A novel approach to aeroelastic design of unconventional configurations

Merging FSI solvers and LFT/μ tools

Rauno Cavallaro, Rocco Bombardieri.
Andres Marcos, Andrea Iannelli.

AGENDA

- Introduction
- Unconventional Aircraft Configuration: the Box Wing/PrandtlPlane case
- CSHELL: An Inhouse Aeroelastic Computational Tool
- UC3M – UoB Collaboration: Preliminary Results
- Conclusions

Introduction

UC3M

Expertise in FSI tool development and Aeroelastic Design of Box Wings (unconventional configuration).

UoB

Long experience in Robust Control. Recently started a project on RC applied to aeroelasticity.

How to combine UC3M & UoB expertise to solve practical aeroelastic design problems?

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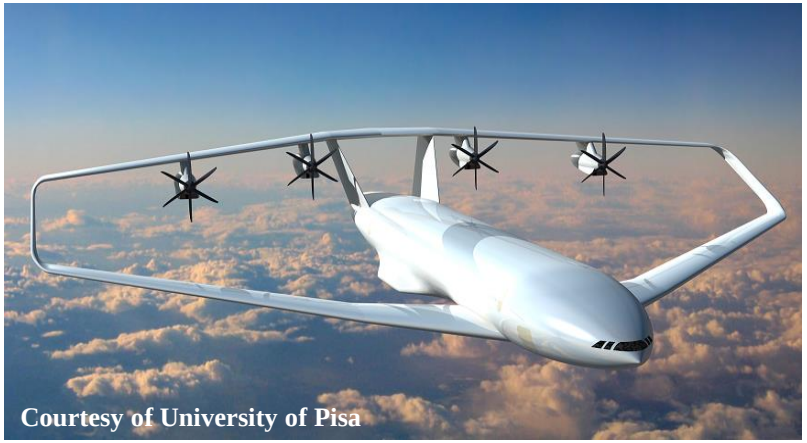
Unconventional Aircraft Configurations: the Box Wing/PrandtlPlane



Why a Box-Wing Configuration?

Induced drag

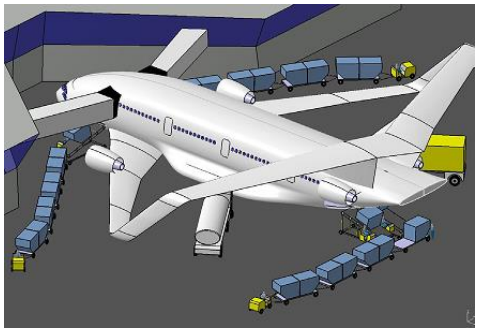
Structural design

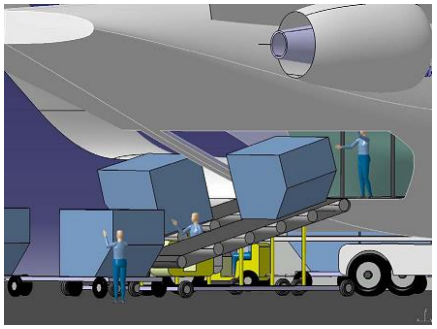
Flight mechanics/dynamics

Engine integration

Big Cargo/Freighter Concept

SciTech 2014, Lockheed Martin, Exhibition Hall.





Current Projects

IDINTOS

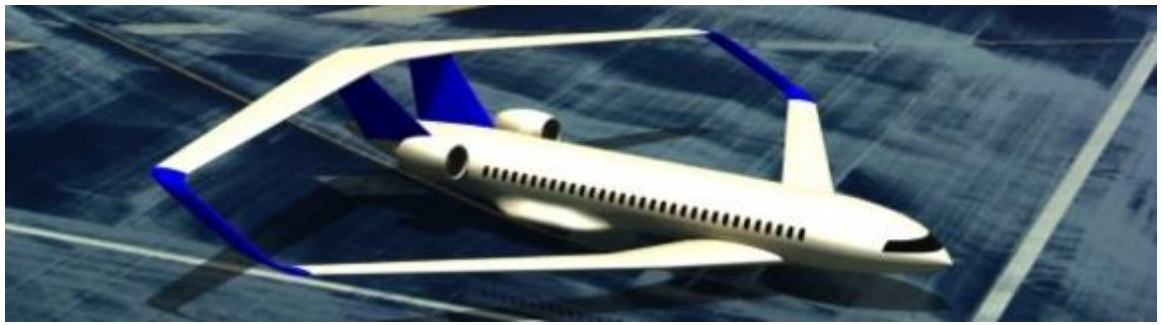
IDrovolante INnovativo TOScano

(Tuscany Region project of an Amphibious-Seaplane)

PARSIFAL

(Prandtlplane ARchitechture for the Sustainable Improvement of Future AirpLanes)

EU project



PARSIFAL. Kick-off meeting 11th May 2017, Pisa, Italy

PrandtlPlane and Aeroelasticity

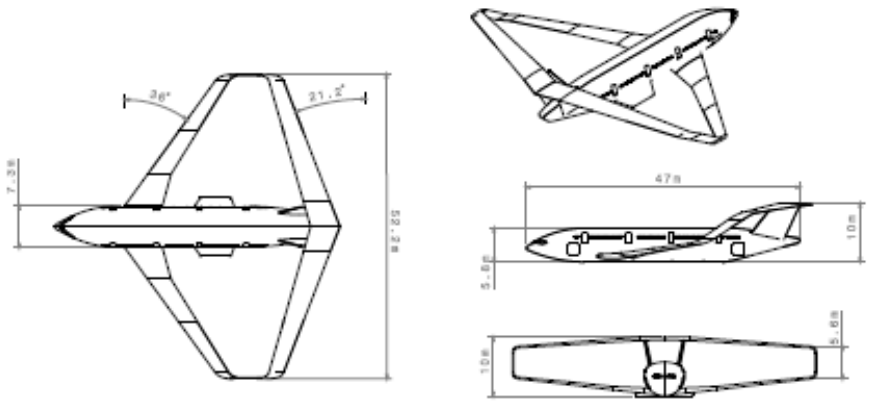
Dynamic Aeroelasticity: Flutter

Previous studies (Lockheed ’74) identified Flutter as a major issue for Box Wings!

Considered PrandtlPlane Concept – PrP250

Frediani et al. “***The PrandtlPlane Configuration: Overview on Possible Applications to Civil Aviation***”, **2009.**

Aeroelasticity of PrP250



250 passenger aircraft
6000 nm range
230 tons MTOW
362.6 m^2 wing's surface
(Concept of Università of Pisa)

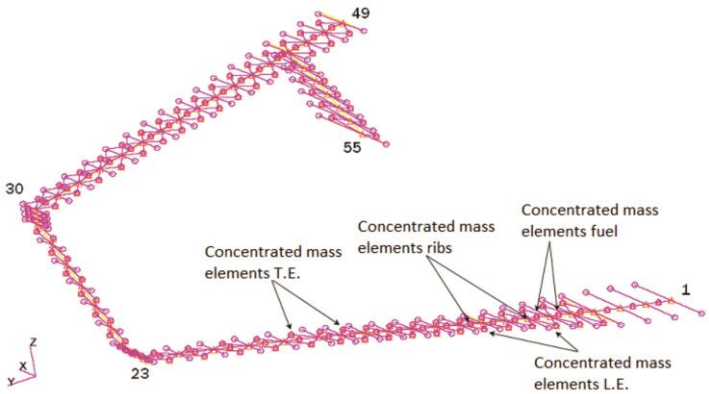
MDO (Università of Pisa and Politecnico di Milano).

Beam model of full wing-box, structural mass (ribs, etc), fuel.

Dal Canto et al, "*The Lifting System of a PrandtlPlane, Part 1: Design and Analysis of a Light Alloy Structural Solution*", 2009

Flutter constraint was responsible for large weight penalties.

Divoux et al, "*The Lifting System of a PrandtlPlane, Part 2: Preliminary Study on Flutter Characteristics*", 2009



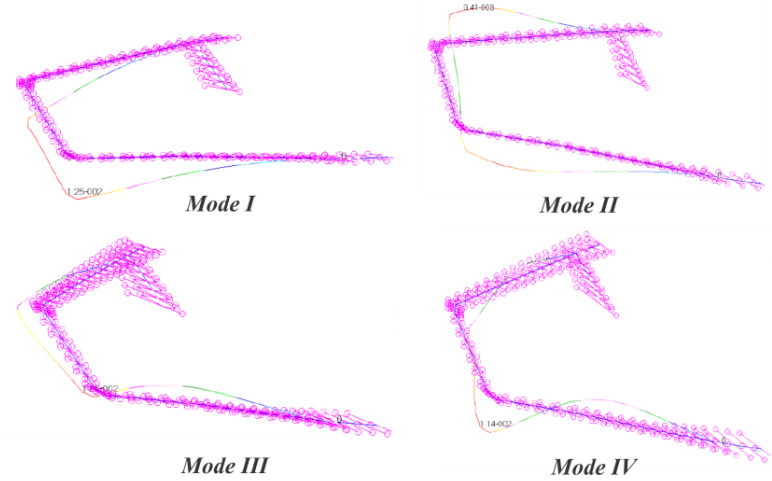
PrP250: Flutter Studies

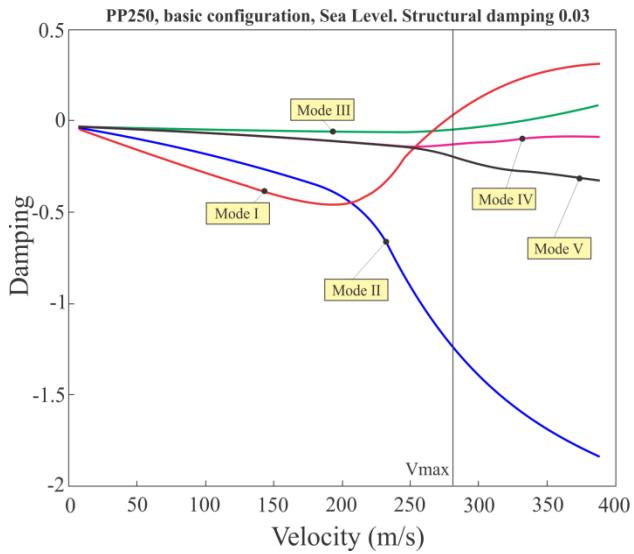
"Cantilever" and symmetric matched flutter analyses.

