A Framework for Adaptive Aeroelastic Wing Shaping Control

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## Adaptive Aeroelastic Shape Control

### NASA / Industry / Academic Team Acknowledgment

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<th>Boeing Team</th>
<th>University of Washington Team</th>
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<td>David Rodriguez</td>
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Outline

• Introduction

• Adaptive Aeroelastic Shape Control (AASC) Framework

• Variable Camber Continuous Trailing Edge Flap (VCCTEF) Concept

• Overview of Aeroelasticity

• Summary
The Need for Flexible Wing Shaping Control Technology

- Current and future-generation aircraft wing technology is moving toward lightweight, flexible, high aspect ratio wing design

- Wing flexibility can adversely impact aircraft performance, structural integrity, stability and control
  - Increased drag penalty at off-design
  - Increased gust and maneuver loads and reduced flutter margins
  - Ride and handling quality issues

- Adaptive aeroelastic wing shaping control can potentially address these issues
Adaptive Aeroelastic Wing Shaping Control – a Bio-Inspired Concept

• Nature inspires

• Man devises
Wing Shaping Control in Modern Transports

- Trailing Edge Variable Camber (TEVC) in Boeing 787

The next decade in commercial airplane aerodynamics – a Boeing perspective

- Trailing edge variable camber allows
  - Load optimization
  - Cruise drag optimization

- In cruise, trailing edge elements are adjusted at regular intervals to minimize drag
  - Simplified actuation system
  - Small angle variations
  - Up and down movements

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Future Wing Shaping Control Technologies

- Turbulent skin friction reduction
- Advanced transonic wing concepts
- Laminar flow
- Advanced trailing edge device concepts
- Integration of advanced engine concepts
- Relaxed stability
- Advanced variable camber concepts
- Multi-disciplinary optimization
- Active flow control
- Advanced leading edge device concepts

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Adaptive Aeroelastic Shape Control

• Adaptive Aeroelastic Shape Control (AASC) is a research area under Aerodynamic Efficiency sub-project of NASA ARMD Fixed Wing project

• Research objective – Develop wing shaping control technology for flexible wing N+3 transport aircraft for improved aerodynamic efficiency

• Variable Camber Continuous Trailing Edge Flap (VCCTEF)
Wing Shaping Control

- **Section angle of attack**

\[ \alpha_c = \alpha - \gamma - \Theta \cos \Lambda - W_x \sin \Lambda + \frac{\partial \alpha}{\partial \delta} \delta + \left( \frac{\partial \Theta}{\partial \delta} \cos \Lambda + \frac{\partial W_x}{\partial \delta} \sin \Lambda \right) \delta \]

- **Span load can be optimized throughout flight envelope by combined camber control and wing shaping control – mission adaptive wing**
  - Camber control – wing morphing applicable to stiff and flexible wings
  - Aeroelastic wing shaping control – leveraging wing flexibility to change wash-out twist

Fundamental Aeronautics Program
Fixed Wing Project
Adaptive Aeroelastic Shape Control Framework

• MDAO framework for evaluation of future advanced adaptive wing technology concepts

Multi-Fidelity Modeling
• Multi-fidelity aero modeling (Cart3D, OVERFLOW, Panair, Vorview)
• Aeroelastic FEM (in-house FEM, NASTRAN)
• Capabilities to couple aeroelastic FEM with aero codes (Cart3D, Panair, Vorview)
• Flutter analysis

Multi-Disciplinary Optimization
• Aerodynamic optimization for drag reduction (Cart3D, OVERFLOW, Panair, Vorview)
• Multidisciplinary optimization with coupled aeroelasticity (Cart3D, OVERFLOW, Panair, Vorview)

Flight Dynamics
• Dynamics of control actuation
• Dynamic aeroelastic FEM coupled with 6-dof rigid-body flight dynamics

Aeroservoelastic Control
• Aeroservoelastic control (flutter suppression, load alleviation)
• Multi-objective flight dynamics to take advantage of multiple distributed flap system

Control Actuation
• VCCTEF
• Distributed propulsion
• Others (distributed control, active flow control, etc...)

Performance Analysis
• Trajectory optimization to minimize fuel burn
• Mission analysis to quantify fuel efficiency
Platforms

- Older-generation transport, Generic Transport Model (GTM), 2012 – 2015
- N+3 transport, Truss-Braced Wing (TBW), 2014 – 2017 (notional)
- Modern transport, Common Research Model (CRM), TBD

Generic Transport Model

Truss-Braced Wing

Common Research Model
**VCCTEF Development**

- **Development of VCCTEF system concept by NASA and Boeing Research & Technology**

<table>
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<th>Year</th>
<th>Activities</th>
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<td>FY 2010</td>
<td>Initial concept funded by NASA Innovative Partnership Program (IPP)</td>
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<tr>
<td>FY 2011</td>
<td>NASA in-house investigation</td>
</tr>
<tr>
<td>FY 2012</td>
<td>- BR&amp;T VCCTEF installation layout and SMA / EMA actuation</td>
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<td></td>
<td>- NASA and BR&amp;T aeroelastic analysis of stiff wing Generic Transport Model (GTM)</td>
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<td>- Flight control requirements</td>
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<td>FY 2013</td>
<td>- NASA and BR&amp;T aeroelastic analysis of flexible wing GTM</td>
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<td>- NASA and BR&amp;T aeroservoelastic state-space modeling</td>
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<td></td>
<td>- Wind tunnel test of cruise configuration at University of Washington Aeronautical Laboratory (UWAL)</td>
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<td>FY 2014</td>
<td>- NASA and BR&amp;T aeroelastic flutter suppression</td>
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<td>- NASA and BR&amp;T design trade study of VCCTEF</td>
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<td></td>
<td>- UWAL wind tunnel test of high-lift configuration</td>
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NASA VCCTEF Development

- **Initial NASA concept developed in 2010**
  - Elastic wing shapes
  - Wing shaping control
  - VCCTEF
  - Continuous LE slat

Boeing VCCTEF Development

- Boeing Research & Technology concept developed in 2012

**FINAL 54 INCH EQUAL CHORD FLAP SECTIONS:**
- TWIST SECTIONS WITH 8" SKIN SEPARATOR SECTIONS
- MAIN FLAP - 3 SECTIONS 75" WIDTH – NO TWIST

75 Inch Main Flap Actuation Panel Includes –
- Linear Extend Actuator (1-2)
- Shaped Memory Alloy Actuators (4)
- Elector-Mechanical Actuators (2)

Twist Flap Motion:
- Not Extensible – No Air Gap
- Three Sections of Camber

Electrical Power & Control Wiring - Both Sides of MF

SMA and EMA Hinge Line Actuation

Conformal Mold Line Material

VCCTEF Development
Wind Tunnel Test

- Wind tunnel test was conducted in University of Washington Aeronautical Laboratory (UWAL) in August 2013

- Flexible wing model of 10% scale of full-scale B757 wing with 5 spanwise VCCTEF flap segments

- Wing stiffness tailored to achieve 10% wing tip deflection (similar to B787)
Jig Shape Twist Optimization

- Wind tunnel model has original B757 jig shape twist which is non-optimal for two-fold increase in flexibility

- Twist optimization conducted by Cart3D, but optimized twist was not incorporated in final construction

Optimized twist recovers 11 drag counts vs. 14 drag counts for non-optimal twist
UWAL Test of Cruise Configuration

Figure 5: VCCTEF wind tunnel model installed in UWAL test section
UWAL Test of Cruise Configuration

Flaps Fully Deflected  Alpha: 3°  Q = 20 psf
UWAL Wind Tunnel Test – Lift Curve

Cₜ 0.51

2.63 4.20 4.70
The fully deployed configuration effectively re-optimizes span load to correct for non-optimal jig shape twist.
High-Lift Wind Tunnel Test Plan

- Inboard slotted flap with Fowler motion and variable camber Krueger (VCK) leading edge device

- Test scheduled to take place in June 2014
Aeroelasticity

- Multi-fidelity aeroelastic modeling capabilities enable aerodynamic performance prediction and stability and control of flexible wing transports

- Coupled FEM with potential flow solvers
  - Static aeroelasticity
  - Dynamic aeroelasticity and flutter analysis
  - Coupled 6-dof flight dynamics
Static Aeroelasticity

- Static aeroelasticity by Cart3D CFD coupled with structural analysis code using Blender
Aeroelastic Trim Solution

- Vortex-lattice trim solution method

Outputs:
- \( \bar{a} \), trim angle of attack
- \( \bar{\delta}_e \), trim elevator deflection
- \( \bar{T} \), trim engine thrust
- \( \bar{\theta} \), wing aeroelastic twist, about elastic axis
- \( \bar{W} \), wing aeroelastic flapwise bending
- \( \bar{V} \), wing aeroelastic chordwise bending
Aeroelastic Trim Solution

Aerodynamic Performance Prediction

- Cart3D prediction of UWAL wind tunnel model lift coefficient is in excellent agreement with wind tunnel test data

![Graphs showing lift coefficient vs. angle of attack and normal deflection vs. distance along elastic axis.]

Thrust-Induced Aeroelasticity

- FEM includes capability for thrust-induced aeroelasticity

\[
f^L_z = \delta (x - x_e) \left[ (T \sin \Lambda + m_{eg} \Gamma) W_x + T \cos \Lambda (\Theta + \gamma) + T \sin \Lambda \Gamma - m_{eL} \right]
\]

\[
m^L_x = \delta (x - x_e) \left[ -T y_e \sin \Lambda \Gamma - T z_e \cos \Lambda + m_{eg} y_e + (-T x_e \Gamma + m_{eg} x_e + T z_e \sin \Lambda + m_{eg} z_e \Gamma) V_x 
- (T x_e \cos \Lambda + T y_e \sin \Lambda + m_{eg} y_e \Gamma) W_x \right]
\]
Thrust-Induced Lift

- Wing flexibility causes lift changes resulting from wing twist due to thrust forces produced by wing-mounted engines
Dynamic Aeroelasticity

- Dynamic aeroelasticity deals with interactions of structural dynamics with unsteady aerodynamics and rigid-body aircraft flight dynamics.

- NASTRAN doublet-lattice method is widely used in aircraft industry
  - Theory developed by Albano and Rodden (1969)
  - FEM coupled with doublet potential flow solution

- CFD methods provide high-fidelity aeroelastic prediction that can handle viscous-dominated flow fields, transonic flow with shock-induced separation, and separated flow
  - CFD unsteady aerodynamic analysis computes generalized aerodynamic forces from structural dynamic mode shapes (e.g., FUN3D, Bartels and Silva, NASA LaRC)
  - Aerodynamic mass, damping, and stiffness matrices are obtained for flutter and forced response analysis
Dynamic Aeroelasticity

- **Current approach is based on coupling potential flow solvers to FEM**
  - Steady aerodynamic analysis using vortex-lattice and panel methods (CFD can be added later on)
  - Unsteady aerodynamic corrections are implemented directly in FEM using Theodorsen function for 2-D unsteady doublet potential flow
  - Coupling to FEM provides capabilities for future nonlinear aeroelasticity
Downwash Analysis

- **Unsteady downwash due to deflections**

\[
\frac{w(x, y, z)}{V_\infty \cos \Lambda} = \alpha_c(x, y, z) = \alpha_r(x) + \alpha_e(x, y, z)
\]

