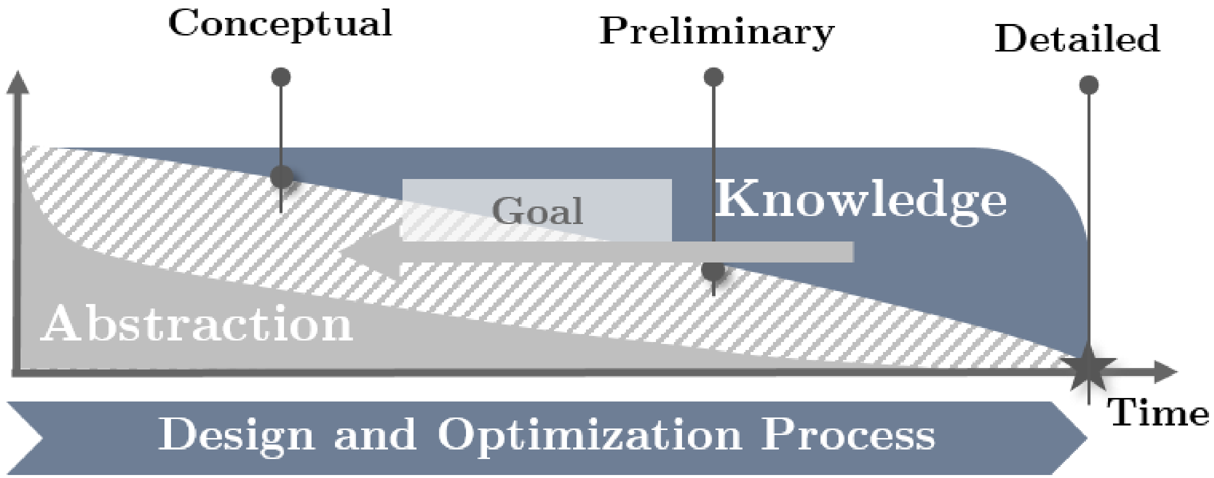
The classic vs modern approach



In the **classic approach**, the number of **modeling details increases with time**, being **reduced** the number of **parameters** which **can be modified**. [1]

THE AIRCRAFT DESIGN PROCESS

The classic vs modern approach



Modern approach challenges

- **Automatization**
- **Robustness**

Modern aircraft design approaches try to **increase the level of details** and **fidelity** in the **early phase** of the design process. [2]

Reducing the design process time and cost

THE PURPOSE OF THE THESIS

Developed tools

NOI - Nastran Optimization Interface

FAEDO - Framework for Aeroelastic Design and Optimization

Optimization platform

OpenMDAO

Capable of supporting gradient-based optimization

Optimization framework

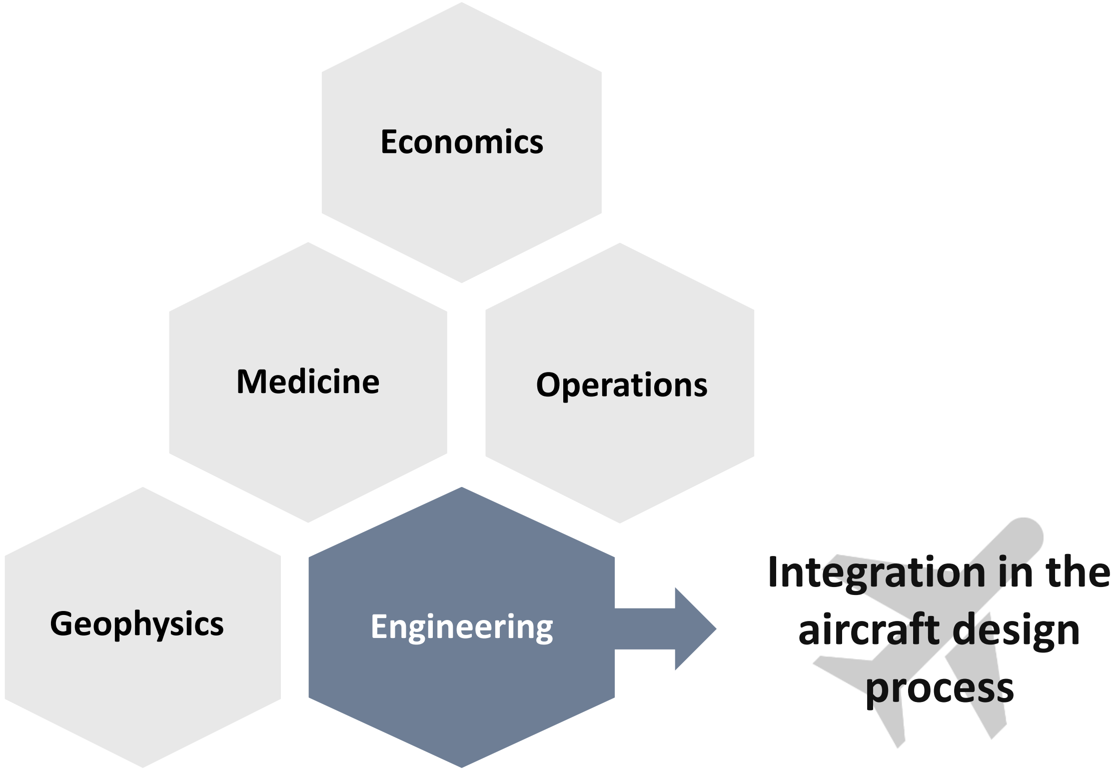
- **Able to deal with flutter analysis** in the conceptual phase.
- **Automatized** and streamlined **the use of *Nastran.***
- **Evaluation** of different **test cases**, increasing the **flexibility and robustness** of the tools.

THE OPTIMIZATION PROBLEM

Optimization

The **aim of optimization** is to achieve the **"best" design** relative to a set of **prioritized criteria or constraints.** **[3]**

$$\begin{cases} \text{Minimize } f(x,y) \text{ with respect to } x \text{ and } y \\ \text{Subject to } \begin{cases} \text{Behavioral constraints on } y \\ \text{Design constraints on } x \\ \text{Equilibrium constraints} \end{cases} \end{cases}$$



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Formulation

Objective function (*f*): Denotes the function that points out the goodness of the design. Usually f indicates the weight, stress or displacement in the structure.

Design variables (x): The design variables can be a function or a vector that represents the design. They are usually related to a geometry feature or even to a choice of material.

State variables (y): Conform the responses of the problem for a given design condition. In structural optimization state variables are mainly related to stresses, strains, or forces.

THE OPTIMIZATION PROBLEM

Optimization

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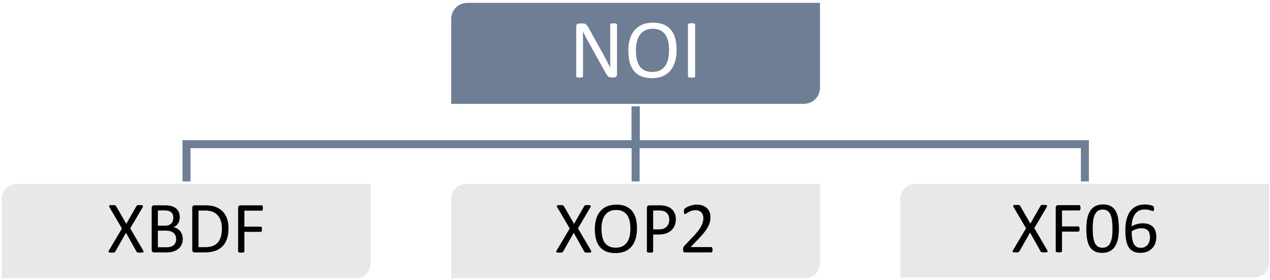
Sensitivity analysis

- Provides the **variation of the responses with respect to the design variables.**
- Allows identifying **how a certain change in a design variable** may **impact the product.**
- Serves as an input to **guide the optimizer in the proper direction.**

$$\lambda_{ij} = \left.\frac{\partial g_i}{\partial x_j}\right|_{x^0}$$

What is NOI?