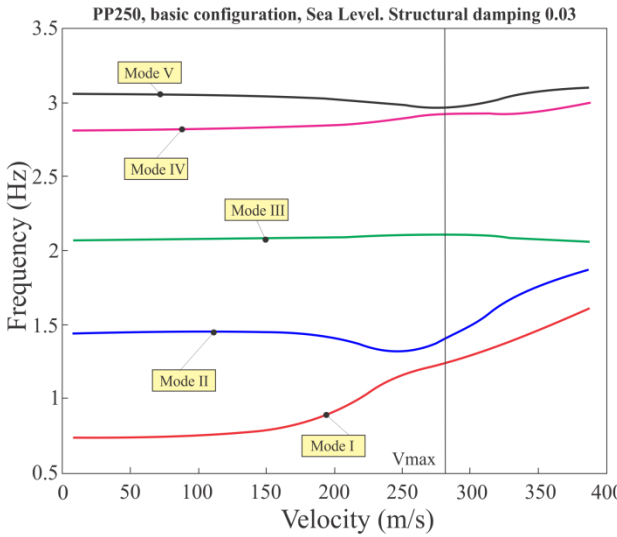
Low natural frequencies:
1st mode 0.74 Hz,
2nd mode 1.45 Hz
5th mode ~3 Hz

Mode I: in-phase vertical deflection of the two wings.

Mode II: out-of-phase bending of the two wings and tilting of the joint.



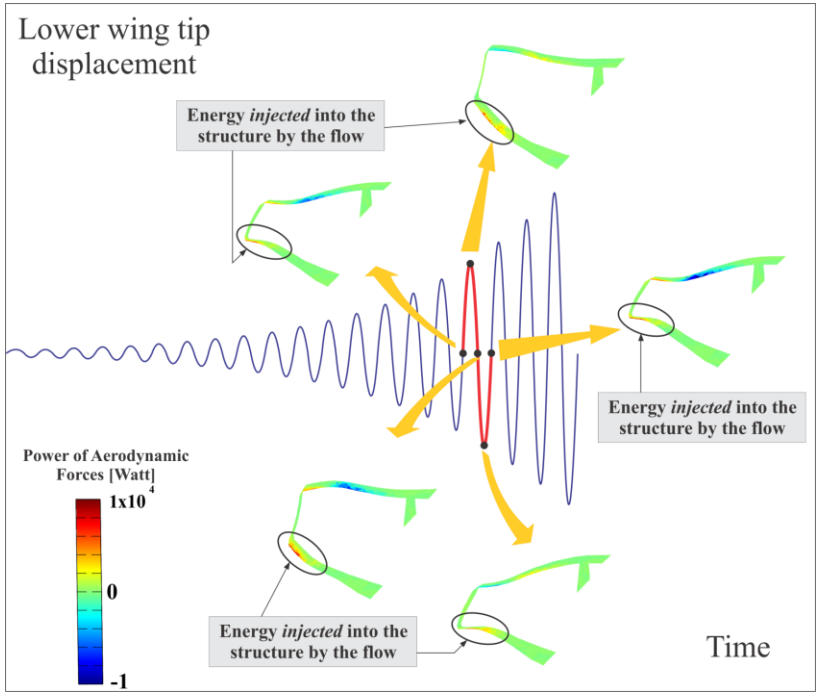




Flutter speed do not comply regulations. Coalescence of modes I and II.

Advanced Aeroelasticity of the PrandtlPlane

2014-2017: Aeroelasticity of the "PrP250" concept has been further investigated.

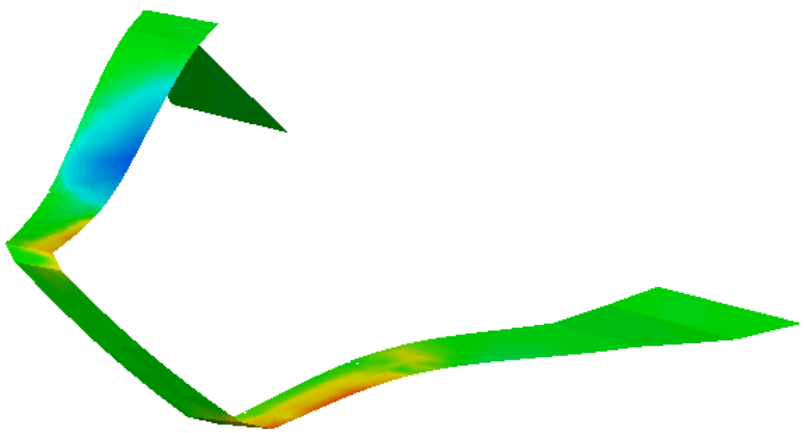


- **Energy Interpretation of Flutter**
- **Post-flutter (Limit Cycle Oscillation)**
- **Body-freedom flutter (BFF)**
- **Freeplay: Flutter and LCO**
- **Antisymmetric Flutter**
- **Flight Dynamics + Aeroelasticity**
- **Gust Response**

Flutter Analysis: Energy Interpretation

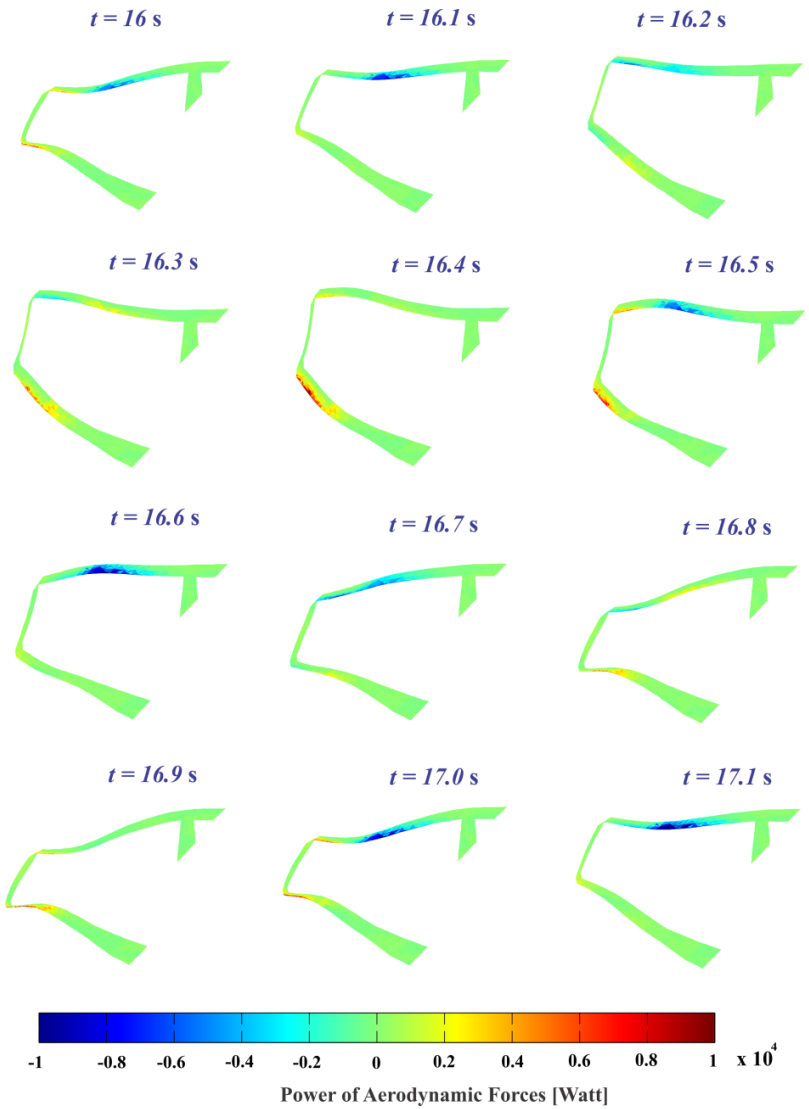
Lower wing does mostly extract energy from the fluid (tip region).

Upper wing alternates between transferring and extracting energy.



