Flight Control of Flexible Aircraft

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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
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

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

Noise
Stage 4 – 52 dB CUM

Emissions (LTO)
CAEP6 – 80%

Emissions (cruise)
2005 best – 80%

Energy Consumption
2005 best – 60%
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.
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

LAVA CFD

VORLAX Static & Dynamic FEM / NASTRAN
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

\[
\begin{bmatrix}
M_{rr} & M_{re} & M_{r\delta} & M_{rs} \\
M_{er} & M_{ee} & M_{e\delta} & M_{es} \\
M_{r\delta} & M_{e\delta} & M_{\delta\delta} & M_{\delta s} \\
M_{sr} & M_{se} & M_{s\delta} & M_{ss}
\end{bmatrix}
\begin{bmatrix}
\dot{x}_r \\
\dot{x}_e \\
\dot{x}_{\delta} \\
\dot{x}_s
\end{bmatrix}
=
\begin{bmatrix}
S_{rr} & S_{re} & S_{r\delta} & S_{rs} \\
S_{er} & S_{ee} & S_{e\delta} & S_{es} \\
S_{r\delta} & S_{e\delta} & S_{\delta\delta} & S_{\delta s} \\
S_{sr} & S_{se} & S_{s\delta} & S_{ss}
\end{bmatrix}
\begin{bmatrix}
x_r \\
x_e \\
x_{\delta} \\
x_s
\end{bmatrix}
+
\begin{bmatrix}
T_r \\
T_e \\
T_{\delta} \\
T_s
\end{bmatrix}
\]
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
  \[ \dot{x} = Ax + Bu + w \]
  \[ \begin{cases} \dot{x}_r = A_{rr}x_r + A_{re}x_e + B_r u_r + w_r \\ \dot{x}_e = A_{er}x_r + A_{ee}x_e + B_e u_e + w_e \end{cases} \]

- Output equation for accelerometers
  \[ y = Cx + Du = C_r x_r + C_e x_e + D_r u_r + D_e u_e \]

- Drag model
  \[ \Delta C_D = C_{Dx} x + C_{Du} u + x^\top C_{Dx2} x + x^\top C_{Dxu} u + u^\top C_{Du2} u \]

- Wing root bending moment measurement
  \[ M_y = M_x x + M_u u + M_w w \]
Multi-Objective Optimal Control

- Multi-objective cost function
  \[ J = J_r + J_e \]
  \[ J_r = \lim_{t_f \to \infty} \frac{1}{2} \int_0^{t_f} \left[ (z - r)^\top Q_r (z - r) + u_r^\top R_r u_r \right] dt \]
  \[ J_e = \lim_{t_f \to \infty} \frac{1}{2} \int_0^{t_f} \left( x_e^\top Q_e x_e + u_e^\top R_e u_e + q_D \Delta C_D + M_y^\top q_M M_y \right) dt \]

- Drag minimization and load alleviation multi-objective optimal control
  \[ u = K_x \dot{x} + K_r r + K_w \dot{w} + \Lambda_0 \]
  \[ K_x = -\bar{R}^{-1} \left( B^\top W + \frac{1}{2} q_D C_{Dxu}^\top + q_M M_u^\top M_x \right) \]
  \[ K_r = -\bar{R}^{-1} B^\top V_r \]
  \[ K_w = -\bar{R}^{-1} \left( B^\top V_w + q_M M_u^\top M_w \right) \]
  \[ \Lambda_0 = -\bar{R}^{-1} \left( B^\top V_0 + \frac{1}{2} q_D C_{Du}^\top \right) \]
Adaptive Gust Estimation

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

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

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

- Least-squares gradient adaptive gust estimation

\[
\begin{align*}
\dot{w}_{wr}^T &= -\Gamma_{wr} \frac{\partial J^T}{\partial \hat{w}_r} = -\Gamma_{wr} \left( \varepsilon_r^T + M_{wr} \varepsilon_M^T \right) \\
\dot{w}_{we}^T &= -\Gamma_{we} \frac{\partial J^T}{\partial \hat{w}_e} = -\Gamma_{we} M_{we} \varepsilon_M^T
\end{align*}
\]
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% L/D 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

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

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

\[
\bar{K}_r = \bar{R}^{-1}\bar{B}_p^T\left(\bar{A}^T - WB_p\bar{R}^{-1}\bar{B}_p^T\right)^{-1}WB_m
\]
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

\[
u = \tilde{K}_x \dot{x} + \Delta K_x \hat{x} + K_y (y - \hat{y})
\]

\[
\Delta \dot{K}_x^T = -\Gamma_x \hat{x}^T \left( P - \nu_x \Delta K_x^T B^T P A_m^{-1} \right) B
\]

\[
\dot{K}_y^T = -\Gamma_y (y - \hat{y}) \left[ \dot{x}^T P - \nu_y (y - \hat{y})^T K_y^T B^T P A_m^{-1} \right] B
\]
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 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

- 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