Autonomous Formation Flight

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Air Transportation Systems Architecting

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Overview

Autonomous Formation Flight: NASA RevCo Program

Boeing is currently engaged with NASA Dryden Flight Research Center on a technically ambitious project, Autonomous Formation Flight (AFF). The project’s primary goal is to investigate potential benefits of flying aircraft in the aerodynamic wake vortex emanating from a lead aircraft’s wing tip. Initial analytic studies predict that a trailing aircraft may experience drag reductions of 10% or more by gaining additional lift in the updraft portion of the lead’s wake vortex. The technical challenge is to be able to find the optimal position within the vortex to fly, then hold that position consistently in what is an extremely turbulent flow field. We know that pilots have been able to do this in the past, but the task involves a very high workload.

The Autonomous Formation Flight system marries an extremely robust flight control and guidance system with a close-coupled GPS/IMU placed on two F-18s. Inter-ship communication allows the multiple GPS/IMU systems to share state data and through and extended Kalman filter technique, they yield a differential carrier phase solution. They resolve the relative position accuracy between the aircraft in formation to less than 10 cm. Through shared state data, the guidance systems aboard both F-18s resolve coordinated trajectories that permit the aircraft to maintain formation. The trailing aircraft is thus capable of maintaining its position within the lead aircraft’s wing tip vortex with extremely high accuracy.

The implications and applications of this technology are far reaching, not just for fuel economy but for other future applications such as aerial refueling, aircraft logistics, air traffic control, and carrier landing systems.
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Test flights began in August and culminated with a drag-reduction demonstration flight in the beginning of December 2001. A total of 28 flights were accomplished, and the full test point matrix was accomplished at both $M=0.56$, 25000 feet, and $M=0.86$, 36000 feet. 415 test points were flown. 5 Project Pilots were involved in AFF Phase One Risk Reduction.
Autonomous Formation Flight

• **Background**
  – Many bird species fly in “V” formation to take advantage of the up-wash field generated by adjacent birds, resulting in less energy expended.
  – Analytical studies and recent AFF flight tests validate these observations.

• **AFF Objectives**
  – Validate drag reduction concept and prediction tools of a system of aircraft in formation in the flight environment
  – Develop and evaluate sensor and control methodologies for autonomous close formation flight

• **Approach**
  – Flight test autonomous station keeping control laws of pair of F-18 aircraft.
  – Validate drag benefits and wing tip vortex behavior using piloted flight tests.
  – Develop and validate advanced relative GPS system capable of 10 cm relative position accuracy.
  – Integrate updated sensors and advanced formation control laws to perform autonomous station keeping within the vortex wake of a lead aircraft.

• **Benefits**
  – Potential commercial fuel savings of $0.5 to 1 million per year per trailing aircraft.
  – Application to UAV Swarming, & Aerial Refueling.
Primary Project Objective: Demonstrate Drag Reduction

Drag Reduction Through Formation Flight

For a transcontinental route, per trailing aircraft per year

$\Delta C_{D_i} = 35\%$
$\Delta C_D = 10 - 15\%$
$\Delta w_f = 10 - 15\%$

Safety
Reliability
Feasibility
Ready for Commercial Application

Theory - 50% Reduction in Induced Drag
Experimental - Early F-18 Data Shows 10-15% Total Drag Loss

TRL LEVEL 3

TRL LEVEL 7

$\Delta S = 0.5M$
$\Delta CO_2 = 10M lbs$
$\Delta NO_x = 0.1M lbs$
Autonomous Formation Flight Program
NAS4-00041 TO-104

Autonomous Formation Flight Partners and Responsibilities

NASA DFRC
- Overall Project Management
- Flight Safety and Mission Assurance
- GN&C Design and Analysis
- Verification and Validation Testing
- Flight Vehicle Integration
- Flight Test Operations

The Boeing Company
- Operational Concept
- GN&C Design and Analysis
- Aerodynamic Models and Simulations
- Formation Flight Information System (FFIS) (Integrated GPS & IMU).
- Formation Flight Computer System (FFCS).
- Formation Flight Control System Software.
- Integration with F-18 Flight Control Computer (PSFCC) Systems.

UCLA
Theoretical Research
- GN&C Design Methodologies
- GPS Algorithm Development
- Advanced System Concepts

Project Has NASA RevCon Status And Is Reported At The Congressional Sub-Committee Level
Revolutionary Technologies

Develop Three Key Technologies:

- Relative Navigation
  - 1st Close Coupled Differential Carrier Phase GPS-IMU capable of 10 cm relative accuracy.

- Vortex Induced Drag Reduction
  - The 1st operational formation drag reduction tests under complete auto-pilot control.

