Formation Flight Optimization

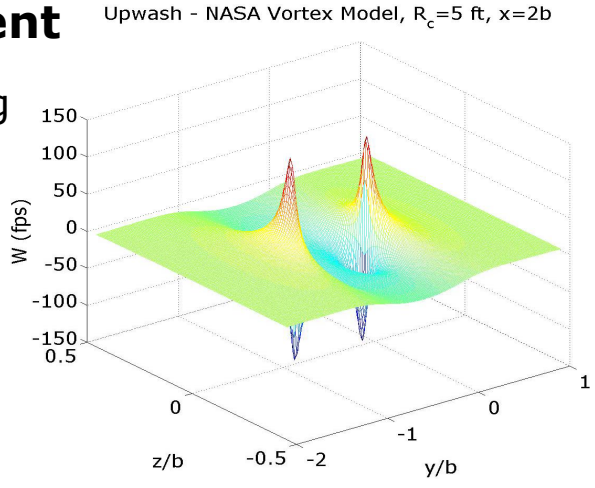
(Acknowledgement: Paolo Binetti)

Benefits of Formation Flight

- Reduction in power demand
- Alleviation of airspace congestion

Obstacles to Attainment

- Sensitivity to positioning
- Difficulty in precise measurements
- Absence of precise modeling



Optimal Formation Flight: Problem Formulation

- The effect of aerodynamic interference is primarily on the wingman
- The effect on the leader is marginal and beneficial

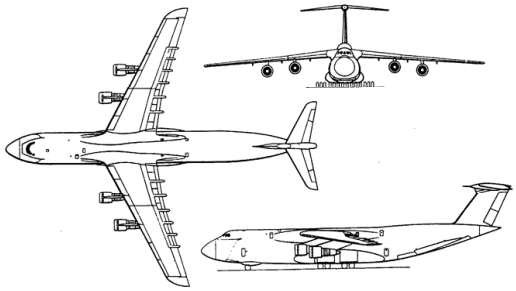
Thus, the natural solution is to have the control system on the wingman

Solution Steps

- Modeling for control design—aerodynamic interference as a multiple feedback nonlinearity
- Speed of convergence—through design of a new wake-robust autopilot
- Guarantees of convergence—through use of systematic design for extremum seeking
- Easily measurable performance objective—pitch angle of the wingman

Selection of the Problem

Why the C-5?



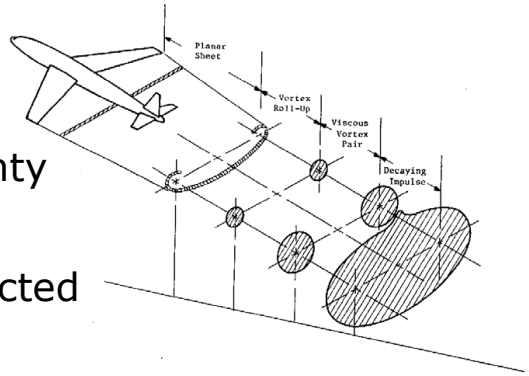
- Large savings in fuel consumption
- Representative of large transports
- They will be in service for the next 40 years
- Availability of wake data

Physics of Aircraft Wakes and Wake Modeling

- Wake structure—modeled as two NASA counter-rotating vortices

$$V_\theta(r) = \frac{\Gamma}{2\pi r}\frac{r^2}{\left(r^2 + r_c^2\right)},\ \Gamma = \frac{W}{\rho V_\infty b_{red}},\ b_{red} = \frac{\pi}{4}b$$

