National Aeronautics and Space Administration

A Framework for Adaptive Aeroelastic Wing Shaping Control

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Adaptive Aeroelastic Shape Control
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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

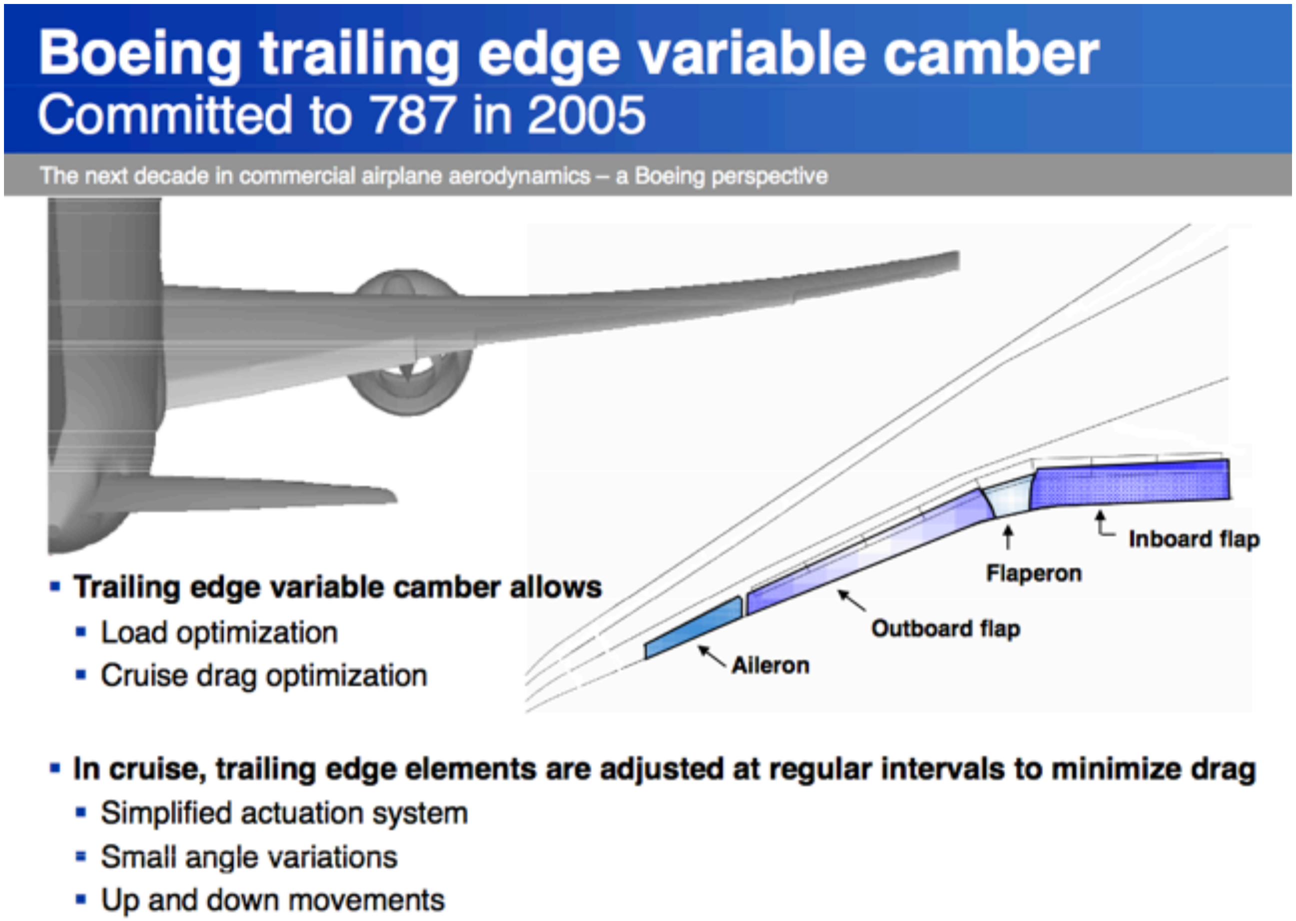
- **Adaptive aeroelastic wing shaping control can potentially address these issues**

Adaptive Aeroelastic Wing Shaping Control – a Bio-Inspired Concept

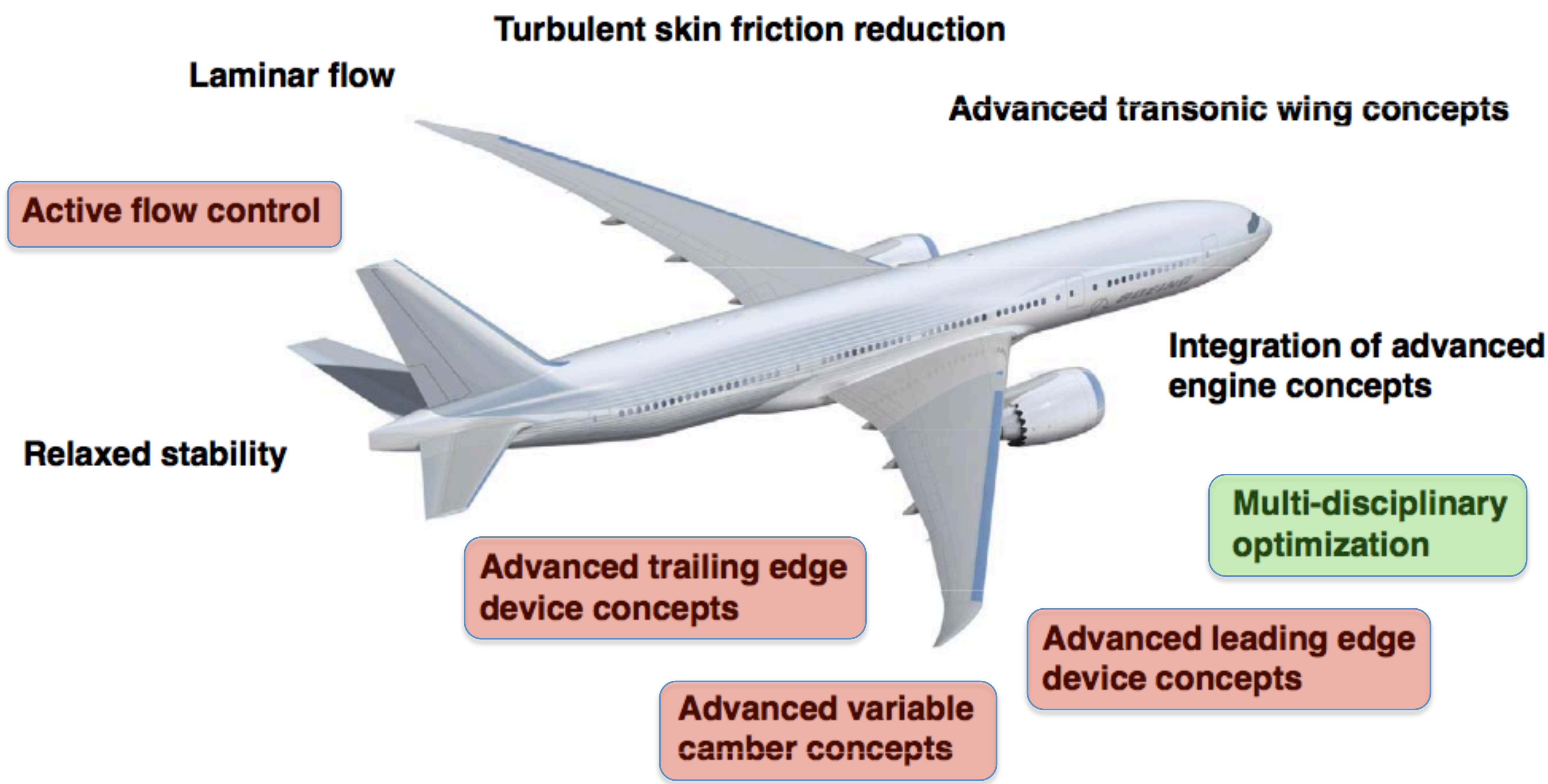
- **Nature inspires**
- **Man devises**

Wing Shaping Control in Modern Transports

- **Trailing Edge Variable Camber (TEVC) in Boeing 787**

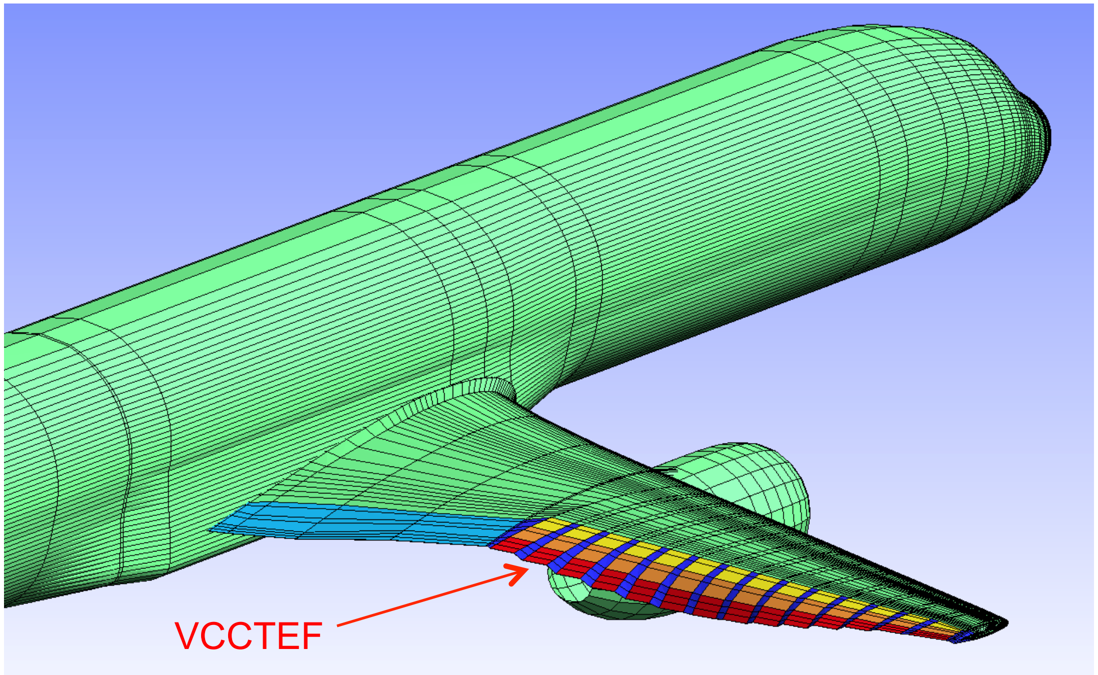


Future Wing Shaping Control Technologies



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**

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

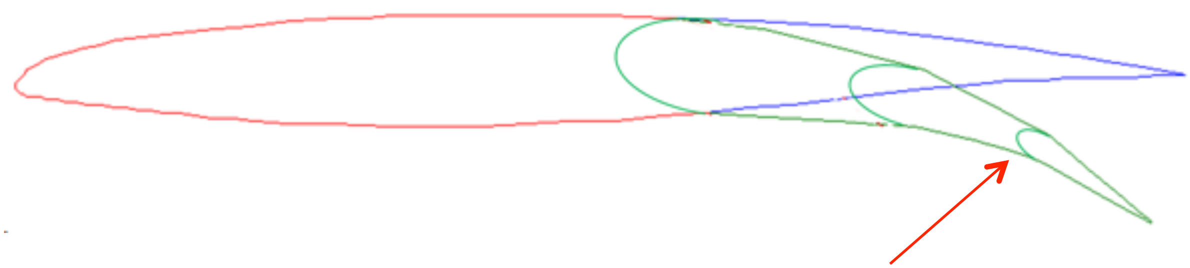
Aircraft AoA

Jig Shape Twist

Wing Deflection (Twist and Bending)

Wing Shaping Control

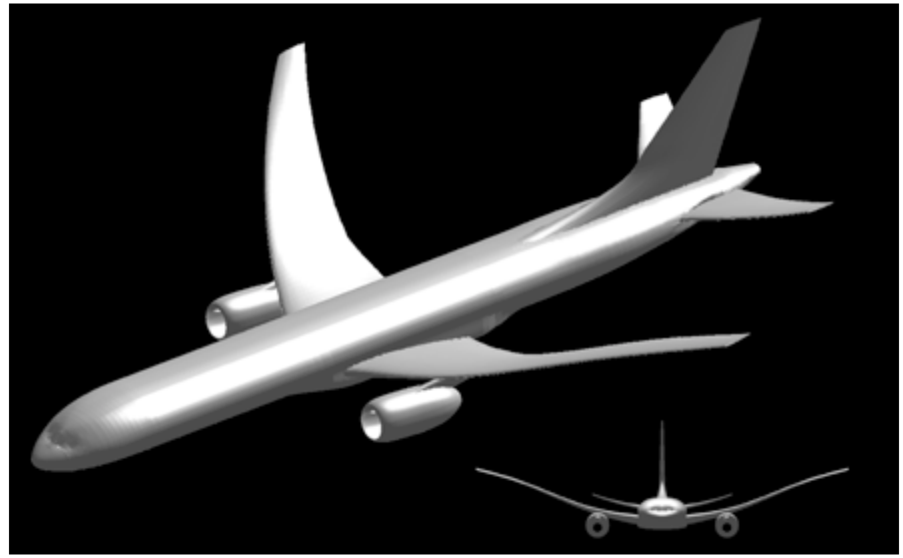
TE Camber Control



- **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

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

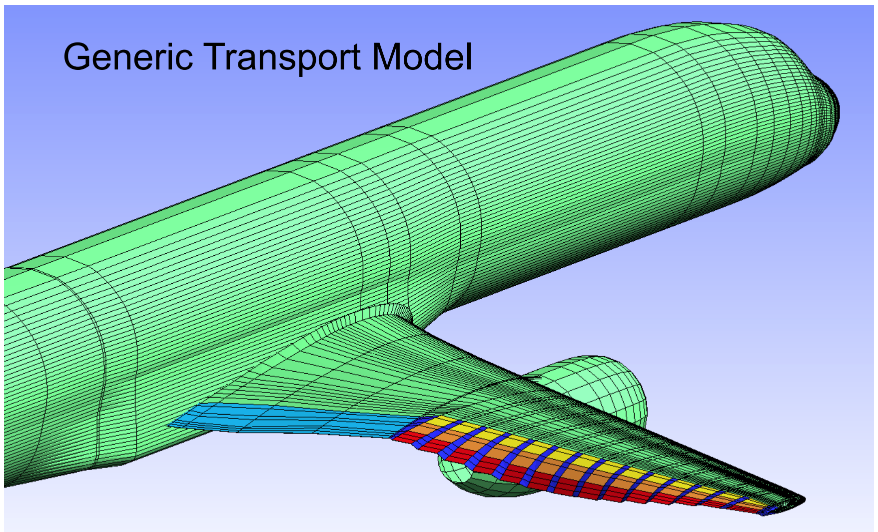
Aeroservoelastic Control
- Aeroservoelastic control (flutter suppression, load alleviation)
- Multi-objective flight dynamics to take advantage of multiple distributed flap system

