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Peak-Seeking Optimization of Spanwise Lift Distribution for Wings in Formation Flight

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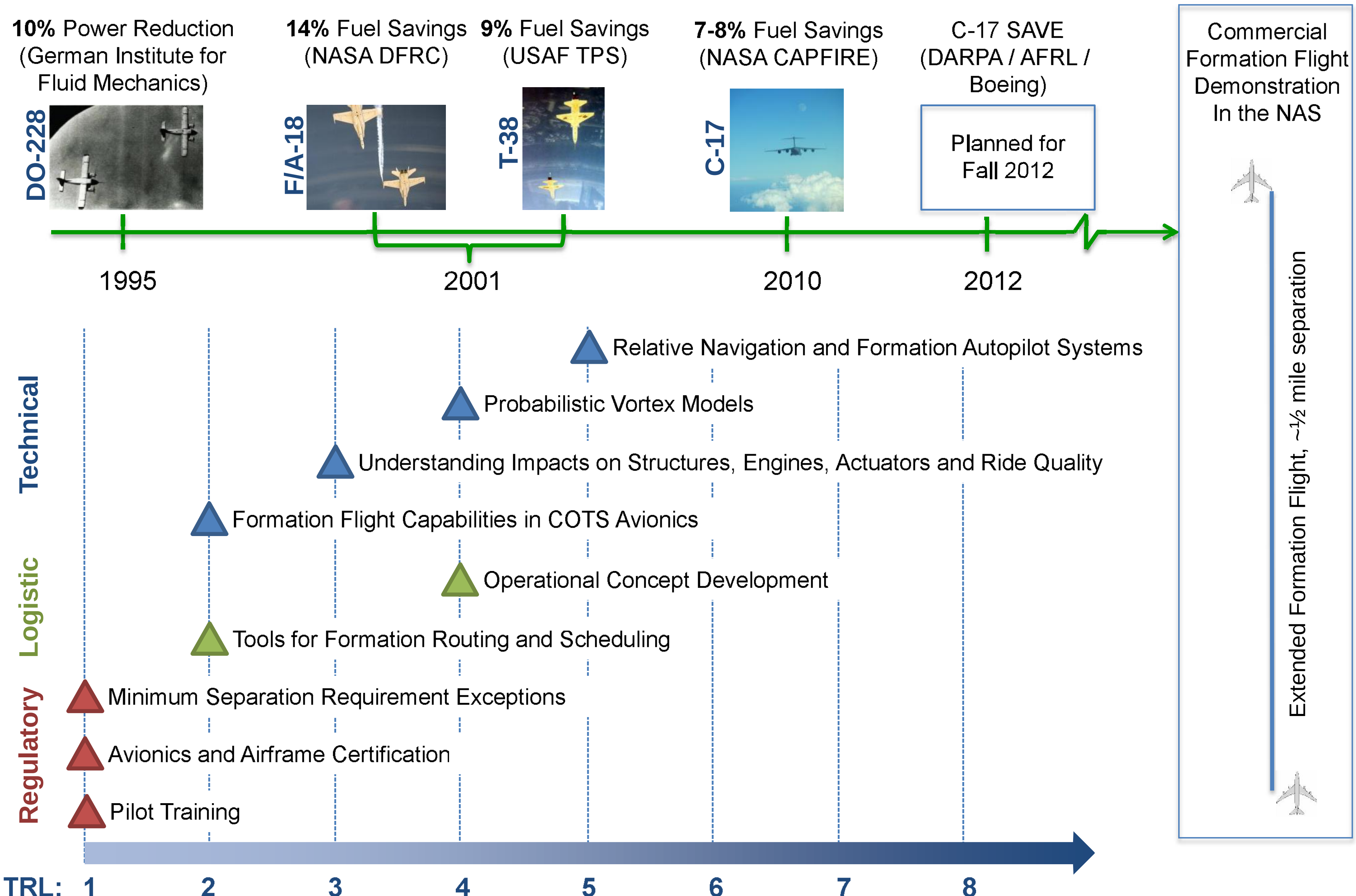
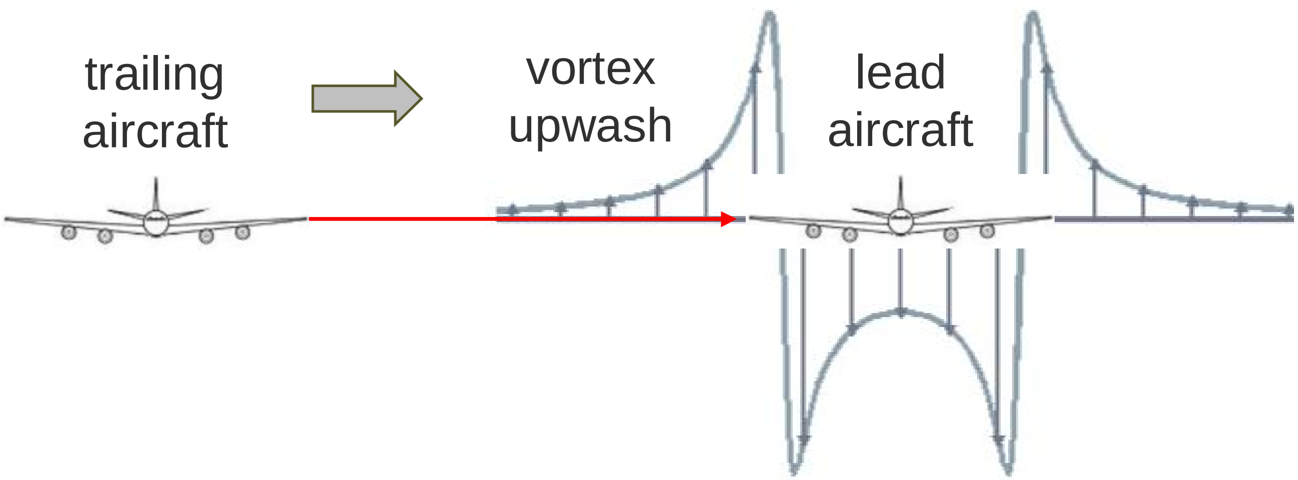
Roadmap to Formation Flight in the NAS