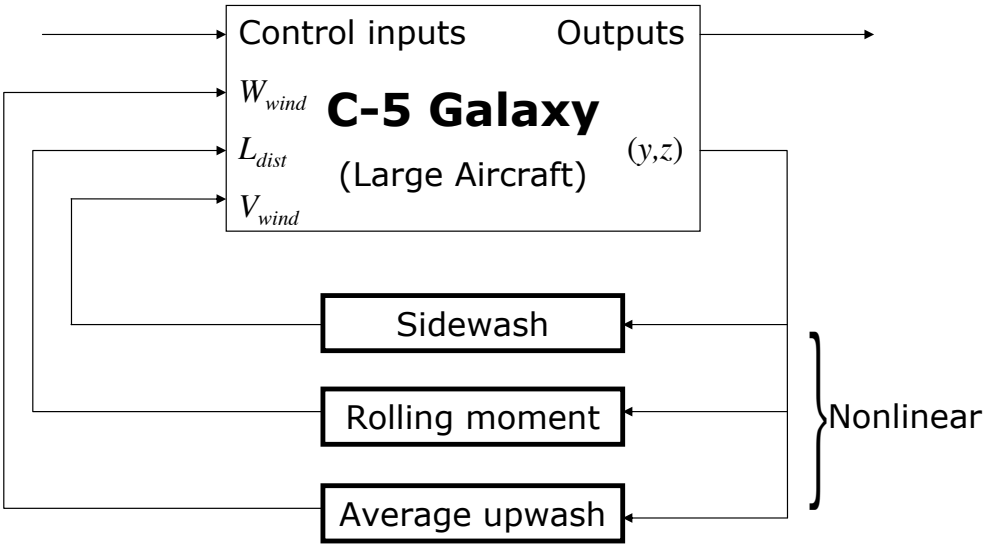
- Wake transport—
  a modeling uncertainty
- Wake decay—neglected



Aircraft in Free Flight

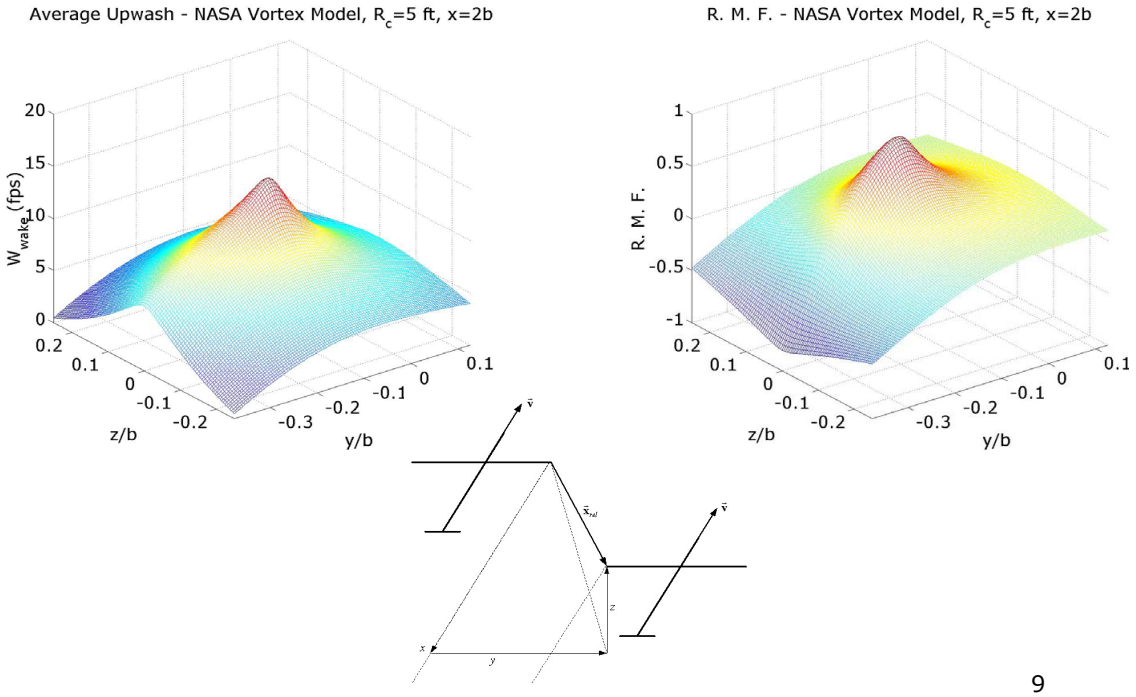
- Classic linear aircraft model with conventional controls
- Full state measurement with INS, DGPS and datalink between the aircraft
- Angle of attack is neither measured nor used for feedback

