Methods of Constructing a Blended Performance Function Suitable for Formation Flight

Jack Ryan

SciTech

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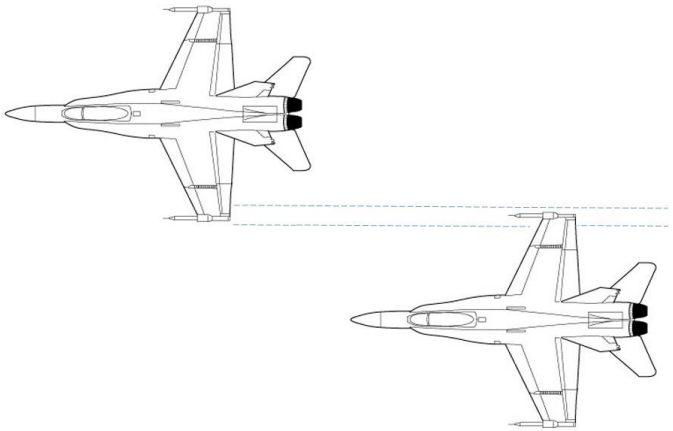
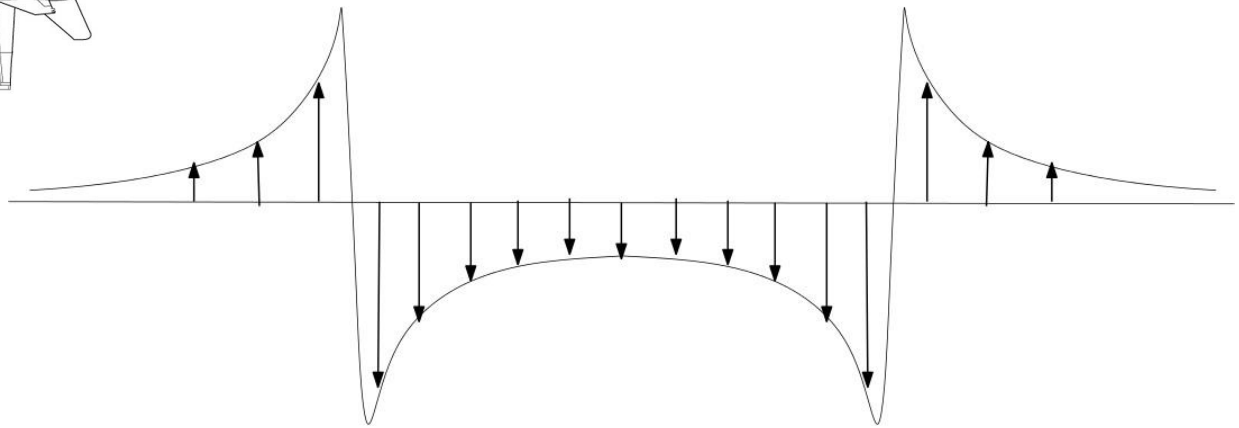
Formation Flight for Drag Reduction

- Promises fuel savings. 14% demonstrated in two-ship formation
- Trailing aircraft positioned in wingtip vortex of leading aircraft
- Optimal position is unknown a priori
- Substantial effect miles behind leading aircraft

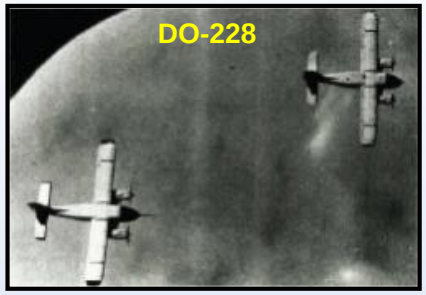




Formation Flight for Drag Reduction Flight Experiments

German Institute for Fluid Mechanics

1995



- Proof of concept
- No data link
- 10% power reduction
- Rudimentary peak-seeking control

NASA Dryden Flight Research Center

2001

- Research data link and autopilot
- 14% fuel savings (manual)
- Validated system requirements
- Detailed wake effect mapping

US Air Force Test Pilot School

2001

- Manually flown
- No data link or autopilot
- 9% fuel savings (2-ship)
- Inconclusive 3-ship evaluation

NASA DFRC / USAF FTC

2010

- Proof of extended formation concept
- Production military data link and autopilot
- 7-8% fuel savings (manual)

DARPA / AFRL / Boeing

2012 - 2013

- Modified C-17 autopilot
- Production military data link
- 10% fuel savings (autopilot)
- Wake avoidance algorithms

