Flight Control of Flexible Aircraft

Dr. Nhan Nguyen

Technical Group Lead
Advanced Control and Evolvable Systems (ACES) Group
Intelligent Systems Division
NASA Ames Research Center
Moffett Field, CA

NESC GNC Meeting at NASA ARC
January 25, 2017
Outline

• Introduction

• Performance Adaptive Aeroelastic Wing

• Aeroservoelasticity Modeling of Flexible Aircraft

• Multi-Objective Flight Control
  – Real-Time Drag Minimization
  – Gust / Maneuver Load Alleviation
  – Adaptive Flutter Suppression

• X-56A Collaboration

• Other Collaborations
Advanced Control and Evolvable Systems Group

- Advanced Control and Evolvable Systems (ACES) Group within the Intelligent Systems Division (code TI) has 21 researchers, 13 with Ph.D.

- Conduct GNC research and multidisciplinary fixed-wing vehicle dynamic modeling and simulations

- More than 90% research supports aeronautics with some space-related GNC
Introduction

• Composite wing technology in modern passenger aircraft affords weight reduction but also causes increased wing flexibility
Impact on Aerodynamics

- Increased wing deflection impacts optimal span load at off-design, causing increase in drag

Increased drag leads to increased fuel consumption
Impact on Flight Load, Stability and Control

- Increased wing flexibility causes reduced flutter margin, aeroservoelastic interactions with dynamics and control, and increased gust response.
AATT Project Research Themes
Based on Goal-Driven Advanced Concept Studies

<table>
<thead>
<tr>
<th>Goals</th>
<th>Noise</th>
<th>Emissions (LTO)</th>
<th>Emissions (cruise)</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metrics (N+3)</td>
<td>Stage 4 – 52 dB</td>
<td>CAEP6 – 80%</td>
<td>2005 best – 80%</td>
<td>2005 best – 60%</td>
</tr>
</tbody>
</table>

Goal-Driven Advanced Concepts (N+3)

1. Lighter-Weight Lower Drag Fuselage
2. Higher Aspect Ratio Optimal Wing
3. Quieter Low-Speed Performance
4. Cleaner, Compact Higher BPR Propulsion
5. Hybrid Gas-Electric Propulsion
6. Unconventional Propulsion Airframe Integration
7. Alternative Fuel Emissions

Research Themes with Investments in both Near-Term Tech Challenges and Long-Term (2030) Vision
Performance Adaptive Aeroelastic Wing Research

- Multidisciplinary design analysis optimization (MDAO) capabilities for development of advanced adaptive wing technology concepts

**Multi-Fidelity Modeling**
- Multi-fidelity aero modeling (Cart3D, Overflow, Lava, Vorlax, Vspaero)
- Coupled FEM (Beam3D, NASTRAN) with aero codes
- Aeroelasticity / Aeroservoelasticity (ASE)

**ASE – Flight Dynamics**
- Coupled ASE – rigid aircraft flight dynamics
- Gust modeling
- Actuator dynamics of ASE control effectors

**Control Effectors**
- VCCTEF / continuous leading edge slat
- Distributed control surfaces
- Other novel concept

**Multidisciplinary Optimization**
- Aerodynamic design optimization for drag reduction
- MDO for drag minimization, load alleviation, and active ASE control

**ASE Flight Control**
- ASE control (flutter suppression, load alleviation)
- multi-objective flight control
- Real-time drag optimization

**Performance Analysis**
- Design trade-study
- Mission analysis / trajectory optimization to minimize fuel burn
Performance Adaptive Aeroelastic Wing

- Variable Camber Continuous Trailing Edge Flap (VCCTEF) developed by NASA and Boeing Research & Technology as adaptive wing control technology for drag reduction

Multi-Segment Variable Camber

SMA and EMA Hinge Line Actuation

Individual Flap Deflection for Spanwise Lift Optimization

Conformal Mold Line Material for Gap Covering to Eliminate Flap Noise and Reduce Drag
Flexible Wing High-Aspect Ratio Transport Models