Aircraft in Wake

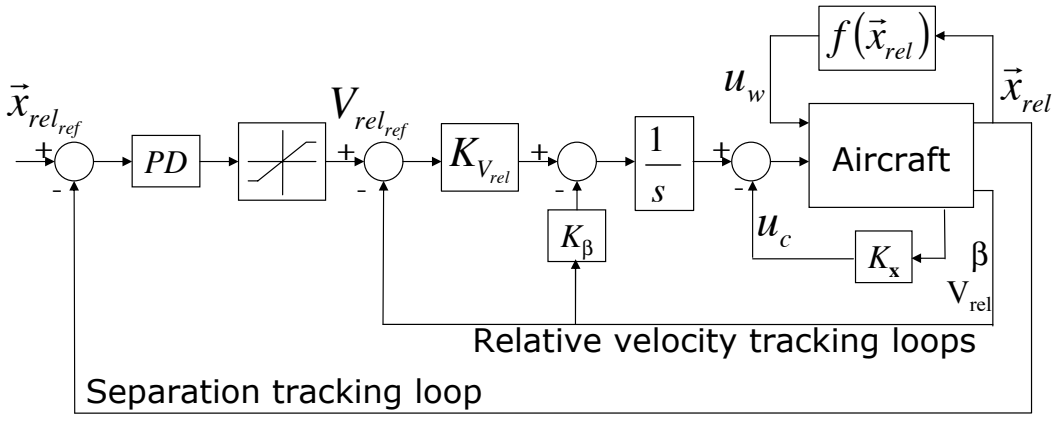


Speyer+Chichka: L_{dist}, V_{wind}– exogenous disturbances
W_{wind}– exogenous and measured

Average Upwash and Rolling Moment

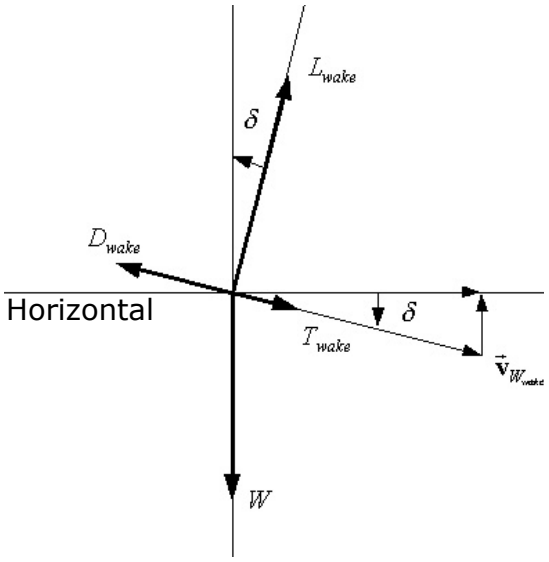


The Formation-Hold Autopilot



Steady-State Pitch Angle

- The wingman has to pitch down in the wake to maintain vertical equilibrium
- The more it pitches down, the more weight helps thrust balance drag



Extremum Seeking Objective

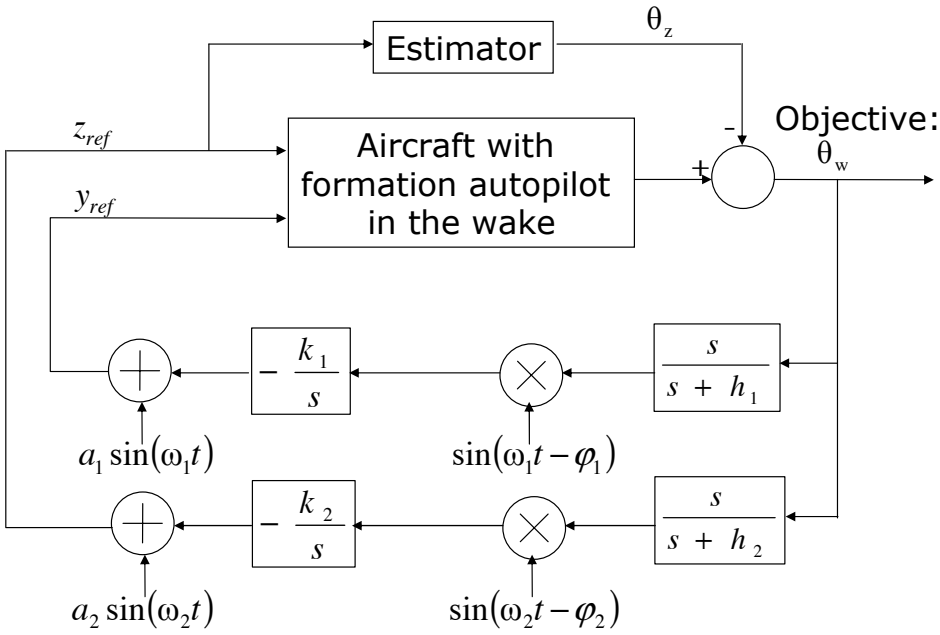
Choices:

- Static functions of the relative position
  - —Difficult to obtain measurements
  - —Permit use of extremum seeking design procedure
- Functions of aircraft state
  - —Measurements available
  - —Use of these does not straightaway permit use of extremum seeking design procedure.

Selection:

Pitch angle due to wake of the wingman

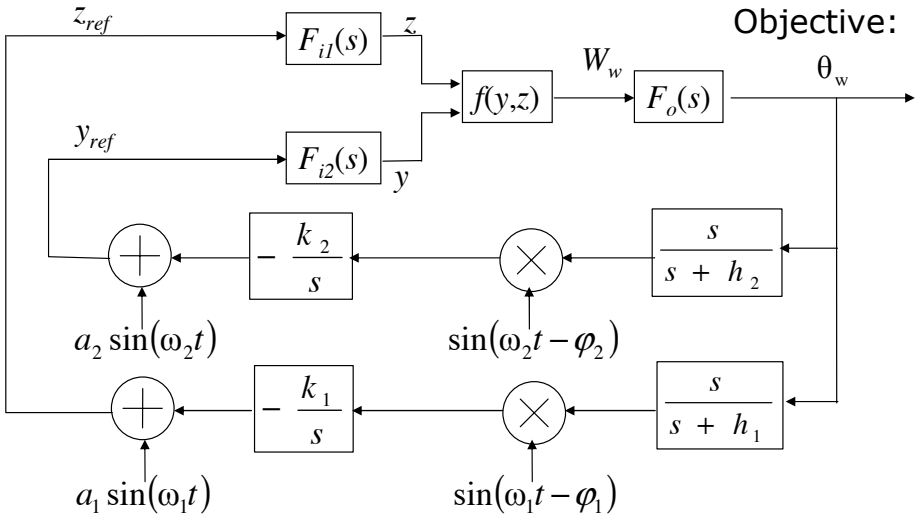
Extremum Seeking for Formation Flight



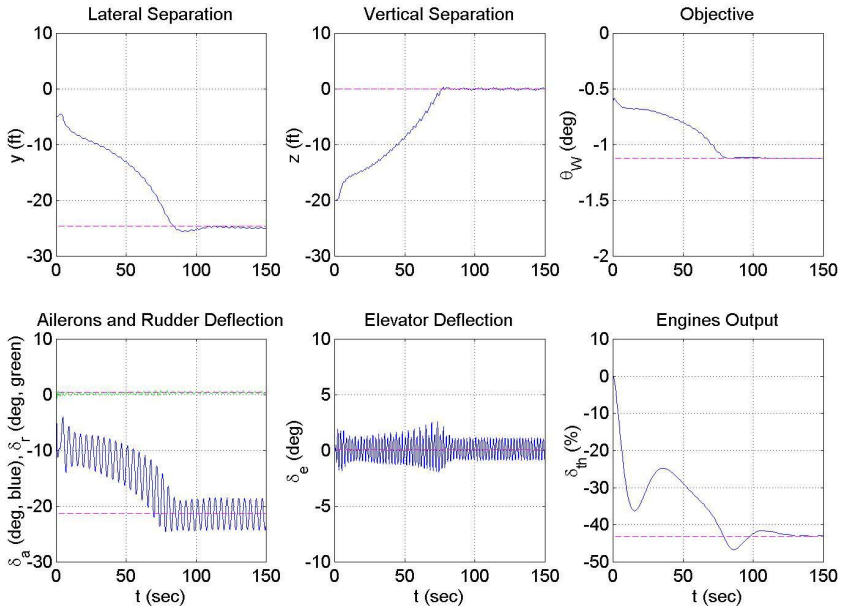