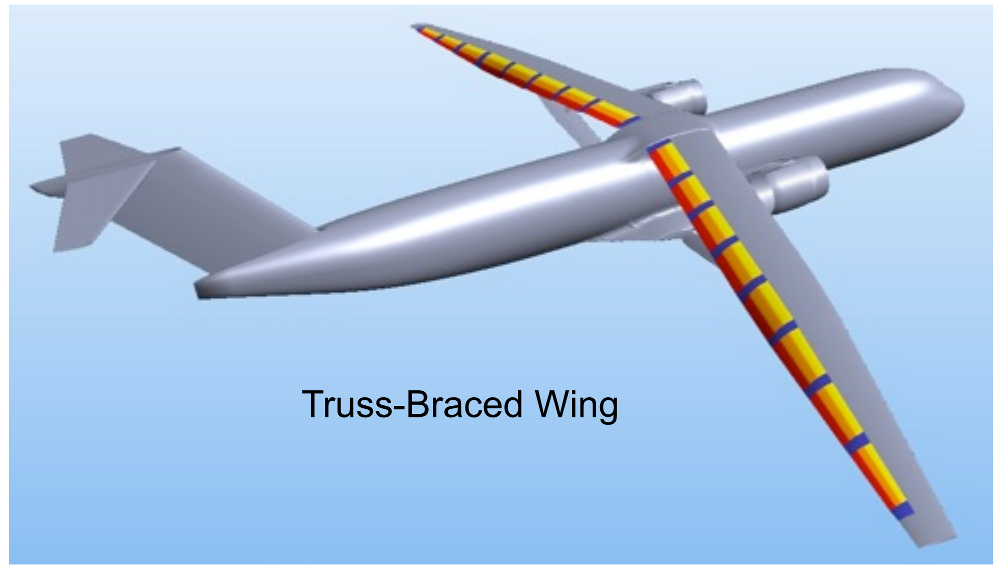
Control Actuation
- VCCTEF
- Distributed propulsion
- Others (distributed control, active flow control, etc…)

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

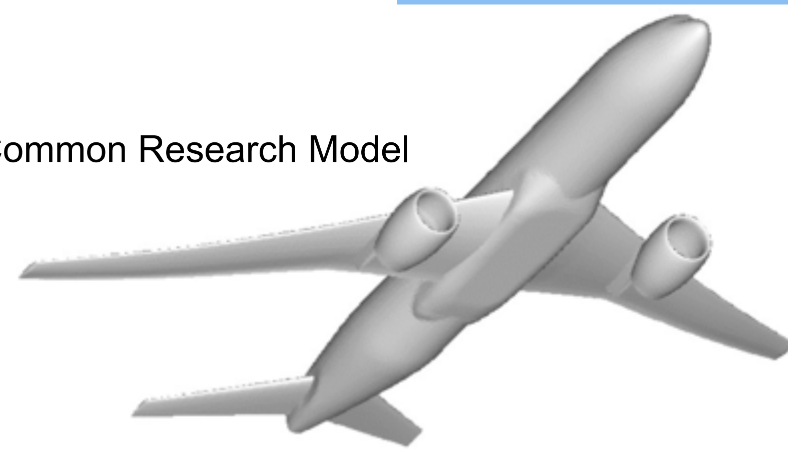
Platforms

- **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**





Common Research Model



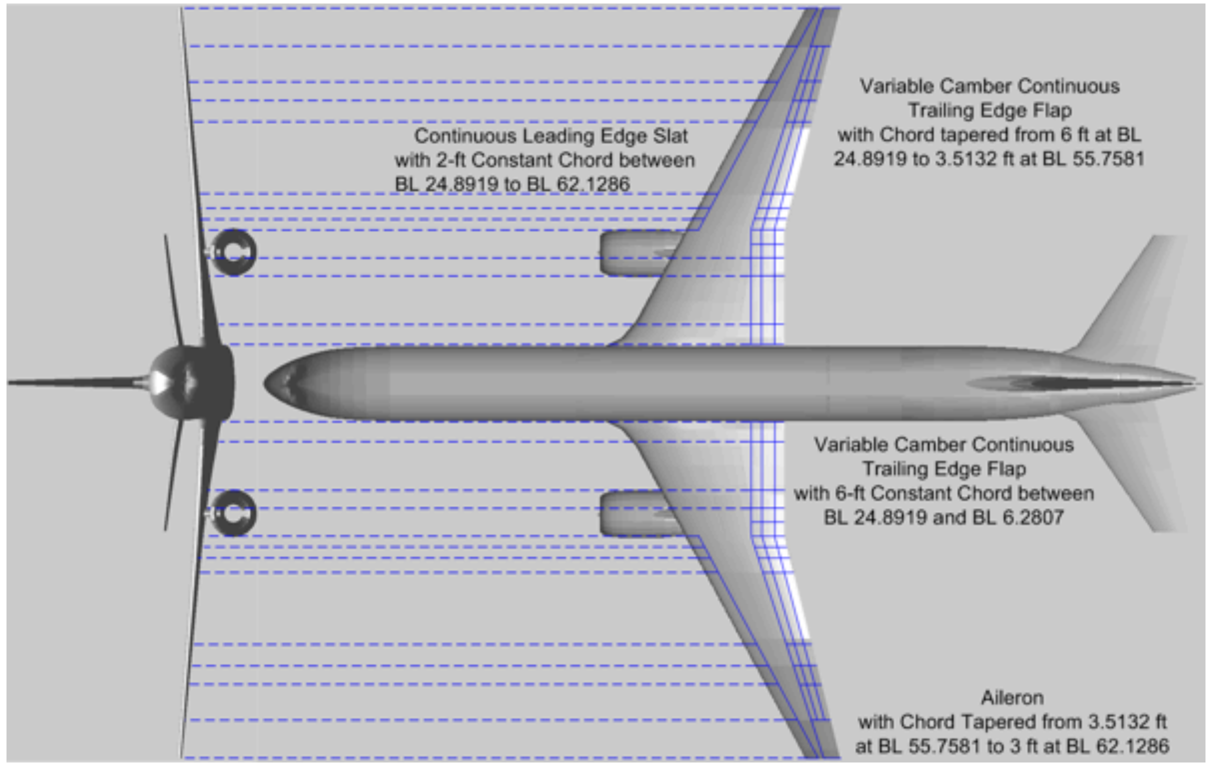
VCCTEF Development

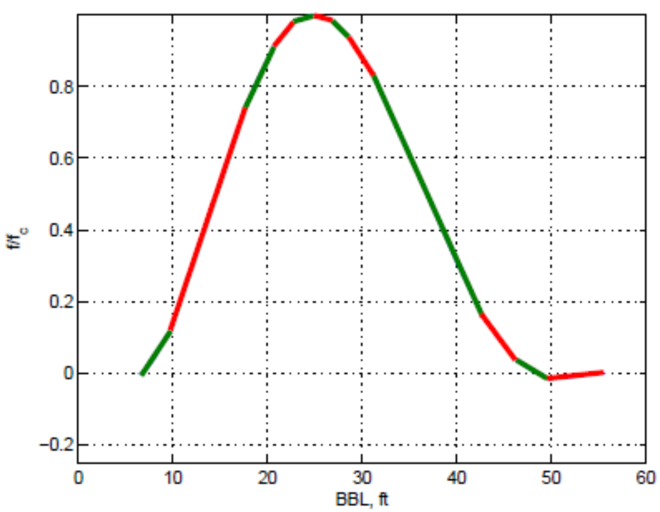
- **Development of VCCTEF system concept by NASA and Boeing Research & Technology**

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

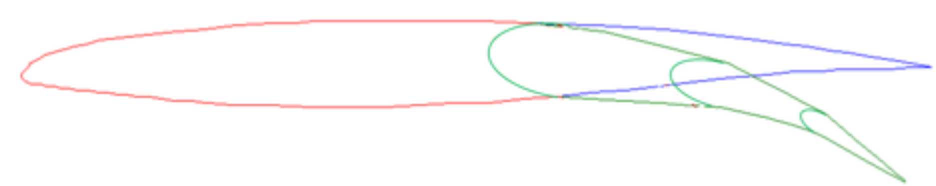
NASA VCCTEF Development

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





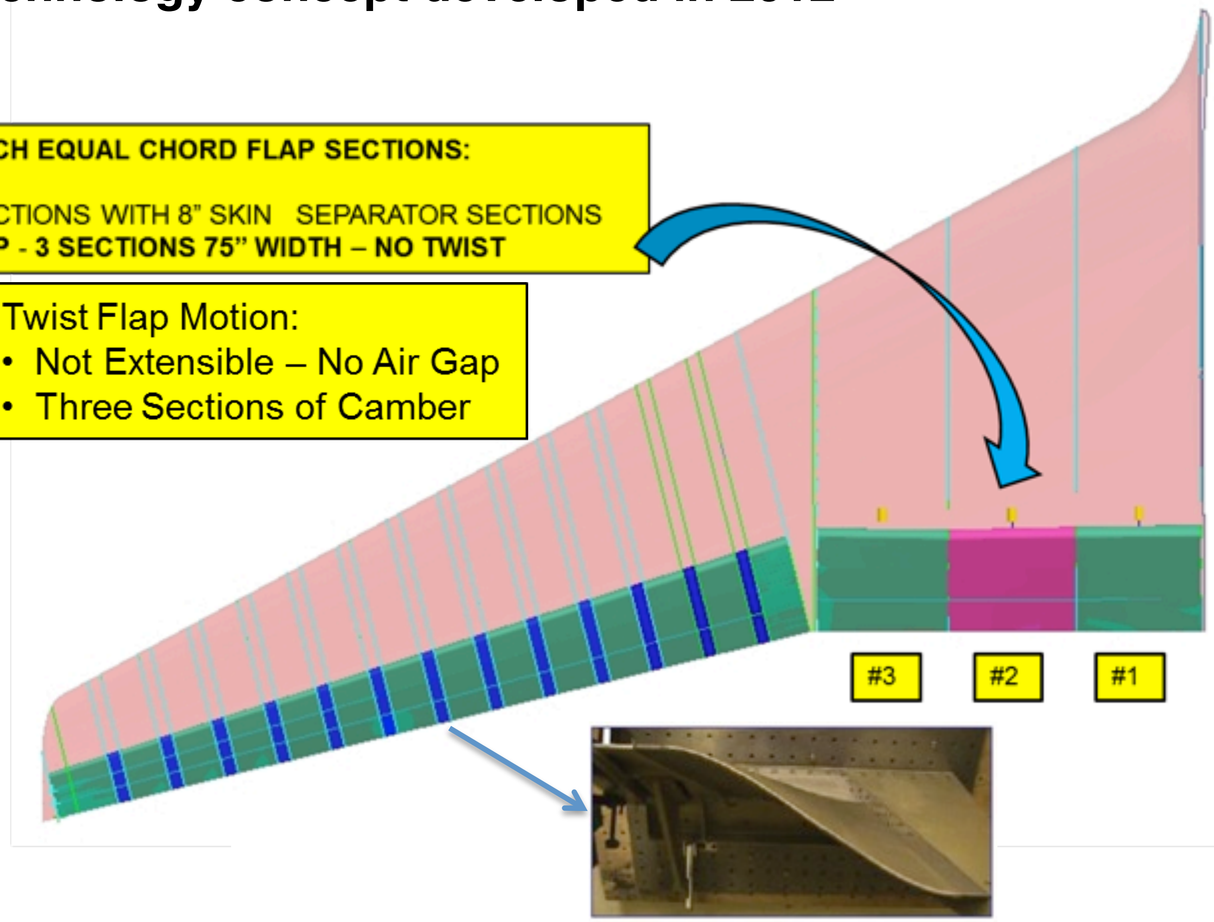
Continuous Flap Deflection

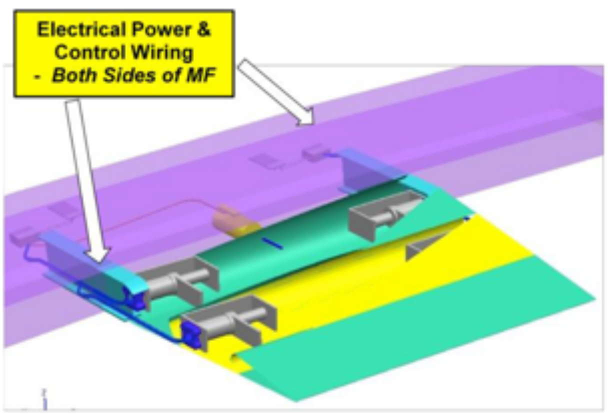


Nguyen, N., "Elastically Shaped Future Air Vehicle Concept," NASA Innovation Fund Award 2010 Report, October 2010, submitted to NASA Innovative Partnerships Program