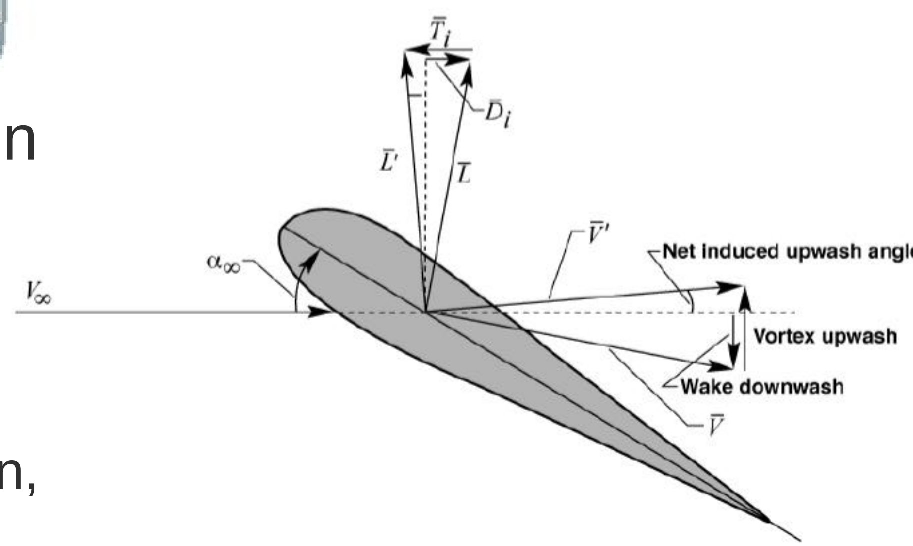
Formation Flight Aerodynamics

- ❑ In-trail flight within another aircraft's wingtip vortex upwash field can lower induced drag



NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC01-0328-3 Date: November 9, 2001 Photo by: Carla Thomas
Smoke generators show the twisting paths of wingtip vortices behind two NASA Dryden F/A-18 jets used in the Autonomous Formation Flight (AFF) program