- Sensitivities are functions of deflections and aircraft states

\[
\alpha_e(x, y, z) = \frac{\partial \alpha_c}{\partial W_x} W_x + \frac{\partial \alpha_c}{\partial V_x} V_x + \frac{\partial \alpha_c}{\partial \Theta} \Theta + \frac{\partial \alpha_c}{\partial W_x \Theta} W_x \Theta + \frac{\partial \alpha_c}{\partial V_x \Theta} V_x \Theta + \frac{\partial \alpha_c}{\partial W_t} W_t + \frac{\partial \alpha_c}{\partial V_t} V_t + \frac{\partial \alpha_c}{\partial \Theta_t} \Theta_t + \ldots
\]

- Camber change from unsteady downwash due to control surface deflections

\[
\frac{dz}{dx'} = -\frac{w_i}{V_\infty \cos \lambda} = -\sum_{j=1}^{i} \delta_j - \sum_{j=1}^{i} \frac{(x' - x'_f)}{V_\infty \cos \lambda} \dot{\delta}_j
\]
Unsteady Lift

- **Circulatory lift from potential flow theory**
  \[ c_{L_{ac}} = c_{L_{ac}}(x, -e, 0) \cos \Lambda + \sum_{i=1}^{n} \Delta c_{Li} \cos \lambda \]
  \[ \Delta c_{Li} = \frac{c_{L_{ac}}}{\pi} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \frac{dz}{dx'} f(\theta) \, d\theta = \frac{c_{L_{ac}}}{\pi} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \left[ -\sum_{j=1}^{i} \delta_{j} - \sum_{j=1}^{i} \frac{(x' - x'_{f_j})}{V_{\infty} \cos \lambda} \dot{\delta}_{j} \right] (\cos \theta - 1) \, d\theta \]

- **Non-circulatory lift due to apparent mass**
  \[ c_{L_{c/2}} = \frac{\pi \alpha_{c}}{2V_{\infty}} \left( x_{c/2}, 0 \right) \cos \Lambda + \sum_{i=1}^{n} \Delta c_{Li}^{*} \cos \lambda \]
  \[ \Delta c_{Li}^{*} = -\frac{c'}{V_{\infty} \cos \lambda} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \frac{d}{dt} \left( \frac{dz}{dy} \right) g(\theta) \, d\theta = \frac{c'}{V_{\infty} \cos \lambda} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \left[ \sum_{j=1}^{i} \delta_{j} + \sum_{j=1}^{i} \frac{(x' - x'_{f_j})}{V_{\infty} \cos \lambda} \ddot{\delta}_{j} \right] \sin^2 \theta \, d\theta \]

- **Total unsteady lift with Theodorsen unsteady aerodynamic corrections**
  \[ c_L(k) = C(k) c_{L_{ac}} + c_{L_{c/2}} \]
  \[ C(k) = F(k) + iG(k) \]
  \[ k = \frac{\omega c}{2V_{\infty}} \]

- **Corrections to potential flow theory can be made using CFD for viscous flow**
Finite-Element Method

- Structural dynamic FEM includes aerodynamic mass, damping, and stiffness matrices

\[
\begin{align*}
[M_i + C_i^k \frac{\bar{c}_i}{2V_\infty} \frac{G(k)}{k}] \ddot{x}_i + \left[ C_i^k F(k) + K_i^k \frac{\bar{c}_i}{2V_\infty} \frac{G(k)}{k} \right] \dot{x}_i + \left[ K_i + K_i^k F(k) \right] x_i &= F_i \left( \dot{x}_r, x_r, \delta, \dot{\delta}, \ddot{\delta} \right)
\end{align*}
\]