Boeing VCCTEF Development

- **Boeing Research & Technology concept developed in 2012**



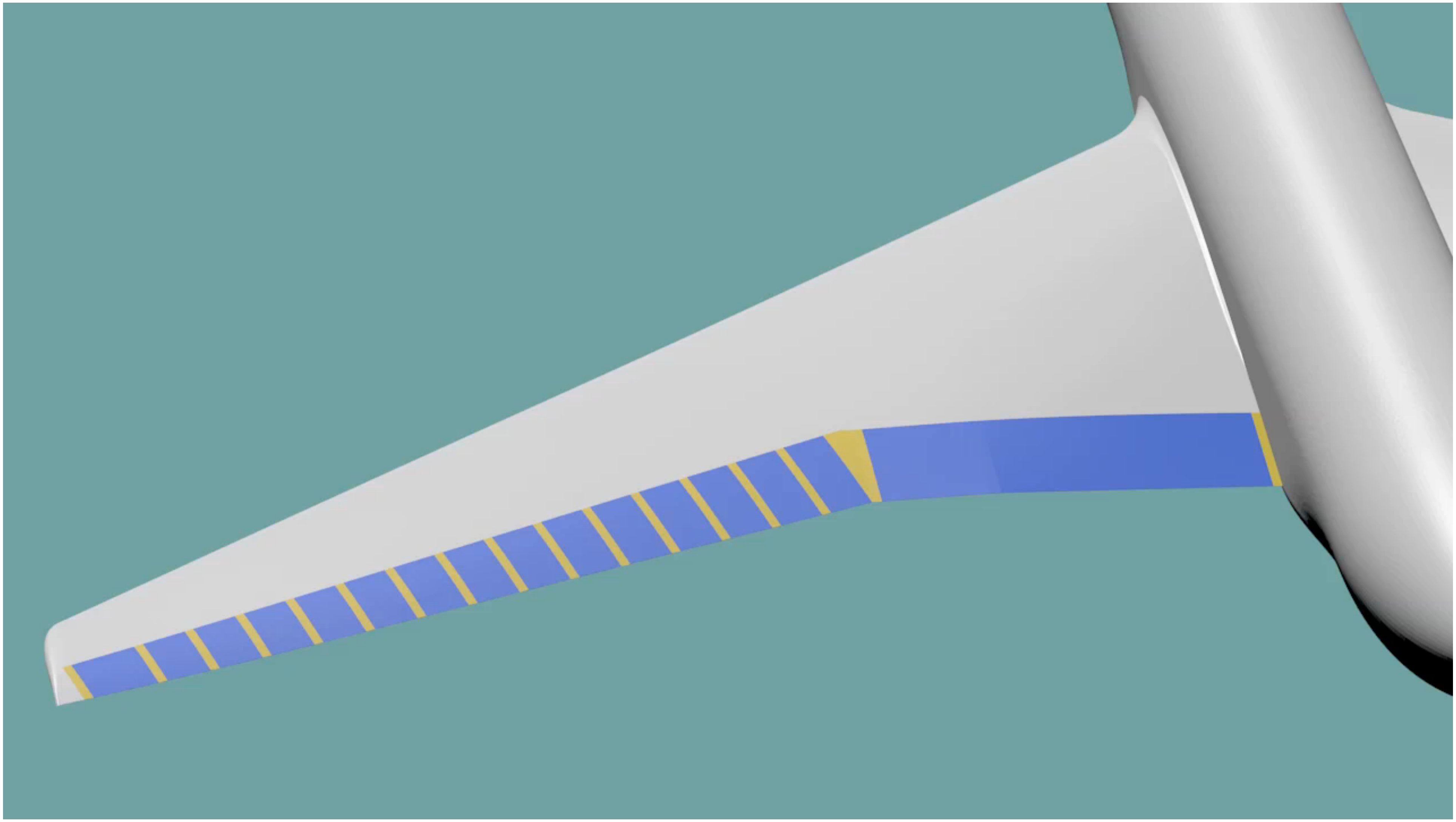


SMA and EMA Hinge Line Actuation

Conformal Mold Line Material

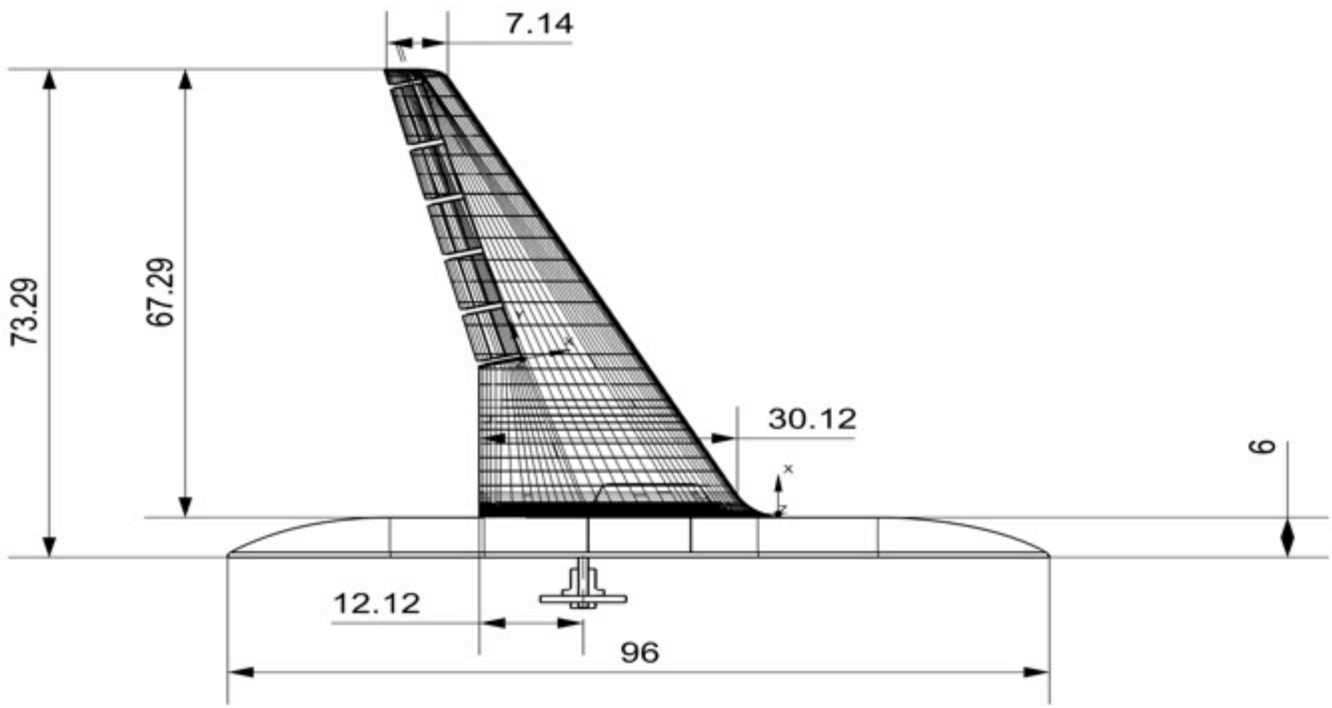
Urnes, J., Nguyen, N., Ippolito, C., Totah, J., Trinh, K., and Ting, E., "A Mission Adaptive Variable Camber Flap Control System to Optimize High Lift and Cruise Lift to Drag Ratios of Future N+3 Transport Aircraft," AIAA Aerospace Sciences Meeting, AIAA-2013-0214, January 2013

VCCTEF Development



Wind Tunnel Test

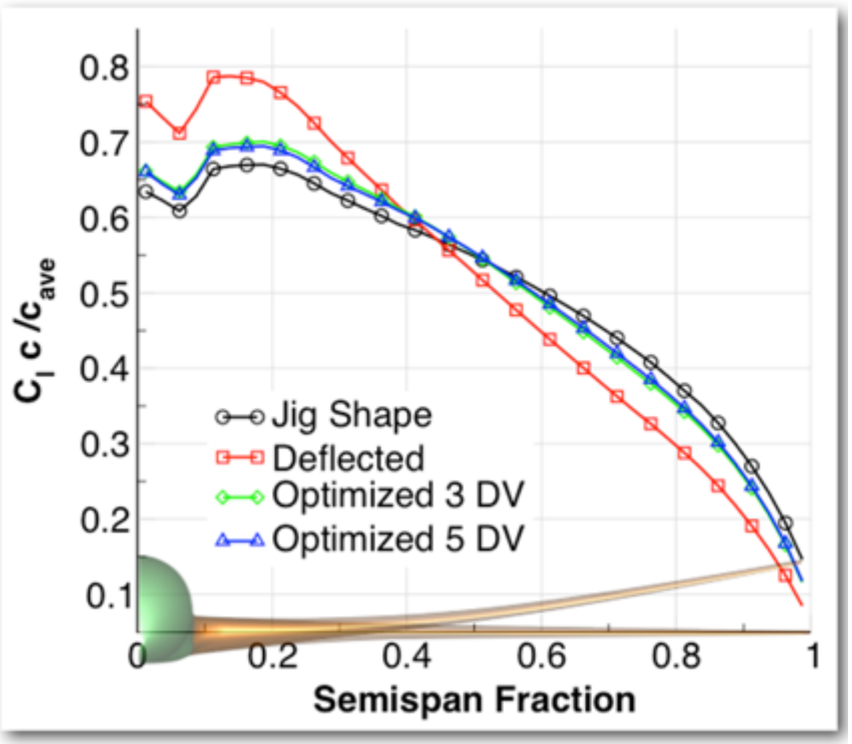
- **Wind tunnel test was conducted in University of Washington Aeronautical Laboratory (UWAL) in August 2013**
- **Flexible wing model of 10% scale of full-scale B757 wing with 5 spanwise VCCTEF flap segments**
- **Wing stiffness tailored to achieve 10% wing tip deflection (similar to B787)**



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**



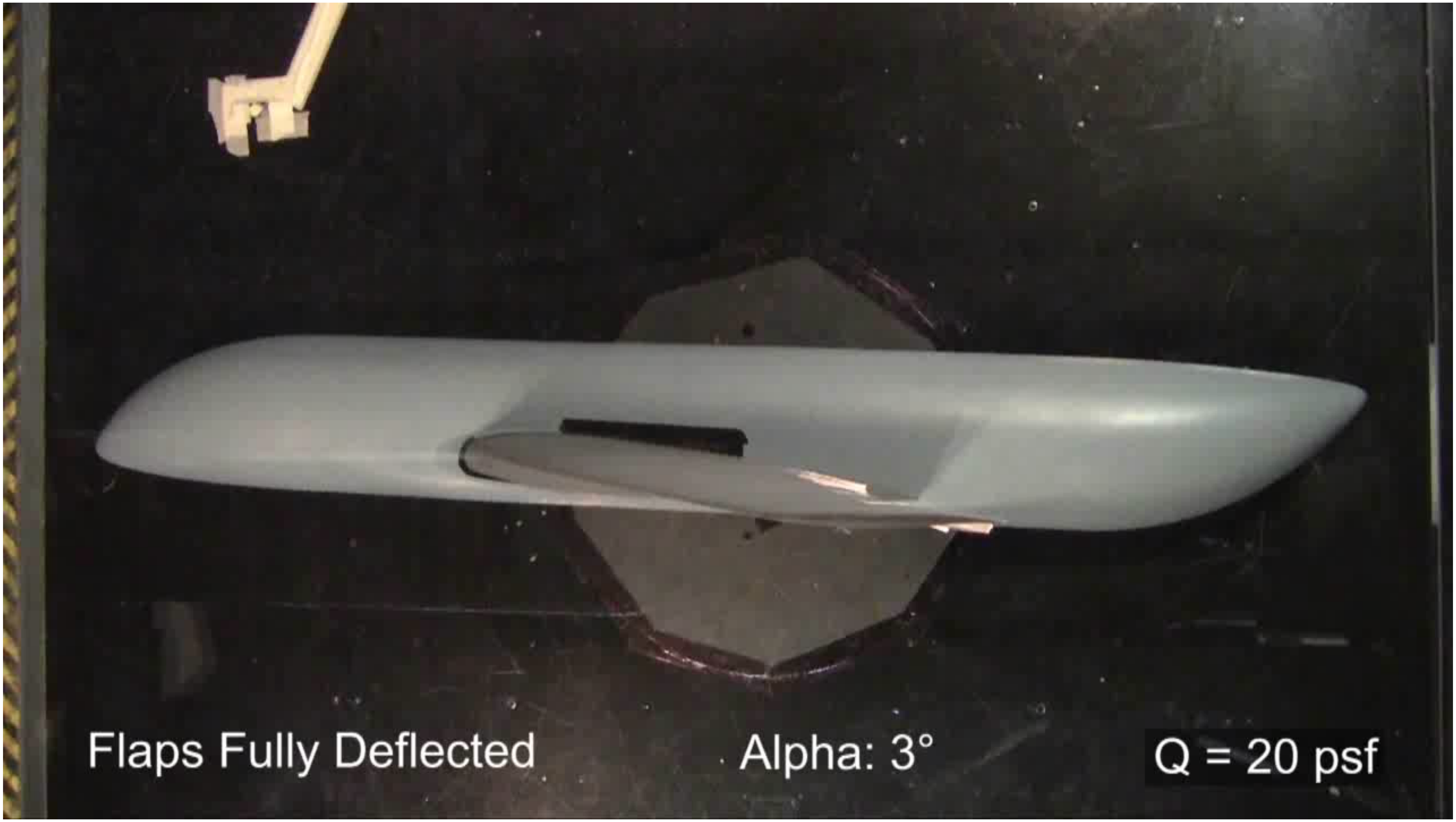
Configuration	C_D (counts)	Angle of Attack
Jig-Shape	112.2	2.844
Deflected	126.5	4.585
Optimized - 3 DV	116.1	2.887
Optimized - 5 DV	115.5	2.918