Transformation to Standard Scheme

- The autopilot is designed robust to aerodynamic interference
- The contribution to pitch angle due to vertical separation tracking is removed with an estimator
- This allows use of the corrected pitch angle in a standard extremum seeking scheme

Model for Extremum Seeking Design



Simulation in Calm Air …



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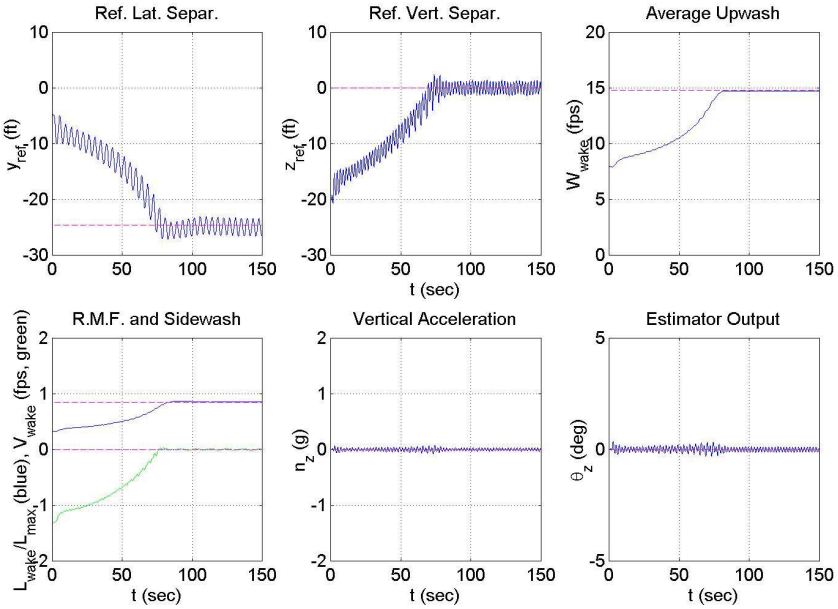
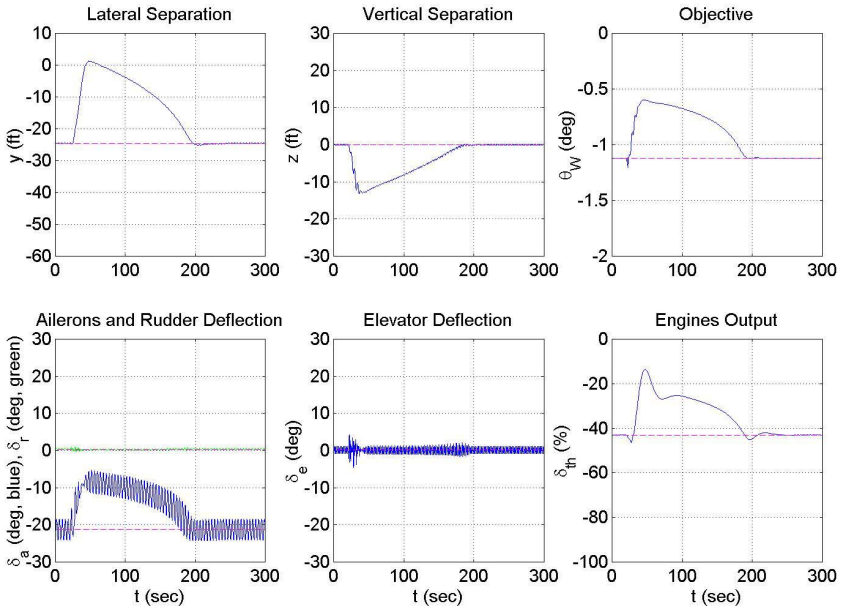


