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
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, %

Longitudinal Separation, %Span

Predicted CDi

Data Range

CDi

CD

WFE
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

Overlap  Separation

Above

Below

-50% -25% 0% 25% 60%

-60%

-40%

-20%

0%

20%

40%

60%

-50% -25% 0% 25%

Vertical Position (Z)

Follower aircraft wingtip positions

Leader

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

Lateral Position (Y)

% Wingspan

-50 -38 -25 -13 0 13 25
Vortex Influence on Lift and Drag

- 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 $D << L$

\[ \Delta D = \cos(\Delta \alpha) D' - \Delta D \]
\[ \Delta D = \sin(\Delta \alpha) L \]

\[ D' \sim D \]

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

\[ L' \sim L \]

$\Delta \alpha = \tan^{-1}(W/V)$

Figure not to scale
Test Point Procedure, Continued

- **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
\( \alpha_{\text{est}} \), Gross Weight, \( V_{\text{inf}} \), \( P_o \)

Engine Data

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

INS Data

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

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

Predicted Performance
\( C_L, C_D \)

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

\( F_{\text{EX}} = GW \cdot A_{XW} \)
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
**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
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Vortex Influence on $C_I$

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

[Graphs showing pilot response comparison]
Vortex Influence on $C_Y$

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