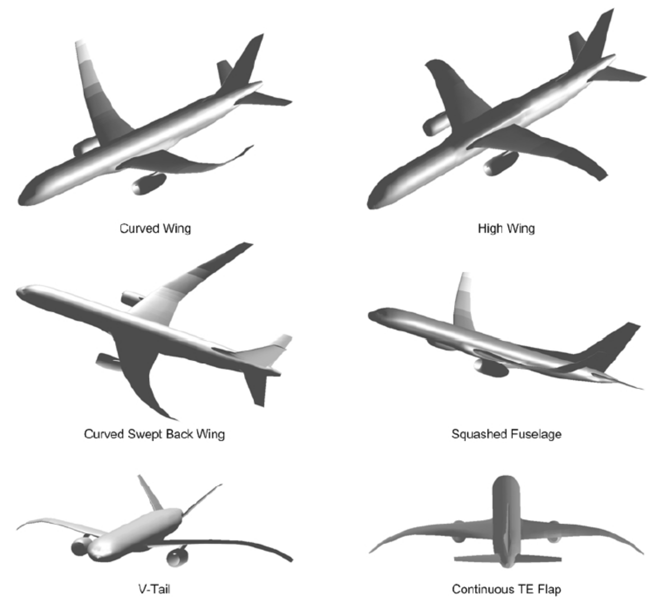
NASA Innovation Fund Award 2010

Elastically Shaped Future Air Vehicle Concept

Dr. Nhan Nguyen, NASA Ames Research Center
Nhan.T.Nguyen@nasa.gov

Motivation

- Economic demands and environmental impacts will likely drive development of next generation aircraft to be more fuel efficient, less noise and environmental polluting
- Current aircraft configurations may have reached equilibrium for past number of decades
- New concepts could shift this equilibrium to a new position that could rejuvenate aeronautics and aviation community by changing conventional thinking on aircraft design
- Economic benefits could be large as civilian aircraft is the largest U.S. export category ($9.4 billion, "U.S. Export Fact Sheet, March 2009)



automated aircraft geometry modeler

Project Description and Objectives

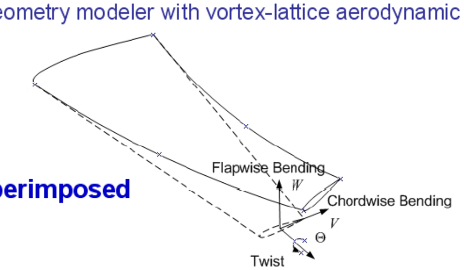
- Address national and global challenge of reducing fuel burn by developing optimal bio-inspired elastic wing shapes for future air vehicle concepts that minimizes induced drag
- Develop elastic wing shaping control methods to change wing shapes in-flight for drag reduction
- Develop novel aerodynamically efficient, low drag variable camber continuous trailing edge flap concept
- Conduct multi-disciplinary investigation in aerodynamic optimization, aeroelasticity, flight dynamics and control, and system analysis to develop integrated solutions that maximize potential drag reduction benefits from these disciplines

New concepts of elastically curved wings

- Remove constraint on conventional thinking of straight wing design as a way to shift aircraft design equilibrium
- Leverage emerging trend toward light-weight flexible airframe design that could allow new elastic curved wing concepts to be developed

Elastic wing shape optimization approach

- Allow substantial degrees of freedom in wing bending and twist
- Parametric optimization based on prescribed 4th-degree polynomial shape functions for bending and twist superimposed on conventional straight wing
- Developed new automated aircraft geometry modeler in MATLAB that can rapidly generate new configurations on the fly during optimization
- Couple aircraft geometry modeler with vortex-lattice aerodynamic code VORVIEW



elastic curves superimposed on straight wing

Typical Weight, W	200,000 lb
Wing Reference Area, S_{ref}	1951 ft^2
MAC, $\bar{c}$	16.6417 ft
Wing Span, b	124.8333 ft

baseline benchmark aircraft geometry

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New elastic wing shape vehicle concepts identified by optimization

- Drooped wing shape
- Inflected wing shape
- Drooped wing shape superimposed on squashed fuselage