Optimized twist recovers 11 drag counts vs. 14 drag counts for non-optimal twist

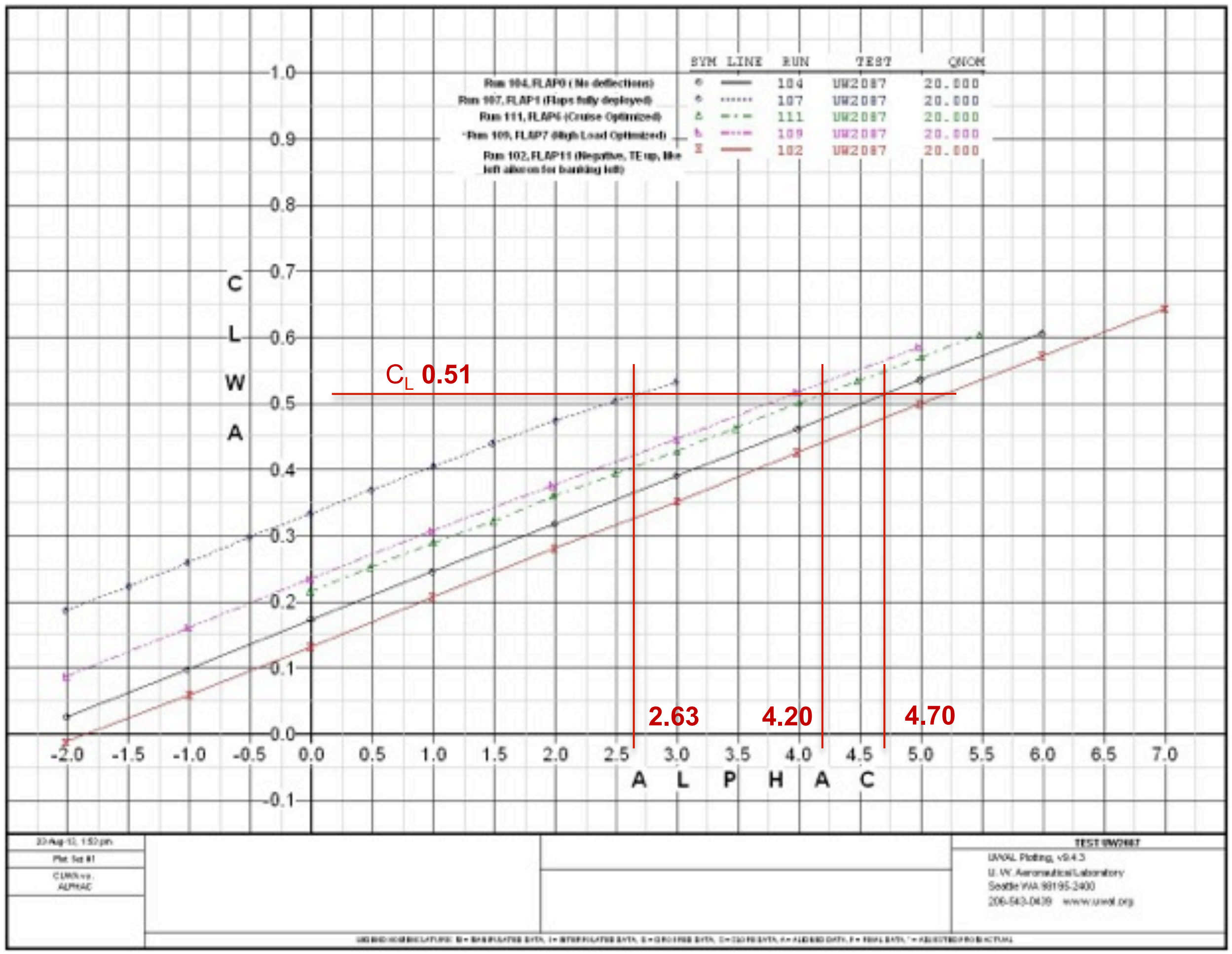
UWAL Test of Cruise Configuration

Figure 5: VCCTEF wind tunnel model installed in UWAL test section

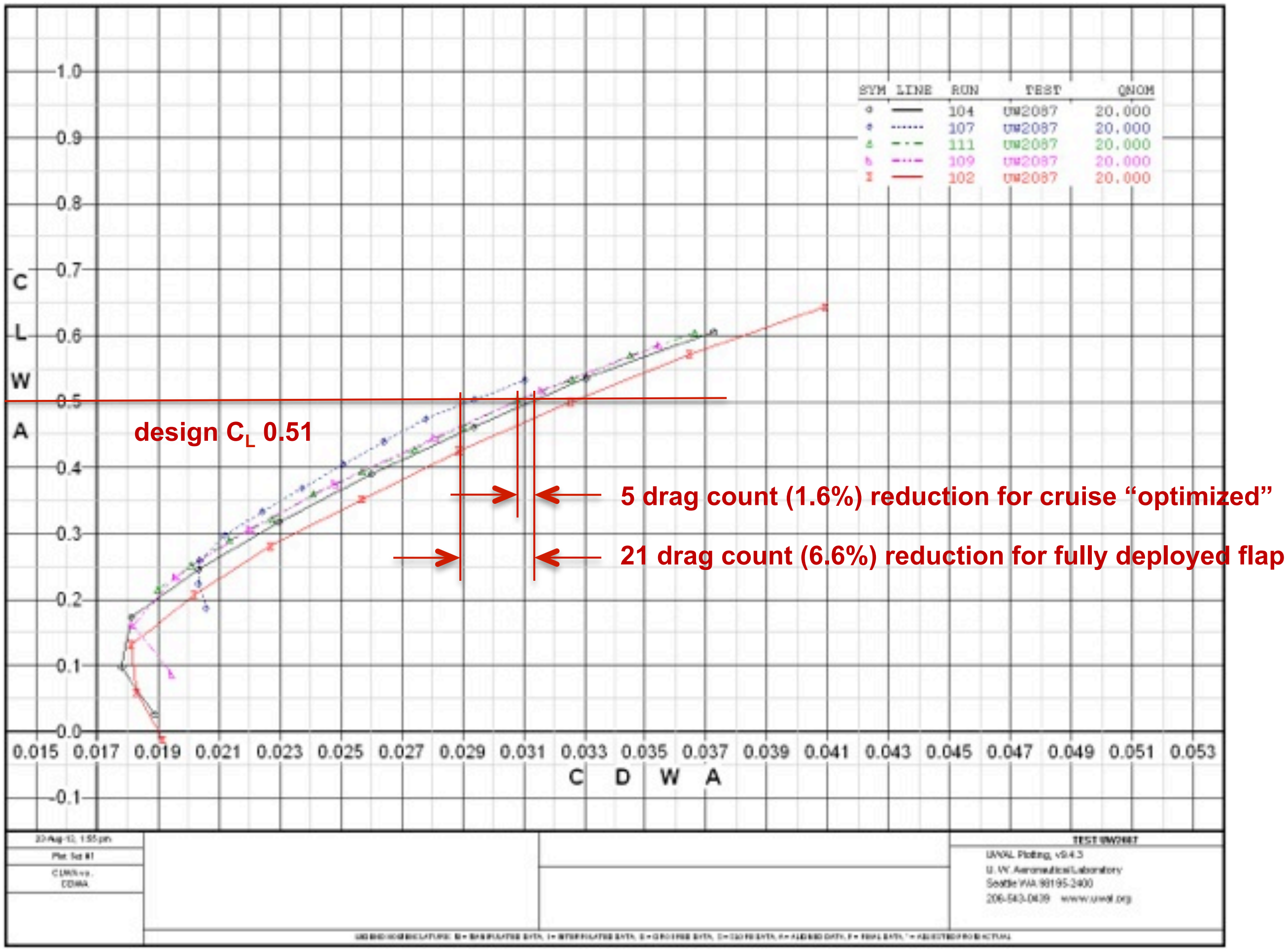
UWAL Test of Cruise Configuration



UWAL Wind Tunnel Test – Lift Curve



UWAL Wind Tunnel Test – Drag Polar

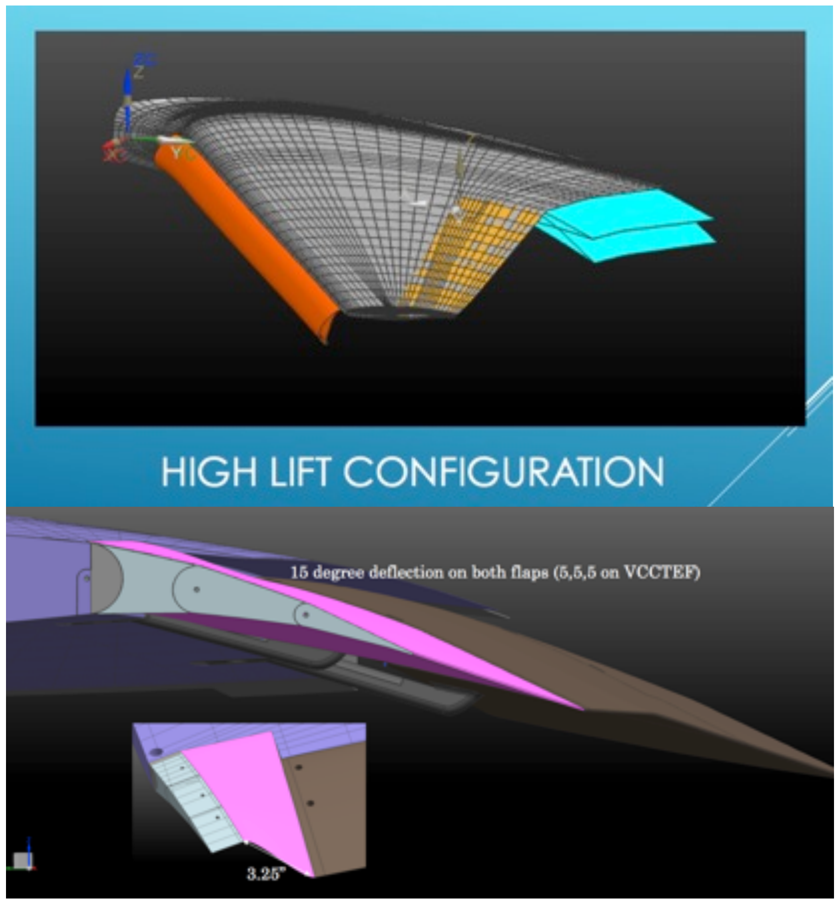


- **The fully deployed configuration effectively re-optimizes span load to correct for non-optimal jig shape twist**

High-Lift Wind Tunnel Test Plan

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

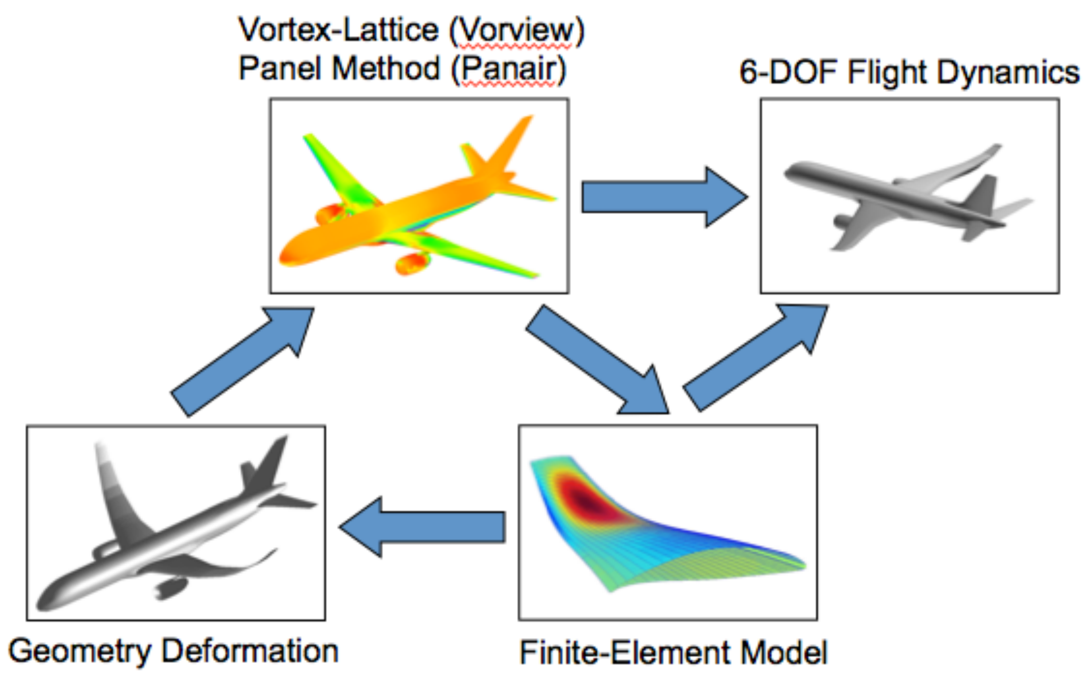
- **Test scheduled to take place in June 2014**



Aeroelasticity

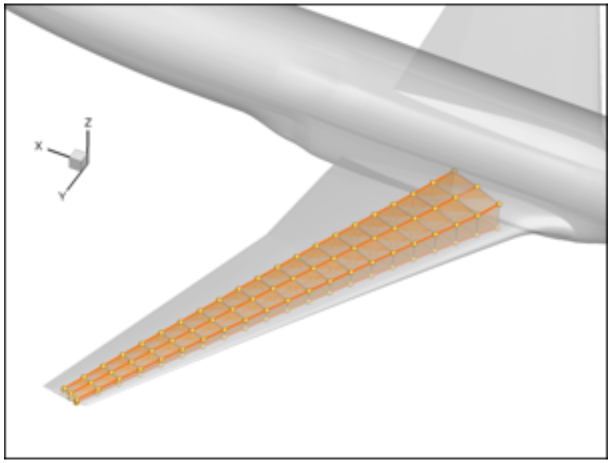
- **Multi-fidelity aeroelastic modeling capabilities enable aerodynamic performance prediction and stability and control of flexible wing transports**

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

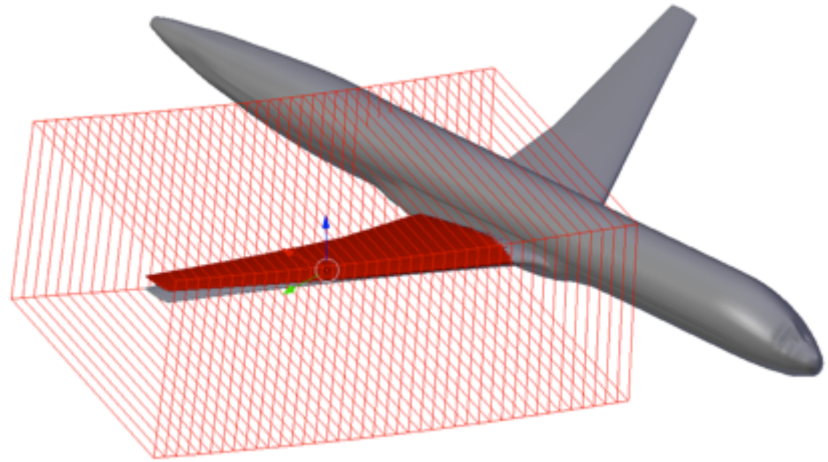


Static Aeroelasticity

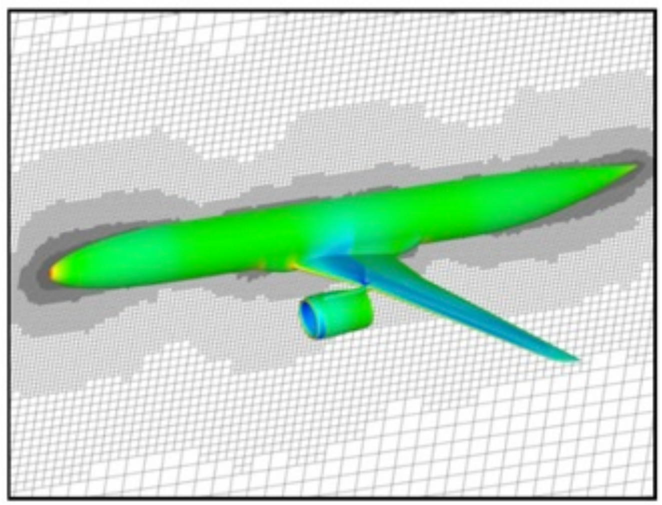
- **Static aeroelasticity by Cart3D CFD coupled with structural analysis code using Blender**