Speed 0.25X

Aerodynamic Power



Cavallaro R., Bombardieri R., Demasi L., Iannelli A., "*PrandtlPlane Joined Wing: Body Freedom Flutter, Limit Cycle Oscillation And Freeplay Studies,*" **Journal of Fluids and Structures, Vol. 59, November 2015, pp. 57–84.**

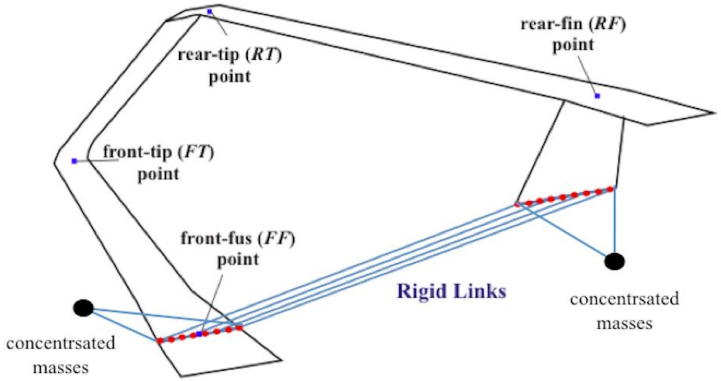
Flutter of Free-Flying PrandtlPlane

Concept of Body-freedom flutter

Interaction between **elastic** and **flight dynamics** modes.

For "free-flying" analysis, rigid **fuselage** with equivalent **inertial** properties.

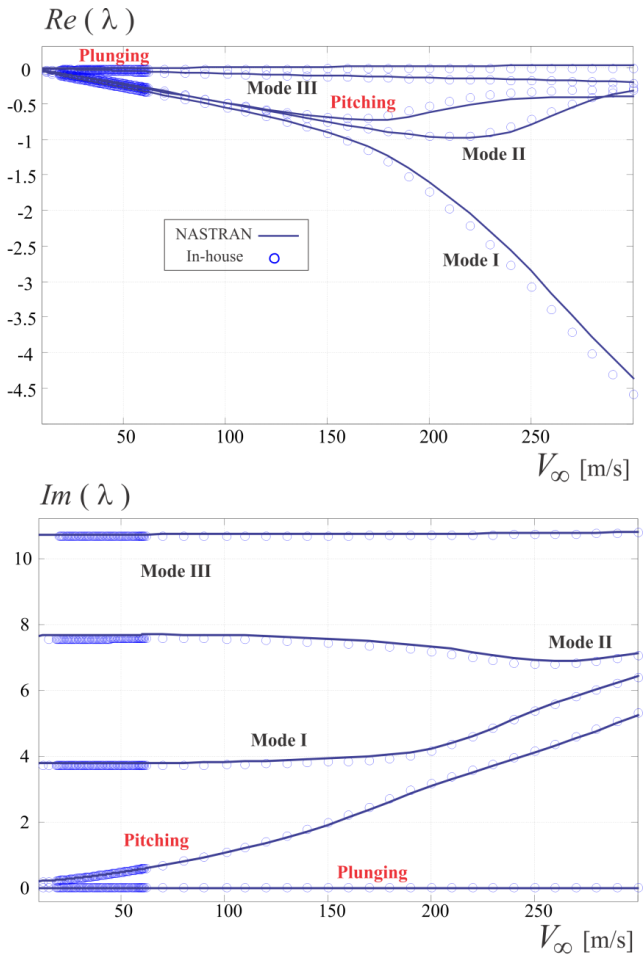
For "free-flying" PrandtlPlane, design was **flutter free**!! What happened?



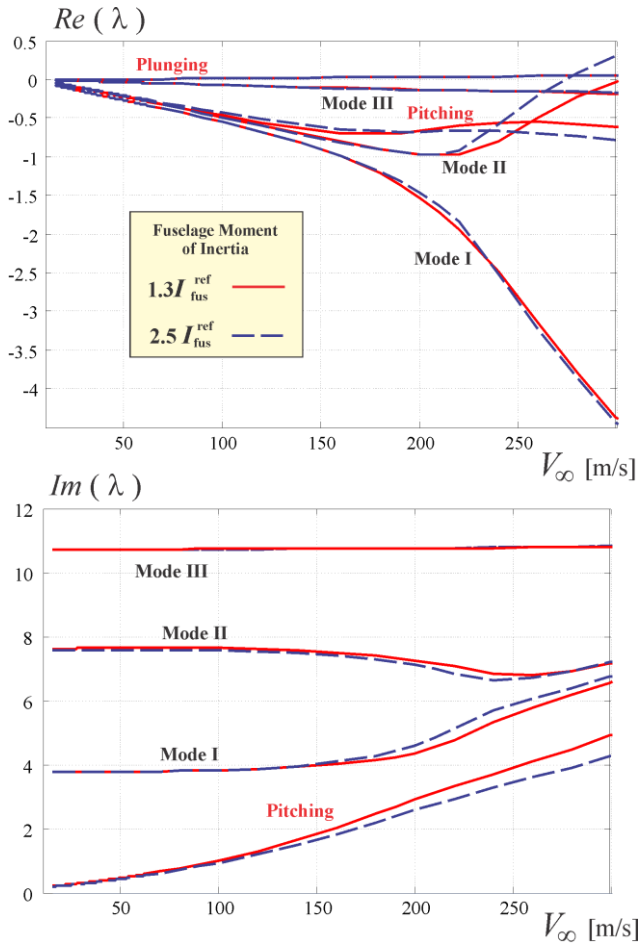
Flutter of Free-Flying Model 2

Sensitivity to fuselage pitching moment of inertia (with fixed CoG)

Free-flying nominal *I*.



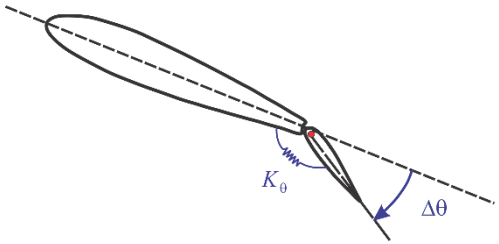
Free-flying, sensitivity to *I*.

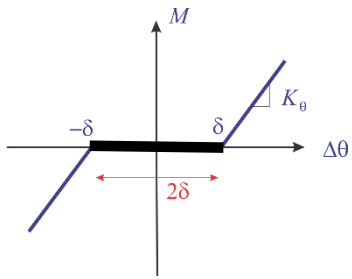


Interpretation:

The flutter main mechanism (interaction of elastic modes I and II) is postponed because of the interaction between first elastic and pitching modes.