Nastran Optimization Interface, also known as NOI, is a self-developed *Python* tool that provides the capability of **writing *Nastran* optimization, modal and flutter input files** given the finite element or design model description.



NOI's modules

BDFWritter.py

XBDF

Class developed to exploit the creation of different types of BDF files incorporates modal, static, flutter and optimization solution sequences.

OP2Reader.py

XOP2

Extension of the OP2 class in order to provide support for the modal, static and sensitivity analysis results stored in an OP2 file.

F06Reader.py

XF06

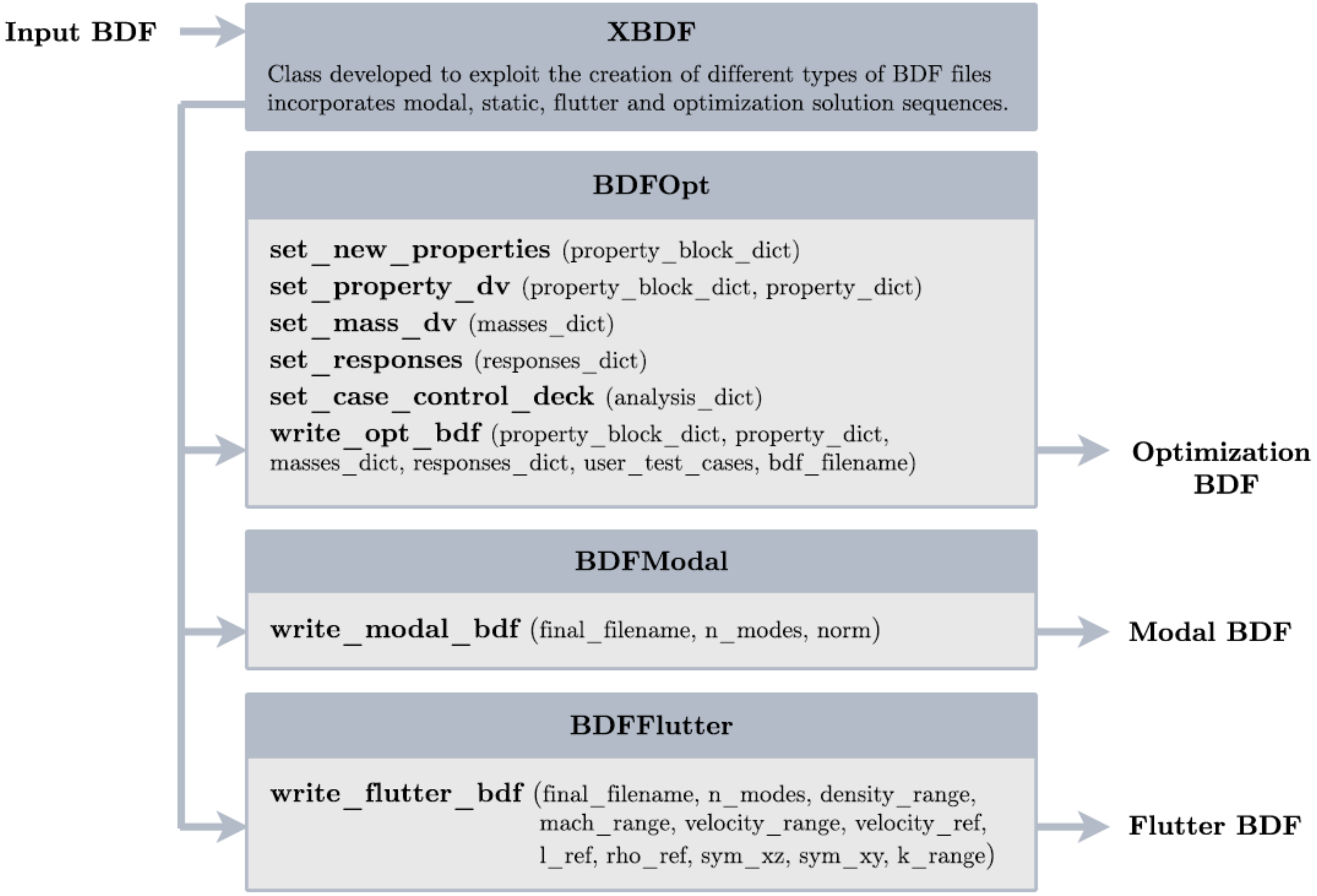
Module that expands the F06 results handling capabilities. Includes the possibility to represent V-g, V-f and root locus plots of flutter results.

CREATION OF *NASTRAN* INPUT FILES

BDFOpt

- Focus on the **optimization input file** creation.
- Possibility to define **size design variables**.
- Accounts for **modal and static analysis**.
- Requires a set of **user-defined dictionaries**.

Definition of objective function, responses and design variables



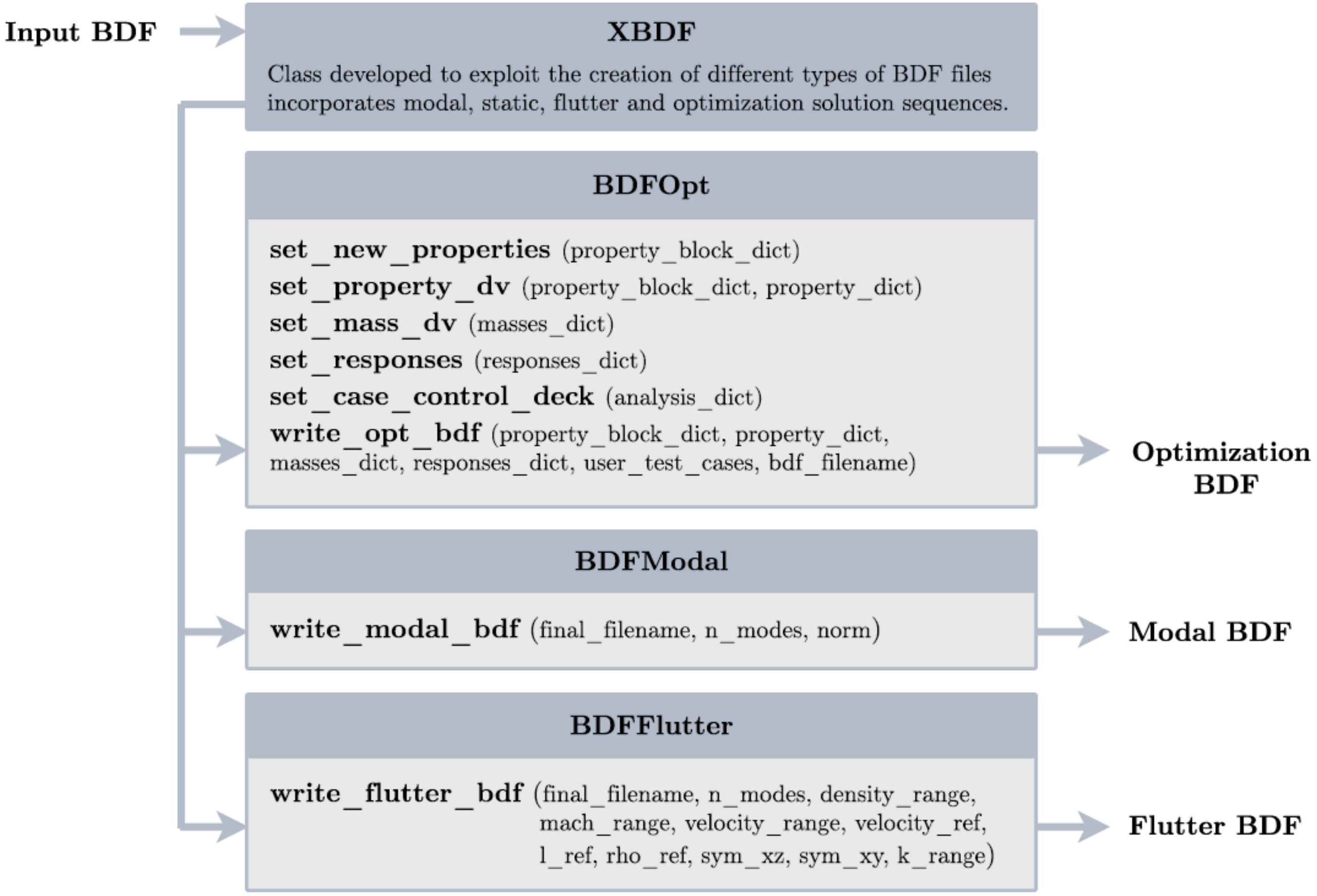
CREATION OF *NASTRAN* INPUT FILES

BDFModal

- Able to create **modal input files**.
- Possibility to **define the number of modes** and **normalization method** of eigenvectors.