Structural Analysis Model



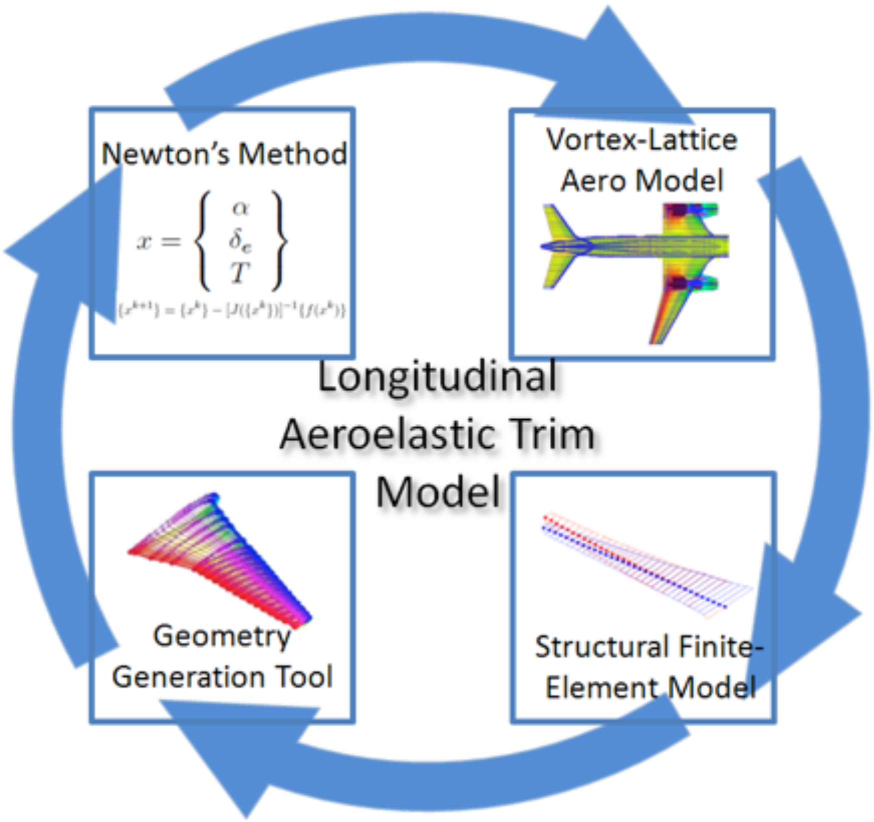
Blender Deformation Tool

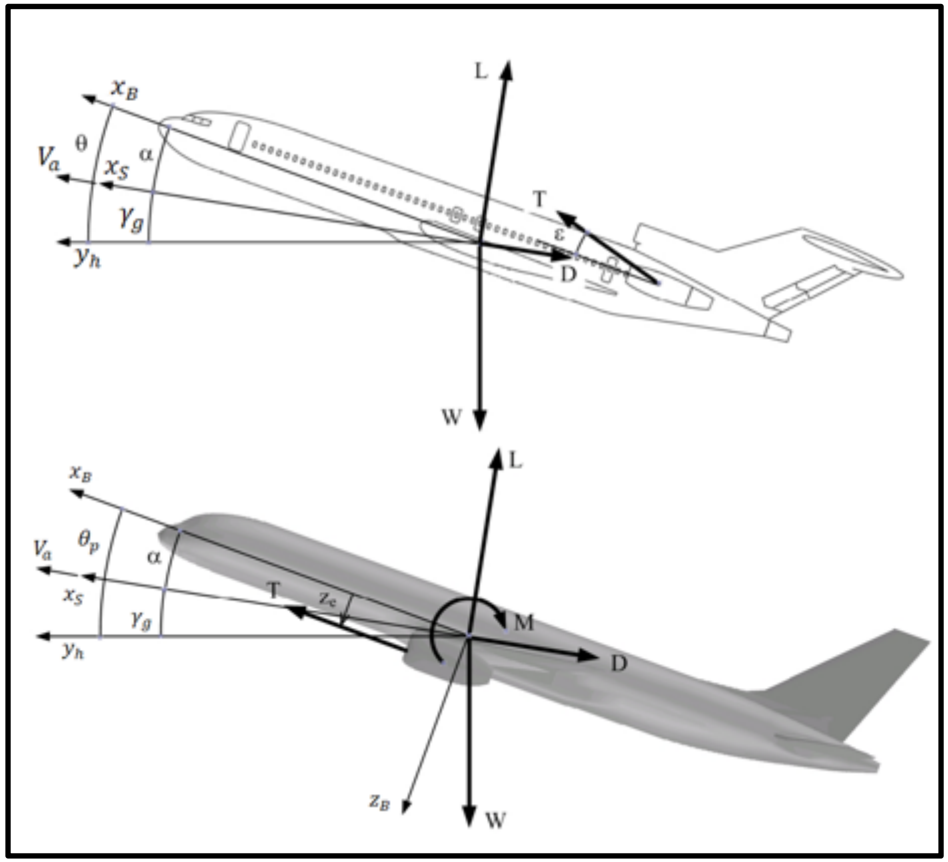


Cart3D

Aeroelastic Trim Solution

- **Vortex-lattice trim solution method**

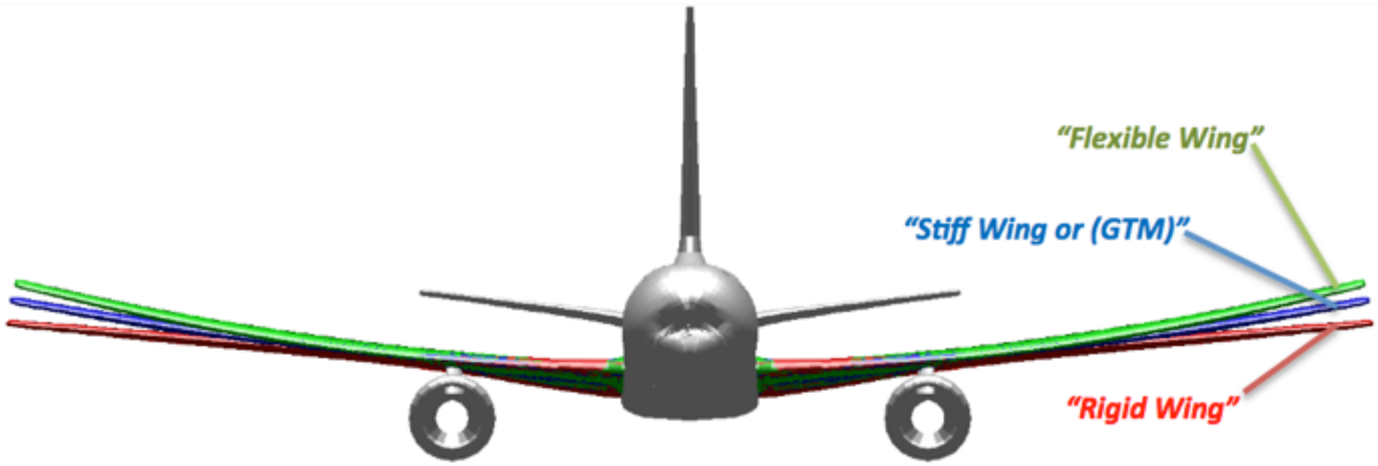


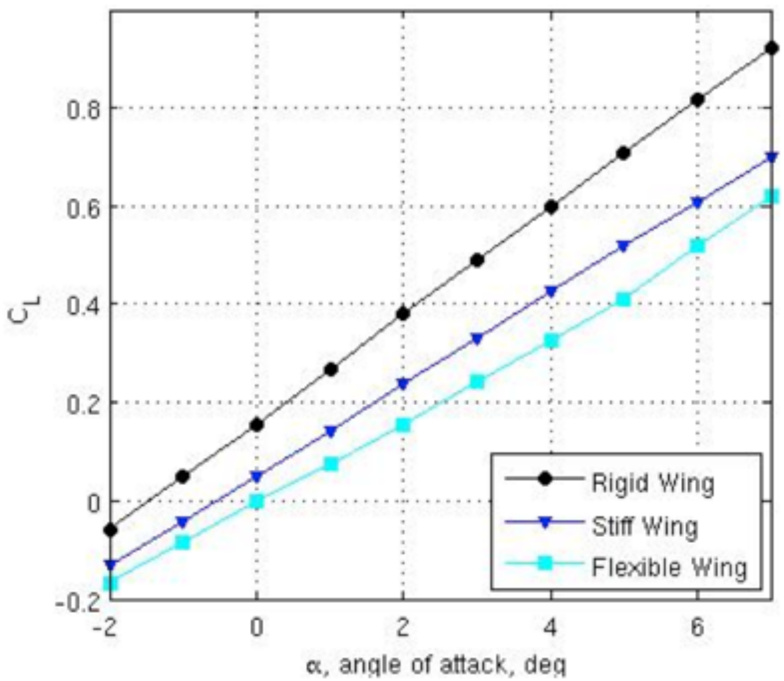


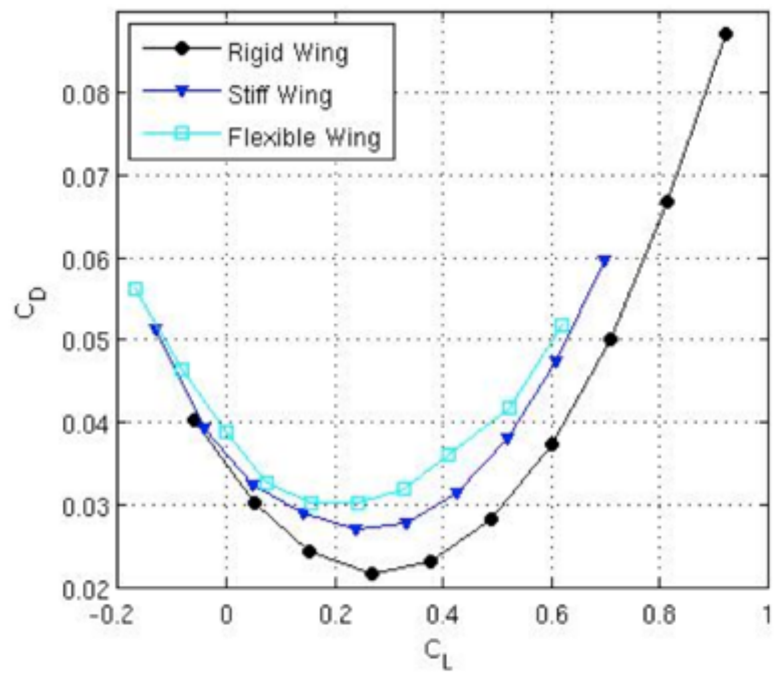
Outputs:

$\bar{\alpha}$, 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



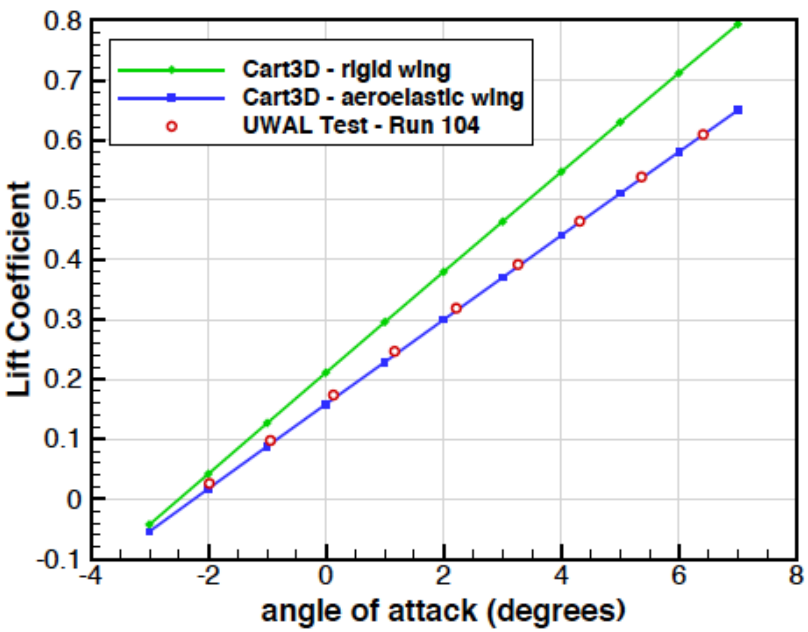


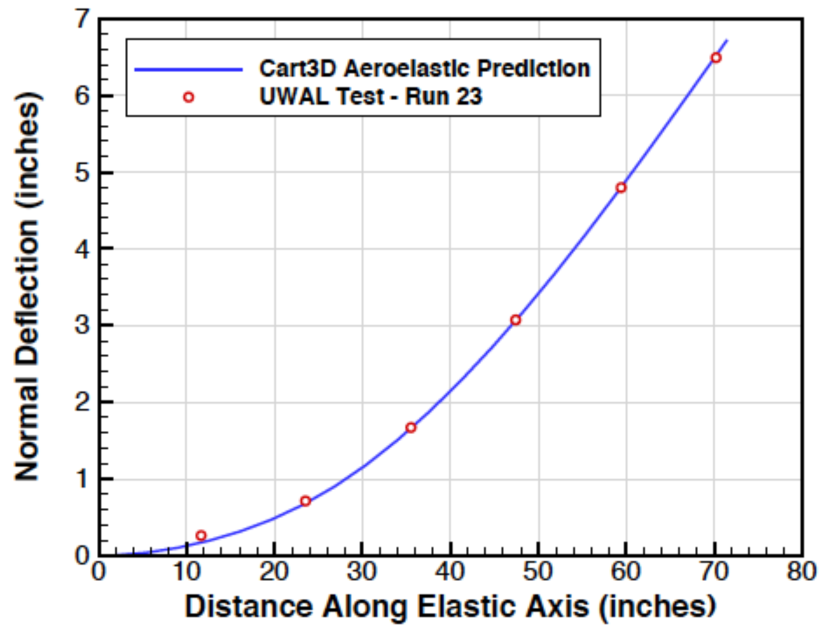


Ting, E., Nguyen, N., and Trinh, K., "Static Aeroelastic and Longitudinal Trim Model of Flexible Wing Aircraft Using Finite-Element Vortex-Lattice Coupled Solution," AIAA Science and Technology Forum, AIAA-2014-0837, January 2014

Aerodynamic Performance Prediction

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

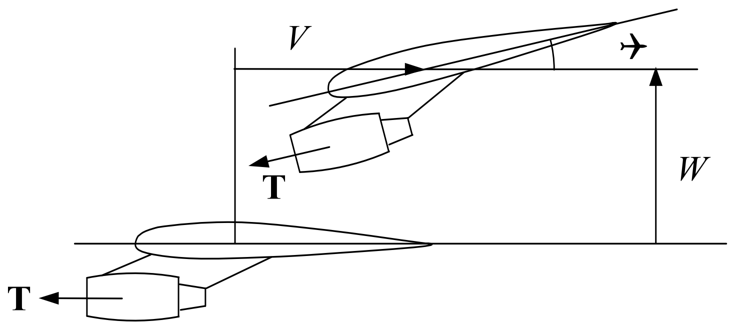


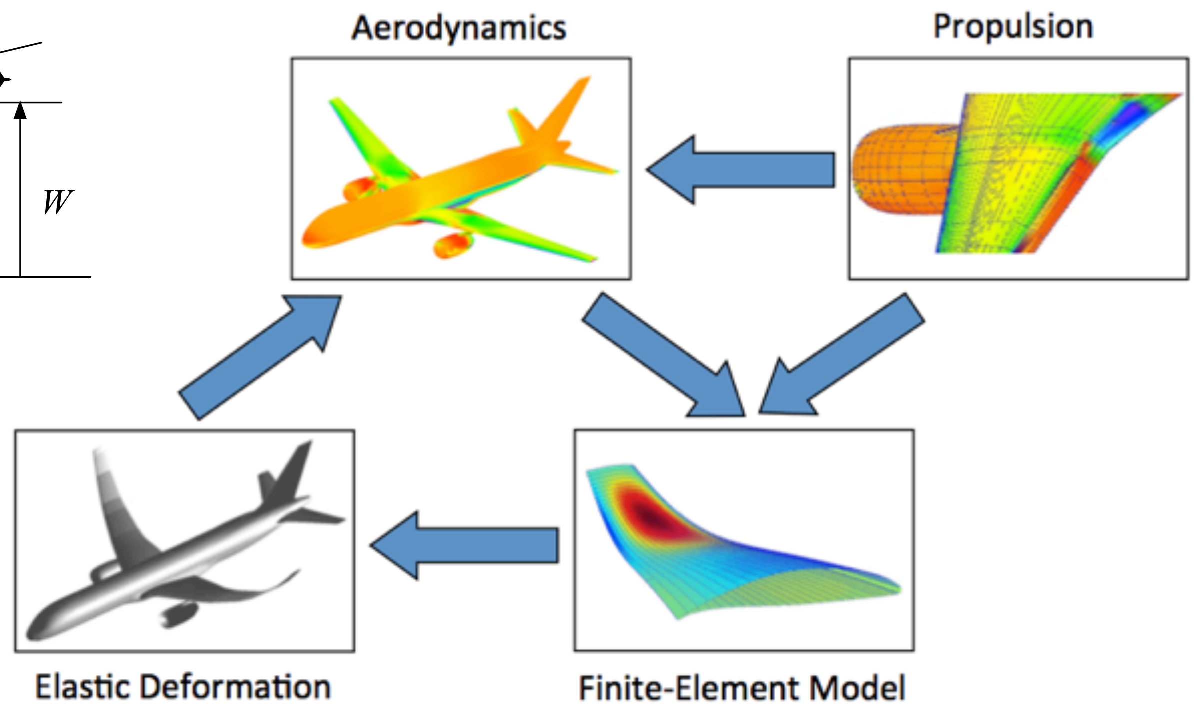


Rodriguez, D., Aftosmis, M., Nemec, M., and Smith, S., "Static Aeroelastic Analysis with an Inviscid Cartesian Method," AIAA Science and Technology Forum, AIAA-2014-0836, January 2014.