- Flexible conventional transport and next-generation Truss Brace Wing

- VCCTEF is equipped as an adaptive wing control technology
Multi-Fidelity Coupled Aerodynamic Tools

- Right fidelity tools – Euler and high-fidelity RANS CFD for optimization and vortex-lattice with transonic and viscous flow corrections for MDAO

CART3D Static Aero-Structure

OVERFLOW Static Aero-Structure

VORLAX Static & Dynamic FEM / NASTRAN

LAVA CFD
Drag and Maneuver Load Control Optimization

- Drag and maneuver load minimization with VCCTEF

CART3D Aero-Structural Drag Minimization

- ~ 1% - 4% Drag Reduction

Coupled FEM-VORLAX Load Alleviation Optimization

- ~ 40% Bending Moment Reduction
Aeroservoelasticity

- Gust and maneuver load responses are important design considerations for flexible wing transports.

- Integrated coupled ASE flight dynamics provides flight prediction capability of combined flexible vehicle stability and control response characteristics.
Integrated Coupled ASE Tool

- Integrated coupled ASE tool can rapidly generate nonlinear and linear ASE state space models with gust models and with transonic and viscous corrections

\[
\begin{bmatrix}
M_{rr} & M_{re} & M_{r\delta} & M_{rs} \\
M_{er} & M_{ee} & M_{e\delta} & M_{es} \\
M_{r\delta} & M_{e\delta} & M_{\delta\delta} & M_{\delta s} \\
M_{rs} & M_{es} & M_{\delta s} & M_{ss}
\end{bmatrix}
\begin{bmatrix}
\dot{x}_r \\
\dot{x}_e \\
\dot{x}_\delta \\
\dot{x}_s
\end{bmatrix}
= 
\begin{bmatrix}
S_{rr} & S_{re} & S_{r\delta} & S_{rs} \\
S_{er} & S_{ee} & S_{e\delta} & S_{es} \\
S_{r\delta} & S_{e\delta} & S_{\delta\delta} & S_{\delta s} \\
S_{rs} & S_{es} & S_{\delta s} & S_{ss}
\end{bmatrix}
\begin{bmatrix}
x_r \\
x_e \\
x_\delta \\
x_s
\end{bmatrix}
+ 
\begin{bmatrix}
T_r \\
T_e \\
T_\delta \\
T_s
\end{bmatrix}u
\]
Simulations of Gust Response of Truss-Braced Wing
Multidisciplinary Flight Control

- ASE flight control enables both adaptive wing performance and safe flight operation

- Increased aircraft performance can be realized by addressing multidisciplinary interactions in flight control design

- Integrated adaptive wing design by incorporating flight control in the MDAO cycle for weight and drag reduction
Multi-Objective Flight Control

- Multi-objective flight control, first introduced in 2012, takes advantage of multi-functional flight control surfaces such as VCCTEF to allow new capabilities in flight control to achieve multiple objectives simultaneously.
ASE State Space Model

- ASE state space model with gust disturbance
  \[ \dot{x} = Ax + Bu + w \]
  \[
  \begin{cases}
  \dot{x}_r = A_{rr}x_r + A_{re}x_e + B_ru_r + w_r \\
  \dot{x}_e = A_{er}x_r + A_{ee}x_e + B_{e}u_e + w_e
  \end{cases}
  \]

- Output equation for accelerometers
  \[ y = Cx + Du = C_rx_r + C_ex_e + D_ru_r + D_{e}u_{e} \]

- Drag model
  \[ \Delta C_D = C_{Dx}x + C_{Du}u + x^\top C_{Dx^2}x + x^\top C_{Dxu}u + u^\top C_{Du^2}u \]

- Wing root bending moment measurement
  \[ M_y = M_{xx}x + M_{uu}u + M_{ww}w \]
Multi-Objective Optimal Control

- Multi-objective cost function

\[ J = J_r + J_e \]

\[ J_r = \lim_{t_f \to \infty} \frac{1}{2} \int_0^{t_f} \left[ (z - r)^\top Q_r (z - r) + u_r^\top R_r u_r \right] dt \]