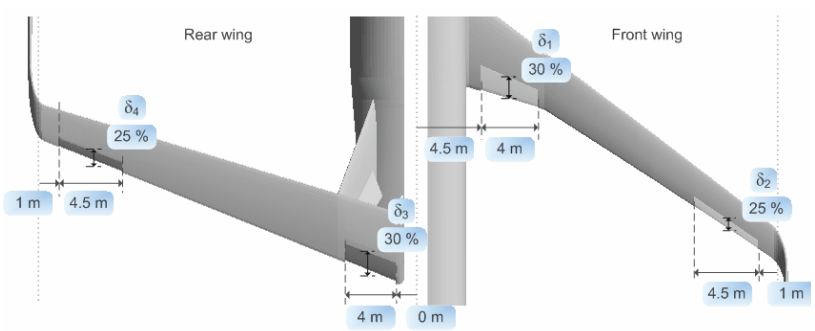
Freeplay: Flutter and LCO



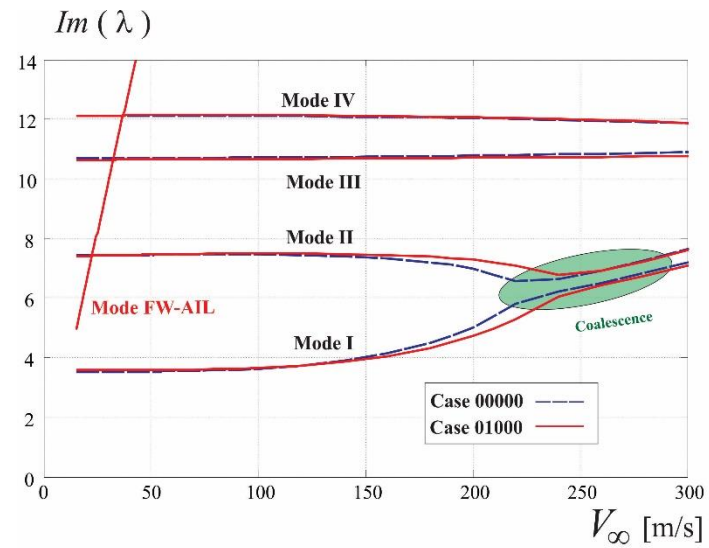


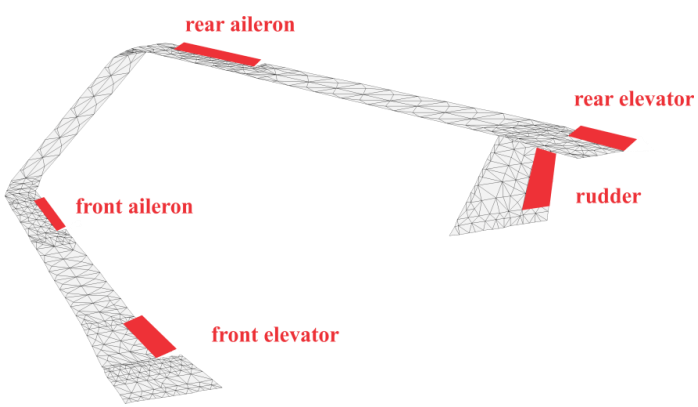
backlash

Free-play of mobile surfaces



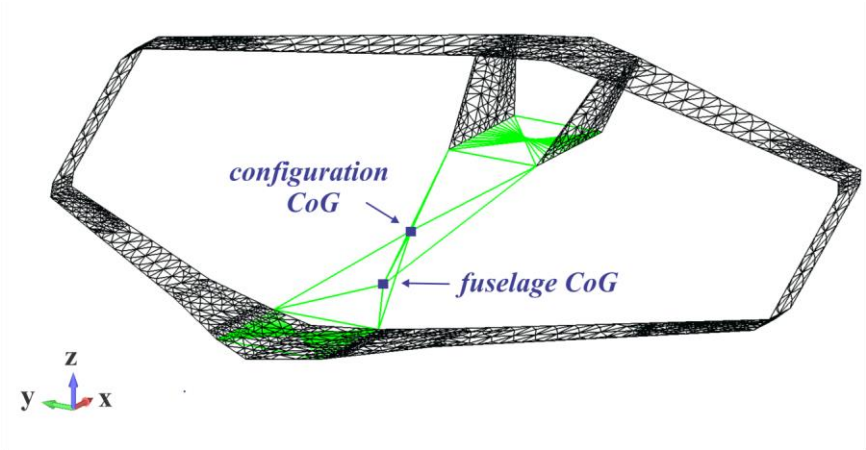
[*Van Ginneken et al, 2010*]

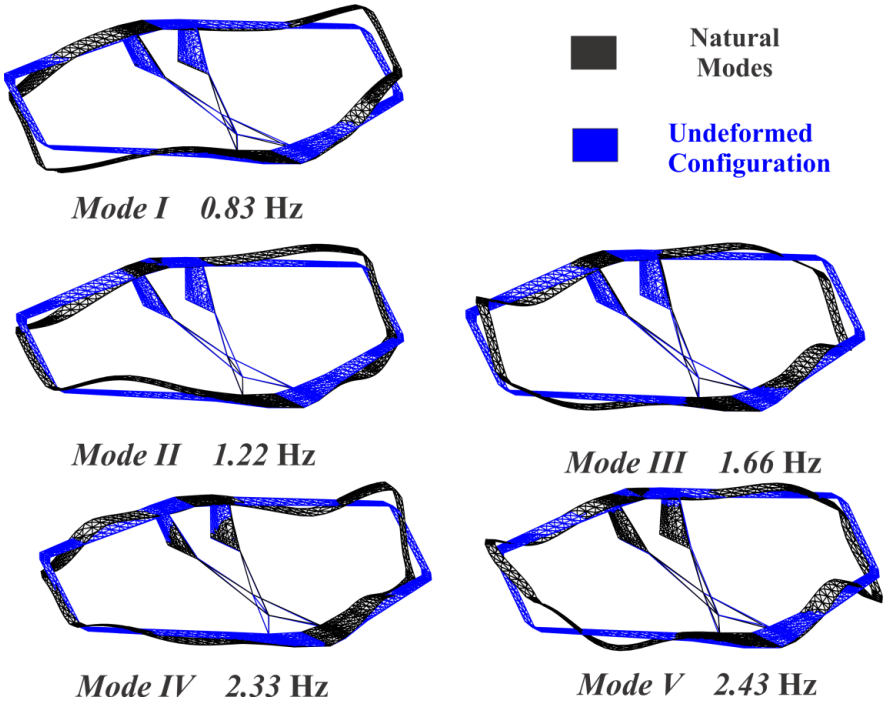




- **Same main instability, but flutter speed is higher.**
- **Passive flutter suppression device.**
- **Interpretation with Energy Diagram.**

Antisymmetric Flutter Analysis



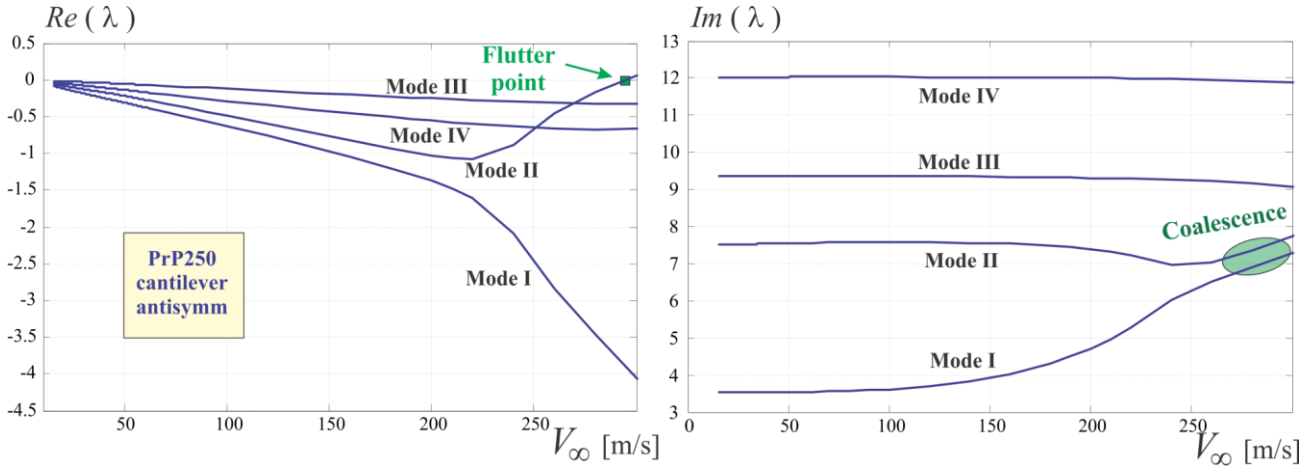


Bombardieri R., Cavallaro R., Demasi L., "A Historical Perspective on the Aeroelasticity of Box Wings and PrandtlPlane with New Findings", Jan 4, 2016, AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech, San Diego, California.

Antisymmetric Flutter Analysis

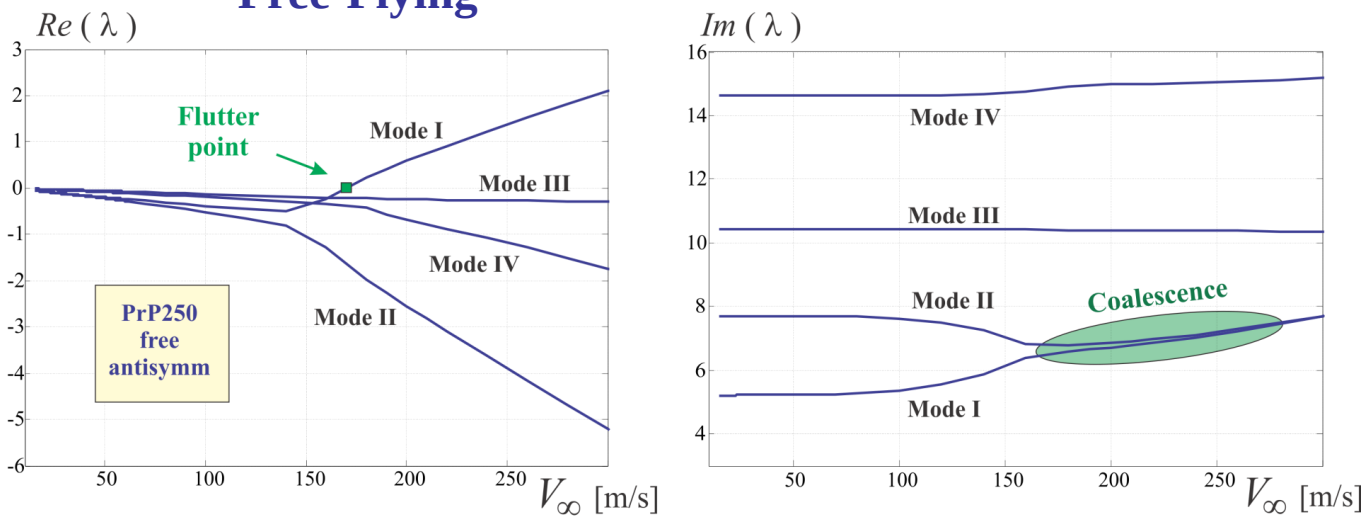
Cantilever

Flutter at 290 m/s. Complies with regulations.