Thrust-Induced Aeroelasticity

- **FEM includes capability for thrust-induced aeroelasticity**

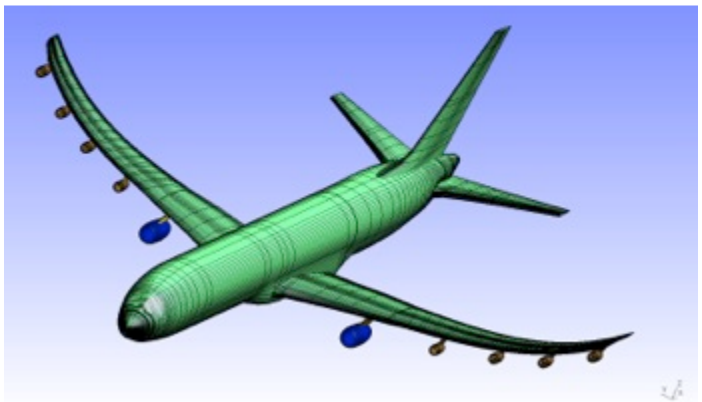




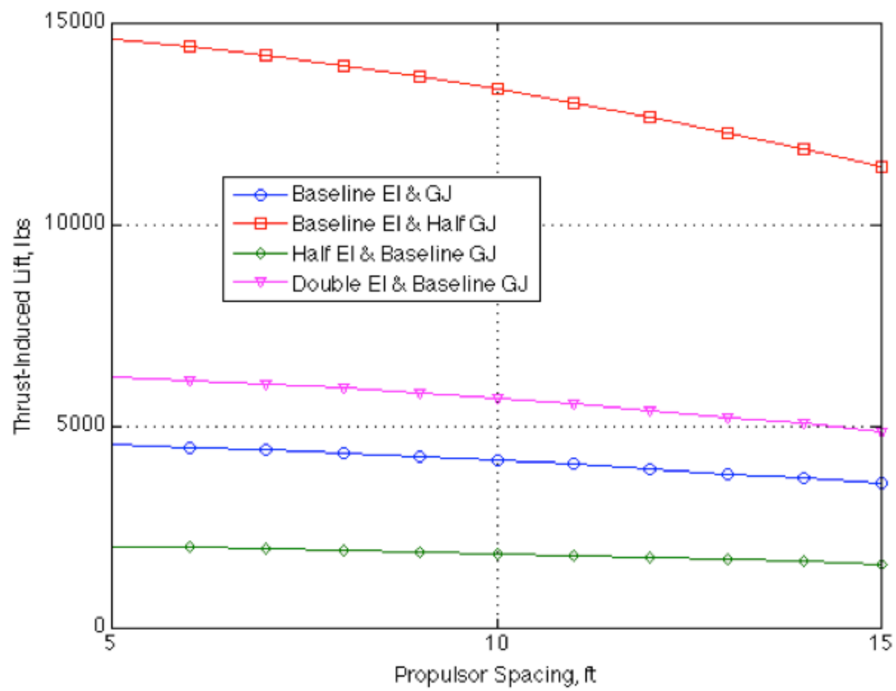
$$
\begin{aligned}
f_z^e &= \delta\left(x-x_e\right)\left[\left(T\sin\Lambda + m_e g\Gamma\right)W_x + T\cos\Lambda\left(\Theta+\gamma\right) + T\sin\Lambda\Gamma - m_e g\right] \\
m_x^e &= \delta\left(x-x_e\right)\left[-Ty_e\sin\Lambda\Gamma - Tz_e\cos\Lambda + m_e g y_e + \left(-Tx_e\sin\Lambda\Gamma + m_e g x_e + Tz_e\sin\Lambda + m_e g z_e\Gamma\right)V_x \right. \\
&\quad \left. -\left(Tx_e\cos\Lambda + Ty_e\sin\Lambda + m_e g y_e\Gamma\right)W_x\right]
\end{aligned}
$$

Thrust-Induced Lift

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



Distributed Propulsion Aircraft



Reynolds, K., Nguyen, N., and Ting, E., "Wing Shaping Concepts Using Distributed Propulsion For Optimizing Spanwise L/D To Reduce Fuel Burn," NASA ARMD Seedling Fund Phase I 2013

Dynamic Aeroelasticity

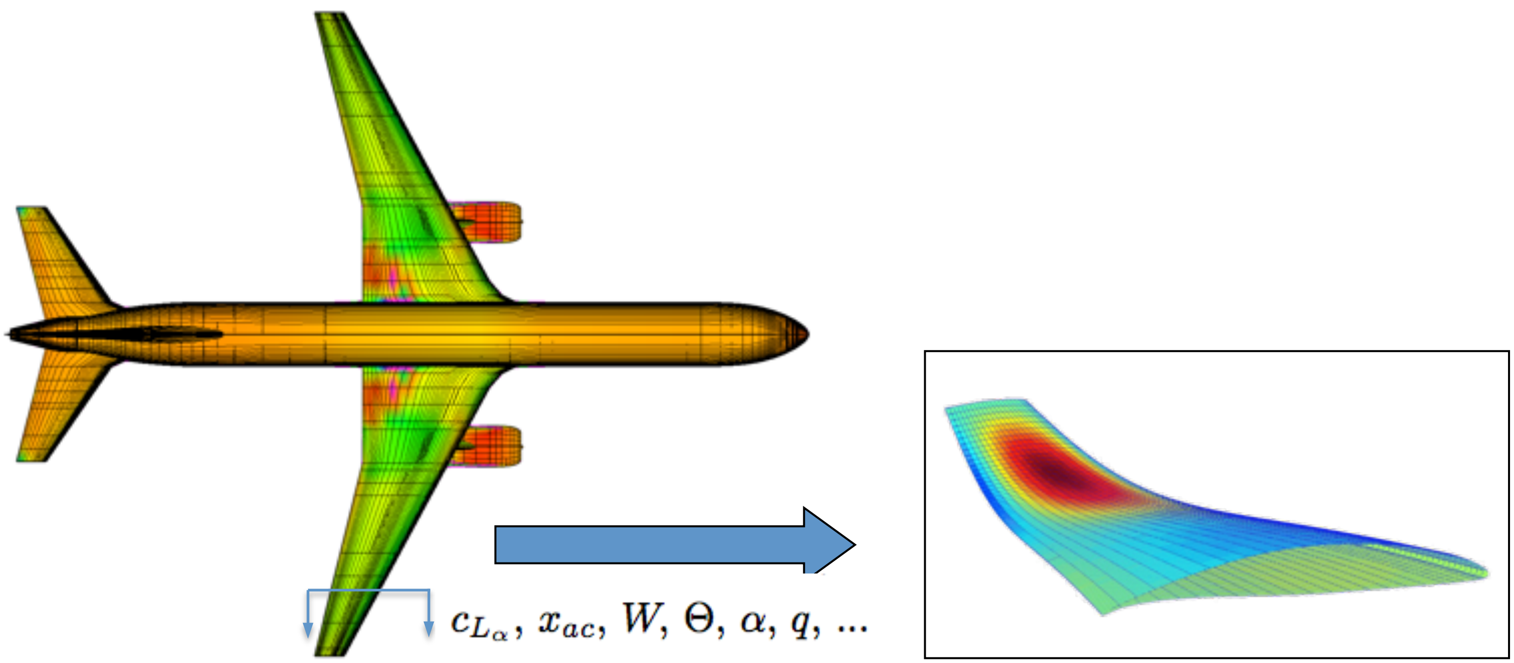
- **Dynamic aeroelasticity deals with interactions of structural dynamics with unsteady aerodynamics and rigid-body aircraft flight dynamics**

- **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

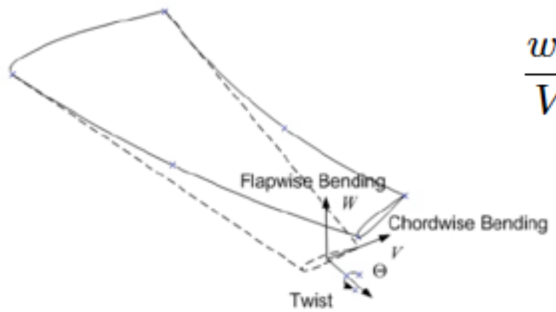


Steady Aerodynamics

FEM with Unsteady Aero Correction

Downwash Analysis

- **Unsteady downwash due to deflections**



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

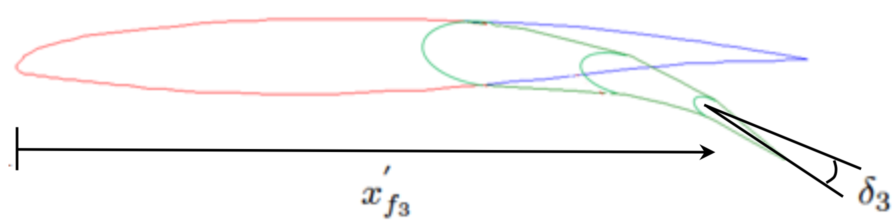
Rigid-Body AoA (α_r) — Elastic AoA (α_e)

$$\alpha_e(x,y,z) = \frac{\partial \alpha_c}{\partial W_x}W_x + \frac{\partial \alpha_c}{\partial V_x}V_x + \frac{\partial \alpha_c}{\partial \Theta}\Theta + \frac{\partial \alpha_c}{\partial W_x\Theta}W_x\Theta + \frac{\partial \alpha_c}{\partial V_x\Theta}V_x\Theta + \frac{\partial \alpha_c}{\partial W_t}W_t + \frac{\partial \alpha_c}{\partial V_t}V_t + \frac{\partial \alpha_c}{\partial \Theta_t}\Theta_t$$
$$+ \frac{\partial \alpha_c}{\partial W_x\Theta}W_x\Theta + \frac{\partial \alpha_c}{\partial V_x\Theta}V_x\Theta + \frac{\partial \alpha_c}{\partial \Theta W_t}\Theta W_t + \frac{\partial \alpha_c}{\partial \Theta V_t}\Theta V_t + \frac{\partial \alpha_c}{\partial W\Theta_t}W\Theta_t + \frac{\partial \alpha_c}{\partial V\Theta_t}V\Theta_t + \frac{\partial \alpha_c}{\partial \Theta\Theta_t}\Theta\Theta_t + \cdots$$

  - Sensitivities are functions of deflections and aircraft states

- **Camber change from unsteady downwash due to control surface deflections**

$$\frac{dz}{dx'} = -\frac{w_i}{V_\infty \cos\lambda} = -\sum_{j=1}^{i}\delta_j - \sum_{j=1}^{i}\frac{\left(x' - x'_{f_j}\right)\dot{\delta}_j}{V_\infty \cos\lambda}$$



Unsteady Lift

- **Circulatory lift from potential flow theory**

$$c_{L_{ac}} = c_{L_\alpha} \alpha_c \left(x, -e, 0\right) \cos \Lambda + \sum_{i=1}^{n} \Delta c_{L_i} \cos \lambda$$

$$\Delta c_{L_i} = \frac{c_{L_\alpha}}{\pi} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \frac{dz}{dx'} f\left(\theta\right) d\theta = \frac{c_{L_\alpha}}{\pi} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \left[-\sum_{j=1}^{i} \delta_j - \sum_{j=1}^{i} \frac{\left(x' - x'_{f_j}\right) \dot{\delta}_j}{V_\infty \cos \lambda} \right] \left(\cos \theta - 1\right) d\theta$$

- **Non-circulatory lift due to apparent mass**

$$c_{L_{c/2}} = \frac{\pi \dot{\alpha}_c \left(x, e_{c/2}, 0\right) \cos \Lambda c}{2 V_\infty} + \sum_{i=1}^{n} \Delta c^*_{L_i} \cos \lambda$$

$$\Delta c^*_{L_i} = -\frac{c'}{V_\infty \cos \lambda} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \frac{d}{dt} \left(\frac{dz}{dy}\right) g\left(\theta\right) d\theta = \frac{c'}{V_\infty \cos \lambda} \int_{\theta_{f_i}}^{\theta_{f_{i+1}}} \left[\sum_{j=1}^{i} \dot{\delta}_j + \sum_{j=1}^{i} \frac{\left(x' - x'_{f_j}\right) \ddot{\delta}_j}{V_\infty \cos \lambda} \right] \sin^2 \theta d\theta$$

- **Total unsteady lift with Theodorsen unsteady aerodynamic corrections**

$$c_L\left(k\right) = C\left(k\right) c_{L_{ac}} + c_{L_{c/2}}$$

$$C\left(k\right) = F\left(k\right) + iG\left(k\right) \qquad k = \frac{\omega c}{2 V_\infty}$$

- **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**

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

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

$$C(k) \approx \bar{C}(\bar{s}) = \frac{0.5\bar{s}^2 + a_1\bar{s} + a_2}{\bar{s}^2 + a_3\bar{s} + a_2}$$

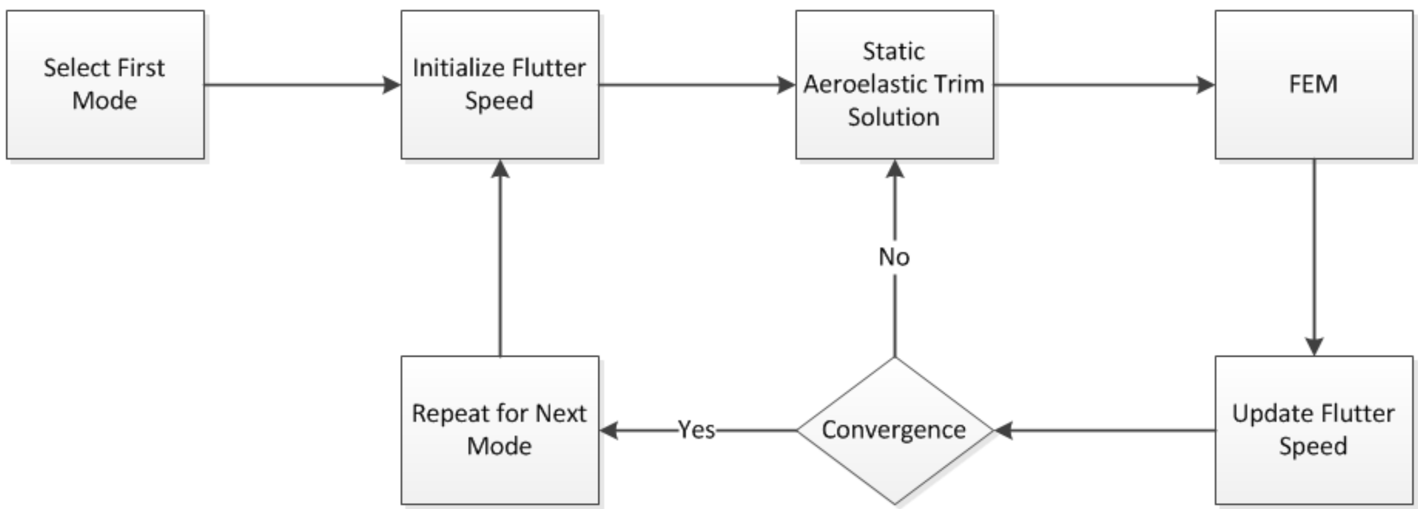
$$M_i\ddot{x}_i + \left(C_i + 0.5C_i^k\right)\dot{x}_i + \left(K_i + 0.5K_i^k + \frac{2V_\infty a_4}{c}C_i^k\right)x_i + C_i^k y_i + K_i^k z_i = F_i\left(x_r, \dot{x}_r, \delta\right)$$

$$\left(\frac{\bar{c}_i}{2V_\infty}\right)^2 \ddot{y}_i + a_3\left(\frac{\bar{c}_i}{2V_\infty}\right)\dot{y}_i + a_2 y_i = a_5\left(\frac{\bar{c}_i}{2V_\infty}\right)\dot{x}_i + a_6 x_i$$

$$\left(\frac{\bar{c}_i}{2V_\infty}\right)^2 \ddot{z}_i + a_3\left(\frac{\bar{c}_i}{2V_\infty}\right)\dot{z}_i + a_2 z_i = a_4\left(\frac{\bar{c}_i}{2V_\infty}\right)\dot{x}_i + 0.5a_2 x_i$$