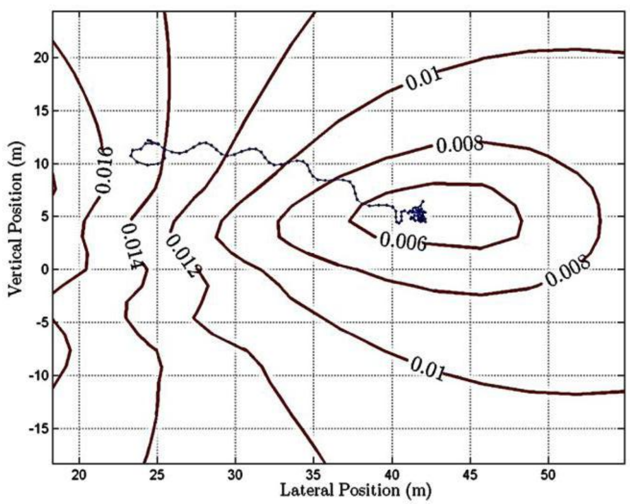
- ❑ The primary effects of flight within the wingtip vortex upwash are:
  - forward rotation of the lift vector, lowering induced drag
  - asymmetric span-wise lift distribution, causing roll trim imbalance



Formation Flight Optimization

Real-time determination of optimal relative position to the lead aircraft

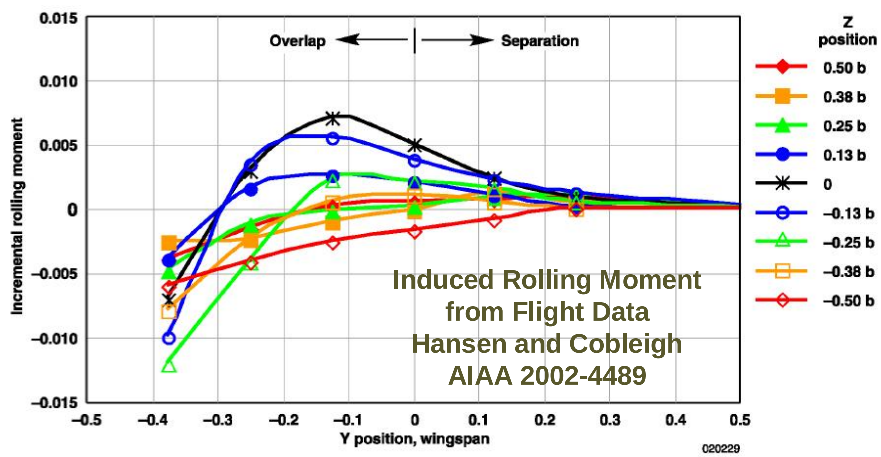
- ❑ lateral and vertical drift of the vortex field
- ❑ uncertainty regarding the best location within the upwash field



- ❑ Ryan and Speyer, ACC (2010)

Real-time determination of the optimal roll trim solution

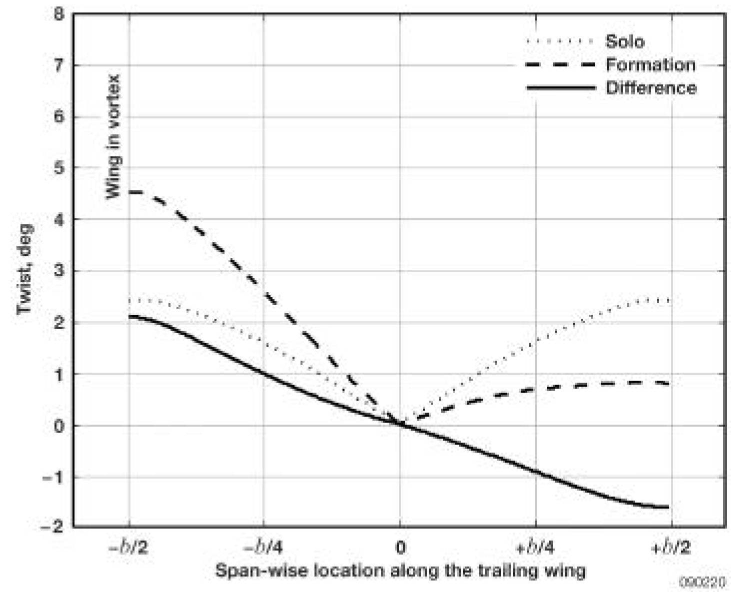
- ❑ traditional anti-symmetric roll trim using ailerons can lower the effectiveness of formation flight
- ❑ optimal deployment of trailing-edge wing surfaces can balance induced rolling moments and enhance drag reduction

