FLEXOP Project
Flutter Free FLight Envelope eXPansion for ecOnomical Performance improvement

Balint Vanek
coordinator

International Workshop on Robust Modeling, Design and Analysis
University of Bristol
• Project Duration: 42 months
• Budget: 6.7 m EUR

Scientific Advisory Group
• UofM – Pete Seiler
• Airbus – Frank Theurich
• Aerospace Control Dynamics - Dagfin Gangsaas
• Imperial College – Rafael Palacios

In memory of Gary Balas, and in cooperation with Pete Seiler and the Performance Adaptive Aeroelastic Wing (PAAW) program
Flutter is a dynamic instability of an elastic structure in a fluid flow, caused by positive feedback between the body's deflection and the force exerted by the fluid flow.

- Equations of Motion:
  \[ m\ddot{h} + S_{\phi} \ddot{\phi} + K_{h} h = -L; \]
  \[ I_{\phi} \ddot{\phi} + S_{\phi} \dot{h} + K_{\phi} \phi = M; \]
Overview on flutter suppression systems

- Flutter Suppression was already successfully applied in the past:

  - First flutter suppression research by NASA
    - B-52 CCV (1973)
  - Research for military application by MBB:
    - Fiat G91 (1978)
    - F-4F (1980)
  - Two certified applications:
    - F/A-18 Active Oscillation Suppression System dampens Limit Cycle Oscillation caused by certain external mass configurations (1985)
    - Boeing 747-8/-8F Outboard Aileron Modal Suppression system dampens Limit Cycle Oscillation occurring in certain flight condition
  - No application where divergent flutter occurs
  - No comparable European application

- Continued research:
  - PAAW
  - X-56
  - FLEXOP
Modern large aircrafts have to (among other important points!)
  - Minimize the fuel consumption
  - Propose a very high level of comfort

The trade-off structure/efficiency must guarantee a good level of comfort

**DESIGNING THE AIRCRAFT:**
- Absolutely essential to ensure a sufficiently stiff structure
- Possibility to minimize the structural vibrations with additional means
The Key elements to design such a function:

1. Aeroelastic model of the aircraft:
   - Pre-flight mathematical models: theoretical model
   - Identification in flight: identified model

2. Sensors:
   - Defined on the pre-flight model
   - Validated in flight

3. Criteria:
   - EASA/FAA international standards
   - Internal manufacturer know-how criteria

4. Design of the control law

5. Flight tests

6. Certification
Move towards methods and tools enabling multidisciplinary design analysis and optimization in the aeroservoelastic domain
Validate the developed tools with the demonstrator
Aerodynamic Specifications from Airbus

- Development of baseline requirements for 3 Wings based on overall A/C requirements by TUM
- Aerodynamic Design
- High Fidelity Simulation (TAU CFD)
- Static Aeroelasticity – Jig shape computation using CFD-CSM

- Joint development of requirements
- Wing section design
- 3D wing shape design
- Design to meet lift & span-loading req.
- Evaluation of aerodynamic data
- Investigations into Pitch-up stability
- Trades performed on mass, c.g., twist (rigid trimmed)
- 20m/s 1g is the most challenging flight point
- Trailing edge flap reserved as risk mitigation option
- Assessment of Flexibility effects using CFD-CSM
- Ongoing work to investigate control surface aerodynamics

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Flutter (-1) Wing Design

Objectives:
- Flutter Speed below 55 m/s
- Structural Sizing to 5g
- Low Flutter frequency - in best case <10Hz
- No control Reversal
- Sufficient high divergence speed

Results:
- Opposing trends in stiffness requirements – Low Wing Stiffness:
  
  + Low Flutter Speed  
  + Low Flutter Frequency  
  - low divergence speed  
  - high structural wing deformation (aerodynamic problems worsen by wing sweep)  
  - control reversal  

- Additional flutter tuning masses:
  + Low Flutter Frequency
  - Additional structural dynamic loads

Preliminary Aeroelastic model:
- Parametric
- Design development
- Parameter studies

Detailed Aeroelastic model:
- Include of Shell offsets
- No smeared stiffness approach
- Adaption necessary due to manufacturing issues
- Detail adjustment of wing torsional stiffness by wing shell layer
- Detail adjustment of flutter trim masses
## Dynamic Model Aircraft Integration Process

### Data Sources
- Nastran data set provided by TU Munich and DLR-AS

### Preprocessing
- Nastran model required some modifications
- Varloads data base for DLR-SR tools
- Rational function approximation of DLM results