- Aerodynamic Mass
- Aerodynamic Damping
- Aerodynamic Stiffness

- Unsteady aerodynamic approximation by R. T. Jones method
  - Reduced-frequency dependent form is valid only at the frequency of oscillation – not useful for flight dynamics and control over a frequency range
  - Unsteady aerodynamics approximated by adding unsteady aerodynamic states
  - R. T. Jones method is alternative to Roger Rational Fraction Approximation method

\[
C(k) \approx \tilde{C}(\tilde{s}) = \frac{0.5\tilde{s}^2 + a_1\tilde{s} + a_2}{\tilde{s}^2 + a_3\tilde{s} + a_2}
\]

\[
M_i \dddot{x}_i + \left( C_i + 0.5C_i^k \right) \dot{x}_i + \left( K_i + 0.5K_i^k + \frac{2V_\infty a_4}{c} C_i^k \right) x_i + C_i y_i + K_i z_i = F_i \left( x_r, \dot{x}_r, \delta \right)
\]

\[
\begin{align*}
\left( \frac{\bar{c}_i}{2V_\infty} \right)^2 \dddot{y}_i + a_3 \left( \frac{\bar{c}_i}{2V_\infty} \right) \dot{y}_i + a_2 \dot{y}_i &= a_5 \left( \frac{\bar{c}_i}{2V_\infty} \right) \dot{x}_i + a_6 x_i \\
\left( \frac{\bar{c}_i}{2V_\infty} \right)^2 \dddot{z}_i + a_3 \left( \frac{\bar{c}_i}{2V_\infty} \right) \dot{z}_i + a_2 \dot{z}_i &= a_4 \left( \frac{\bar{c}_i}{2V_\infty} \right) \dot{x}_i + 0.5a_2 x_i
\end{align*}
\]
Flutter Analysis

- Flutter analysis computes flutter speed at the onset of aeroelastic instability (i.e., total damping becomes zero)

- Iterative process with aeroelastic trim solution in between iterations
Flexible Wing GTM

• GTM wing is relatively stiff with about 5% wing tip deflection, similar to B757 wing deflection

• To enable effective aeroelastic wing shaping control, a flexible wing GTM with 50% reduced stiffness and 20% wing mass reduction is proposed

• Wing tip deflection for flexible wing GTM is about 10%, similar to B787
Frequency Prediction

Stiff Wing

Flexible Wing

Fundamental Aeronautics Program
Fixed Wing Project
Aerodynamic Damping Prediction

**Stiff Wing**

GTM 80% Fuel Anti-Symmetric Aerodynamic Damping vs. Mach @ 35K ft

**Flexible Wing**

ESAC 80% Fuel Anti-Symmetric Mode Aerodynamic Damping vs. Mach @ 35K ft

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<tr>
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<th>Symmetric Mode</th>
<th>Anti-Symmetric Mode</th>
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<tbody>
<tr>
<td>GTM Flutter Mach @ 35K ft</td>
<td>1.358</td>
<td>1.310</td>
</tr>
<tr>
<td>GTM Flutter Frequency @ 35K ft, Hz</td>
<td>4.31</td>
<td>3.87</td>
</tr>
<tr>
<td>ESAC Flutter Mach @ 35K ft</td>
<td>0.938</td>
<td>0.925</td>
</tr>
<tr>
<td>ESAC Flutter Frequency @ 35K ft, Hz</td>
<td>6.94</td>
<td>2.85</td>
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NASTRAN predicts anti-symmetric flutter mode at Mach 0.954, a 3% difference

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Flutter Boundary

• FAA flutter clearance requires 15% - 20% over dive speed

• Flutter boundary is sensitive to torsional stiffness

• Multi-disciplinary optimization can be used to determine optimal wing design that can achieve a balance between weight, drag, and stiffness
A Note on Nonlinear Aeroelasticity

• Nonlinear aeroelasticity is due to deflection and aircraft state dependency

• Aerodynamic damping can increase with deflection amplitude, which results in a higher flutter speed than linear analysis

• Limit cycle oscillation (LCO) occurs when neutral stability is reached
Loads and Flight Dynamics

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

- Active gust load alleviation control system, called “smoother ride technology”, is implemented in B787.

