A novel approach to aeroelastic design of unconventional configurations
Merging FSI solvers and LFT/µ tools

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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

www.lockheedmartin.com

Courtesy of University of Pisa
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 ARchitecture for the Sustainable Improvement of Future AirpLanes)
EU project

IDINTOS. Presented 21 November 2013, Italy

PARSIFAL. Kick-off meeting 11\textsuperscript{th} 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

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.

Flutter constraint was responsible for large weight penalties.


PrP250: Flutter Studies

“Cantilever” and symmetric matched flutter analyses.

Low natural frequencies:
1\textsuperscript{st} mode 0.74 Hz,
2\textsuperscript{nd} mode 1.45 Hz
5\textsuperscript{th} 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.
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.

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

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

Flutter at 290 m/s. Complies with regulations.

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

Cantilever

Free-Flying
Current Research Topics

Flight Dynamics of the Flexible PrandtlPlane

Elasticity changes Short-period damping properties!


Discrete Gust Response of a PrandtlPlane

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

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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 (and not only).
CSHELL Architecture

- Structural dynamics
  - Structural Module
    - flexible flight dynamics
    - interface module (splines)
  - Aerodynamic Module
    - rigid flight dynamics

- Flight Dynamics Module

- Aeroelasticity
CSHELL - Structural Module

**Highlights**

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

**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)
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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.
Aerodynamic (CFD / DLM) Structural (FEM) / flutter analysis Structural Model Integration

Development 1 Hi-Fi model 2 ROM

>1000 states >1000 states
Transfer Function (TF) Transfer Function (TF)
Maybe state-space (SS) Maybe state-space (SS)
+ Measure of reduction (error) + Measure of reduction (error)

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)
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

C SHELL solver (FEM+DLM)

Example: LOCAL MASS MATRIX (BEAM $j$)

\[
[M_{Bj}] = \begin{bmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{bmatrix}
\]

\[
M_{11} = f_1(L_j, m_j, J_{tj})
\]

\[
M_{22} = f_2(L_j, m_j, J_{tj})
\]

\[
M_{12} = f_3(L_j, m_j, J_{tj})
\]

\{$L_j, m_j, J_{tj}$ are potential physical uncertainties $\delta_i$}

Structural modes $\Phi$

Symbolic definition of the uncertain parameters

Symbolic physical matrices

- $M(\delta_1, ..., \delta_n)$
- $C(\delta_i)$
- $K(\delta_i)$

Step S2

\[
\bar{M}(\delta_i) = \Phi^T M(\delta_i) \Phi
\]

\[
\bar{C}(\delta_i) = \Phi^T C(\delta_i) \Phi
\]

\[
\bar{K}(\delta_i) = \Phi^T K(\delta_i) \Phi
\]

Steady Modal Matrices

Step S3

Step S4

Modular LFTs

- $\mathcal{F}_u(\bar{M}, \Delta M)$
- $\mathcal{F}_u(\bar{C}, \Delta C)$
- $\mathcal{F}_u(\bar{K}, \Delta K)$

Drawback: effect of perturbations on modes is not captured

Aeroelastic LFT

- $\mathcal{F}(\Delta M, \Delta C, \Delta K)$
- $\mathcal{B}(\Delta M, \Delta C, \Delta K)$
- $\mathcal{C}(\Delta M, \Delta C, \Delta K)$
**Approach: Iterative cycle for worst-case flutter speed**

- The Modal matrix $\Phi$ 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 $\Phi$ based on the worst-case (WC) found by $\mu$.

$\mathbf{M,C,K} \rightarrow \begin{bmatrix} \bar{A}(\Delta_M, \Delta_C, \Delta_K) \\ \bar{B}(\Delta_M, \Delta_C, \Delta_K) \\ \bar{C}(\Delta_M, \Delta_C, \Delta_K) \\ \bar{D}(\Delta_M, \Delta_C, \Delta_K) \end{bmatrix}$

$\mu$ analysis @ $V_\mu < V_f \rightarrow \Delta_{WC-i}$

$V_{FP}$: flutter speed based on $\Delta_{WC-i}$

$(V_\mu - V_{FP}) < tol$

Update AIC

MODES from the WC $\Phi_i$

Identified worst-case perturbation which makes wing flutter at $V_\mu$

$V_f$: nominal flutter speed

$V_\mu$: speed below $V_f$ at which we check robustness

$\Delta_{WC-i}$: worst-case perturbation (given by $\mu_{LB}$) at iter $i$
Results: Reconciliation with previous results

SENSITIVITY TO STRUCTURAL PARAMETERS
One uncertainty is considered for each:
- Concentrated (fuel) mass $\delta_{M_i}$
- Span-wise bending stiffness distribution $\delta_{K_i}$

$\mu$-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 $\mu$

**MODES PARTICIPATION TO THE INSTABILITY**

Consider first $N$ modes uncertainties:
- Concentrated (fuel) mass $\delta_{M-N}$
- Span-wise bending stiffness distribution $\delta_{K-N}$

- $N=2$ captures well flutter associated to $1^\circ-2^\circ$ modes
- $N=3$ captures well flutter associated to $3^\circ$ mode
- $N=4$ shows it is not part of the instability mechanism

$N=2$ is unable to predict an identical peak at higher freq.
Results: application for flutter envelope enlargement

PASSIVE DESIGN STRATEGIES INFORMED BY $\mu$

Aim: increase flutter speed of configuration

Approach: [1] take the more sensitive uncertain parameters
[2] find the worst-case $\Delta_{WC}$ using the iterative cycle
[3] apply a perturbation to their normalized values opposite to $\Delta_{WC}$

DLM analysis considering 3 configurations:
- worst-case
- nominal
- *opposite to worst-case

for Opp. WC Iter3
Flutter greatly improved for 1st-2nd mode instability $V_f$ from 296 to 310 m/s

for Opp. WC Iter3
3° mode flutter decreases with respect to nominal case !!!

$\Rightarrow$ unstable mechanism must be result from different WC

This was predicted by previous $\mu$ analysis !!
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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/$\mu$ 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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