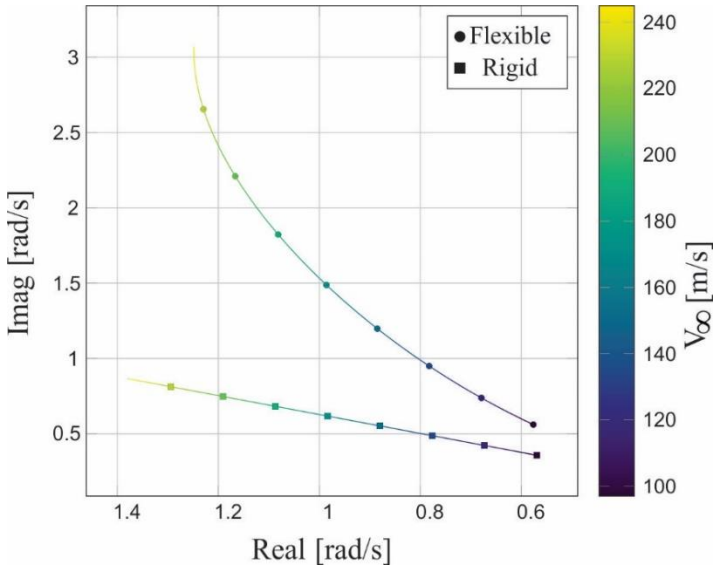
Free-Flying

Flutter at 170 m/s.
Mode I becomes unstable.
Coalescence of modes I and II.



Current Research Topics

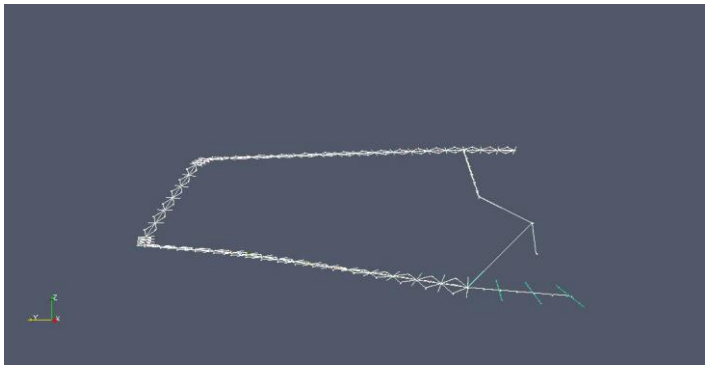
Flight Dynamics of the Flexible PrandtlPlane



Elasticity changes Short-period damping properties!

Bombardieri R., Auricchio F., Cavallaro R., "Unified Flight-dynamic and Aeroelastic Analysis of a PrandtlPlane Configuration", to be presented at Aerospace Europe 6th CEAS Conference 2017.

Discrete Gust Response of a PrandtlPlane



Gust induced loads induce stress-state different than the ones induced by static limit-load condition.

Cavallaro R., Palacios J.S., Bombardieri R., "Discrete Gust Response of a Box-wing Configuration", to be presented at Aerospace Europe 6th CEAS Conference 2017.

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- CSHELL: An Inhouse Aeroelastic Computational Tool
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CSHELL
Inhouse Aeroelastic Computational Tool

WHAT IS CSHELL?

- **It is a numerical FSI tool capable of performing several analyses, ranging from purely structural and aerodynamic, to aeroelastic ones.**

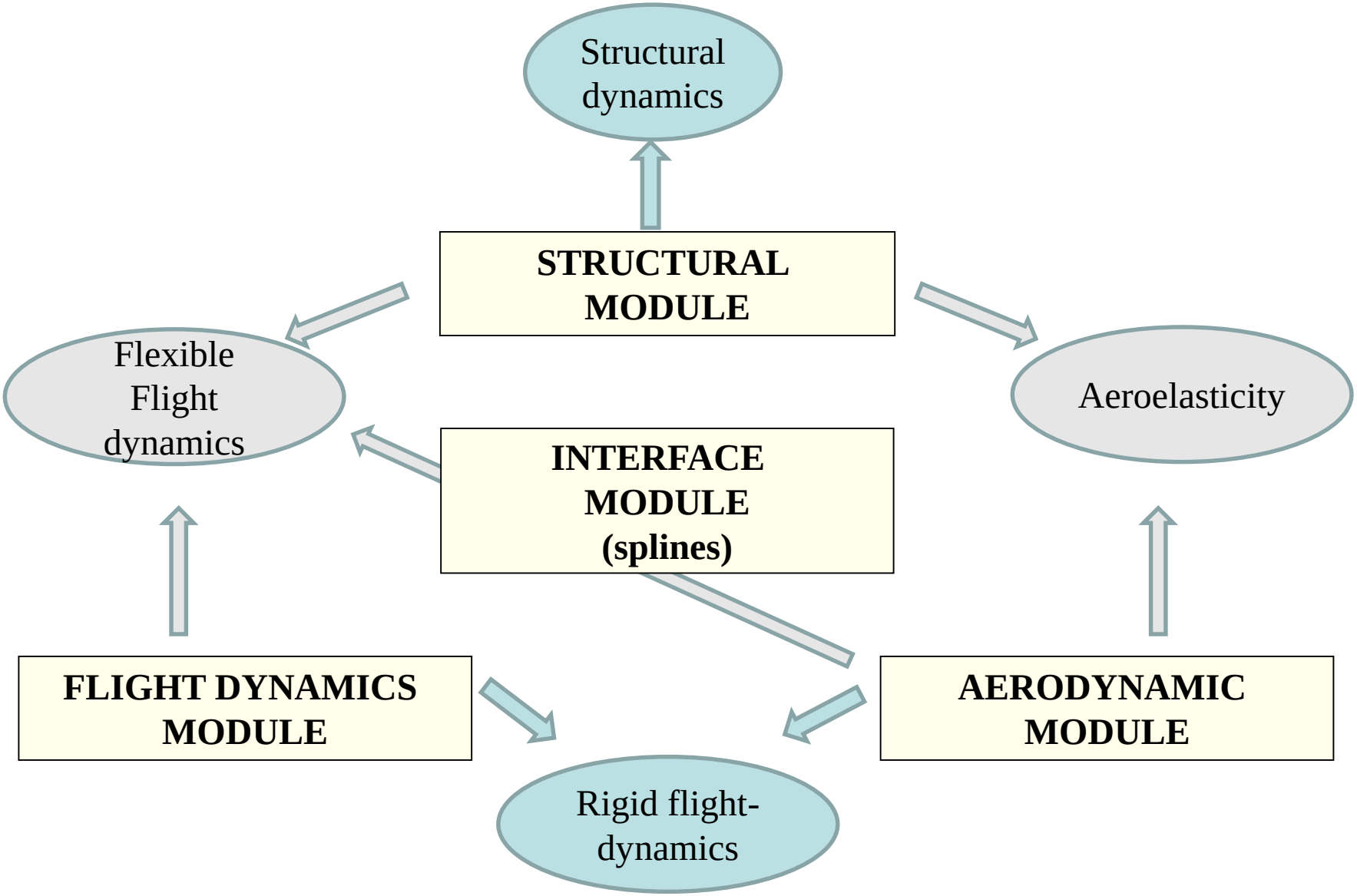
HISTORY

- **Conceived and initially programmed by L. Demasi (SDSU - San Diego State University)**
- **Currently under development (new submodules, e.g., Flight Dynamics module) at UC3M and SDSU.**

FLEXIBILITY

- **Developed in Fortran/C++, Matlab. At the price of an increased maintenance cost, Matlab allows to faster develop, validate, and integrate new features (<u>and not only</u>).**

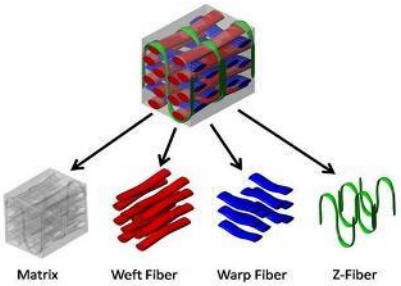
CSHELL Architecture

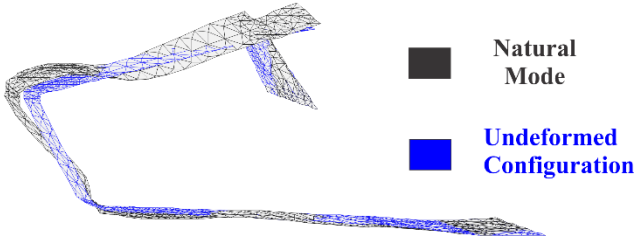


CSHELL - Structural Module

Highlights

- **Shell Elements**
- **Beam Element**
- **RODS, RBEs, Nonlinear MFC**
- **Nonlinear springs, free-play springs**
- **Multilayer Composites**
- **Nonlinear Updated Lagrangian formulation.**

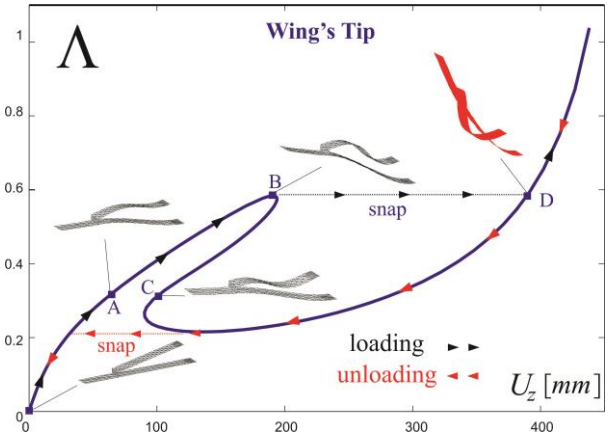




Mode VIII *4.91* Hz

Solvers

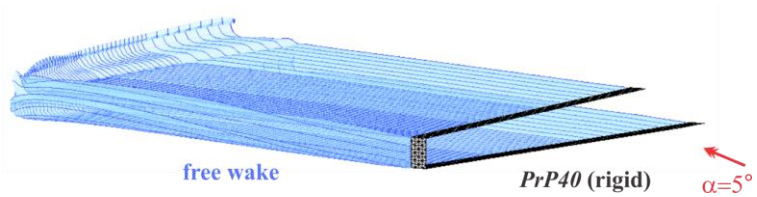
- **Linear Static and Dynamic**
- **Eigenvalue Analysis**
- **Nonlinear Static**
  - **Advanced Continuation sub-module**
- **Nonlinear Dynamic**
  - **Generalized Alpha Method**