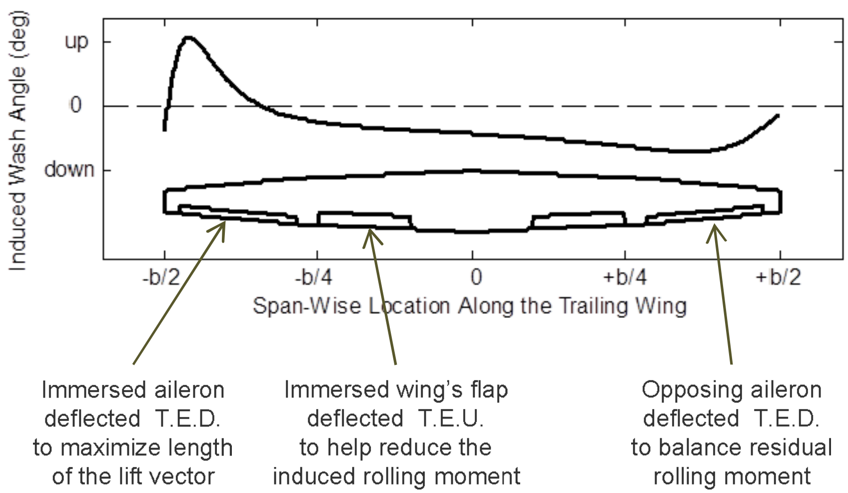


Roll Trim Optimization

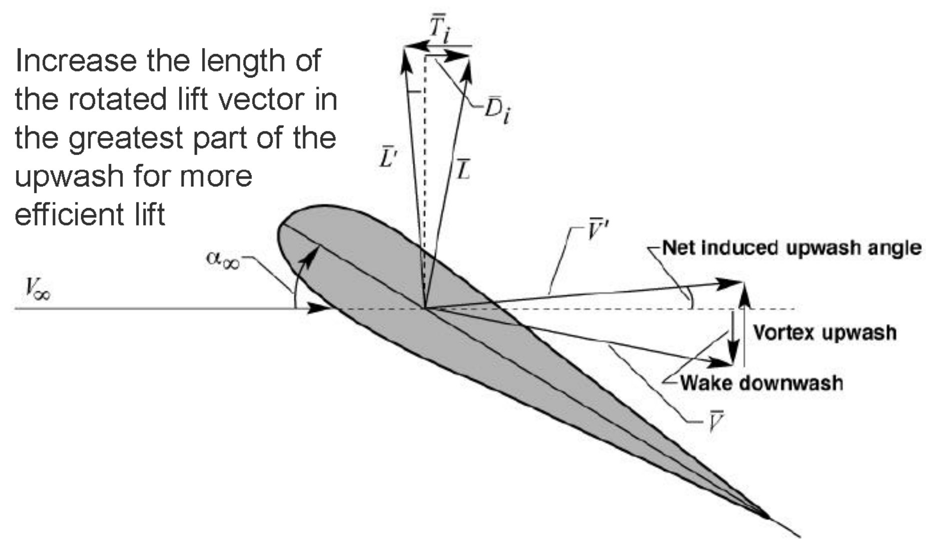
- Analysis of flexible unswept wings has shown that increased wing twist (leading-edge-up) corresponds to greater drag reduction in formation
- Trailing-edge control surfaces can be re-trimmed to alter the spanwise lift distribution and further reduce drag in an asymmetric upwash field

Hanson, NASA TM 2009-214649





Increase the length of the rotated lift vector in the greatest part of the upwash for more efficient lift



Peak-Seeking Algorithm

Approximation to the cost function Drag vs. Immersed Aileron Command

$$\Delta J_k = \Delta\delta_k^{ib} b_J + \tfrac{1}{2}\left(\Delta\delta_k^{ib}\right)^2 m_J \qquad where \qquad b_J = \frac{\partial J}{\partial \delta^{ib}}\ , \quad m_J = \frac{\partial^2 J}{\partial {\delta^{ib}}^2}$$

Multi-Sample Implementation

$$\Delta J_k = H_k \zeta_k + r_k \qquad \{\Delta J_k\} = \begin{bmatrix} \Delta J_{k,1} \\ \Delta J_{k,2} \\ \vdots \\ \Delta J_{k,N} \end{bmatrix} \qquad \{H_k\} = \begin{bmatrix} \delta_{k,1}^{ib} & \tfrac{1}{2}\left(\Delta\delta_{k,1}^{ib}\right)^2 \\ \delta_{k,2}^{ib} & \tfrac{1}{2}\left(\Delta\delta_{k,2}^{ib}\right)^2 \\ \vdots & \vdots \\ \delta_{k,N}^{ib} & \tfrac{1}{2}\left(\Delta\delta_{k,N}^{ib}\right)^2 \end{bmatrix} \qquad \zeta_k = \begin{bmatrix} b_J \\ m_J \end{bmatrix}$$