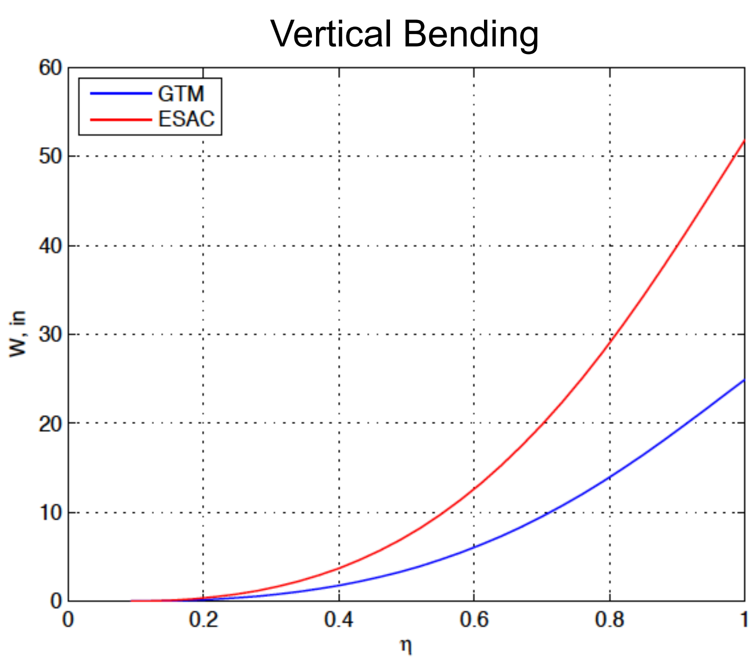
Flutter Analysis

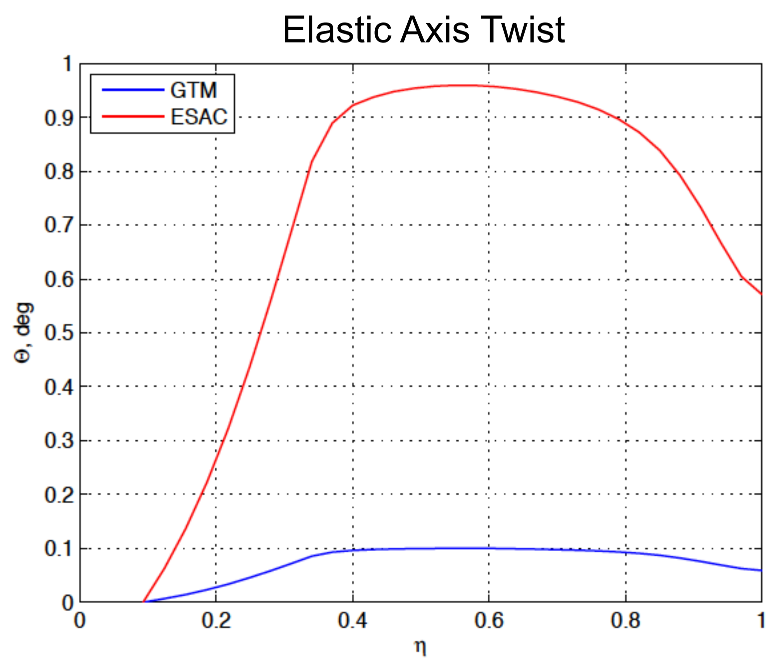
- **Flutter analysis computes flutter speed at the onset of aeroelastic instability (i.e., total damping becomes zero)**
- **Iterative process with aeroelastic trim solution in between iterations**



Flexible Wing GTM

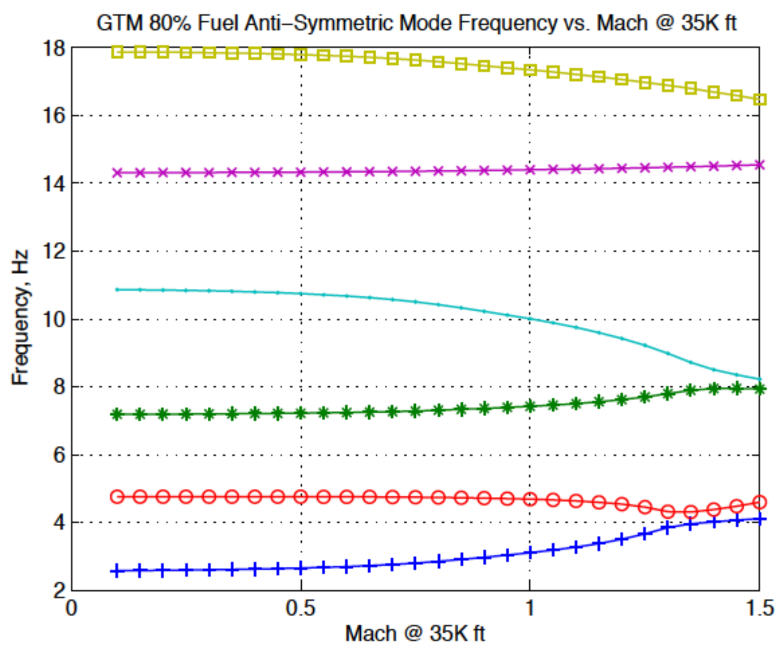
- **GTM wing is relatively stiff with about 5% wing tip deflection, similar to B757 wing deflection**
- **To enable effective aeroelastic wing shaping control, a flexible wing GTM with 50% reduced stiffness and 20% wing mass reduction is proposed**
- **Wing tip deflection for flexible wing GTM is about 10%, similar to B787**



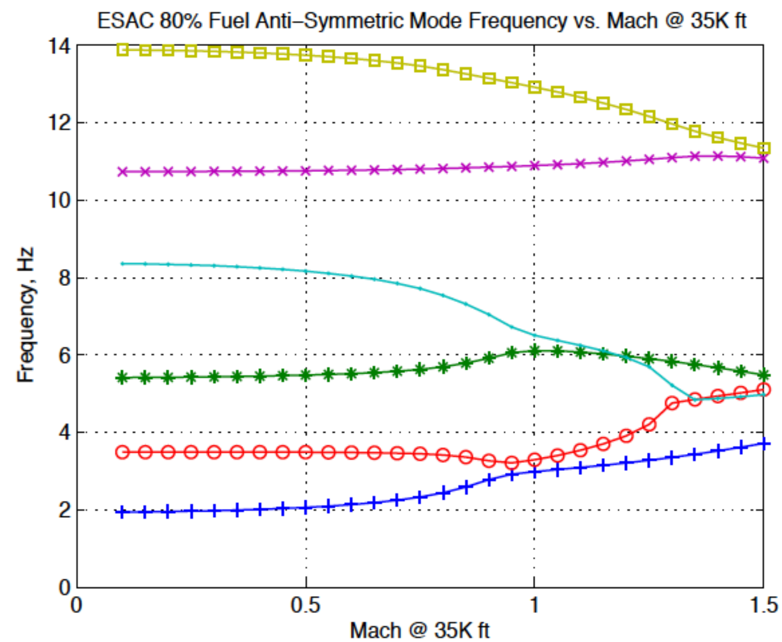


Frequency Prediction

Stiff Wing

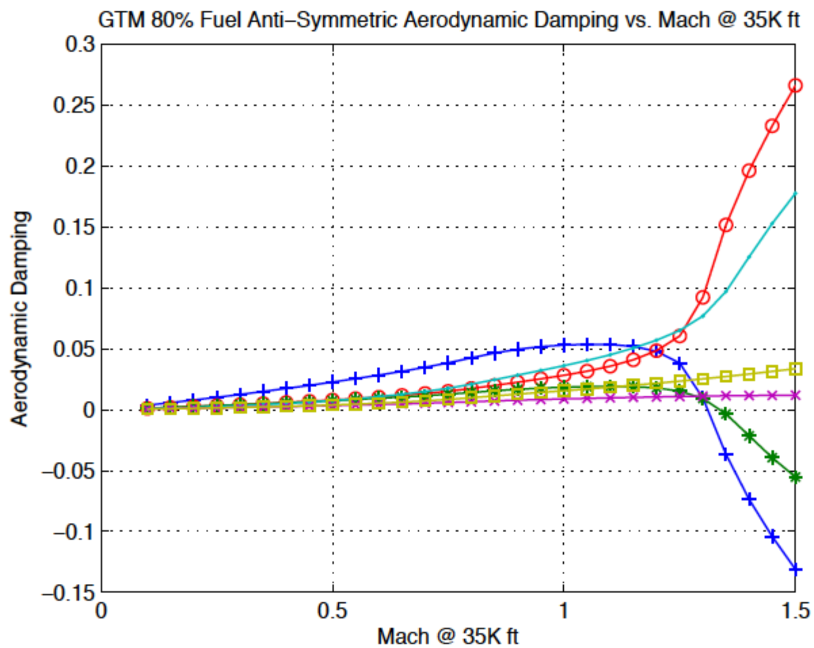


Flexible Wing

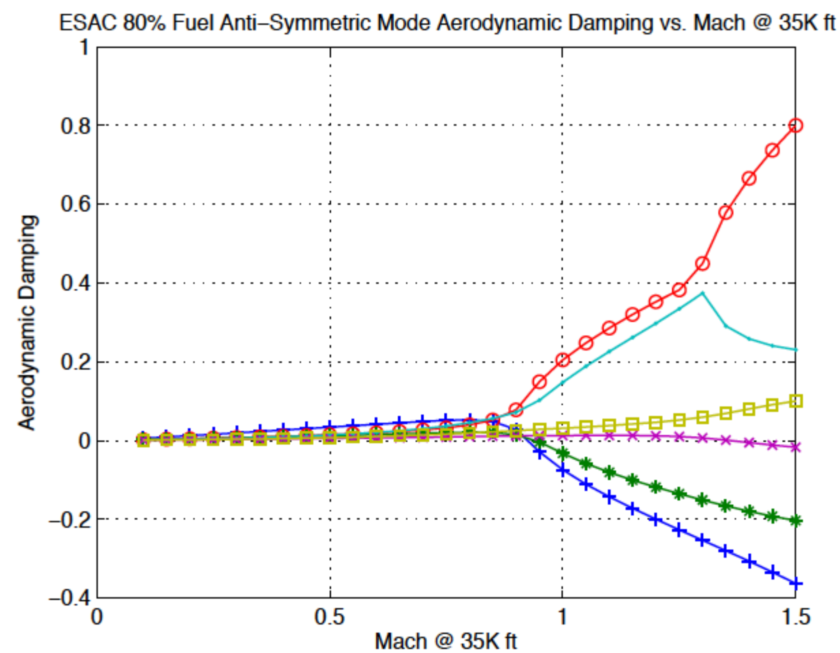


Aerodynamic Damping Prediction

Stiff Wing



Flexible Wing



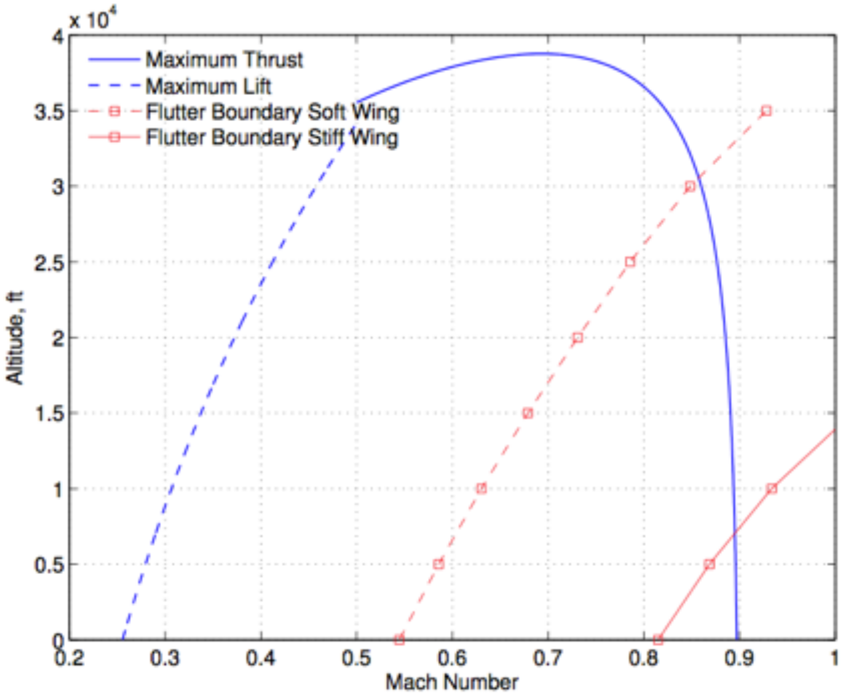
	Symmetric Mode	Anti-Symmetric Mode
GTM Flutter Mach @ 35K ft	1.358	1.310
GTM Flutter Frequency @ 35K ft, Hz	4.31	3.87
ESAC Flutter Mach @ 35K ft	0.938	0.925
ESAC Flutter Frequency @ 35K ft, Hz	6.94	2.85

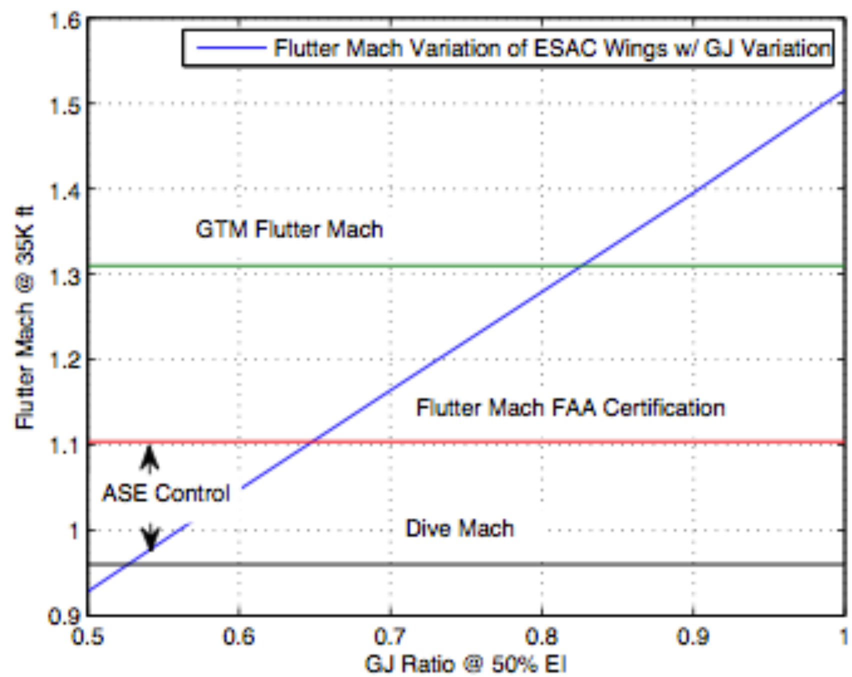
NASTRAN predicts anti-symmetric flutter mode at Mach 0.954, a 3% difference