- Drag minimization and load alleviation multi-objective optimal control

\[ u = K_x \dot{x} + K_r r + K_w \dot{w} + \Lambda_0 \]

\[ K_x = -\bar{R}^{-1} \left( B^\top W + \frac{1}{2} q_D C_{Du}^\top + q_M M_u^\top M_x \right) \]

\[ K_r = -\bar{R}^{-1} B^\top V_r \]

\[ K_w = -\bar{R}^{-1} \left( B^\top V_w + q_M M_u^\top M_w \right) \]

\[ \Lambda_0 = -\bar{R}^{-1} \left( B^\top V_0 + \frac{1}{2} q_D C_{Du}^\top \right) \]
Adaptive Gust Estimation

- Kalman filter state estimation of flexible aircraft dynamics
  \[ \dot{x}_e = A_{ee}\hat{x}_e + A_{er}x_r + L(y - \hat{y}) + B_e u_e + \hat{w}_e \]

- Plant modeling error
  \[ \varepsilon_r = \hat{x}_r - x_r = (A_{rr} + B_r K_{xr})(\hat{x}_r - x_r) + A_{re}(\hat{x}_e - x_e) + \hat{w}_r - w_r \]

- Wing root bending moment estimation error
  \[ \varepsilon_M = \hat{M}_y - M_y = M_x\hat{x} + M_uu + M_w\hat{w}_r + M_{we}\hat{w}_e - M_y \]

- Least-squares gradient adaptive gust estimation
  \[
  \begin{align*}
  \dot{\hat{w}}_r^T &= -\Gamma_{wr} \frac{\partial J^T}{\partial \hat{w}_r} = -\Gamma_{wr} \left( \varepsilon_r^T + M_{wr} \varepsilon_M^T \right) \\
  \dot{\hat{w}}_e^T &= -\Gamma_{we} \frac{\partial J^T}{\partial \hat{w}_e} = -\Gamma_{we} M_{we} \varepsilon_M^T
  \end{align*}
  \]
Real-Time Adaptive Drag Minimization Control

- Real-time drag minimization is a technology that can truly harvest full potential of adaptive aeroelastic wing technology
Adaptive Drag Optimization Wind Tunnel Test

- A wind tunnel test will be conducted in University of Washington Aeronautical Laboratory (UWAL) in FY17 to demonstrate adaptive drag optimization technique.

- Wind tunnel model will be a flexible CRM (Common Research Model) wing with 10% wing tip deflection.
Wind Tunnel Tests

- Two wind tunnel tests conducted in University of Washington Aeronautical Laboratory (UWAL) in August 2013 and July 2014

5% Lift/Drag Improvement

~ 6% Drag Reduction

Cruise Configuration Test in FY13

High-Lift Test in FY14
UWAL Test of Cruise Configuration

Flaps Fully Deflected  Alpha: 3°  Q = 20 psf
Flight Path Angle Control with Drag Minimization

- Flight Path Angle
- Wing Tip Deflection
- Drag Coefficient
- L/D

1.25% L/D Improvement
2.5 g Pull-Up Pitch Rate Control with Load Alleviation

Pitch Rate

Wing Tip Deflection

Drag Coefficient

Wing Root Bending Moment
Pareto Frontier Multi-Objective Optimization Analysis

Design 1 provides best compromise between drag minimization and load alleviation.
Multi-Objective Flight Control Simulations

Aeroservoelasticity Control
Conceptual Design Model

Intelligent Systems Division
NASA Ames Research Center
Adaptive Maneuver Load Alleviation

• Many physical plants are designed to meet performance specifications or constraints. For example, aircraft wing structures are designed to meet certain load limits which cannot be exceeded in-flight.

• Conventional adaptive control generally does not take into account performance optimality.

• Physical plant performance optimization can achieve performance objective.

