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**
  - $M = 0.56$, 25,000 feet (**Subsonic** condition)
  - $M = 0.86$, 36,000 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%

Drag Reduction, %

WFE Reduction, %

Longitudinal Separation, %Span

Predicted CDi

Data Range
• 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
- Above
- Below
- 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
- % Wingspan
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 $D \ll L$.
• **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, $V_{inf}$, $P_o$
  - Predicted Performance: $C_L$, $C_D$
- **Engine Data**
  - In-Flight Thrust Model: $F_G$, $F_{RAM}$, $F_{DRAG}$
  - Performance Model:
    $$D = \cos(\alpha_{est}) F_G - F_{RAM} - F_{DRAG} - F_{EX}$$
    - $C_L$, $C_D$
  - Vortex Effect = Vortex – Baseline
    - $\%\Delta C_D$, $\%\Delta WFT$
- **INS Data**
  - Wind Axis Accelerations: $A_{XW}$, $A_{YW}$, $A_{ZW}$
  - $F_{EX} = GW \times A_{XW}$
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
Incremental Yawing Moment at $M=0.56$, 25000 feet, 55’ N2T

Vortex Influence on $C_n$
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