- Formation Control
  - The 1st coordinated formation flight of an auto-pilot controlled aircraft to within sub-meter accuracy.
AFF Development Roadmap

Phase 0

- AFF Station Keeping
- Funding: $13M Over 4 Years

Phase 1

- Aero-Vortex Mapping, Bandwidth Assessment, Differential Carrier Phase GPS/INS Demo
- AFF Drag Reduction Flight
- Test Demonstrate Complete Functionality of the AFF System, Flight Control Avionics, Differential Carrier Phase GPS/INS Hardware and Aircraft Telemetry

Phase 2

- AFF Transport Flt Conditions & Ops Demo
- Autonomous Aerial Refueling
- AFF Optimal Performance Demo

Timeline:
- Phase 0: 12/00
- Phase 1: 06/01
- Phase 2: 07/02
- 2000
- 2001
- 2002
- 2003

Autonomous Formation Flight Program
NASA-00041 TO-104
Program Approach

Create the Autonomous Formation Flight Project (AFF) Using two NASA F/A-18 airplanes

- Phase 0 - Demonstrate Autonomous Station-Keeping
  - Fall of 2000
- Phase 1 Risk Reduction - Map the Vortex Effects
  - Fall of 2001
- Phase 1 - Autonomous Formation Flight
  - Incomplete
Lift and Drag Force Basics

• Aerodynamic forces on an aircraft
  – Drag is parallel to flight path
  – Lift is perpendicular to flight path
  – Lift is an order of magnitude greater than drag
The most common theory on Formation Flight states that “drag reduction” is actually obtained due to a rotation of the lift vector that occurs while a trailing aircraft is in the upwash field of the lead aircraft. The figure above illustrates this concept showing how the baseline (non-formation flight) lift and drag values, L and D, rotate by the change in angle of attack, \( \Delta \alpha \), due to the upwash effect while in the vortex flowfield.

Because of traditional bookkeeping methodology, the actual lift and drag values are maintained relative to the vehicle’s global, rather than local, flight path during formation flight. The term, \( \Delta D \), is used to represent the drag change due to the rotation of the lift force from L to L’. The drag during formation flight, DFF, is obtained by:

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

where:
\( \Delta D = \sin(\Delta \alpha) L \)

In a similar manner the term \( \Delta L \), is used to represent the lift change due to the rotation of the drag force from D to D’. The lift during formation flight, LFF, is obtained by:

\[
LFF = L' \cos(\Delta \alpha) + \Delta L
\]

where:
\( \Delta L = \sin(\Delta \alpha) D \)

Because lift tends to be an order of magnitude greater than drag (L>>D), drag is influenced significantly more by the rotation effect than lift is. A considerable reduction in drag can be realized by a small upwash angle, while an insignificant increase in lift occurs.

\[
\text{Resultant Aerodynamic Force:} \quad \sqrt{L'^2 + D'^2}
\]
F-18 Wing Vortices & Cross Flow Gradient
3-View, F/A-18E: Mach 0.85, AOA 3deg

Trailing Aircraft In This Wake Experience
An Asymmetric, Turbulent Flow Field

Contours of Pressure Coeff (Cp)
0.00
-0.25
-0.50

CFD Results: Courtesy of Dave Stookesberry, Boeing STL.
Vortex Influence on Induced Drag

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

Calculated induced drag change obtained from flight data, with similar results at ALL flight conditions!

Rapid Drag Increase

Flight Test

The flight results also measure higher drag increases inboard than predicted, but this is also the region where data quality is worse because the points are more difficult to fly. Some of these points were very unstable as the vortex seemed to impinge on the tail or other surfaces causing the trailing aircraft to continually wander from the target position. Higher trim drag effects could also contribute to the large drag increases. The line of zero benefit is also located further outboard than predicted. These results indicate substantially higher sensitivity to lateral positioning inboard of the sweet spot than predicted. Small changes in lateral positioning in this region can result in large changes in benefits (drag increase). The overall vertical sensitivity is less than predicted; the overall shape of the region of most benefit is more round than oval as predicted for a generic wing. Induced drag results are similar at all flight conditions and separation distances:

The induced drag change measured at the transport flight condition (not presented) correlated very well to those obtained at the reference condition shown above in both shape and magnitude. This is a significant result indicating an accurate model of induced drag change could potentially be used to model drag benefits at other conditions.

*Adapted from: Blake and Multhopp, AIAA-98-4343, August 1998.*
F-18A Wake Vortex Characteristic Aero-Increments Vary Greatly With Offset Distance \( \Delta Y \) Between A/C

**Induced Yawing Moment (\( \phi = 0 \))**

**Induced Pitching Moment (\( \phi = 0 \))**

**Induced Rolling Moment (\( \phi = 0 \))**

**Drag Reduction (\( \phi = 0 \))**

Optimal, Min Drag Near Point Where Wingtips Align

Linear Panel Method Results
Two NASA F-18 aircraft were used for this research. Both aircraft were equipped with instrumentation and telemetry systems as well as identical GPS receiver units. The Systems Research Aircraft (SRA) was designated as the follower and outfitted with the formation autopilot, consisting of a research computer and specially modified flight control computers. A NASA chase aircraft acted as the formation lead. A third NASA chase aircraft was occasionally used for photographic documentation of the experiment.
NASA’s F-18s Are Uniquely Modified Production Versions

- Fully Instrumented Engines, Inlets, & A/B
- AFF Avionics Tied Into F-18 A/C Bus Directly
- Boom & Drogue Refueling
- F-18 A Production Equipped Avionics, Digital 4x FCS, GPS, RLG-IMU.
- AFF 2 Mb/s 9GHz Inter-Ship LAN
- NASA-EAFB Flight Test Telemetry
AFF System H/W Couple The Aircraft Through A Wireless LAN

Pilot Interface

CPB \rightarrow FFCS \rightarrow AMUX \rightarrow PSFCC

Outer-Loop Guidance and Control
Multiplex / Filter
Inner-Loop Control Envelope Monitoring

Differential Carrier Phase GPS & