Aeroelastic analysis of a regional aircraft with morphing wing using PyPAD framework

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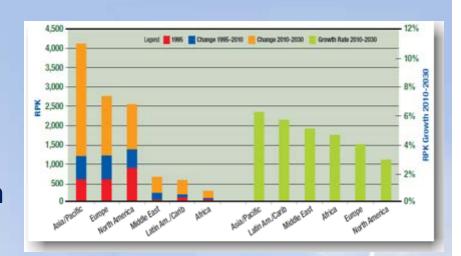
- **Conflicting Challenges**
  - ❑ Air Traffic is growing:
  - ❑ Need to increase capacity;
  - ❑ Reduce travel time;
- **Environmental Impact reduction**
  - ❑ Noise Regulations
  - ❑ Emissions Regulations
- **Enabling Tools**
  - ❑ New aircraft technologies (innovative materials, morphing technologies, unconventional configurations, etc...)
  - ❑ Flight Operation Optimization

**Air Travel Growth Forecast
(Source: ICAO-Airbus)**

Some lessons learned about Morphing

- **Old** or **new** technology?
- **Lights** and **shadows** resulting from available applications
- Very difficult to prove **the real benefits**
- Need for **reliable test case** data to perform accurate comparisons
- Morphing as a **mission-based concept** to be validated by in depth mission analysis
- Need for a **system level analysis** from the beginning of the project
- Still many **open issues**, such as maintenance costs, certification, fatigue, weight penalty...

Some lessons learned about Morphing

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EU-FP7 NOVEMOR: Novel Air Vehicle Configurations, From Fluttering Wings to Morphing Flight

- Overview of FP7-NOVEMOR Project

- The Reference Aircraft

- Design tools for variable camber morphing wings

- Results for Reference Aircraft

- Multi-fidelity aeroelastic analysis

- Experimental validation

- Conclusions

EU-FP7 NOVEMOR project

Aims

The aim of the NOVEMOR (NOvel Air VEhicle Configurations: From Fluttering Wings to MORphing Flight) research project is to investigate **novel air vehicle configurations** with new lifting concepts and **morphing wing solutions** to enable cost-effective air transportation.

Partners

IST, Portugal

Politecnico di Milano, Italy

University of Bristol
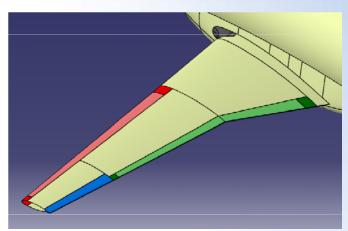
KTH, Sweden
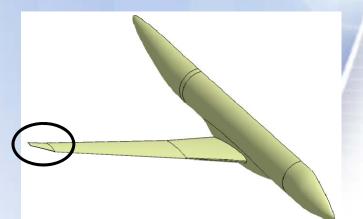
DLR, Germany
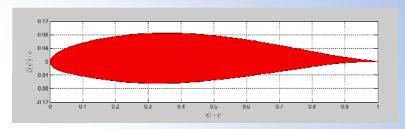
CSIR, South Africa
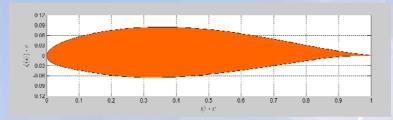
Embraer, Brazil

The morphing concept: Active Camber

Why?

- Potential short term application
- Possibility of retrofit
- Wingbox untouched

To develop and validate the potential impact of the proposed morphing concept we need basically:
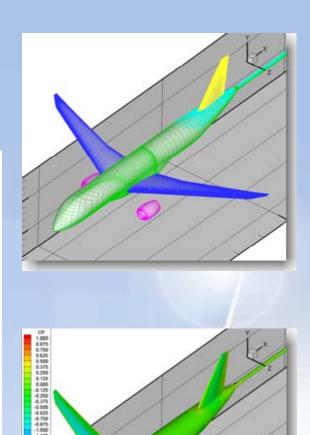
- A Reference Aircraft

- A set of tools to quickly create, manage and optimize aircraft models, to generate the optimal morphing shapes (rigid aircraft) and the related morphing mechanisms

- A global mission based verification strategy

- An experimental validation

- A final assessment including (flexible aircraft)
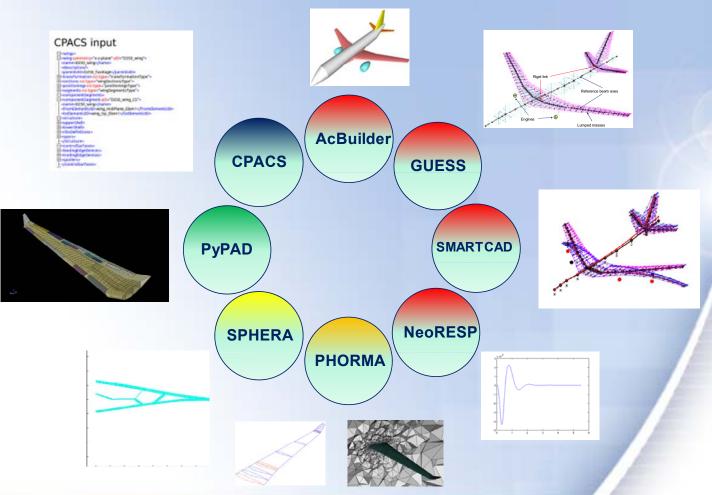
The Reference Aircraft (EMB9MOR)

Aims

To set up a consistent, reliable set of data to be used a reference in evaluating potential morphing benefits.

Reference Aircraft Main Characteristics	
Maximum Takeoff Weight	58,034 kg
Maximum Landing Weight	53,034 kg
Maximum Zero Fuel Weight	48,034 kg
Basic Operating Weight	34,034 kg
Maximum Payload	14,000 kg
Maximum Fuel(1)	18,000 kg
Maximum Operating Speed	Mach 0.82
Time to Climb to FL 350, TOW for 600 nm	17 min
Takeoff Field Length, ISA, SL, MTOW	1,490 m
Takeoff Field Length, ISA, SL, TOW to 600 nm	1,152 m
Landing Field Length, ISA, SL, MLW	1,626 m
Range 113 pax @ 220 lb (100 kg), LRC	4,387 km
Mean Aerodynamic Chord	3.86 m
Reference Wing Area	110 m2
Reference Wing Span	15.73 m

Tools for fast model generation

The family of tools for conceptual aircraft design and morphing evaluation developed @POLIMI during EU pojects like SimSAC, FFAST, NOVEMOR, SARISTU

Tools for morphing shape generation

PHORMA (Parametrical sHapes for aerOdinamic and stRuctural Modeling of Aircraft) is a suite of object oriented tools with the following capabilities:

- Improved CAD export capabilities for CATIA and IGES compatibility;
- Automatic 3D CFD mesh generation for Euler computations based on CSTv3 parameterization;
- Automatic 3D FEM model generation (FVBeam/Beam/Plate/Shell elements) based on CSTv3 parameterization and new PFEM code;
- Embedded post-processing capabilities for CFD analyses;
- New shape-optimization procedure base on 2 nested loop to combine skin structural constraints and CFD analyses.

Tools for morphing shape generation

Airfoil shape description:

$$\zeta(\psi) = C_{N2}^{N1}(\psi)\,S(\psi) + \psi\zeta_{TE}$$

$\zeta = \dfrac{z}{c}$ Non-dimensional coordinates w.r.t

$\psi = \dfrac{x}{c}$ airfoil chord

Class Function   **Shape Function**

$$\zeta_{TE} = \frac{Z_{TE}}{c}$$

$$Z_{TE} = \zeta_{TE} \pm 0.5 \cdot \Delta Z_{TE}$$

Z_{TE} Vertical position of TE
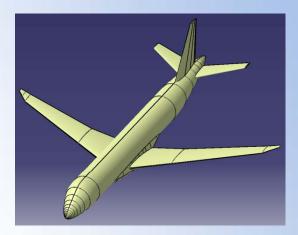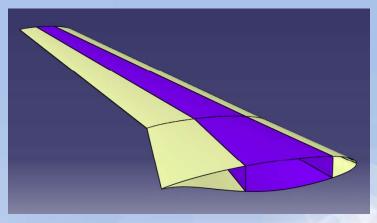
ΔZ_{TE} Thickness of trailing TE