BDFFlutter

- Outputs **flutter input files**.
- Allows specifying the **flutter analysis parameters** such as speed range and reference magnitudes.



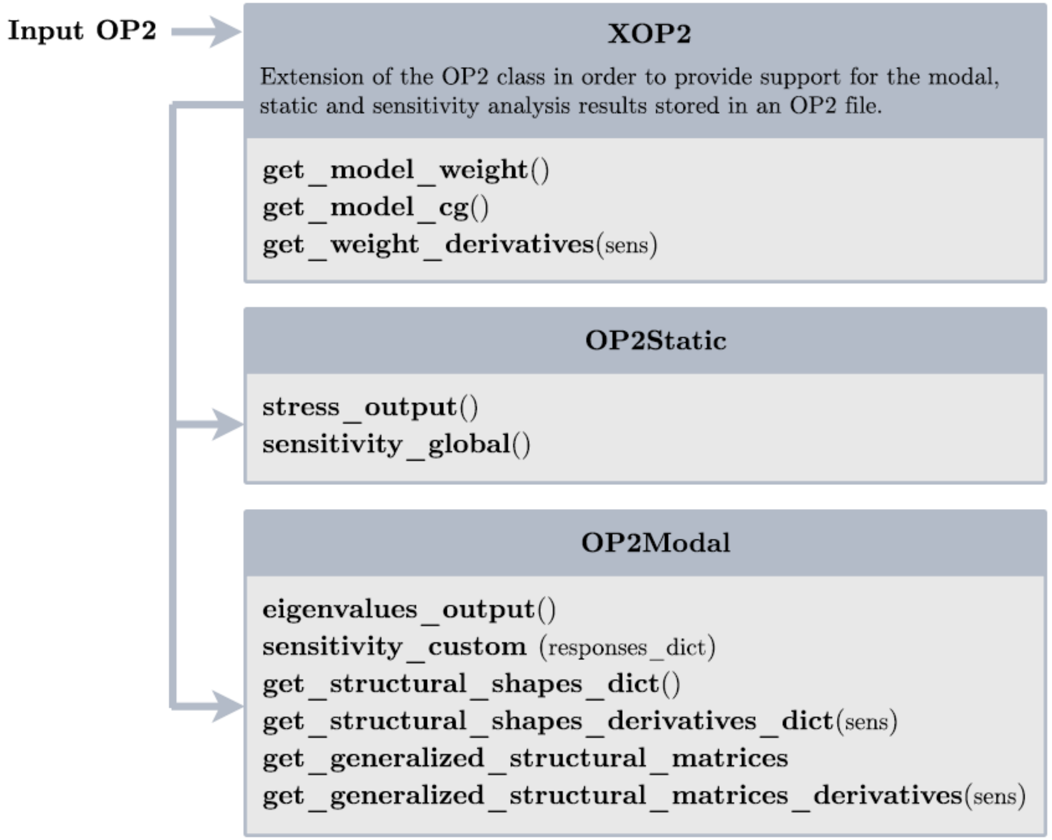
POST-PROCESSING OF RESULTS

OP2Static

- **Stores the stress results** when a static analysis has been performed.
- Accounts for the **global sensitivity matrix**.

OP2Modal

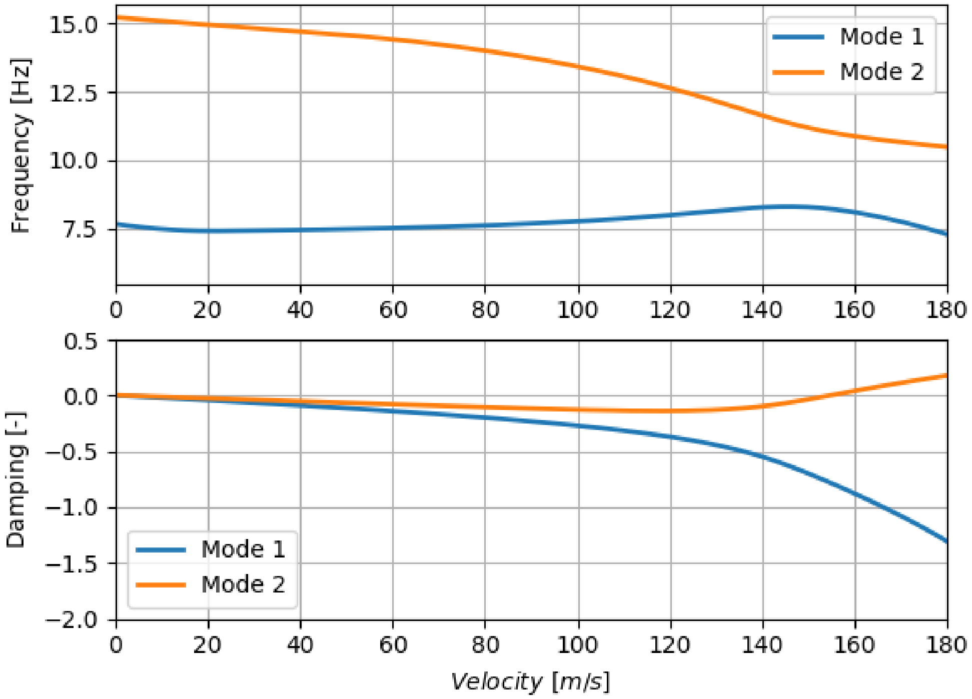
- Outputs the **eigenvalues and eigenvectors.**
- Stores the **sorted version of the sensitivity matrix**.
- Post-processing of the **structural matrices**.



POST-PROCESSING OF FLUTTER RESULTS

XF06

- Eases the task of **post-processing** the *Nastran* **flutter analysis results.**
- Capable of **representing the root locus**.
- Possibility to **display the V-g and V-f plots**.