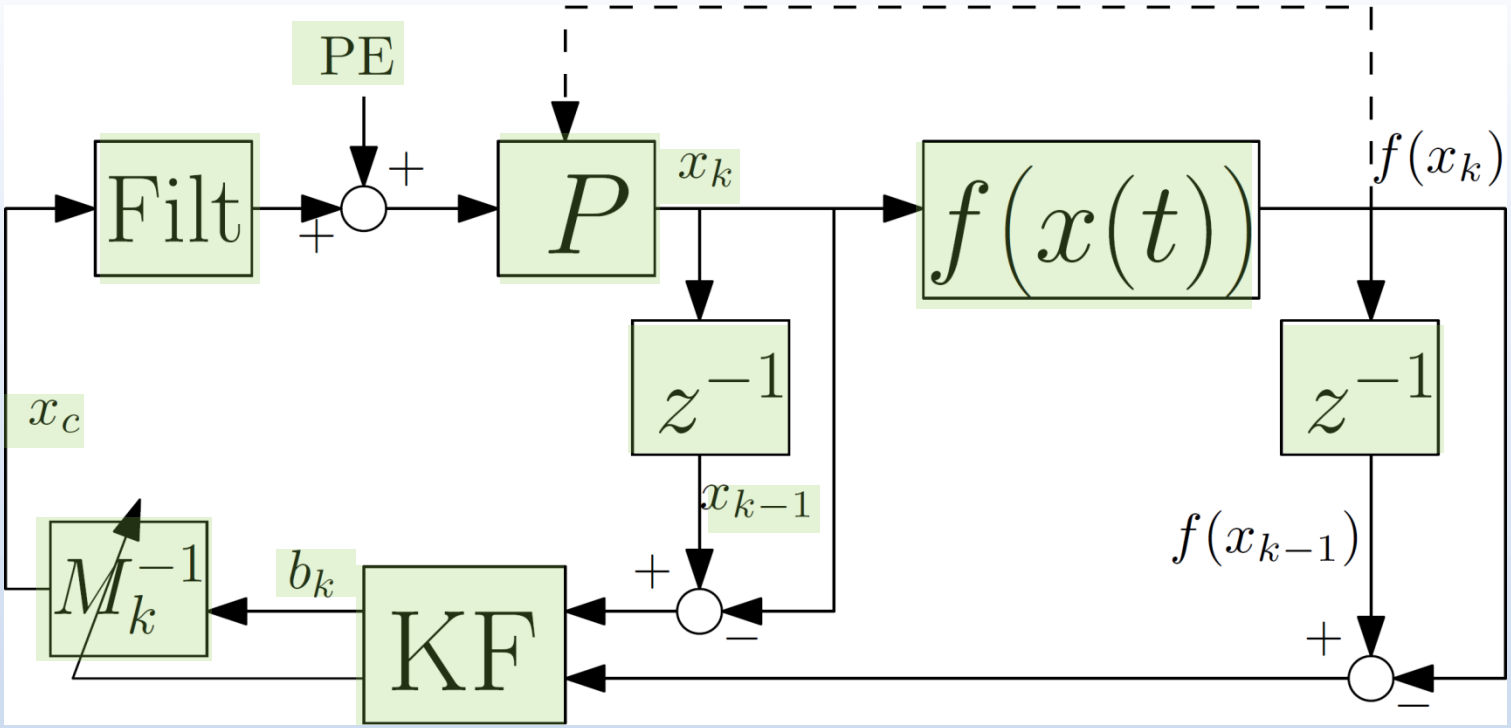
NASA Armstrong Flight Research Center

2013 - 2017

- Suitability of ADS-B for Wake Surfing
- Flight Data: Performance and Ride Quality
- Wake Estimation and Avoidance
- Airspace simulation study
- Hardware-in-the-loop multi-vehicle simulation
- Flight research

Extended Formation Flight Research

Extremum Seeking Control Method



Plant	P
Position	x_k
Performance function	$f(x(t))$
Delay Operator	z^{-1}
Kalman Filter	KF

Gradient estimate	b_k
Hessian estimate	M_k
Position command	x_c
Filter	Filt
Persistent Excitation	PE

Performance Function Candidates

Approaches:

- Lavretsky[10] minimizes throttle activity,
- Chichka[8] maximizes the induced rolling moment, and
- Binetti[9] maximizes the induced pitch angle.
- Others assume fuel flow is measureable

Draw backs

- The true fuel-flow extremum coordinates do not necessarily coincide with that of the analogous measurement,
- The measurement may possess undesirable characteristics such as significant lag.