Fully analytic description of the airfoil based on few parameters

Easy to calculate length and curvature

Possibility to predict axial and bending stresses in the skin
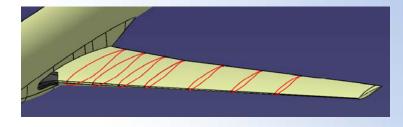
Typical models generated by PHORMA
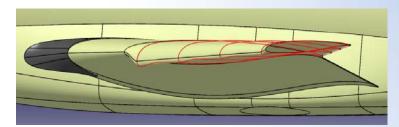
CAD geometry of Reference Aircraft
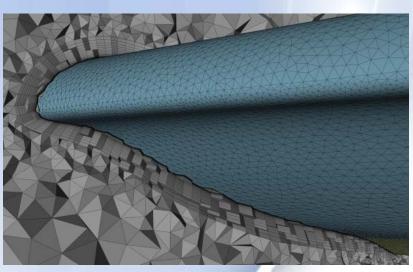
Wingbox extension

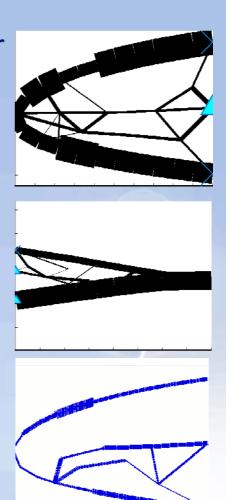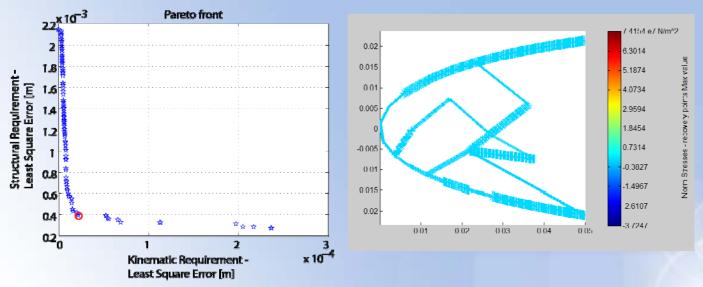mTE and mLE morphing airfoils distribution

CFD mesh

Tools for morphing mechanisms

SPHERA (Synthesis of comPliant mecHanisms for EngineeRing Applications) is the part of a more general tool for the synthesis of compliant mechanisms dedicated to the design of morphing airfoils. It is used to optimize the internal structure able to match the optimal shape generated by PHORMA and includes:

- Load path representation of internal structures
- A non linear beam solver
- A multi-objective genetic optimizer to solve both sizing and topological problem
- An FSI tool for aero loads transfer.
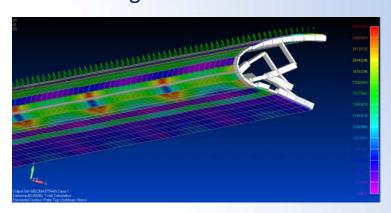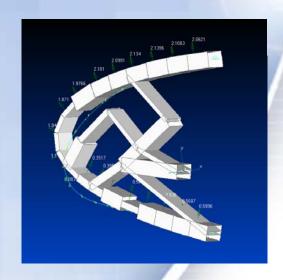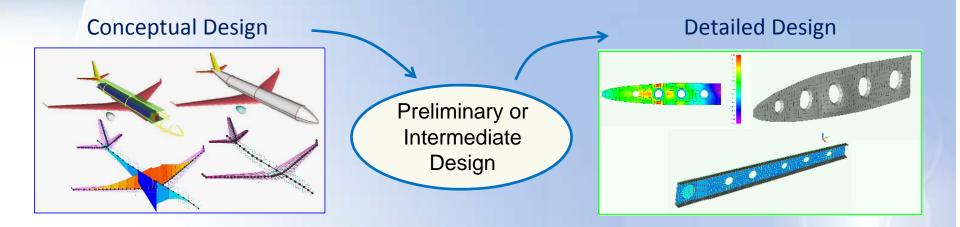
Tools for morphing mechanisms