Kalman Filter Estimate of Gradient and Curvature

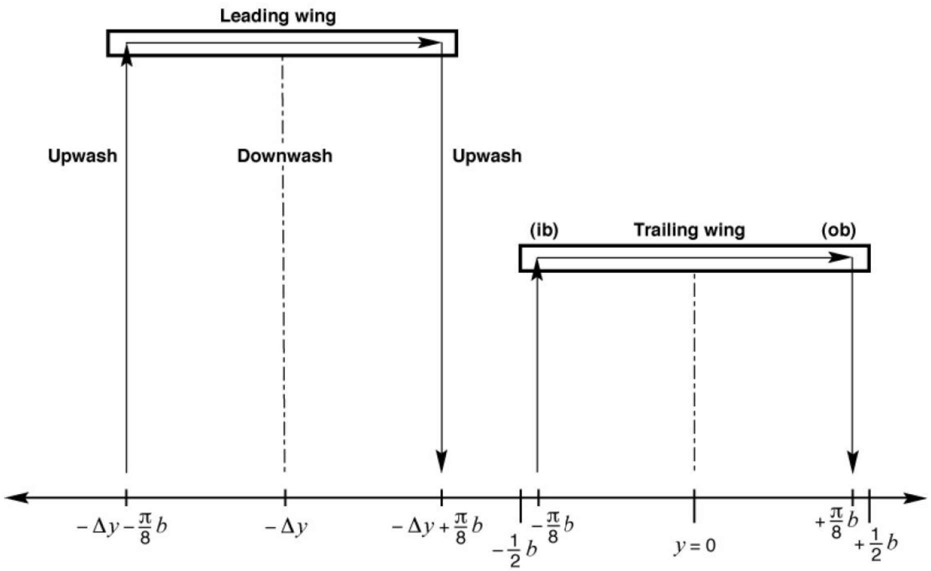
$$\zeta_k = \Phi\zeta_{k-1} + q_{k-1}$$

Newton-Raphson Command Update

$$u_k^{ib} = u_{k-1}^{ib} - \frac{\hat{b}_J}{\hat{m}_J} \quad \Longrightarrow \quad u_k = \begin{cases} u_{k-1} - k_u \dfrac{\hat{\zeta}_{k,1}}{\hat{\zeta}_{k,2}}, & \left|\hat{\zeta}_{k,1}\right| < \varepsilon_1, \quad \left|\hat{\zeta}_{k,2}\right| > \varepsilon_2 \\ u_{k-1} - k_u \hat{\zeta}_{k,1}, & \left|\hat{\zeta}_{k,1}\right| < \varepsilon_1, \quad \left|\hat{\zeta}_{k,2}\right| \le \varepsilon_2 \\ u_{k-1} - k_u \varepsilon_1 sgn\left(\hat{\zeta}_{k,1}\right), & \left|\hat{\zeta}_{k,1}\right| \ge \varepsilon_1 \end{cases}$$

Evaluation

- Aerodynamic Modeling
  - Horseshoe vortex models
  - Vortex strength calculated using the Kutta-Joukowski theorem



$$\Gamma \rho V b \frac{\pi}{4} = mg$$

  - Induced angle-of-attack calculated from the Burnham-Hallock tangential velocity profile