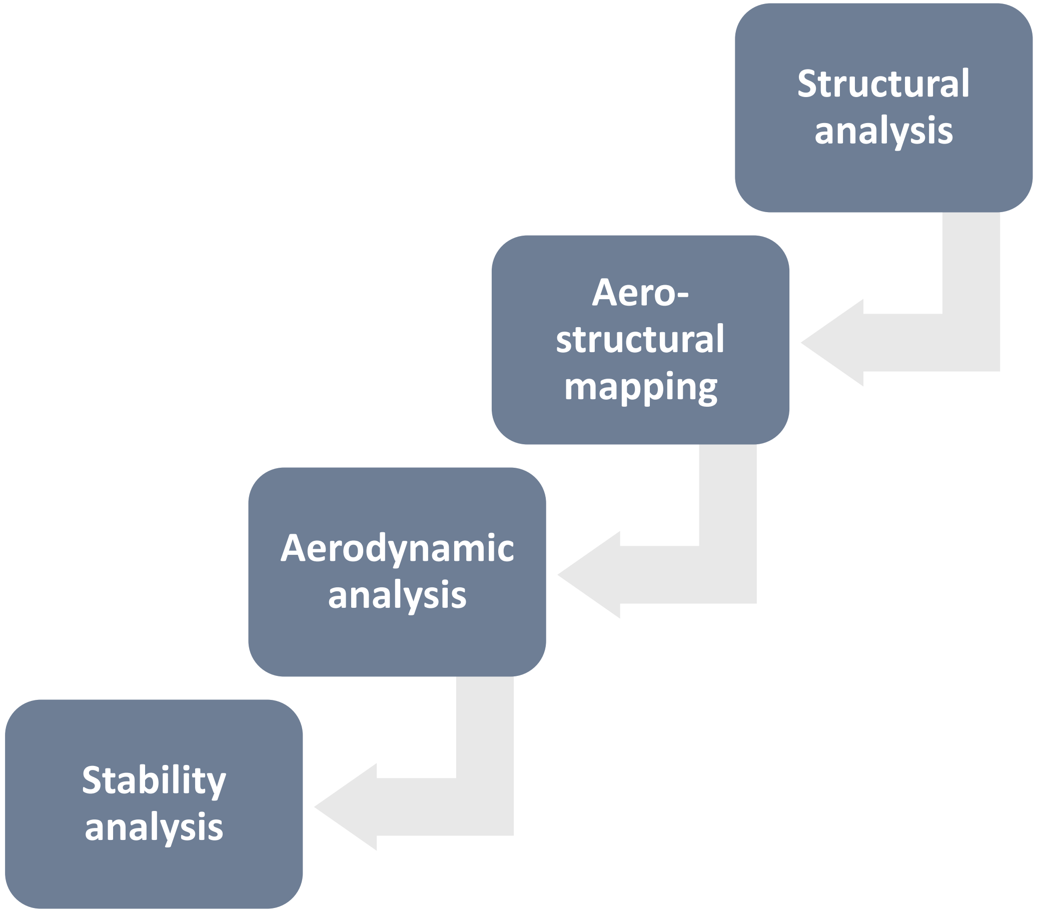
Goland wing V-g V-f plots obtained with the XF06 class [4]

3. FAEDO

Framework for Aeroelastic Design and Optimization

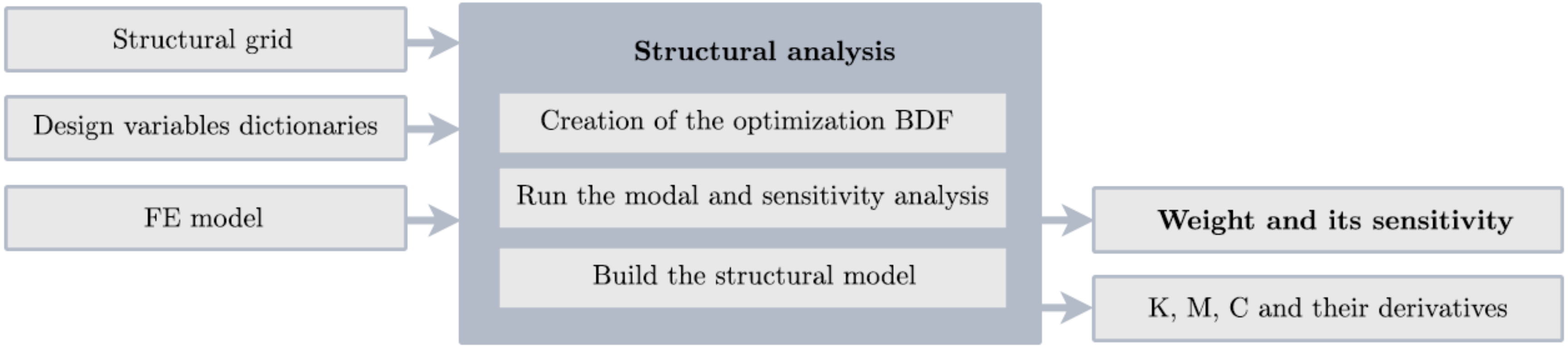
What is FAEDO?

Framework for Aeroelastic Design and Optimization, also known as FAEDO, is a *Python* tool that provides the capability of **carrying out an optimization process considering an aeroelastic constraint.**



STRUCTURAL ANALYSIS

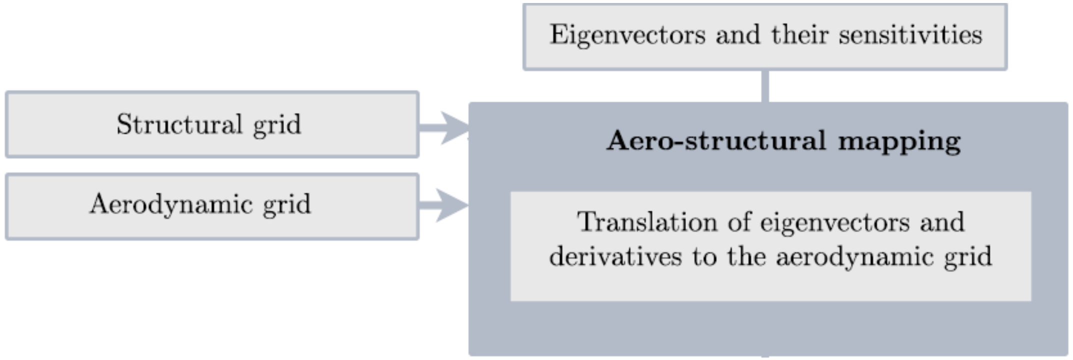
Integration of NOI in order to solve for the **modal and sensitivity analysis** of the FE model and to post-process the structural matrices.

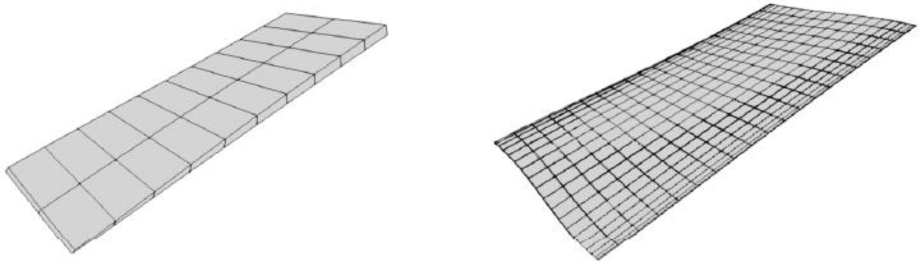


AERO-STRUCTURAL MAPPING

This section of FAEDO **performs a mapping** of the structural modal displacements, and sensitivities, to **the aerodynamic grid** of the geometry.

- Requires the **aerodynamic and structural grids**.
- The **eigenvectors** computed in the structural analysis block **must be provided**.
- Uses a **Infinite Plate Spline method**. **[5]**



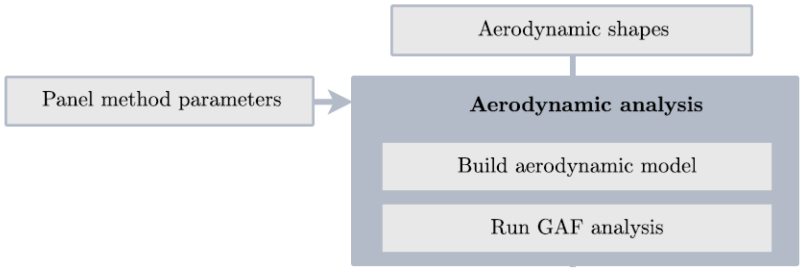


(a) Structural grid (b) Aerodynamic grid

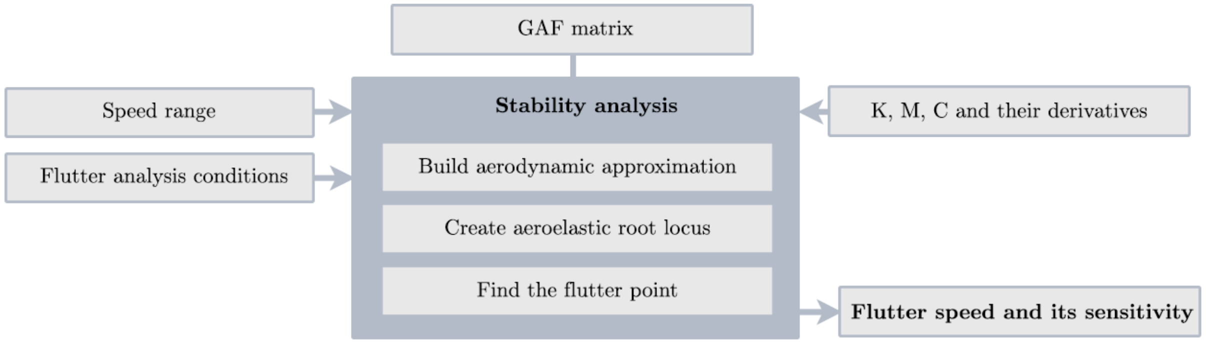
Structural and aerodynamic Goland+ grid torsion mode comparison

AERODYNAMIC AND STABILITY ANALYSIS

The aerodynamic analysis has been performed by means of an **unsteady panel method** that formerly goes under the name of GAF analysis in the framework. **[6]**



The stability analysis computes the **finite state approximation** for the aerodynamic results and provides the **flutter speed and its derivative** with a simple root locus method. **[7]**

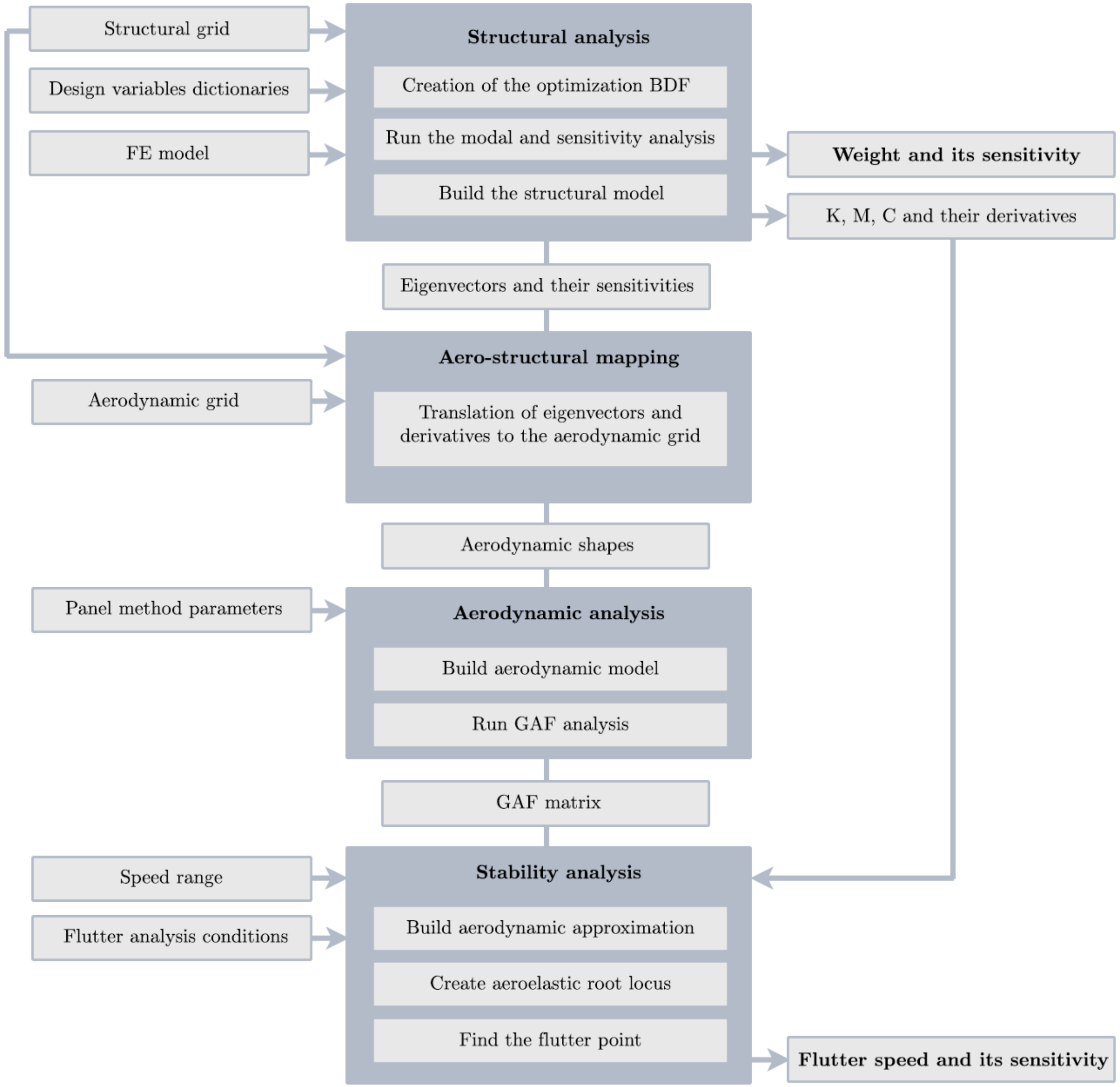


3. FAEDO

Overview of the framework

- Eases the task of **evaluating aeroelastic responses in optimization problems.**
- Capable of computing the **flutter speed and sensitivity**.
- **Integration of NOI** in the structural analysis section.
- Requires the **structural and aerodynamic grid**.
- Solves the **aerodynamic analysis** based on the **GAF method**.
- Possibility to be **coupled with an optimization platform**.

OpenMDAO [8]



4. CASES OF STUDY

Objectives

- Verifying **NOI's integration** in FAEDO.
- Check the **proper flow of information** inside **FAEDO**.
- **Assessment of FAEDO** when computing the **aeroelastic constraint and its sensitivity.**
- **Coupling** of **FAEDO** and **OpenMDAO.**

DOE for the flutter speed derivatives

Test case focused on verifying that the flutter speed derivatives computed with respect the design variables are reliable and accurate enough.

Optimization of the Goland+ model

Optimization process taking the mass as objective function and including a constraint on the flutter speed. The selected design variables represent the set of lumped masses that compose the front and rear spars.

Optimization of the Goland beam model

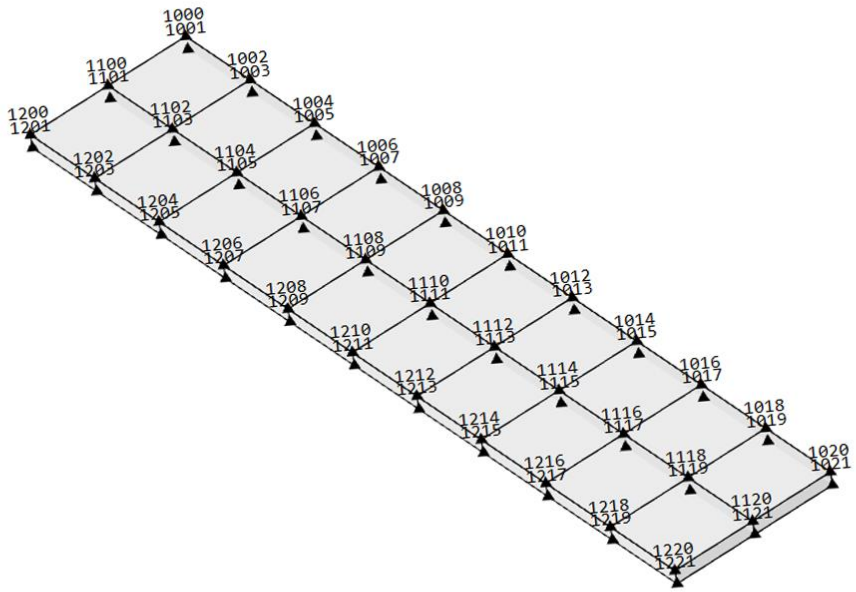
Optimization of the classic Goland wing mass modifying its cross-sectional area and restrincting the flutter speed within a given bounds.