### Integration
- LTI state space system model integration

### Implementation
- Matlab state space system objects (delivered to Partners)

### Application
- Flutter analysis and comparison with TUM results
- Estimation of achievable performance
Model properties

- Aerodynamics → DLM/VLM
  - Steady
  - Unsteady
  - NO camber
  - NO twist
- Structural dynamics → linear
  - Structural flaps added (-1 wing)
  - Condensed (reduction of grid points)
- Linearised (trimpoints)
- Airbrakes:
  - included in model equations
- Drag:
  - drag polar from TUM included (assumed in c.g.)
  - Correction with CFD-CSM results is underway
- Engine:
  - Thrust vector, no engine dynamics
Flutter suppression control (for the BAH wing)

**Aeroservoelastic modeling:**

FEM based structural model + DLM aerodynamics + linear actuator = 115 state LPV model scheduled with the airspeed

Flutter speed 343.11 m/s, 11 rad/s

**Model order reduction:**

→ 23-state LPV model

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**Robust control synthesis**

\[ W_f = 0.2I, \]
\[ W_d = 1, \]
\[ W_n = 0.001I \]

Sigma plots of the closed and open loop systems around the flutter speed

Sigma plots of the controller around the flutter speed
Controllability Study

- Controller design for Actuator positions at different trim states
  - Separate design of symmetric and antimetric controller
- Sensor: Acceleration in Z, Rotational rate around Y-Axis at 91.26% wingspan
- Control Surface: Flap3 or Flap4

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<th>Actuator position</th>
<th>Sym $V_{crit}$</th>
<th>Anti $V_{crit}$</th>
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Multidisciplinary iteration of aeroelasticity control and manufacturing:
• 7’ – similar to 7, 4, 1 (around the leading edge) but 125 mm more outboard (aligned with flap 4 hinge)
• 7'’ – aligned spanwise with the hinge but 50 mm forward from 7’
• 8’ – aligned spanwise with the hinge but 50 mm backward from 7’

Most likely 7’ is a suitable candidate, but we have to do a little sensitivity calculation, how precise we have to be with positioning

According to TUM the kinematics should be fine with actuator rod parallel to global x axis
### Analysis on the location of DD actuator

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<tr>
<th>Control Surface Flap 3</th>
<th>Sym</th>
<th>Act 7</th>
<th>Act 8</th>
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Performance gain: open-loop vs. closed-loop
**Evaluation Criteria**

Main Criteria:
- Gain Margin 6dB
- Phase Margin 45°

Actuator position: 7

Control surface: Flap 4
Current Status DD
Efforts & Outcome:
• Fuselage Structural Design, Internal Layout & CAD Modelling
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**Flight Control Architecture**

- Develop a custom Flight control architecture including HW and SW
- Minimal delay between the controller and physical components
- Distributed redundant flight control architecture
- High variety of I/O ports for custom sensors and actuators

**Starting point**

- Working flight control software stack from a previous project – Sindy
- Working core of the RX-MUX (safety switch) from a previous project
Mission Design and Baseline Control

Baseline control concept

Flight modes & Control actions
FM1 - IAS HOLD
  - WP TRACK
  - ALT-HOLD
FM2 - CHI-TRACK
  - ALT-HOLD
  - ENG-SPEEDUP
FM3 - CHI-TRACK
  - IAS-HOLD
  - ALT-TRACK
  - ACC, DEC
FM4 - ALT-HOLD
  - CHI-TRACK
  - IAS HOLD

Test track

UTC time
φ, θ, ψ
p, q, r
x_A, y_A, -h
v_N, v_E, v_D
a_x, a_y, a_z
h, α, β
p_{st}, p_{dyne}
IAS
xEssense, ADS

Control surfaces reserved for flutter suppression control are marked by dark red.
Toolchain:

- Tool for wing structure sizing (TUD)
- Tool for aeroelastic analysis (AGI-G)
- Tool for conceptual aircraft design (RWTH)

**Proteus**
- AGI-G and TUD obtain promising wing planforms and all external wing loads
- AGI-G and TUD perform structural sizing
- RWTH obtain the wing (structural) mass and aeroelastic behaviour to perform overall performance calculation

**Deadalus**
- Geometry of flight shape

**Scale-Up**
- Top-level aircraft requirements (TLARs)
- Configurational Decisions
- Weight Estimation
- Aerodynamic Design
- Mission Analysis
- Aircraft Performance Analysis
- Mass Estimation
- Polar Estimation
- Structures
- Systems
- Stability and Control

*FLEXOP, IWRMDA, Bristol, 18-19 09 2017*
End & Thanks