Selection of most promising configuration

Automatic generation of 3D models

Preliminary design

Conceptual Design

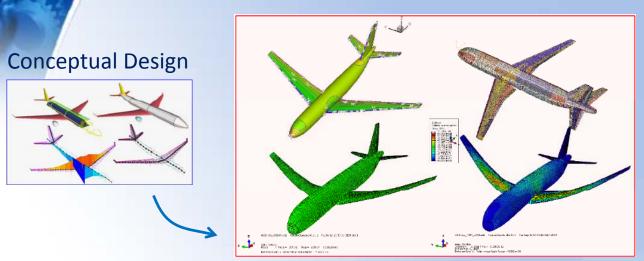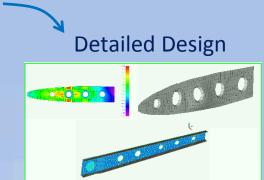Preliminary or Intermediate Design

Detailed Design

Preliminary design
- One or more conceptual designs are available
- Changes at conceptual level are still possible
- Changes at this project level are still not much expensive

The problem is strongly interdisciplinary!

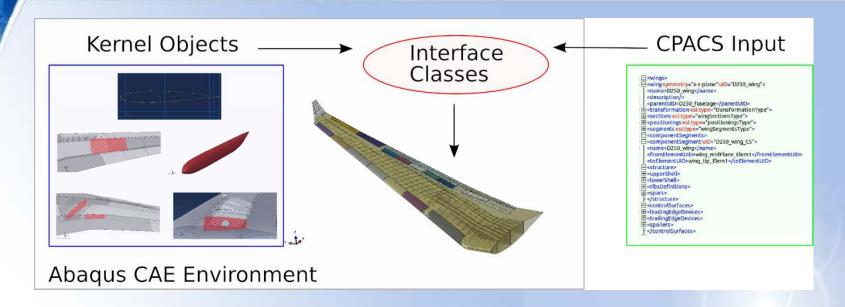# PyPAD (Python module for Preliminary Airframe Design)

Conceptual Design

Detailed Design

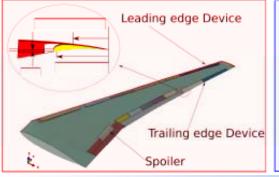## PyPAD (Python module for Preliminary Airframe Design)

- PyGFEM: a models generator (in Abaqus-CAE environment), able to define FE and aerodynamic models starting from a fully parametric aircraft description based on CPACS
- PyAERO: a package for loads computation and aeroelastic analysis
- PySIZE: a package for the structural sizing, able to deal with different sizing criteria
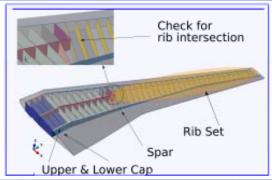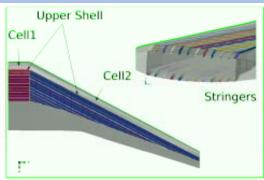
- Abaqus CAE environment allows to use all the CAD/CAE functionality by Python scripts
- The core classes providing the definition of basic objects, like edges, airfoils, planes, cuts, lofts, materials, properties, etc.
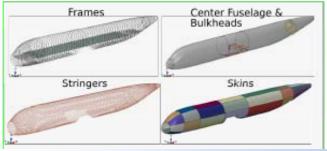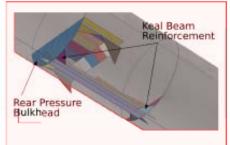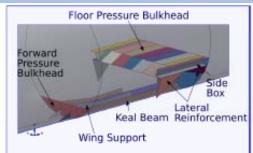- The interfaces classes providing the coupling between CPACS input and core objects