4. CASES OF STUDY

FINITE ELEMENT MODELS

GOLAND+ MODEL [9]

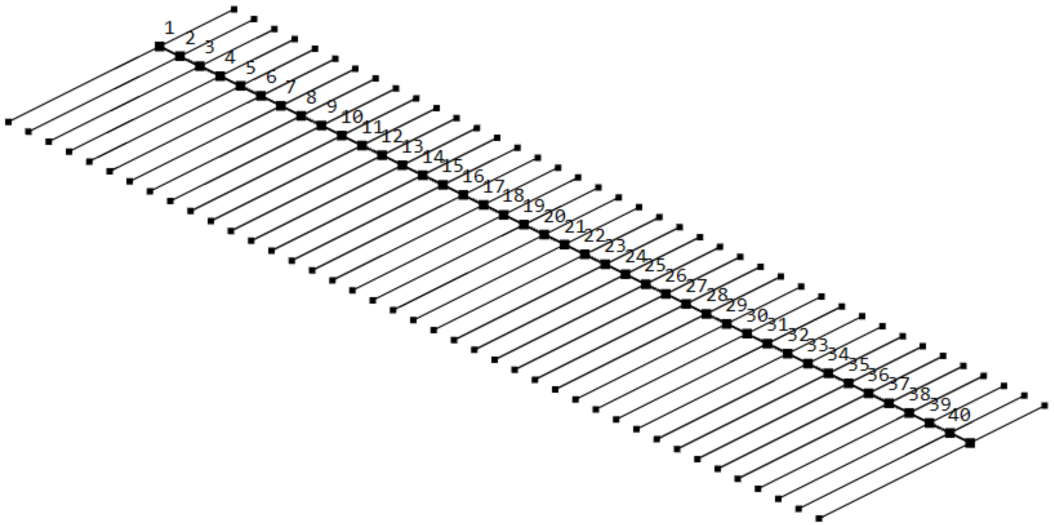
- **Variation of the classic Goland wing model**.
- Wing **modeled with CQUAD elements**.
- **Includes lumped masses** to get a certain aeroelastic response.
- **Used to assess the lumped masses as design variables.**
- **Flutter speed of 119.09 m/s**.



FE model identifier	Value
1000, 1001, 1020, 1021	14.338 kg
1002 ... 1019	28.677 kg
1100, 1101, 1120, 1121	28.780 kg
1102 ... 1119	57.561 kg
1200, 1201, 1220, 1221	38.964 kg
1202 ... 1219	77.928 kg

GOLAND+ lumped masses values

FINITE ELEMENT MODELS



Property	Value
A	0.01323 m^2
I_1	0.00262 m^4
I_2	0.0001396 m^4
J	$3.809 \cdot 10^{-5}$ m^4

Property	Value
Young Modulus	71.02 GPa
Shear Modulus	25.9 GPa
Poisson ratio	0.35
Density	2700 kg/m^3

Goland beam model properties

GOLAND BEAM MODEL [4]

- **Replicates the classic Goland wing behavior.**
- Wing **modeled with CBEAM elements**.
- Allows **defining the distance between** the **elastic** and the **inertial axis.**
- **Used to assess the element properties as design variables.**
- **Flutter speed of 154.8 m/s.**

DESIGN OF EXPERIMENTS

Objectives

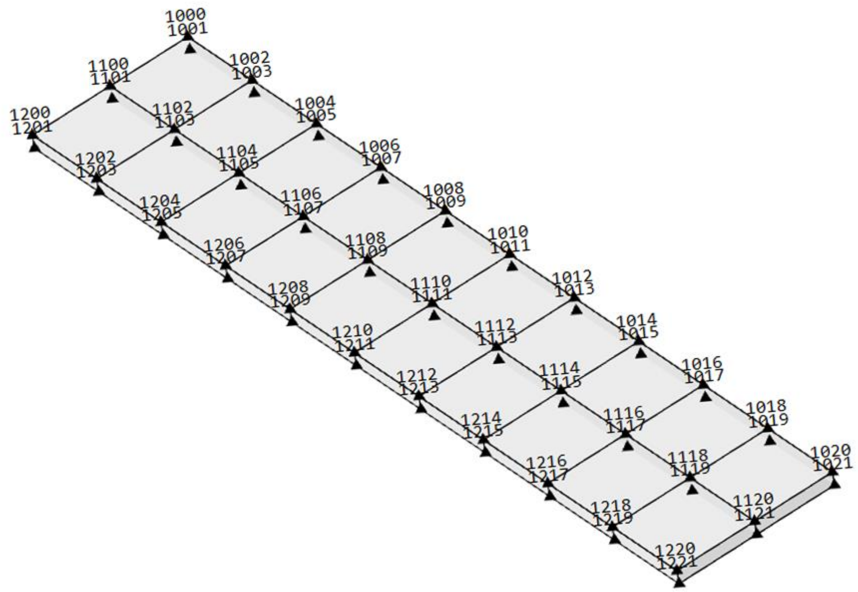
Verifying that the **flutter speed derivatives** computed by the optimization framework are **reliable and accurate enough**.

Methodology

Comparison of the **analytical flutter speed derivatives** provided by **FAEDO with the ones obtained with finite differences.**

Set-up

Definition of a **toy optimization problem** with a **set of the lumped masses of the Goland+ model as design variables.**

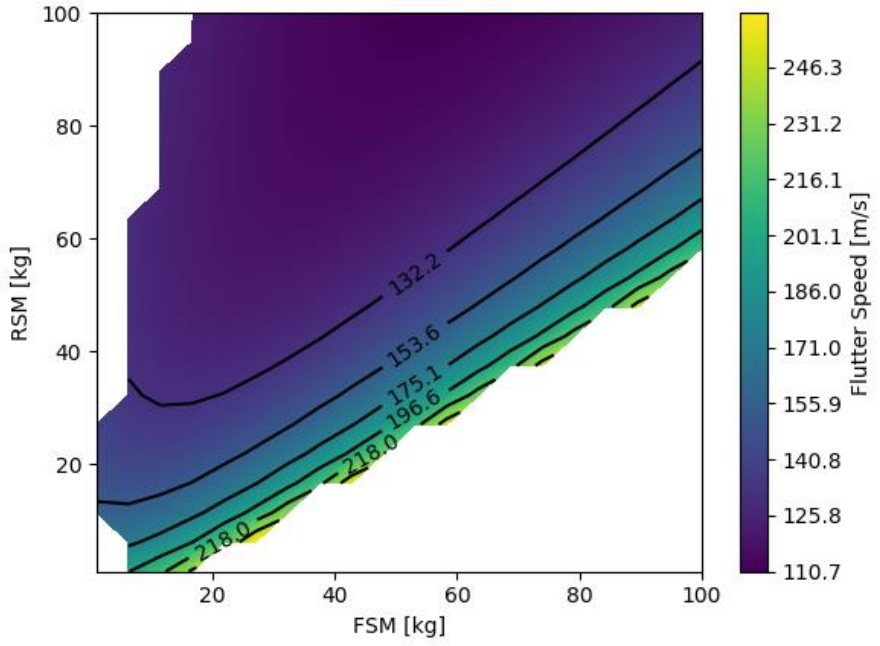


Design variable	Set of masses identifiers
FSM	1000 ... 1021
RSM	1200 ... 1221

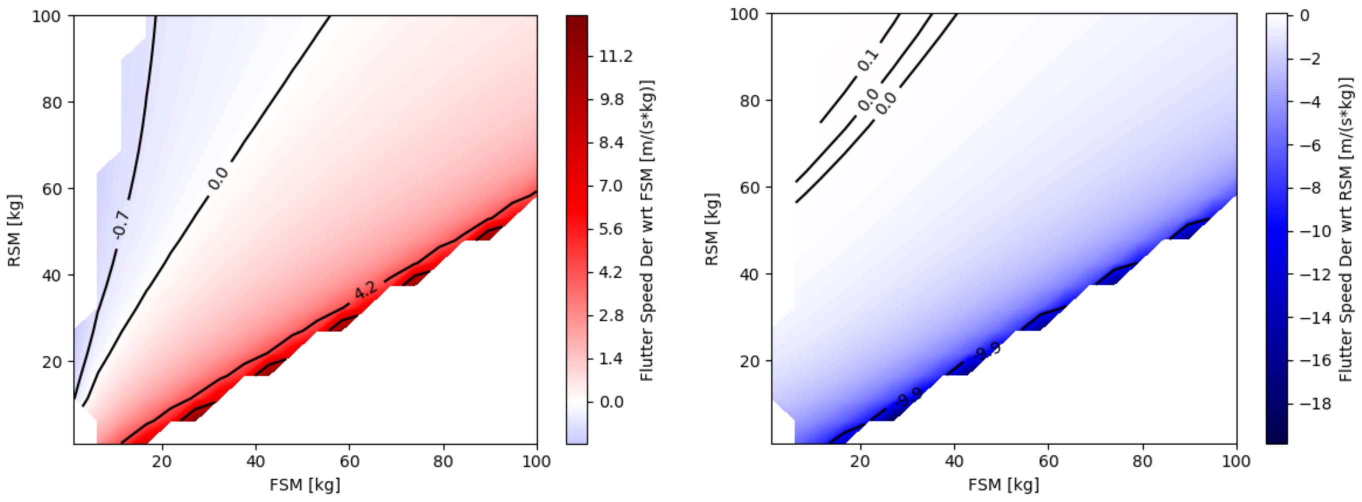
DOE design variables definition

DESIGN OF EXPERIMENTS

Mapping of the flutter speed

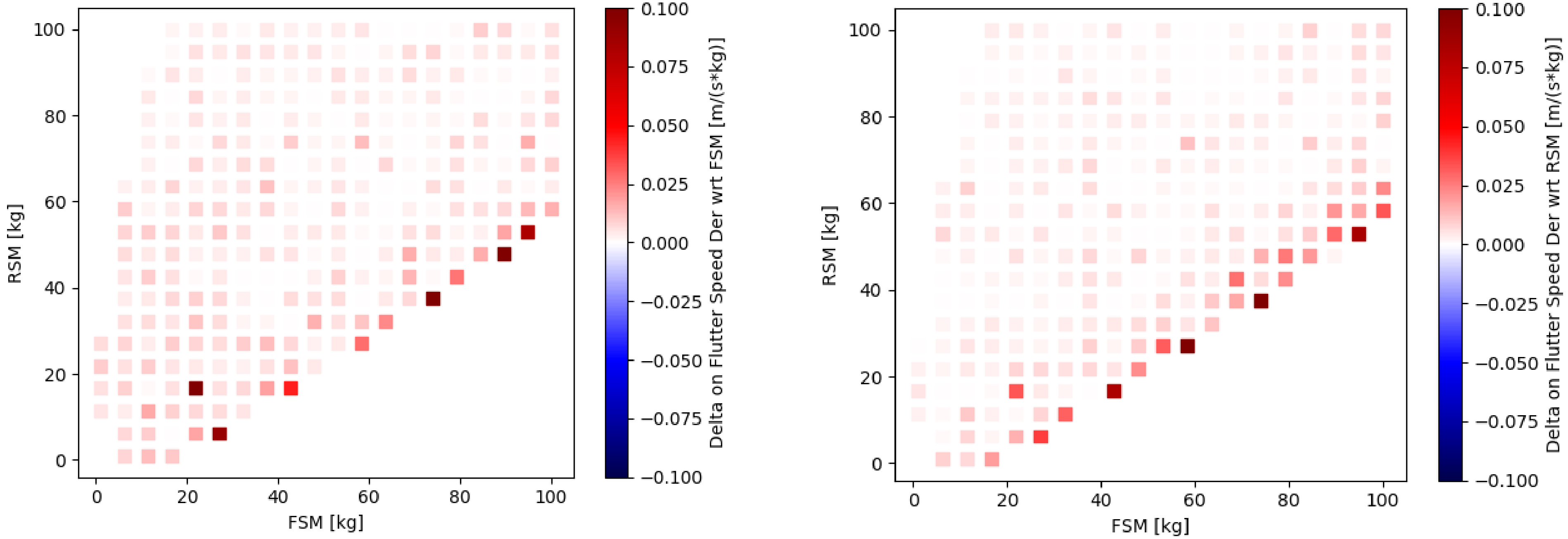


Analytical derivatives provided by FAEDO



DESIGN OF EXPERIMENTS

Comparison between the analytical and FD derivatives



OPTIMIZATION

Objectives

Verifying that **FAEDO** coupled with OpenMDAO **is able of properly carrying out an optimization with aeroelastic constraint.**

Optimization of the Goland+ model

Optimization process taking the mass as objective function and including a constraint on the flutter speed. The selected design variables represent the set of lumped masses that compose the front and rear spars.

Objective function: Mass of the Goland+ model.
Design variables: Lumped masses that compose the front and rear spar.
Aeroelastic constraint: Flutter speed between 100 and 140 m/s.

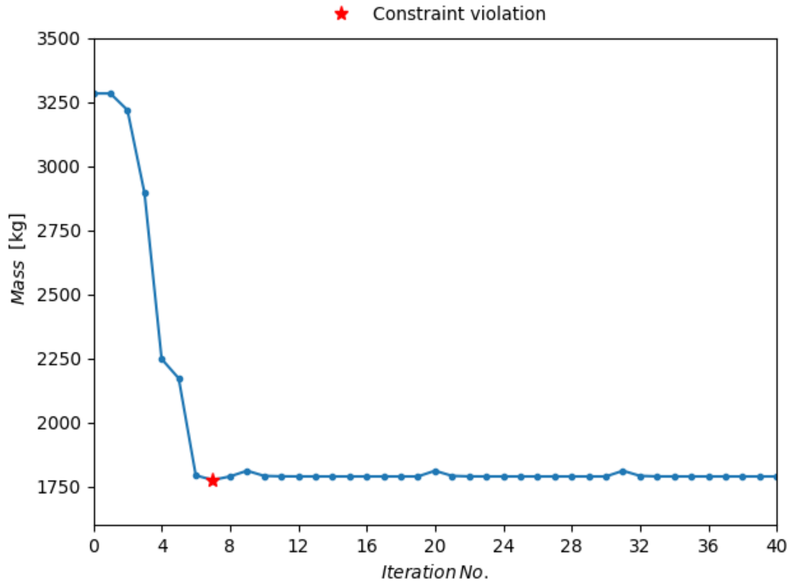
Optimization of the Goland beam model

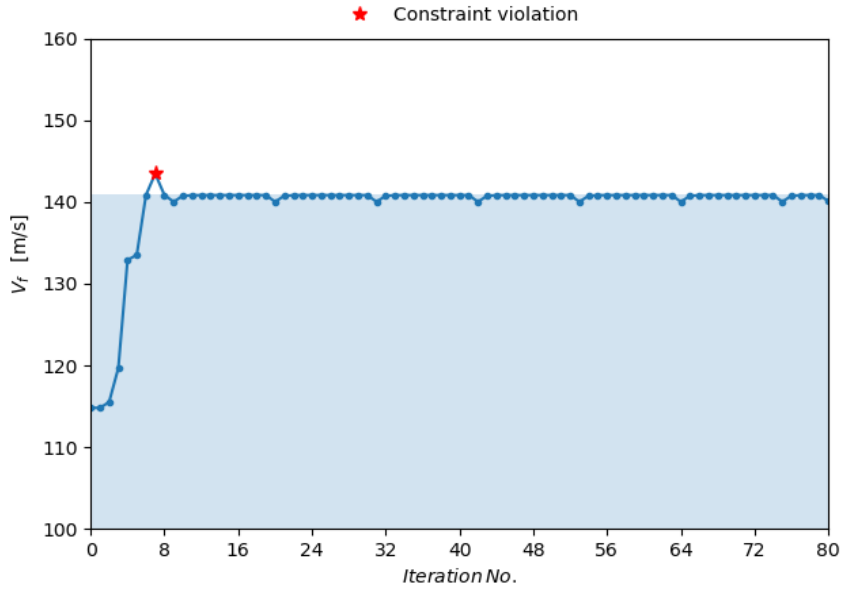
Optimization of the classic Goland wing mass modifying its cross-sectional area and restrincting the flutter speed within a given bounds.

