Methods of Constructing a Blended Performance Function Suitable for Formation Flight

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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

- **1995**
  - **German Institute for Fluid Mechanics**
  - DO-228
  - Proof of concept
  - No data link
  - 10% power reduction
  - Rudimentary peak-seeking control

- **2001**
  - **NASA Dryden Flight Research Center**
  - F/A-18
  - Research data link and autopilot
  - 14% fuel savings (manual)
  - Validated system requirements
  - Detailed wake effect mapping

- **2001**
  - **US Air Force Test Pilot School**
  - F-29
  - Manually flown
  - No data link or autopilot
  - 9% fuel savings (2-ship)
  - Inconclusive 3-ship evaluation

- **2010**
  - **NASA DFRC / USAF FTC**
  - C-17
  - Proof of extended formation concept
  - Production military data link and autopilot
  - 7-8% fuel savings (manual)

- **2012 - 2013**
  - **DARPA / AFRL / Boeing**
  - C-17
  - Modified C-17 autopilot
  - Production military data link
  - 10% fuel savings (autopilot)
  - Wake avoidance algorithms

- **2013 - 2017**
  - **NASA Armstrong Flight Research Center**
  - G-III
  - 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

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**Extended Formation Flight Research**
Extremum Seeking Control Method

Plant
Position
Performance function
Delay Operator
Kalman Filter

Gradient estimate
Hessian estimate
Position command
Filter
Persistent Excitation
Performance Function Candidates

Approaches:
- Lavretsky\textsuperscript{10} minimizes throttle activity,
- Chichka\textsuperscript{8} maximizes the induced rolling moment, and
- Binetti\textsuperscript{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.

\[ D = \frac{1}{2} X^T A_D X + X^T b_D \]

\[ P_i = \frac{1}{2} X^T A_i X + X^T b_i \]

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

\[ B = \sum_{i=1}^{m} w_i \left( \frac{1}{2} X^T A_i X + X^T b_i \right) \]
Example

• Data taken from


• 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?