Simulation for brief CAT Encounter …



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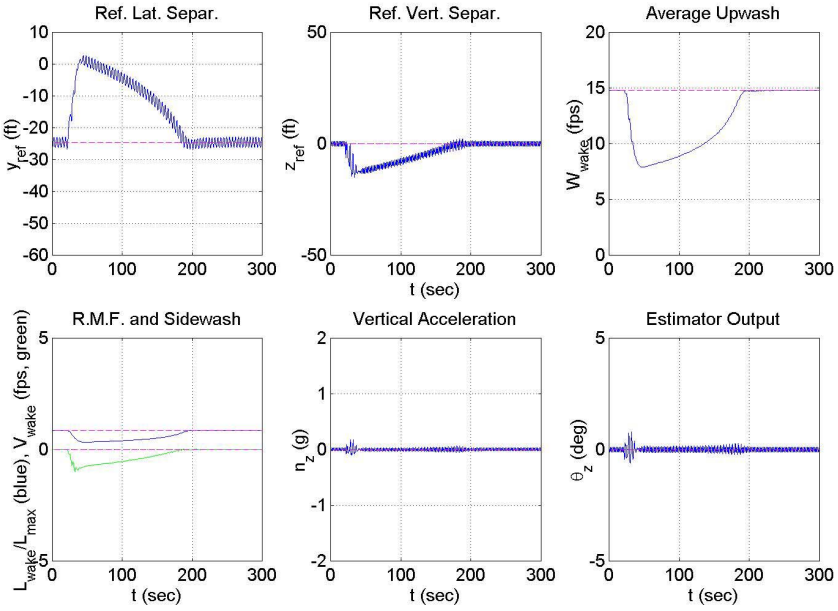


Previous Work

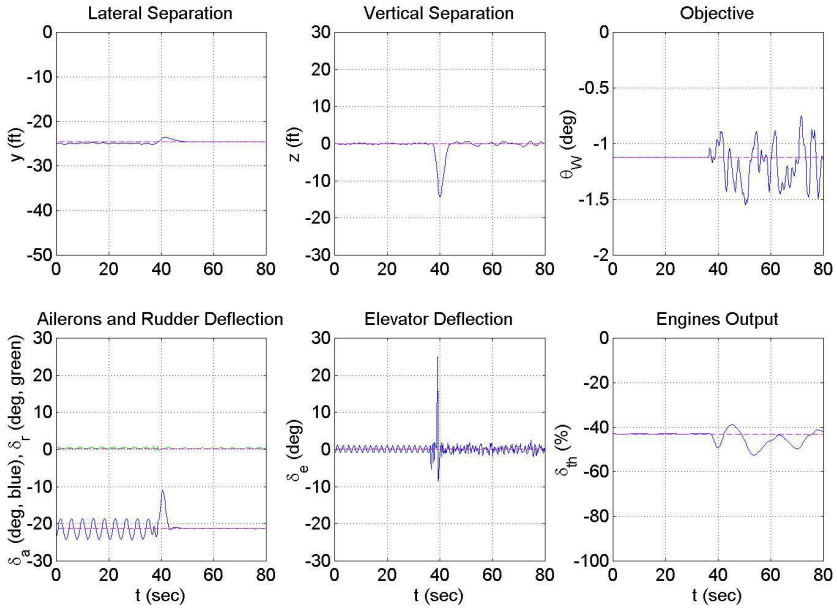
All control systems on wingman:

- Open loop formation-hold autopilot (Pachter, D'Azzo, Proud, 2001; Giulietti, Pollini, Innocenti, 2000; Schumacher, Singh, 2000)

- Discrete time extremum seeking
  - Objective: maximize induced upwash at aircraft centerline and aileron deflection (Hummel, 1996)

- Continuous time extremum seeking
  - Objective: maximize induced lift (Speyer, Chichka, Park, 1999)

Simulation with Persistent CAT …



… Simulation with Persistent CAT