Drag reduction benefits

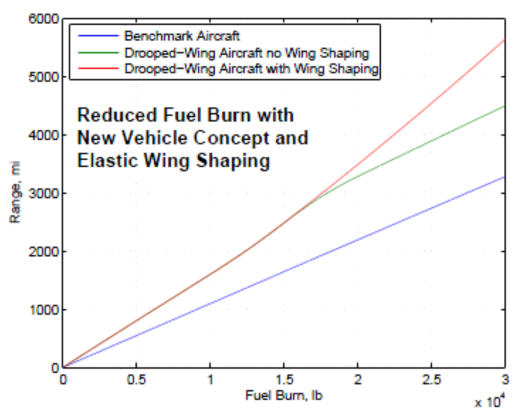
- Squashed fuselage generates lift that offsets wing lift, thus lowering wing induced drag
- Bio-inspired seagull-like drooped wing appears to be aerodynamically efficient
  - Possible explanation by aeroelasticity theory: negative wing curvature increases local α (angle of attack) which causes aircraft trim α to move closer to minimum drag α

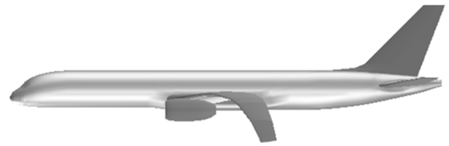
$$\alpha_c = \frac{\alpha}{\cos\Lambda} - \gamma - W_x \tan\Lambda - \Theta$$

  - Negative wing curvature also reduces tendency for high pressure flow field under wing to develop flow circulation around wing tip as a result of low pressure on the upper wing surface

New elastic wing shaping control concept

- Optimal wing shape unlikely to be maintained in cruise due to changes in fuel weight that cause changes in aerodynamics
- Goal is to maintain optimal wing shape by active wing shaping control - a bio-inspired feature in bird's highly adaptable wing
- Study shows promising results for reducing fuel burn for long-range cruises (17% at 4500 mi range from performance analysis)





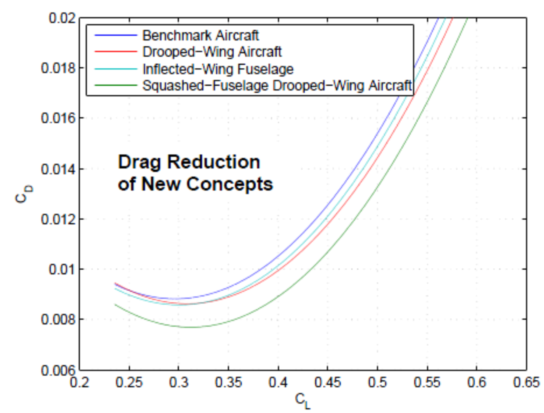
Drooped-Wing Vehicle Concept
5.3% Drag Reduction

Squashed-Fuselage Drooped-Wing Vehicle Concept
15% Drag Reduction

Inflected-Wing Vehicle Concept
3.5% Drag Reduction

folded wing for take-off and landing

unfolded drooped wing at cruise



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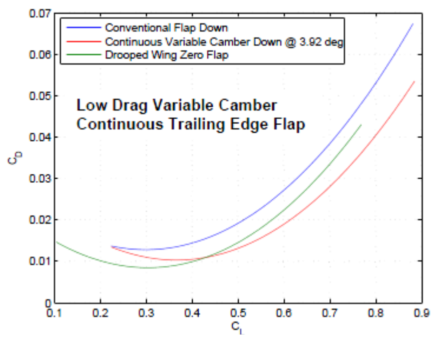
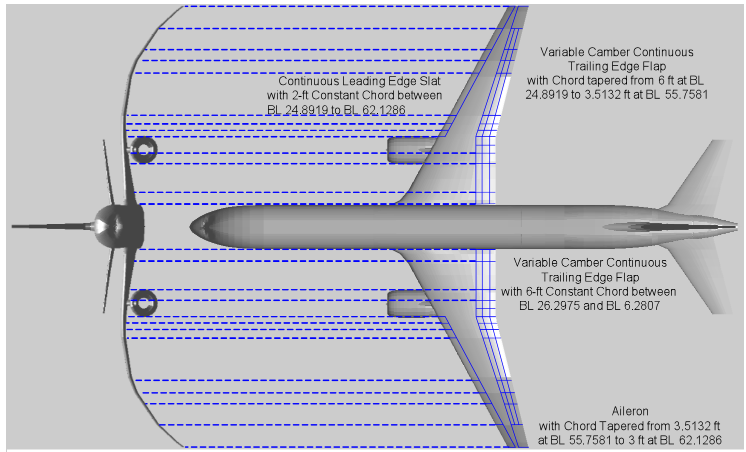
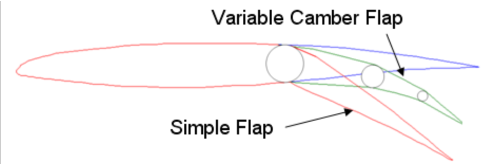
New variable camber continuous trailing edge flap concept for drag reduction

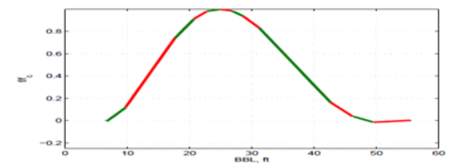
- Conventional flaps generate too much drag that negates benefits of elastic wing shaping control
- New flap concept can substantially reduce drag over conventional flaps
- Elastic wing shaping control uses only flap-down configurations as flap-up configurations reduce lift-to-drag ratio which penalizes cruise efficiency





Flap Layout





12-segment spanwise continuous TE curve prescribed by 5th degree polynomial

zero deflection enforced at end points to reduce tip vorticities that can cause drag

Aeroelastic flight dynamics and control of new vehicle concepts

- Account for aeroelastic effects on vehicle performance and stability

$$\frac{\partial}{\partial x}\left\{\left[GJ+EB_1\left(\gamma'\right)^2\right]\Theta_x - EB_2\gamma' W_{xx}\right\} = \left[\bar{c}_L + c_{L_\alpha}\left(\frac{\alpha}{\cos\Lambda}+\frac{q x_{ac}}{V_\infty\cos\Lambda}-\gamma - W_x\tan\Lambda - \Theta - \frac{W_t - e\Theta_t}{V_\infty\cos\Lambda}\right)+c_{L_f} f\right] e q_\infty \cos^2\Lambda c + \rho I_{xx}\Theta_{tt} \quad (5.31)$$

$$\frac{\partial^2}{\partial x^2}\left(-EB_2\gamma'\Theta_x + EI_{yy}W_{xx}\right) = \left[\bar{c}_L + c_{L_\alpha}\left(\frac{\alpha}{\cos\Lambda}+\frac{q x_{ac}}{V_\infty\cos\Lambda}-\gamma - W_x\tan\Lambda - \Theta - \frac{W_t - e\Theta_t}{V_\infty\cos\Lambda}\right)+c_{L_f} f\right] q_\infty \cos^2\Lambda c - \rho g A - \rho A W_{tt} \quad (5.32)$$

- Wing flexibility can cause aeroelastic instability that needs stabilization by flight control

New concept of multi-objective optimal flight control for drag minimization

$$J_1 = \frac{1}{2}\int_0^{t_f}\left(\bar{x}^\top Q\bar{x} + u^\top R u\right) dt \quad \longleftarrow \text{Command Tracking Objective}$$

$$J_2 = \int_0^{t_f}\left|C_{D_f}\right| |f| \, dt \quad \longleftarrow \text{Drag Minimization Objective}$$

Accomplishments

- Invention disclosure on "Variable Camber Continuous Aerodynamic Control Surfaces and Methods for Active Wing Shaping Control" filed with NASA Ames
- Invention disclosures on new aircraft concepts to be filed
- Invention disclosure on aircraft optimization tool to be filed and further development of tool for future NASA work
- Transfer idea on variable camber continuous trailing edge flap to NASA Subsonic Fixed Wing project for further development
- Share knowledge with Boeing Research and Technology on variable camber continuous flap concept and elastic wing shaping control for possible future partnership to further advance concepts for future aircraft applications
- Possible knowledge sharing of new aircraft concepts with Boeing Airplane Company

Recommendations for future work

- Further development of variable camber continuous trailing edge flap concept (also Boeing's recommendation)
- Further optimization to identify other improved vehicle configurations
- Verification of concepts with Navier-Stokes CFD codes
- Development of drag minimization multi-objective wing shaping flight control
- Further development of aeroelastic flight dynamic model
- Development of coupled aeroelastic-aerodynamic modeling capability