Autonomous Formation Flight

Project Overview

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Overview of Experiment

- **Objectives**
  - Map the vortex effects
  - Formation Auto-Pilot Requirements
- **Two NASA F/A-18 aircraft in formation**
  - NASA 845 Systems Research Aircraft
  - NASA 847 Support Aircraft
- **Flight Conditions**
  - $M = 0.56$, 25000 feet (*Subsonic* condition)
  - $M = 0.86$, 36000 feet (*Transonic* condition)
- **Nose-To-Tail (N2T) Distances**
  - 20, 55, 110 and 190 feet
• Once on condition and in position,
  – Hold position for 30 sec of stable data
  – Engage auto-throttle velocity hold and maintain position for 20 sec of stable data
  – Laterally slide out of position (away from leader a/c), engage altitude-hold and stabilize outside of vortex for 20 sec

• F404 Engine In-Flight Thrust Instrumentation
  – Flight-test, volumetric fuel-flow meter installed ($WF_E$)
• Manufacturer’s In-Flight Thrust Model used to calculate thrust
Vortex Influence on Drag

M=0.56, 25,000ft 55’ N2T

M=0.86, 36,000ft 55’ N2T
Drag and Fuel-Flow Change with Longitudinal Spacing

0.56 M, 25,000 feet, Y=-18 to -8%, Z=-10 to 0%

Predicted CDi

Drag Reduction, %

WFE Reduction, %

Longitudinal Separation, %Span
Cruise Mission Demonstration

- Summary of cruise demonstration data
  - Simulated mission profile with independent chase of similar configuration
  - Estimated 110 nm of range improvement if formation cruise continued
Lessons Learned

- Controllable flight in vortex is possible with pilot feedback (displays)
- Position hold at best $C_D$, is attainable
- Best drag location is close to max rolling moment
  - Drag reductions demonstrated up to 22% ($W_{F_E}$ up to 20%)
- Induced drag results compare favorably with simple prediction model
  - ‘Sweet Spot’ (lateral & vertical area > 25%) is larger than predicted
- Larger wing overlaps result in sign reversals in roll, yaw
- As predicted, favorable effects degrade gradually with increased nose-to-tail distances after peaking at 3 span lengths aft
- Demonstrated - over 100 N mi (>15%) range improvement and 650 lbs (14%) fuel savings on actual simulated F/A-18 cruise mission
  - Significant results achieved despite problems with speed brake and positioning software
Presentation Outline

- Objectives of AFF Phase 1 Risk Reduction
  - Mitigation of risks associated with flying in the vortex
- Explanation of Test Point Matrix and Procedure
- Description of Data Analysis
  - Drag Model
  - Moment Model
- Drag Results
- Moment Results
- Lessons Learned
- Inquiries
Test Point Matrix

Overlap | Separation
---|---
-50% | 60%
-25% | 40%
0% | 20%
25% | 0%
50% | -20%
75% | -40%
100% | -60%

Vertical Position (Z)

Lateral Position (Y)

Follower aircraft wingtip positions
- 50% low
- 38% low
- 25% high
- 13% high
- level
- 13% low
- 25% low
- 38% low
- 50% low

Leader

Vertical Position (Z)
Basic theory states drag reduction, $\Delta D$, is caused by the rotation of the lift vector due to the upwash effect of the vortex.

- The associated lift increase is very small because $D \ll L$.

\[
\Delta D = \sin(\Delta \alpha) \ L
\]

\[
\Delta L = \sin(\Delta \alpha) \ D
\]

$\Delta \alpha = \tan^{-1}(W/V)$
Rationale for Test Point Procedure

- 30 sec of stable data needed to estimate vortex effects on moment model
- 20 sec of stable data (with auto-throttle) taken to improve estimated vortex effects on fuel-flow
  - auto-throttle difficult to set properly and hold separation
  - drag data shows little effect of auto-throttle during formation
- 20 sec of stable data (outside vortex) needed to calculate “baseline” (non-formation) drag values
  - auto-throttle responds to drag change after slide-out to maintain speed providing an accurate fuel-flow change
- This technique provides “back-to-back” comparisons of formation and baseline data
Lift and Drag Analysis

Flight Test Database

- Air Data
  - Air Data Computations
    - \(\alpha_{est.}\), Gross Weight, \(V_{inf}\), \(P_0\)
- Engine Data
  - In-Flight Thrust Model
    - \(F_G\), \(F_{RAM}\), \(F_{DRAG}\)
- INS Data
  - Wind Axis Accelerations
    - \(A_{XW}\), \(A_{YW}\), \(A_{ZW}\)

Performance Model
\[
D = \cos(\alpha_{est}) F_G - F_{RAM} - F_{DRAG} - F_{EX}
\]
\[
C_L, C_D
\]

Predicted Performance
\[
C_L, C_D
\]

Vortex Effect = Vortex – Baseline
\[
%\Delta C_D, %\Delta WFT
\]

\(F_{EX} = GW * A_{XW}\)
Moment Analysis

Flight Test Database

- Total Weight, $a_Y, p, q, r, q_{\infty}, S, b$
- Derivative of Rates
- F/A-18 Inertial Model
- Equations of Motion
- Vortex Model $C_l, C_m, C_n, C_Y$
- Vortex Effect = Vortex - Free Flight - SG Correction

Surface deflections, $\alpha, M, \text{TAS}, p, q, r, q_{\infty}, \theta, \psi$

- $\beta$ estimation using heading

F/A-18 Aerodynamic Database (look-up tables)

- Free Flight Model $C_l, C_m, C_n, C_Y$
Percent change in Fuel-Flow versus position at M=0.56, 25,000ft 55’ N2T
Vortex Influence on Induced Drag

Percent Induced drag change, M=0.56, 25,000 ft, 55 ft N2T

Measured induced drag change obtained from flight data

Predicted induced drag change using horseshoe vortex model*

*Adapted from: Blake, W., and Dieter Multhopp, AIAA-98-4343, August 1998
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Vortex Influence on $C_l$

Incremental Rolling Moment at $M=0.56$, 25000 feet, 55’ N2T
Vortex Influence on $C_n$

Incremental Yawing Moment at $M=0.56$, 25000 feet, 55’ N2T
Vortex Influence on $C_m$

Incremental Pitching Moment at $M=0.56$, 25000 feet, 55’ N2T
Pilot Response - Comparison
55’ N2T, Reference Condition

Wingtips Aligned, Level

25% wing Overlap, Level
Vortex Influence on $C_Y$

Incremental Side Force at $M=0.56$, 25000 feet, 55’ N2T