Combine measurements into a Blended Performance Function

Blended Performance Function

Using a priori data:

Analogous measurements

$$\mathbf{P} = \left[\mathcal{P}_1(\mathbf{X})^T, \mathcal{P}_2(\mathbf{X})^T, \ldots, \mathcal{P}_m(\mathbf{X})^T\right]^T$$

Optimal weighting vector calculated

$$\hat{\mathbf{w}} = \arg_{\mathbf{w}} \min \left(\mathcal{D}(\mathbf{X}) - \mathbf{wP}\right)^T V^{-1} \left(\mathcal{D}((\mathbf{X}) - \mathbf{wP}\right)$$

Blended performance function formed

$$\mathbf{B} = \hat{\mathbf{w}}\mathbf{P}$$

If near real-time measurements are available:

Measured data fit to unimodal function.

$$\mathcal{D} = \frac{1}{2} X^T \mathbf{A_D} X + X^T \mathbf{b_D}$$

$$\mathcal{P}_i = \frac{1}{2} X^T \mathbf{A}_i X + X^T \mathbf{b}_i$$

Optimal weighting vector formed as previously shown.
Blended performance function formed.

$$\mathbf{B} = \sum_{i=1}^{m} \mathbf{w}_i \left(\frac{1}{2} X^T \mathbf{A}_i X + X^T \mathbf{b}_i \right)$$

Example

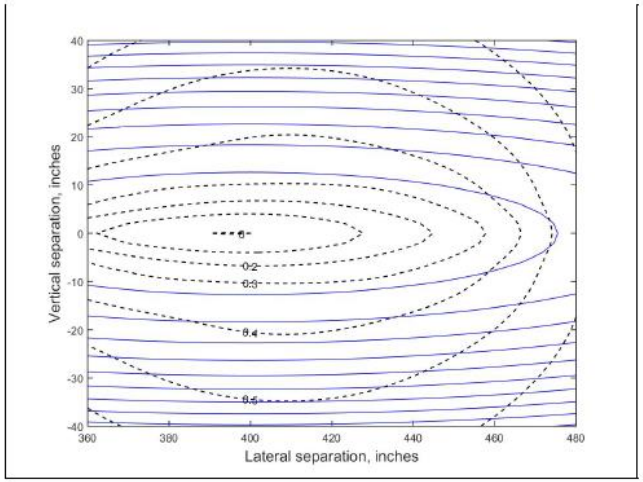
- Data taken from

[11]Vachon, M. J., Ray, R. J., Walsh, K. R., and Ennix, K., "F/A-18 Aircraft Performance Benefits Measured During the Autonomous Formation Flight Project," AIAA-2003-4491, 2002.

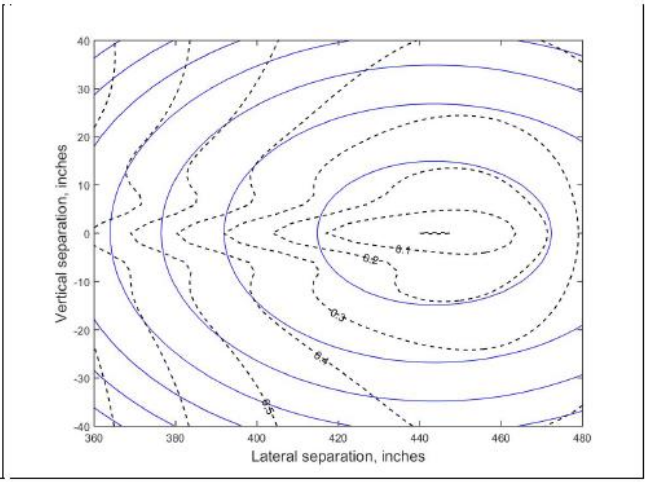
[12]Hansen, J. L. and Cobleigh, B. R., "Induced Moment Effects of Formation Flight Using Two F/A-18 Aircraft," AIAA-2002-4489, 2002.

