Autonomous Formation Flight

Project Overview

Presented by Jennifer Cole
with contributions from
Brent Cobleigh
Ron Ray
Jake Vachon
Kim Ennix

NASA Dryden Flight Research Center
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
Test Point Procedure and Flight Data

- 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%

Drag Reduction, %

WFE Reduction, %

CD

Data Range

Predicted CDi

WFE

Longitudinal Separation, %Span

0% -100% -200% -300% -400% -500% -600% -700% -800% -900% -1000%

-30% -20% -10% 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

-50% -40% -30% -20% -10% 0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
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% ($WF_E$ 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

Vertical Position (Z)

Lateral Position (Y)

Follower aircraft wingtip positions

Leader

50% low
38% low
25% high
13% high
level
13% low
25% low
38% low
50% low

-60% -40% -20% 0% 20% 40% 60%

-50% -25% 0% 25%
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 $D \ll L$.

$$D_{FF} = \cos(\Delta \alpha) \, D' - \Delta D$$

$$\Delta D = \sin(\Delta \alpha) \, L$$

$$D' \sim D$$

$$L_{FF} = \cos(\Delta \alpha) \, L' + \Delta L$$

$$\Delta L = \sin(\Delta \alpha) \, D$$

$$L' \sim L$$

$$\Delta \alpha = \tan^{-1}\left(\frac{W}{V}\right)$$
• 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

Engine Data

INS Data

Air Data Computations
\( \alpha_{\text{est}}, \) Gross Weight, \( V_{\text{inf}}, P_o \)

In-Flight Thrust Model
\( F_G, F_{\text{RAM}}, F_{\text{DRAG}} \)

Wind Axis Accelerations
\( A_{XW}, A_{YW}, A_{ZW} \)

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

Predicted Performance
\( C_L, C_D \)

Vortex Effect = Vortex – Baseline
\( \%\Delta C_D, \%\Delta WFT \)

\( F_{\text{EX}} = G W \times A_{XW} \)
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
\( C_l, C_m, C_n, C_Y \)

Surface deflections, \( \alpha, M, \)
TAS, \( p, q, r, q_\infty, \theta, \psi \)

\( \beta \) estimation using heading

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

Free Flight Model
\( C_l, C_m, C_n, C_Y \)

Vortex Effect = Vortex - Free Flight - SG Correction
Vortex Influence on Fuel-Flow

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