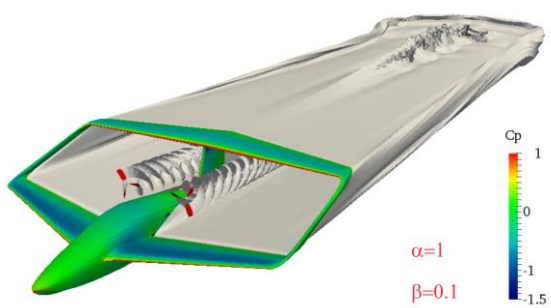


CSHELL - Aerodynamic Module/Solver

Static and Time Domain

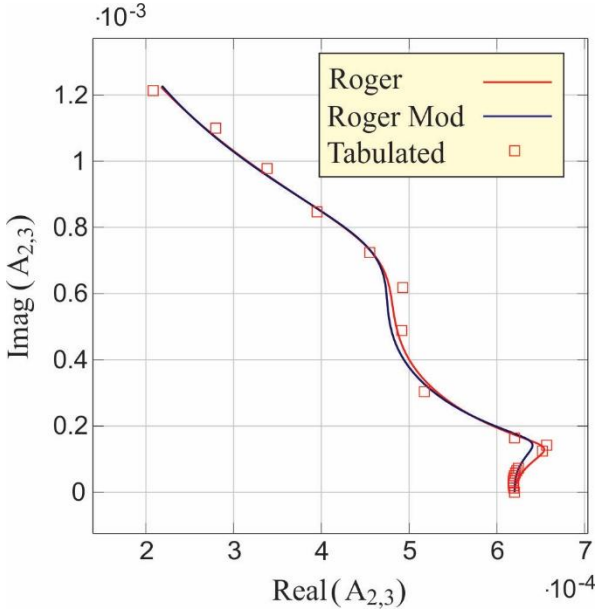
- **Panel/Vortex Lattice Method**
  - **free-wake**
  - **advanced wake-body interaction formulation**
  - **Jacobian/sensitivity**





Frequency Domain

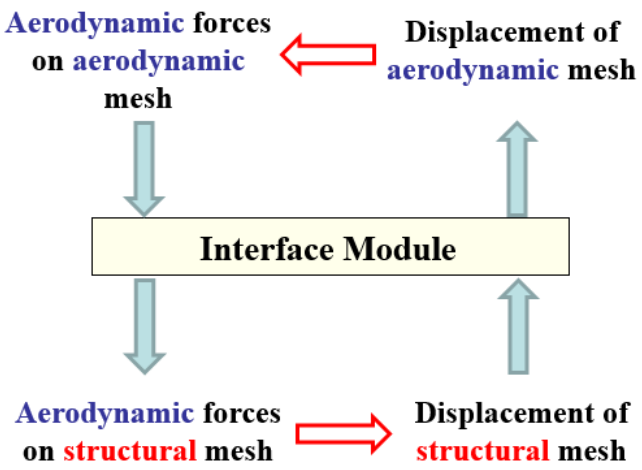
- **Doublet Lattice Method**
- **Morino BEM**
- **Rational Function Approximation**
  - **Modified Roger method**
  - **Minimum-State (Karpel)**



CSHELL – Aeroelastic/Interface Modules

Interface Module

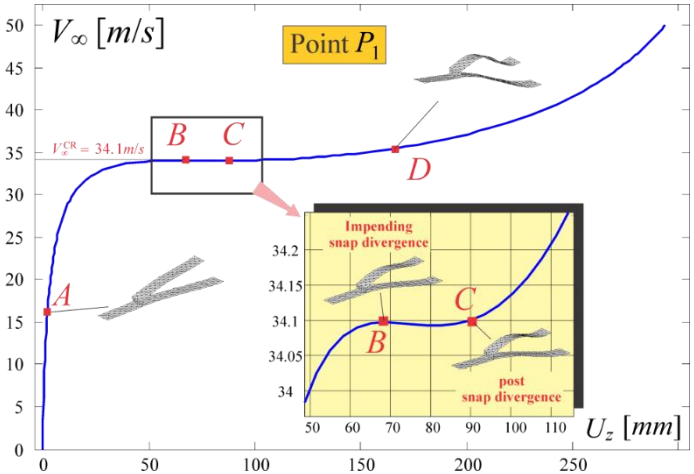
- Infinite Plate Spline (IPS)
- Moving Least Squares (with Meshless shape functions)



Aeroelastic Solvers

- Linear Static and Dynamic
- Static Stability Analysis (Divergence)
- Nonlinear Static
  - Advanced Continuation sub-module
- Nonlinear Dynamic
- Dynamic Stability Analysis (Flutter)

Snap-Divergence



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UC3M – UoB Collaboration

Statement: Is it possible to overcome the actual issues in the aeroelastic design of Box Wings through a different approach (robust control techniques)?

Possible advantages

Further physical understanding of the problem.

Hints in the aeroelastic design of the configuration.

Reconciliation of "Hi-Fidelity" models with LFT + robust control techniques).

Standard modeling approach

Development → 1 → **Hi-Fi model** → 2 → **ROM**

Aerodynamic (CFD / DLM)

Structural (FEM) / flutter analysis

Structural Model Integration

>1000 states

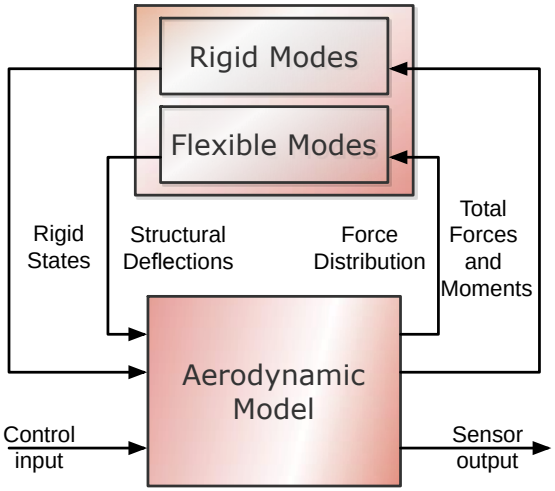
Transfer Function (TF)

~200/400 states

Transfer Function (TF)
Maybe state-space (SS)

+ Measure of reduction (**error**)

3



Lo-Fi model → 4 → **Simplified Lo-Fi model**

<100 states

Frequency Response Function (FRF)
Transfer Function (TF)
State-Space (SS)
Nonlinear Equations-of-Motion (EoM)

+ Measure of fidelity (**uncertainty**)

Used for analysis and design:

Linear Time Invariant (LTI)
Linear Fractional Transformation (LFT)
Linear Parameter Varying (LPV)

Approach: A *symbolic* FEM+LFT modeling approach

- **Aim**: to propose an approach addressing the well-known issue of reconciling:

  physical sources of uncertainties (well distinguishable in **Hi-Fi model**)

  and uncertain parameters (defined in **simplified Lo-Fi model**)

- **Approach**: Build symbolic objects of the structural (*physical*) operators

  and apply a modal decomposition (with *frozen* modes)

This requires a comprehensive framework featuring

the standard LFT modelling steps *inside* the Hi-Fi FEM solvers

- **Advantages**:
  - ❑ close connection to physical uncertainties
  - ❑ ability to capture very localized uncertainties (e.g. a single concentrated mass at a wing station)

Approach: A *symbolic* FEM+LFT modeling approach

Drawback: effect of perturbations on modes is not captured

STRUCTURAL MODES Φ

CSHELL solver (FEM+DLM)

Step-S1

Symbolic definition of the uncertain parameters

Step-S2

$\mathbf{M}(\delta_1, \ldots, \delta_n)$,
$\mathbf{C}(\delta_i)$,
$\mathbf{K}(\delta_i)$

SYMBOLIC PHYSICAL MATRICES

Step-S3

$$\tilde{M}(\delta_i) = \Phi^T \mathbf{M}(\delta_i)\Phi$$
$$\tilde{C}(\delta_i) = \Phi^T \mathbf{C}(\delta_i)\Phi$$
$$\tilde{K}(\delta_i) = \Phi^T \mathbf{K}(\delta_i)\Phi$$

SYMBOLIC MODAL MATRICES

Step-S4

$$\mathcal{F}_u(\tilde{\mathbf{M}}, \Delta_{\mathbf{M}})$$
$$\mathcal{F}_u(\tilde{\mathbf{C}}, \Delta_{\mathbf{C}})$$
$$\mathcal{F}_u(\tilde{\mathbf{K}}, \Delta_{\mathbf{K}})$$