• Adaptive control with performance optimization has been developed in connection with time-varying modification of reference model

\[
\dot{\hat{x}}_m = (A_m + B_p\hat{K}_x)\hat{x}_m + (B_m + B_p\hat{K}_r)r
\]

\[
\hat{K}_x = -\hat{R}^{-1}\left(B_p^TW + \hat{D}_p^Tq\hat{C}\right)
\]

\[
\hat{K}_r = \hat{R}^{-1}B_p^T\left(\hat{A}^T - WB_p\hat{R}^{-1}B_p^T\right)^{-1}WB_m
\]
Adaptive Maneuver Load Alleviation

- **Simulations of flexible wing transport aircraft**

  - Original Ref. Model Response
  - Performance Optimizing Ref. Model

  Pitch Rate

  Wing Root Bending Moment
Adaptive Flutter Suppression

- Aeroelastic uncertainty can degrade ASE flutter suppression control

- Adaptive control could be used to improve robustness to uncertainty – leverage previous adaptive flight control work on F-18 with Optimal Control Modification with NASA AFRC

Adaptive Linear Quadratic Gaussian control

\[
\begin{align*}
\dot{\mathbf{u}} &= \mathbf{K}_x \hat{\mathbf{x}} + \Delta \mathbf{K}_x \hat{\mathbf{x}} + \mathbf{K}_y (y - \hat{y}) \\
\Delta \mathbf{K}_x & = -\mathbf{\Gamma}_x \hat{\mathbf{x}} \hat{\mathbf{x}}^T \left( \mathbf{P} - \mathbf{\nu}_x \Delta \mathbf{K}_x \mathbf{B}^T \mathbf{P} \mathbf{A}_m^{-1} \right) \mathbf{B} \\
\mathbf{K}_y & = -\mathbf{\Gamma}_y (y - \hat{y}) \left[ \hat{\mathbf{x}}^T \mathbf{P} - \mathbf{\nu}_y (y - \hat{y})^T \mathbf{K}_y \mathbf{B}^T \mathbf{P} \mathbf{A}_m^{-1} \right] \mathbf{B}
\end{align*}
\]
Flutter Animation
Flutter Suppression Animation
X-56A Flight Control Collaboration

- Collaboration with AFRC on X-56A flight control validation of ASE flutter suppression and multi-objective flight control
  - POC: Steve Jacobson and Matt Boucher
  - AFRC sent ARC X-56A simulations on January 23, 2016 for control development

X-56A with Interchangeable Wings
X-56A Model

- **Reduced-order model for longitudinal dynamics**
  - 214 states including 5 rigid-body states \(\{h, \theta, u, \alpha, q\}\), elastic and lag states for 25 elastic modes, and sensor and actuator dynamics
  - 16 outputs and 5 symmetric inputs including 1 body flap and 4 wing flaps per wing

- **Reduced-order reference model only includes 5 elastic modes and no sensor and actuator dynamics**
Adaptive Augmentation

• LQR design for flight path angle control with adaptive augmentation for matched uncertainty

\[
\begin{align*}
    u &= (I - K_u^T) K_x x - \Theta^T \Phi(x) \\
    \dot{K}_u &= -\Gamma_u K_x x (e^T P - \nu_u x^T K_x K_u B^T P \mathbf{A}_m^{-1}) B \\
    \dot{\Theta} &= -\Gamma_\Theta \Phi(x) [e^T P - \nu_u \Phi(x) \Theta B^T P \mathbf{A}_m^{-1}] B
\end{align*}
\]

• Demonstrate adaptive flutter suppression at two flight conditions on either side of flutter boundary without gain scheduling
Simulations – Below Flutter Boundary

- Reference model from flutter-free trim point at 115 knots, 60 lbs of fuel
Simulations – Above Flutter Boundary

- Trim point at 145 knots, 60 lbs of fuel above flutter boundary

Adaptive control is able to stabilize flutter modes at different flight conditions without gain scheduling
Other Collaborations

• NASA-funded EPSCoR project with Wichita State University “Active Wing Shaping Control for Morphing Aircraft”
  – Wichita State University, Kansas University, and Missouri University of Science & Technology
  – FY15-18 performance period

• Possible collaboration with Boeing Research & Technology on Integrated Adaptive Wing Technology Maturation NRA funded by AATT project
Thank You