Wing definition steps

- Once the loft is obtained (starting from airfoils definitions) PyGFEM defines the movable surfaces
- All the spars and rib sets are defined
- The skins (both using parametric positions and rib/spar edges) can be defined with the proper stringers.
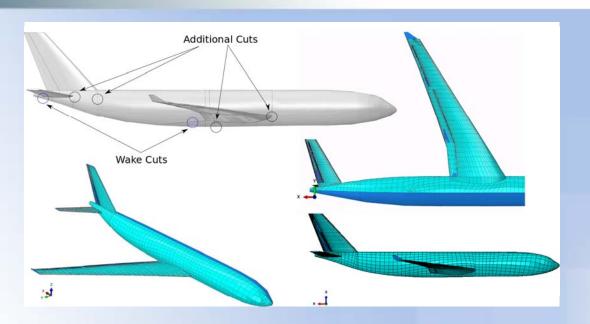
Fuselage definition steps

- Once the loft is obtained, stringers, frames, skins and central fuselage are defined
- All the components are defined in different parts
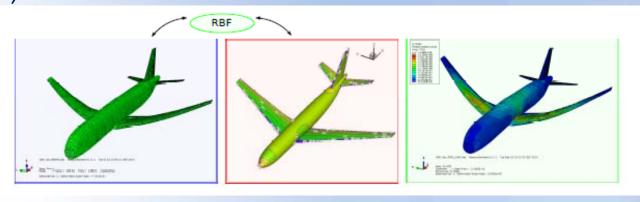- The different parts are then merged together in the assembly

Structured mesh

PyGFEM merges all the component finding each intersection, then checks all the different couple of intersecting parts, adding construction cuts to simplify the geometry, or to define the projections of wing wake on the other part involved in the intersection.

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PyAERO: Aeroelastic module

- Different aeroelastic solvers: Trim, Flutter, Dynamic Response (Both frequency and time domain);
- Core functions written in Fortran and taking advantages of modern libraries (OpenBLAS, Lapack, Plasma, OpenMP, FFTW).
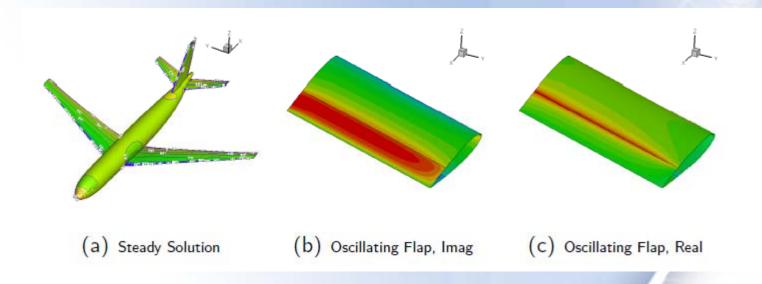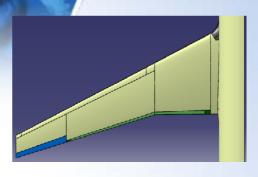

Aero-structural coupling

The aeroelastic coupling between structural and aerodynamic models takes advantage of the automatic definition of both the models by PyGFEM. The structural model is divided in different parts each described by different sets and the same partition is reflected also on the aerodynamic mesh.
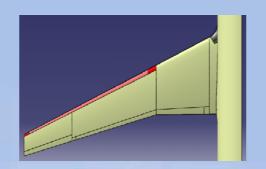
SUnPaM: Subsonic Unsteady Panel Method

It is a panel aerodynamic solver, based on the Morino method, developed in the Department of Aerospace Science and Technology of Politecnico di Milano. The tool solves linearized subsonic compressible flow both in steady and unsteady conditions
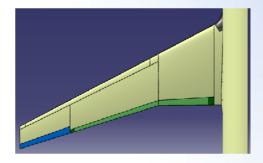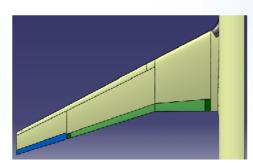

(a) Steady Solution   (b) Oscillating Flap, Imag   (c) Oscillating Flap, Real

Morphing LE and TE configurations for RA
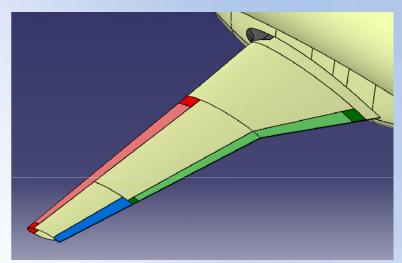

3 morphing devices:
1. Morphing leading edge for low speed;
2. Morphing leading edge for high speed;
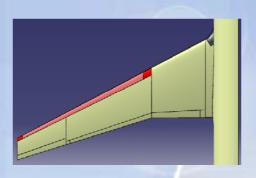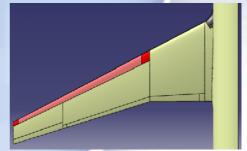3. Morphing trailing edge for low speed;

Optimization variables:
- Chordwise extensions;
- Morphing deflections;
- Size of the transition regions;

Global strategy adopted for full aircraft

2 flight conditions analyzed: low speed (Ma=0.15) and high speed (Ma=0.74 and 0.78)

- Generation of a family of 3D shapes (CAD) using PHORMA

- Preparation of a huge aerodynamic lookup table using a medium fidelity tool (full potential + boundary layer correction).

- Performance analysis during the complete flight mission to select, for each flight condition, the optimal morphing configuration.

- Validation of medium fidelity CFD results by means of high fidelity analysis (RANS).

De Gaspari A., Ricci S. *Application of the Active Camber Morphing Concept Based on Compliant Structures to a Regional Aircraft*, in: SPIE conference, San Diego, CA, USA, 9 Mar. 2014.

De Gaspari A., Ricci S. *Application of Active Camber Morphing Concept to a Regional Aircraft*, Paper presented at: 22nd AIAA/ASME/AHS Adaptive Structures Conference, National Harbor, MD, US, 13-17 Jan. 2014, p. 1-23, AIAA-2014-1259.

mLE Results

Typical mission + 100 nm alternate + 45 minutes holding
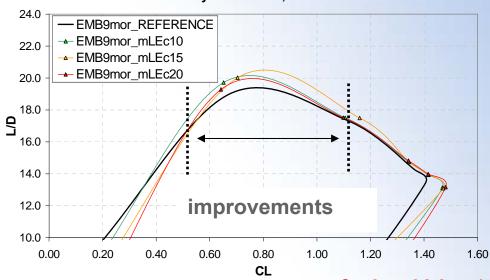
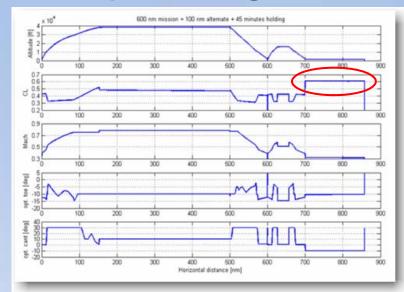Payload = 12000kg