- Coupling with rigid-body flight dynamics provides combined vehicle dynamic and maneuver load response characteristics.
Coupling with Flight Dynamics

- Aeroelastic deflections contribute to unsteady aerodynamic coefficients
  - Symmetric modes coupled to longitudinal motion
    \[ C_m(k) = C_{m_0} + C_{m_x} x_r + C_{m_{\dot{x}}} \dot{x}_r + \sum_{i=1}^{n} \left( C_{m_{\dot{x}_i}} \dot{x}_i^s + C_{m_x} \dot{x}_i^s + C_{m_{\dot{x}_i}}^k C(k) \dot{x}_i^s + C_{m_{x_i}}^k C(k) x_i^s \right) + C_{m_s} \delta + C_{m_{\dot{\delta}}} \dot{\delta} + C_{m_{\ddot{\delta}}} \ddot{\delta} + C_{m_{\epsilon}} \epsilon \]
  - Anti-symmetric modes coupled to lateral-directional motion
    \[ C_i(k) = C_{l_{x_r}} x_r + \sum_{i=1}^{n} \left( C_{l_{\dot{x}_i}} \dot{x}_i^a + C_{l_{x_i}} \dot{x}_i^a + C_{l_{\dot{x}_i}}^k C(k) \dot{x}_i^a + C_{l_{x_i}}^k C(k) x_i^a \right) + C_{l_{\delta}} \delta + C_{l_{\dot{\delta}}} \dot{\delta} + C_{m_{\epsilon}} \epsilon \]

- Generalized elastic forces are due to aerodynamics as well as aircraft rates and accelerations
  \[ \Phi^T M(k) \Phi \dot{\eta} + \Phi^T C_{\alpha} (k) \Phi \dot{\eta} + \Phi^T K (k) \Phi \eta = \Phi^T F \left( \dot{x}_r, x_r, \delta, \dot{\delta}, \ddot{\delta} \right) \]
Coupled Aircraft Flutter Analysis

Eigenvalues

Flutter Analysis of Coupled Aircraft

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<th>Anti-Symmetric Mode</th>
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<td>Uncoupled GTM Flutter Mach @ 35K ft</td>
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<td>Uncoupled GTM Flutter Frequency @ 35K ft, Hz</td>
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<td>Uncoupled ESAC Flutter Frequency @ 35K ft, Hz</td>
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<tr>
<td>Coupled ESAC Flutter Mach @ 35K ft</td>
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<td>Coupled ESAC Flutter Frequency @ 35K ft, Hz</td>
<td>6.93</td>
<td>2.89</td>
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Coupled Aircraft Rigid Body Responses

Longitudinal Response due to Half-Sine VCCTEF Symmetric Input

Lateral-Directional Response due to Half-Sine VCCTEF Anti-Symmetric Input

Next Steps

• Conduct multi-disciplinary optimization of VCCTEF using aerodynamic codes Cart3D, Vorview, Panair

• Transition AASC work to TBW configuration

• Continue development of AASC frame work to incorporate additional capabilities
  – Coupling Panair and Cart3D to FEM
  – High-lift aeroelastic analysis
  – Gust and maneuver load response models
  – Integrated coupled aircraft flight dynamics
  – Nonlinear aeroelasticity

• Develop aeroservoelastic control methods and multi-objective flight control to leverage multiple control surfaces of VCCTEF
  – ASE gust load alleviation and flutter suppression
  – Drag minimization flight control for cruise and maneuvers
Summary

• A framework for adaptive aeroelastic wing shaping control has been presented

• Multi-disciplinary methods and tools are being developed to enable evaluation of future advanced adaptive wing technology

• Validation of these methods will be important and will require experimental capabilities

• The variable camber continuous trailing edge is a concept being developed as an embodiment of adaptive aeroelastic wing shaping control

• Future research will investigate wing shaping control concepts for N+3 aircraft configurations using the current framework
Acknowledgment

• NASA ARMD and Fixed Wing Project for funding support

• Boeing Research & Technology, Boeing Commercial Airplanes, and University of Washington for collaboration with NASA on the development of the variable camber continuous trailing edge concept

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Thank You