Nguyen, N., Ting, E., and Trinh, K., "Flutter Analysis of Mission-Adaptive Wing with Variable Camber Continuous Trailing Edge Flap," AIAA Science and Technology Forum, AIAA-2014-0839, January 2014

Flutter Boundary

- **FAA flutter clearance requires 15% - 20% over dive speed**
- **Flutter boundary is sensitive to torsional stiffness**



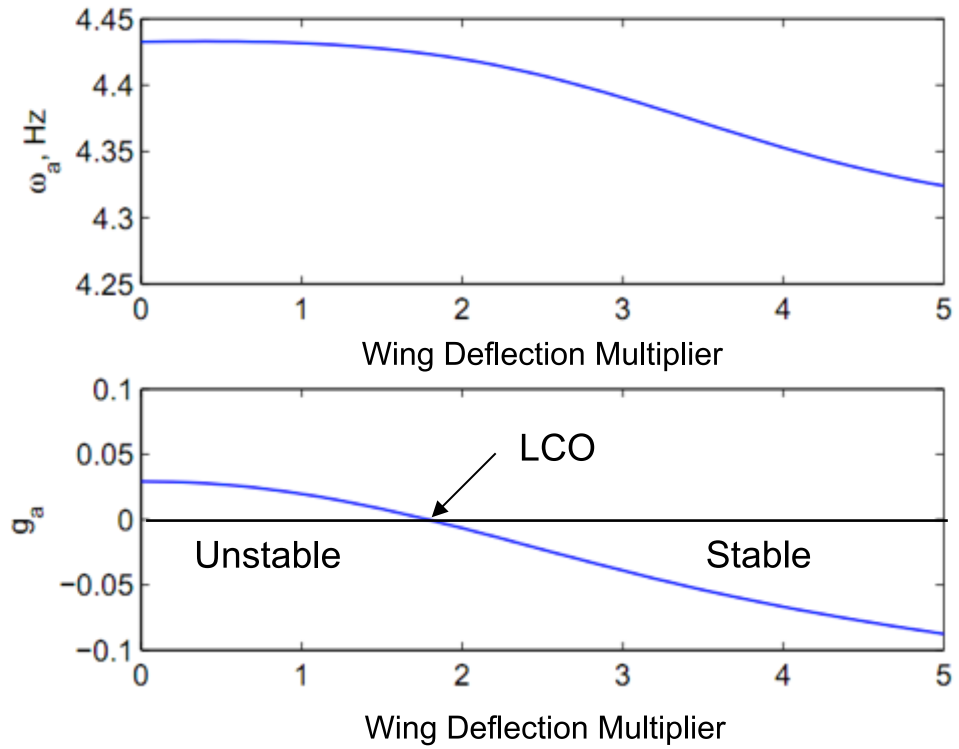


- **Multi-disciplinary optimization can be used to determine optimal wing design that can achieve a balance between weight, drag, and stiffness**

A Note on Nonlinear Aeroelasticity

- **Nonlinear aeroelasticity is due to deflection and aircraft state dependency**

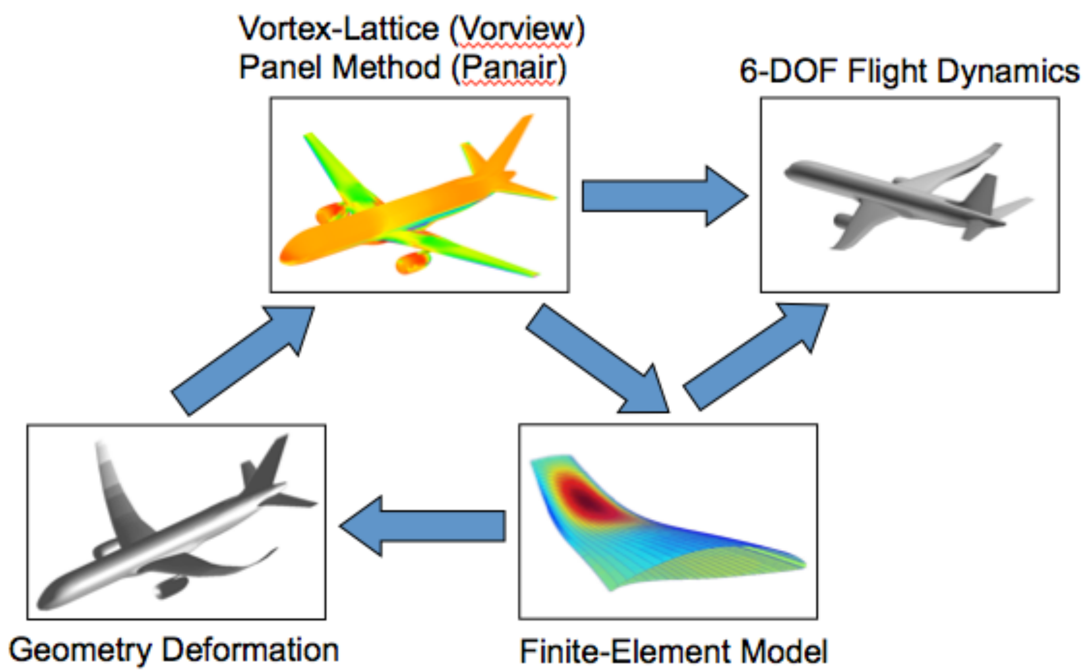
- **Aerodynamic damping can increase with deflection amplitude, which results in a higher flutter speed than linear analysis**



- **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

$$C_m(k) = C_{m_0} + C_{m_{x_r}} x_r + C_{m_{\dot{x}_r}} \dot{x}_r + \sum_{i=1}^{n} \left(C_{m_{\ddot{x}_i}} \ddot{x}_i^s + C_{m_{\dot{x}_i}} \dot{x}_i^s + C_{m_{\dot{x}_i}}^k C(k) \dot{x}_i^s + C_{m_{x_i}}^k C(k) x_i^s \right)$$
$$+ C_{m_\delta} \delta + C_{m_{\dot{\delta}}} \dot{\delta} + C_{m_{\ddot{\delta}}} \ddot{\delta} + C_{m_{\delta_e}} \delta_e$$

  - Anti-symmetric modes coupled to lateral-directional motion

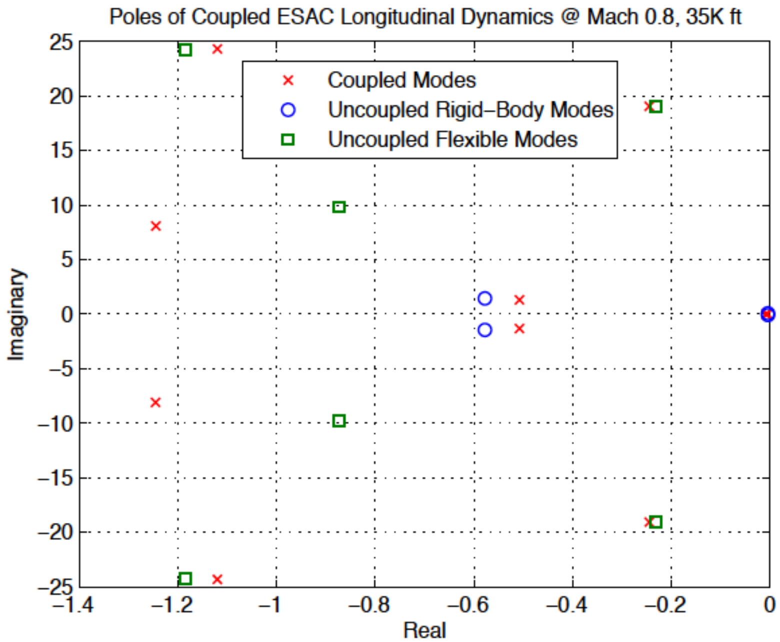
$$C_l(k) = C_{l_{x_r}} x_r + \sum_{i=1}^{n} \left(C_{l_{\ddot{x}_i}} \ddot{x}_i^a + C_{l_{\dot{x}_i}} \dot{x}_i^a + C_{l_{\dot{x}_i}}^k C(k) \dot{x}_i^a + C_{l_{x_i}}^k C(k) x_i^a \right)$$
$$+ C_{l_\delta} \delta + C_{l_{\dot{\delta}}} + C_{l_{\ddot{\delta}}} \ddot{\delta} + C_{m_{\delta_r}} \delta_r$$

- **Generalized elastic forces are due to aerodynamics as well as aircraft rates and accelerations**

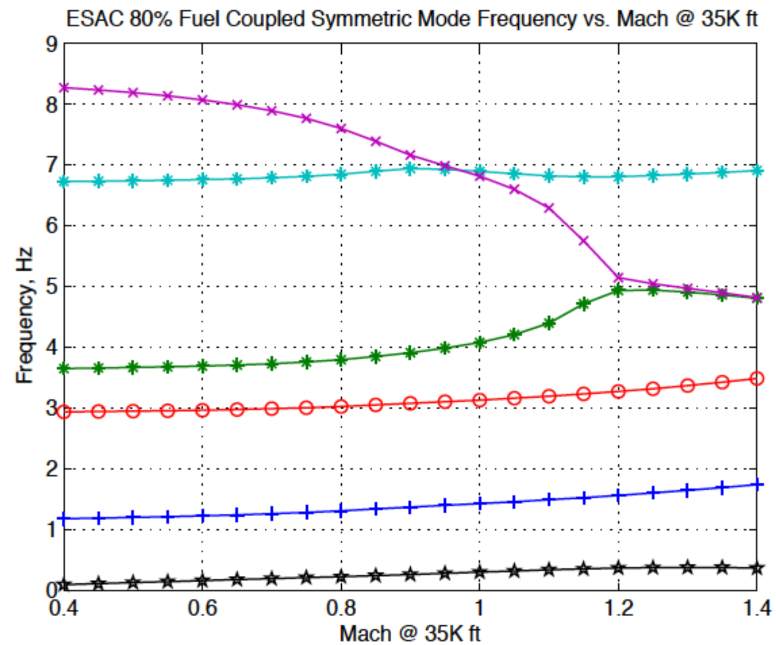
$$\Phi^\top M(k) \Phi \ddot{\eta} + \Phi^\top C_a(k) \Phi \dot{\eta} + \Phi^\top K(k) \Phi \eta = \Phi^\top F\left(\dot{x}_r, x_r, \delta, \dot{\delta}, \ddot{\delta} \right)$$

Coupled Aircraft Flutter Analysis

Eigenvalues



Flutter Analysis of Coupled Aircraft

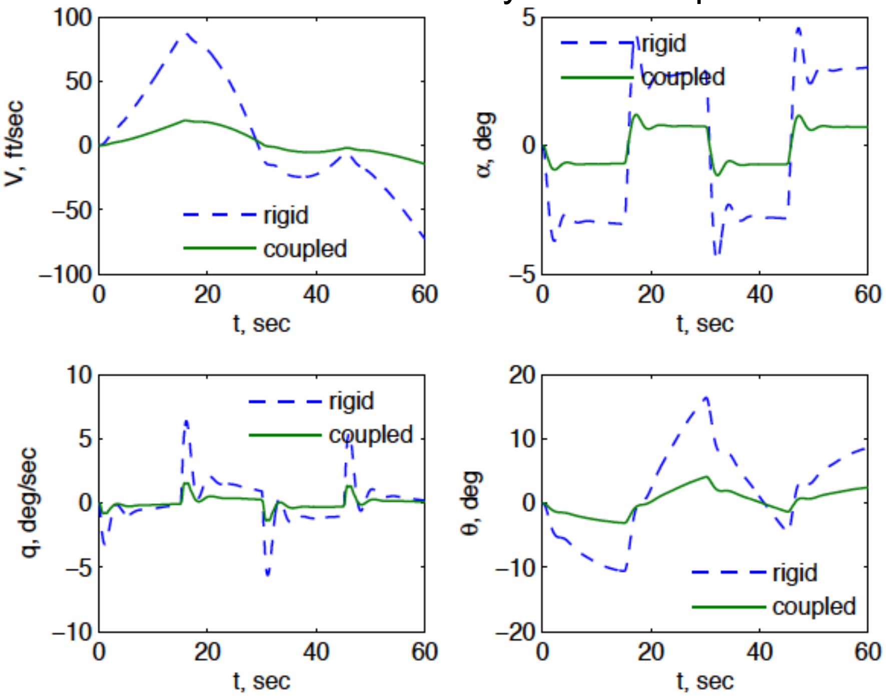


	Symmetric Mode	Anti-Symmetric Mode
Uncoupled GTM Flutter Mach @ 35K ft	1.358	1.310
Uncoupled GTM Flutter Frequency @ 35K ft, Hz	4.31	3.87
Uncoupled ESAC Flutter Mach @ 35K ft	0.938	0.925
Uncoupled ESAC Flutter Frequency @ 35K ft, Hz	6.94	2.85
Coupled ESAC Flutter Mach @ 35K ft	0.940	0.938
Coupled ESAC Flutter Frequency @ 35K ft, Hz	6.93	2.89

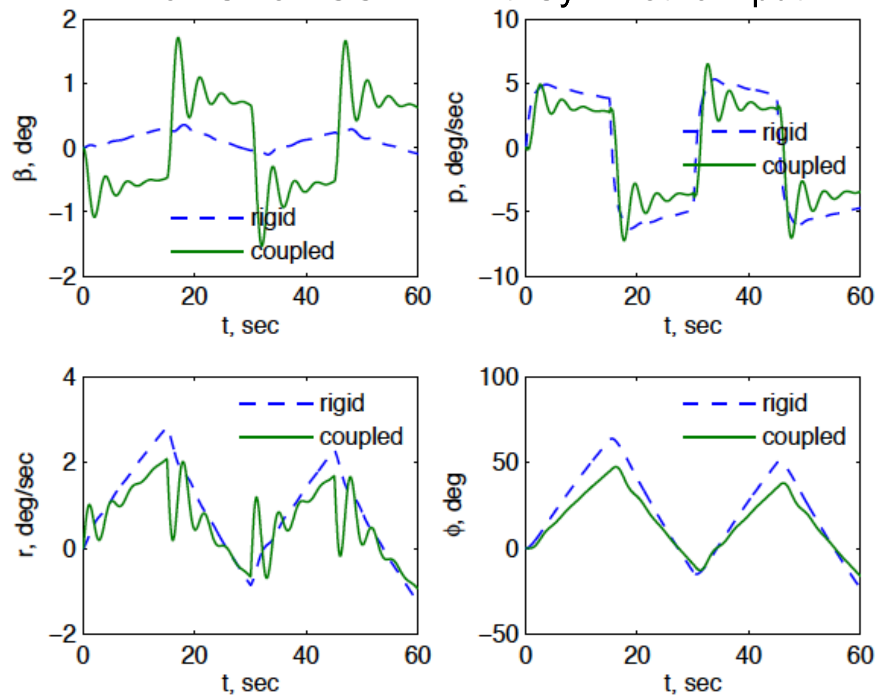
Nguyen, N., Ting, E., and Trinh, K., "Flight Dynamic Modeling and Stability Analysis of Flexible Wing Generic Transport Aircraft," AIAA Science and Technology Forum, AIAA-2014-1040, January 2014.

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



Nguyen, N., Ting, E., and Trinh, K., "Flight Dynamic Modeling and Stability Analysis of Flexible Wing Generic Transport Aircraft," AIAA Science and Technology Forum, AIAA-2014-1040, January 2014.

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

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- 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