Range = 600nm

Mach Number = 0.78

Cruise altitude = 38000ft

TOW = 51126kg

Holding 45 minutes @ CL = 0.6

L/D x CL
Rey = 13 Million , Mach = 0.15

improvements

CL	mLE_c10	mLE_c15	mLE_C20
0.6	5%	0%	3%
0.7	3%	6%	1%
0.8	3%	5%	1%
1.0	1%	3%	1%

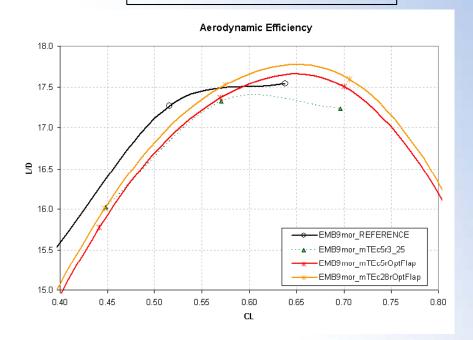**Δ fuel ≈ 62 kg (5% of 1236 Kg)**

mTE Results

Payload   = 14000kg
Range   = 1500nm
Mach Number = 0.74
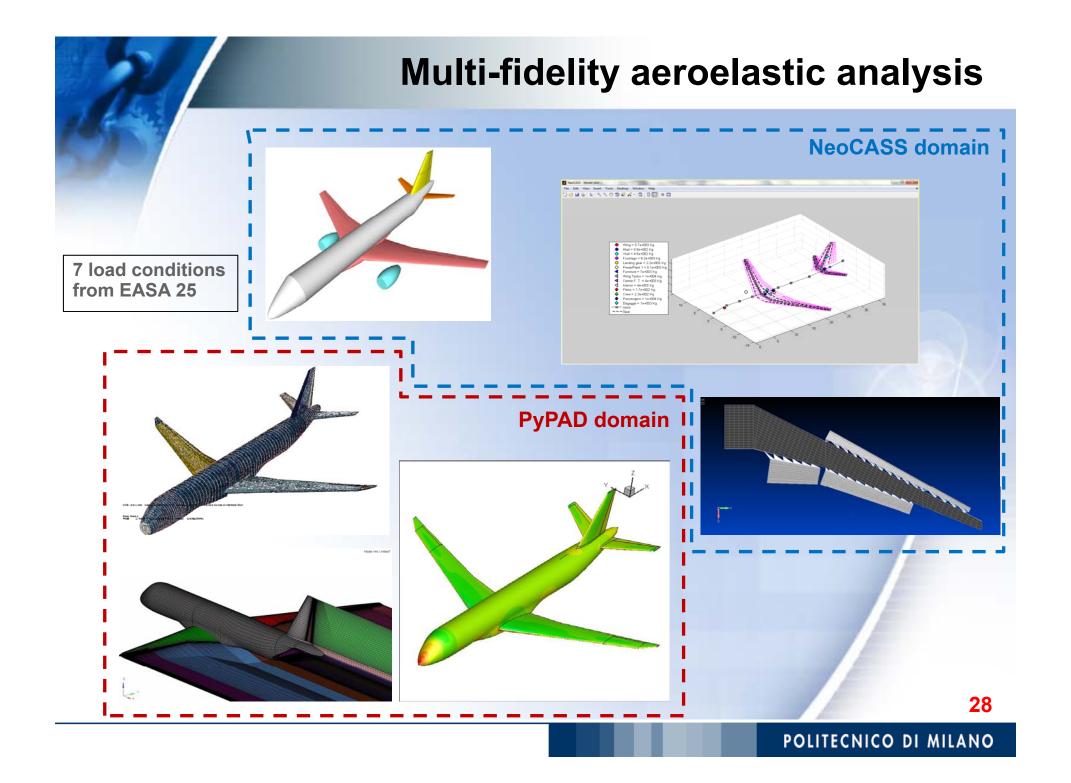Cruise altitude = 38000ft
TOW   = 57252kg
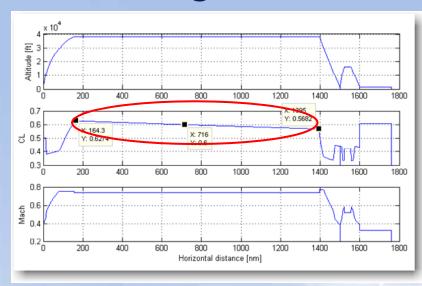
Cruise @ Ma = 0.74

Aerodynamic Efficiency

Legend:
- EMB9mor_REFERENCE
- EMB9mor_mTEc5r3_25
- EMB9mor_mTEc5rOptFlap
- EMB9mor_mTEc28rOptFlap

Fuel saving / Fuel required to accomplish the mission
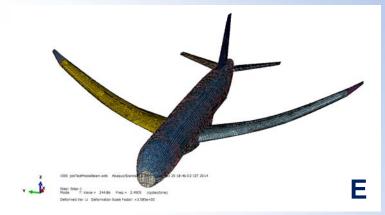
Mach	RANGE		
	600 nM	1000 nM	1500 nM
0.74	0/ 3153	63/4881	75/7136
0.78	0/3064	0/4681	65/6771