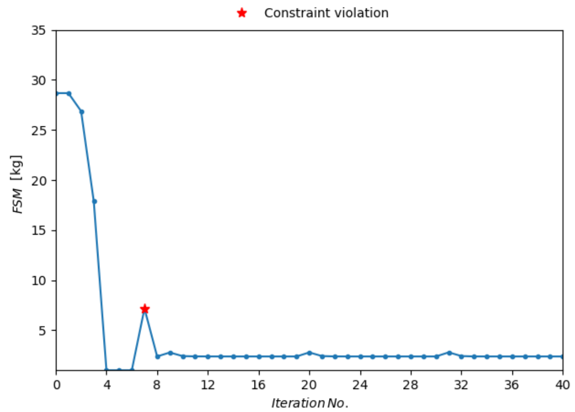
Objective function: Mass of the Goland beam model.
Design variables: Cross-sectional area of the beam.
Aeroelastic constraint: Flutter speed between 100 and 140 m/s

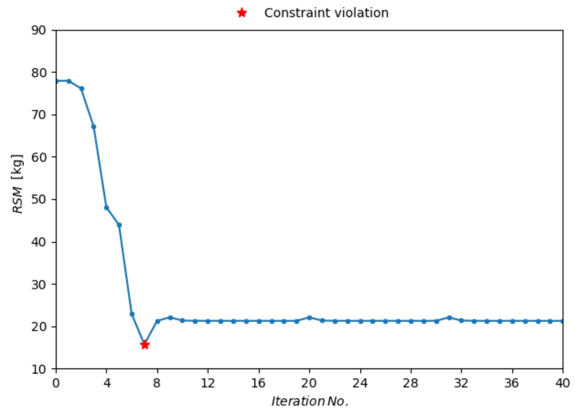
OPTIMIZATION OF THE GOLAND+ MODEL

Parameter	Initial value	Final value	% change
m	3283.33 kg	1812.359 kg	-44%
FSM	28.677 kg	2.787 kg	-90%
RSM	77.928 kg	22.097 kg	-77%
V_f	114.808 m/s	140 m/s	+22%



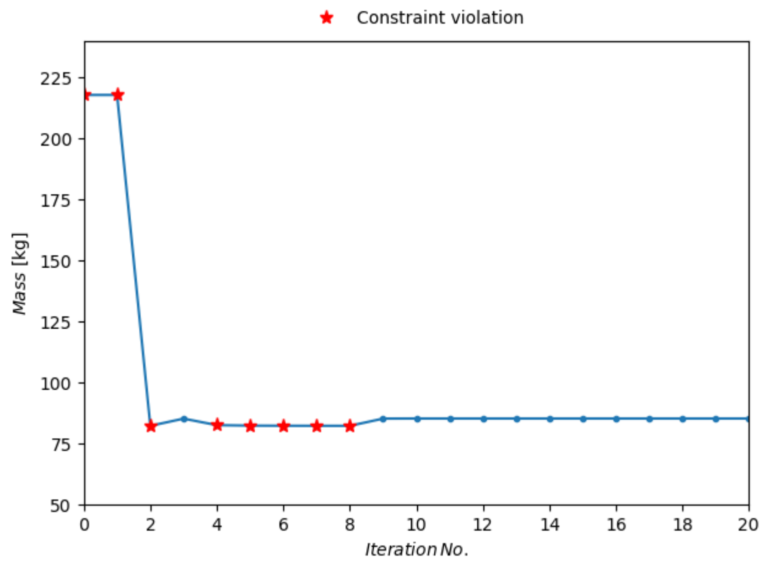


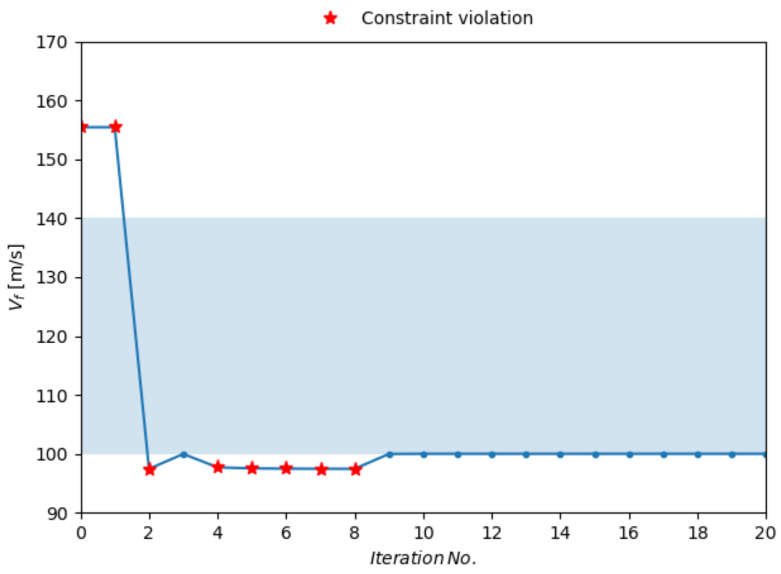


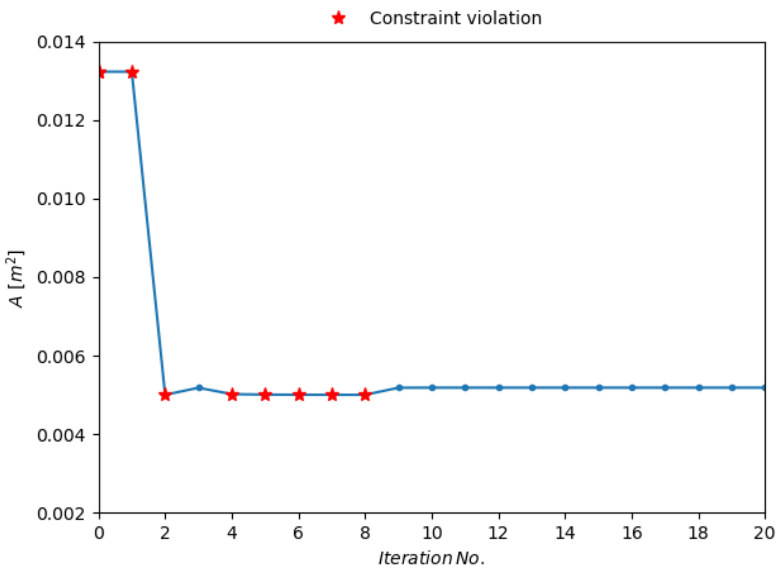


OPTIMIZATION OF THE GOLAND BEAM MODEL

Parameter	Initial value	Final value	% change
m	217.75 kg	85.29 kg	-61%
A	0.0132 m^2	0.0052 m^2	-61%
V_f	155.44 m/s	100 m/s	-36%







5. CONCLUSIONS

NOI

- Tool able to **carry out structural and sensitivity analysis**.
- Possibility to **write optimization, modal and flutter input files**.
- Able to **post-process** *Nastran* **results stored in a f06 or OP2 files.**

FAEDO

- Framework capable of **solving optimization problems with a flutter speed constraint**.
- Possibility to **link FAEDO with any optimization platform**.

Development of **new methods** capable of **dealing with automatization**, and which provide a **high degree of robustness**.

Integration in the aircraft design process

6. REFERENCES

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THANK YOU FOR YOUR ATTENTION

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