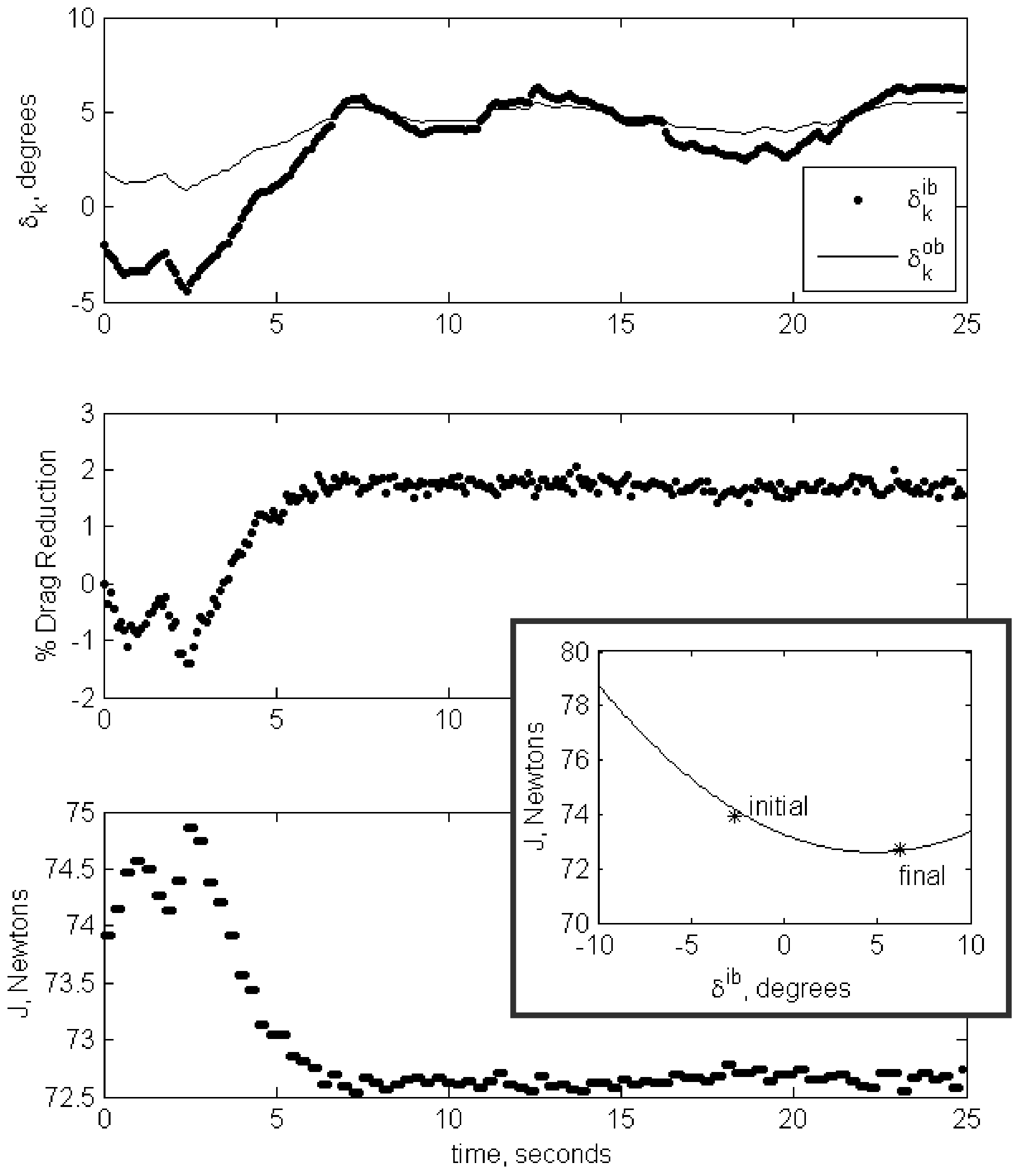
$$\alpha_i(y) = \frac{\Gamma}{2\pi V}\left[\frac{\Delta y - \frac{\pi}{8}b + y}{\left(\Delta y - \frac{\pi}{8}b + y\right)^2 + r_c^2} - \frac{\Delta y + \frac{\pi}{8}b + y}{\left(\Delta y + \frac{\pi}{8}b + y\right)^2 + r_c^2}\right]$$

Assumption
control surface drag is a function of the square of the deflection

- Control Mixing
  - Immersed aileron and flap commanded to equal but opposite deflections
  - Opposing aileron deflected as required to maintain roll trim

Results

- The peak-seeking algorithm located the drag-optimal trim solution
  - relative positions, orientations between the aircraft were fixed
  - trim surfaces were initialized to non-optimal values
  - trim commands were initialized to move the surfaces in the wrong direction
  - noise was applied to both measurements and commands
- Incremental reduction in total drag due to trim modification was approximately 2%



Summary

- Unique trim scheme for flight within asymmetric upwash fields
  - Traditional anti-symmetric aileron trim was found to reduce the effectiveness of formation flight for drag reduction
  - An alternate roll trim scheme was found to improve performance
  - A peak-seeking control algorithm was implemented to determine the optimal trim deflections in real-time
- Future Work
  - Confirm results with CFD analysis (in progress)
  - Remove the restriction of equal but opposite deflections for the immersed aileron and flap (increases dimensionality of the problem)
  - Integrate with a position-optimizing peak-seeking algorithm
  - Evaluate in a full 6DOF simulation
  - Confirm results through flight research

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