- Method applied
  - Combining Rolling moment, Pitching moment, Yawing moment

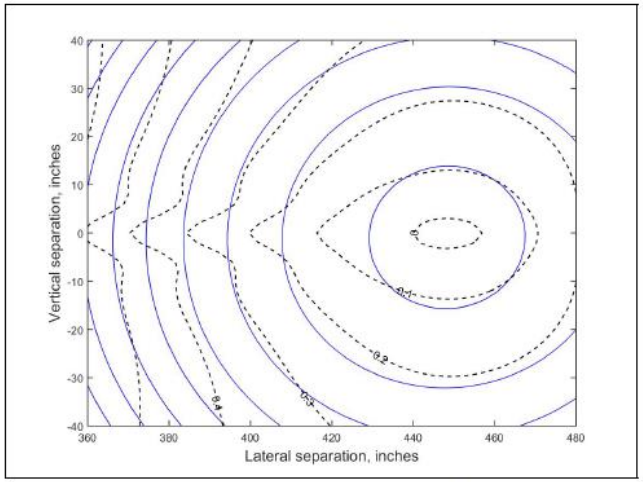
Results of fit to unimodal function



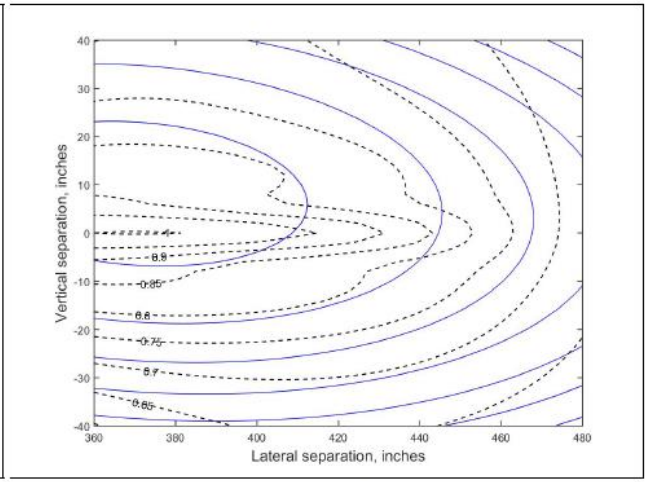
(a) Fuel flow performance function



(b) Rolling moment performance function

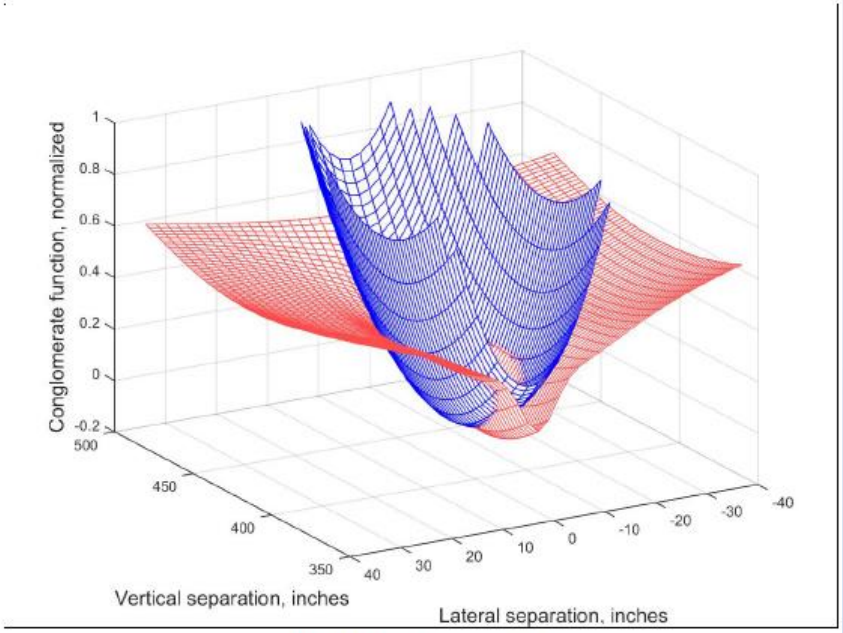