Δ fuel ≈ 75 kg (1.02% of 7136 kg)

Multi-fidelity aeroelastic analysis

7 load conditions from EASA 25

NeoCASS domain
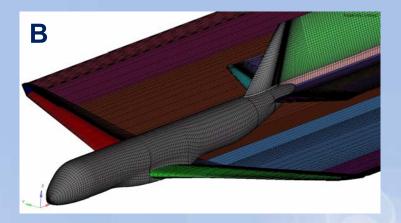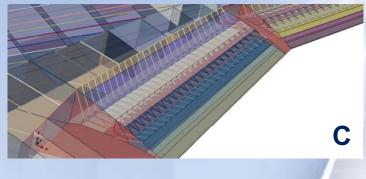
PyPAD domain

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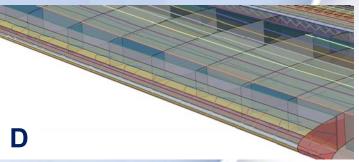# Multi-fidelity aeroelastic analysis

A Complete FEM model
B Aerodynamic model
C,D Details of morphing LE and TE
E Typical mode shape

Experimental validation

The experimental validation is based on a two steps approach:

1. Aerodynamic validation of morphing benefits by means of transonic Wind Tunnel test @CSIR (Mach 0.15 and 0.74) on a rigid model

2. Validation of the aerostructural optimization of compliant morphing LE and TE on a low speed Wind Tunnel model @POLIMI
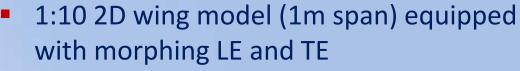
Assembling of the model for WT testing at CSIR

Low Speed WT test at POLIMI

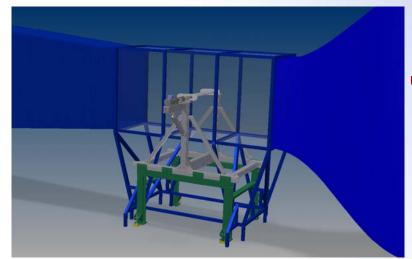- 1:10 2D wing model (1m span) equipped with morphing LE and TE
- Low speed WT: 1 × 1.5m, 55 m/s

Aims:

- Measure the structural deformation (3D) of the wing under aerodynamic loads and compare with the target shapes
- Measure stress and strain levels in the skin and compliant mechanism under aerodynamic loads
- Measure the pressure distribution along one station and compare with CFD for the purpose of validating the aerodynamic load inputs used in the structural codes
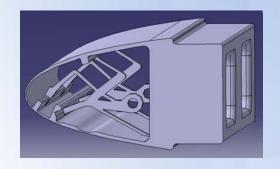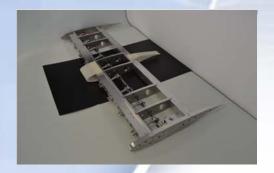
Open issues on testing small scale morphing models based on compliant structures:

1. The down scaling of the compliant structure designed for full aircraft is not possible. A complete redesign is necessary.

2. The scale factor adopted for the wing models poses challenges about the manufacturing technologies (thickness distribution accuracy)

Morphing configurations for wing model to be tested for validation

Conclusions

A complete assessment about the potential benefits of using morphing devices is on the way in the framework of FP7EU-NOVEMOR project. It includes:

- Development of a Reference Aircraft representing a typical 130 pax regional aircraft

- Evaluation of the methodologies to design and implement the Active Camber concept

- A mission based evaluation of potential benefits in terms of fuel saving

- ✓ The preliminary results appear as promising, but only at the end of the assessment it will be possible to draw the final conclusions

Future activities

- Finalization of the experimental validation campaign in low speed WT @POLIMI

- Final aeroelastic assessment on complete aircraft including morphing devices

- Complete the sizing module of PyPAD tool

Acknowledgement

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Thanks for your attention

Any question?

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www.neocass.org