MODAL LFTs

Step-S5

$$\left\{\begin{matrix} \bar{A}(\Delta_M, \Delta_C, \Delta_K) \\ \bar{B}(\Delta_M, \Delta_C, \Delta_K) \\ \bar{C}(\Delta_M, \Delta_C, \Delta_K) \\ \bar{D}(\Delta_M, \Delta_C, \Delta_K) \end{matrix}\right\}$$

AEROELASTIC LFT

Example: LOCAL MASS MATRIX (BEAM *j*)

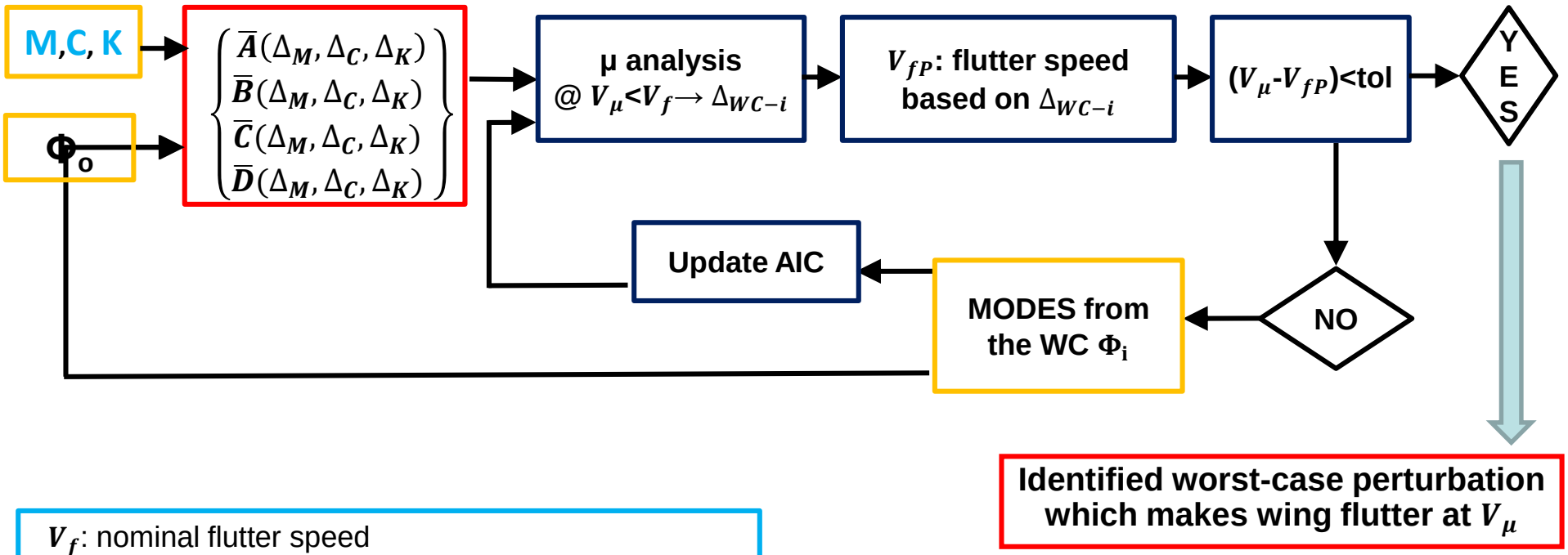
$$[\mathbf{M}_{\mathbf{B}j}] = \begin{bmatrix} \mathbf{M}_{11} & \mathbf{M}_{12} \\ \mathbf{M}_{12} & \mathbf{M}_{22} \end{bmatrix}$$

$$\mathbf{M}_{11} = f_1(L_j, m_j, J_{t_j})$$
$$\mathbf{M}_{22} = f_2(L_j, m_j, J_{t_j})$$
$$\mathbf{M}_{12} = f_3(L_j, m_j, J_{t_j})$$

$\{L_j, m_j, J_{tj}\}$ <u>are potential *physical* uncertainties</u> δ_i

Approach: Iterative cycle for worst-case flutter speed

- The Modal matrix **Φ** used for the SYMBOLIC MODAL MATRICES (Step S-3) must be updated This affects both the structural operators and the AIC matrix
- Proposed iterative cycle updates **Φ** based on the worst-case (WC) found by μ



V_f: nominal flutter speed

V_μ: speed below V_f at which we check robustness

Δ_{WC-i}: worst-case perturbation (given by μ_{LB}) at iter *i*

Results: Reconciliation with previous results

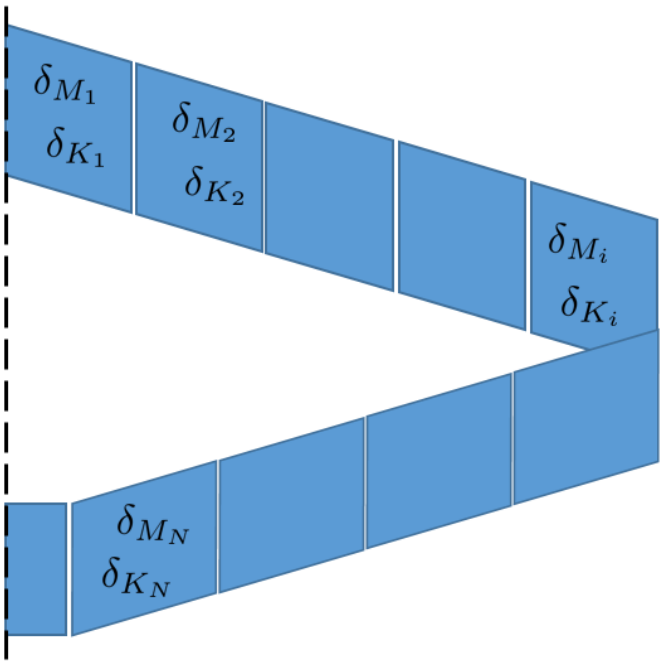
SENSITIVITY TO STRUCTURAL PARAMETERS

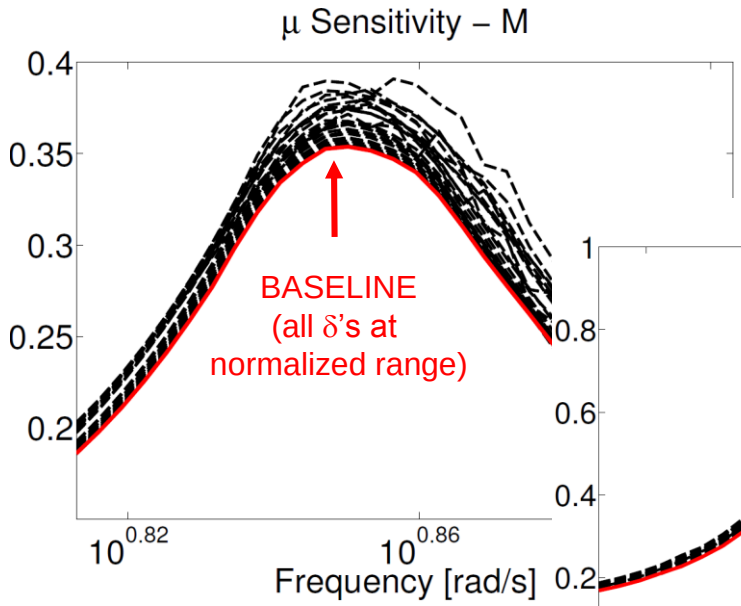
One uncertainty is considered for each:

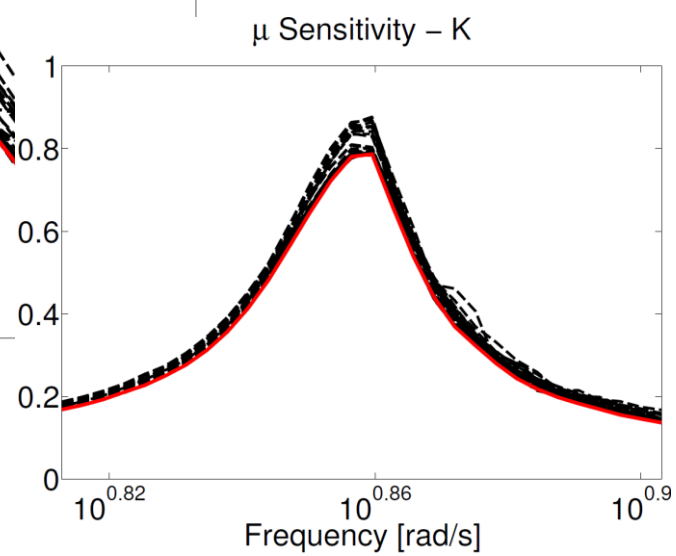
- Concentrated (fuel) mass δ_{Mi}
- Span-wise bending stiffness distribution δ_{Ki}

Divoux, Frediani "*The Lifting System of a Prandtl Plane, Part 2: Preliminary Study on Flutter Characteristics*", Springer Optimization and Its Applications

μ-based sensitivity:
one by one the uncertainty level of each parameter is increased