(c) Pitching moment performance function

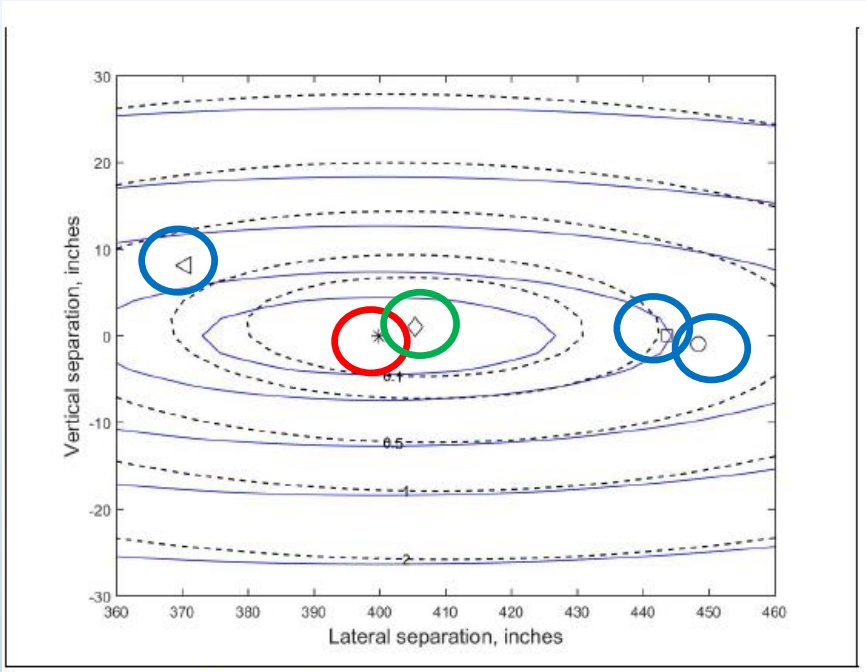


(d) Yawing moment performance function

Result of forming blended performance function

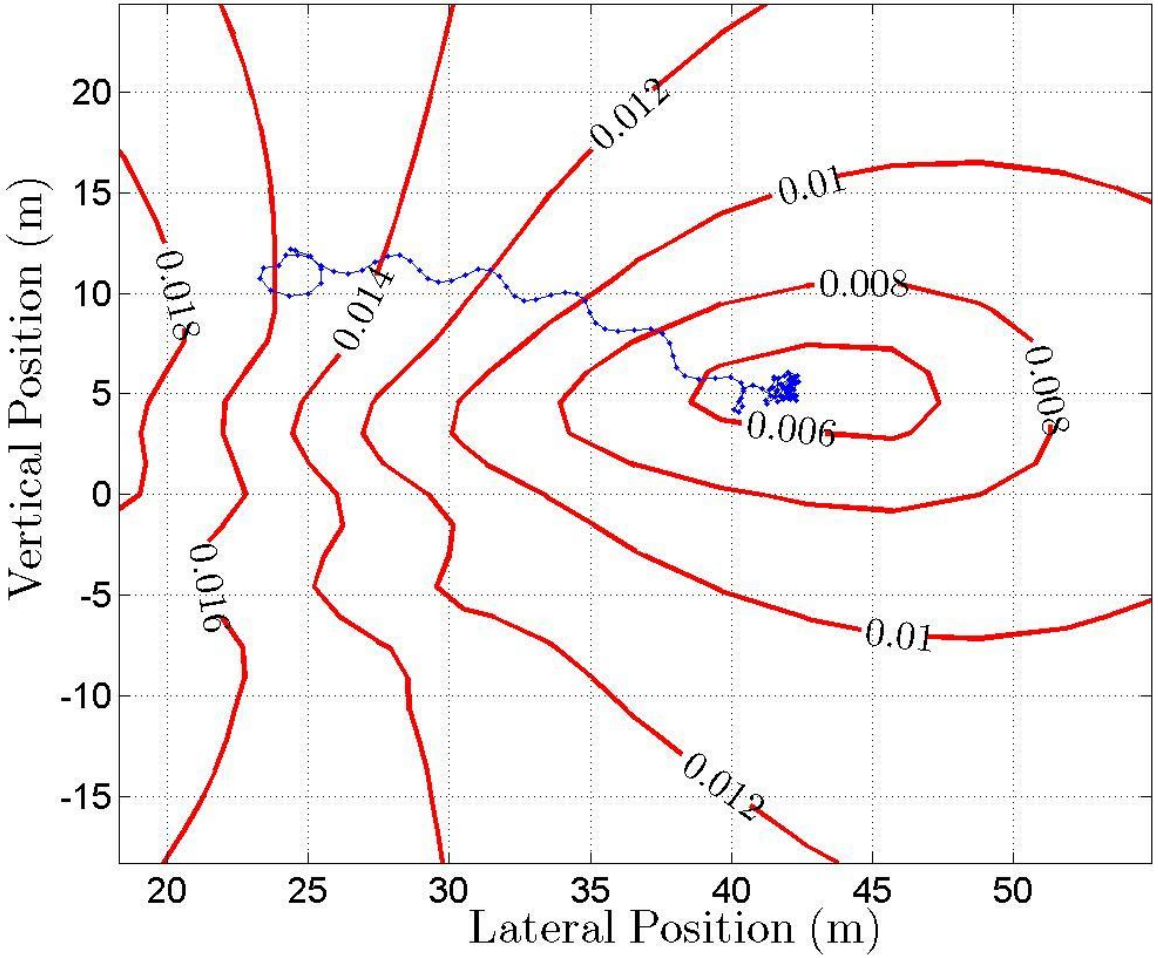


(a) Fuel flow optimization



(b) Fuel flow performance function

Extremum Seeking Algorithm on a Performance Function



Questions?