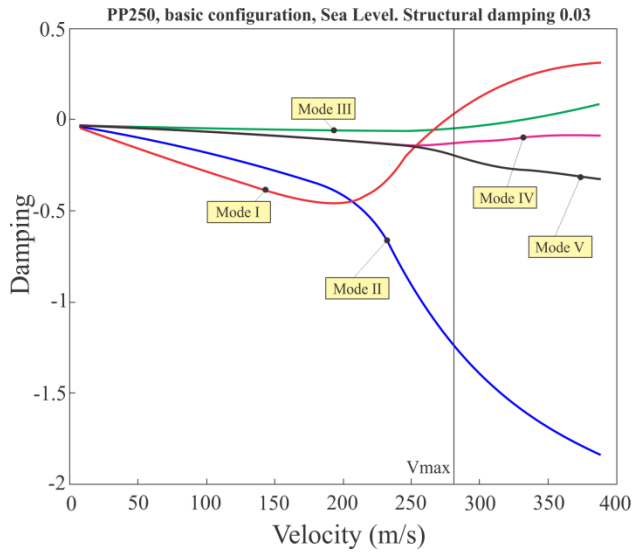


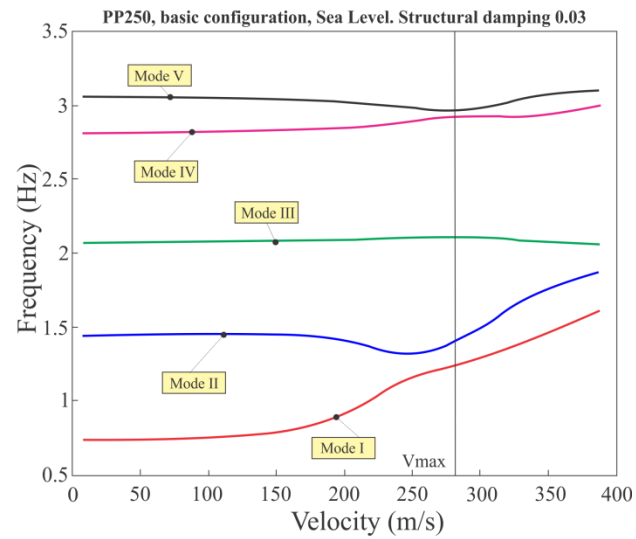


Finding from previous work* are retrieved:

- Worst-case perturbations
- Parameters relevance

Results: Physical insight given by μ

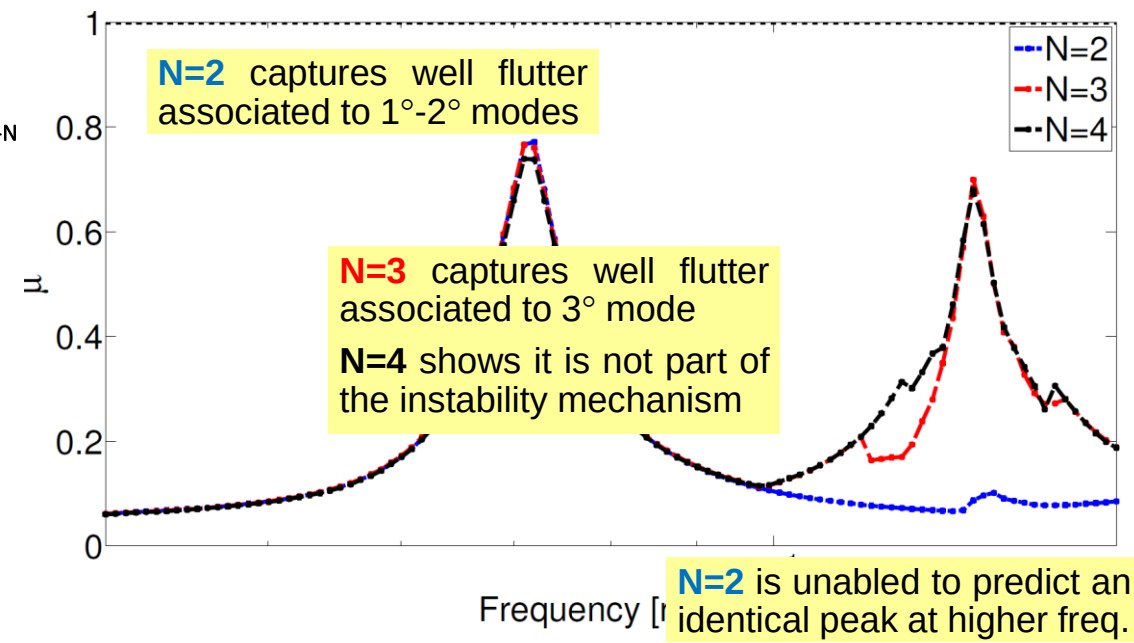




MODES PARTICIPATION TO THE INSTABILITY

Consider first **N modes uncertainties** :

- Concentrated (fuel) mass $\delta_{M\text{-}N}$
- Span-wise bending stiffness distribution $\delta_{K\text{-}N}$



N=2 captures well flutter associated to 1°-2° modes

N=3 captures well flutter associated to 3° mode

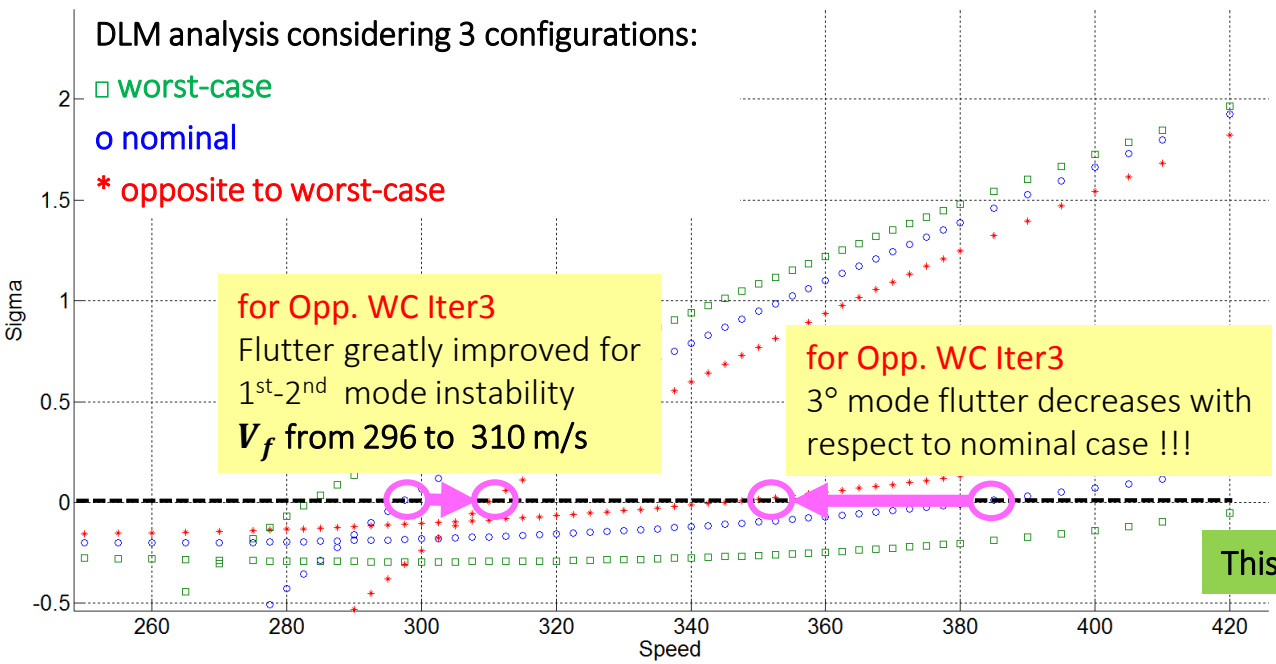
N=4 shows it is not part of the instability mechanism

N=2 is unabled to predict an identical peak at higher freq.

Results: application for flutter envelope enlargement

PASSIVE DESIGN STRATEGIES INFORMED BY μ

Aim: increase flutter speed of configuration
Approach: [1] take the more sensitive uncertain parameters
[2] find the worst-case Δ_{WC} using the iterative cycle
[3] apply a perturbation to their normalized values opposite to Δ_{WC}



➔ unstable mechanism must be result from **different WC**

This was predicted by previous μ analysis !!

AGENDA

- Introduction
- Unconventional Aircraft Configuration: the Box Wing/PrandtlPlane case
- CSHELL: An Inhouse Aeroelastic Computational Tool
- UC3M – UoB Collaboration: Preliminary Results
- Conclusions

Conclusions

- **Aeroelastic design is an involved process that hides difficulties and traps (free-flying, free-play, etc.).**
- **This is particularly true when unconventional configurations are considered, e.g. Box Wings, as new specific issues and challenges must tackled.**
- **A tool/approach merging a "hi-fi" solver and LFT/μ robust techniques has been developed and applied to the study of unconventional configurations.**
- **The approach was able to reproduce established results in the literature as well as show the potential for improved design and understanding**

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TASC

A novel approach to aeroelastic design of unconventional configurations

Merging FSI solvers and LFT/μ tools

Rauno Cavallaro, Rocco Bombardieri.
Andres Marcos, Andrea Iannelli.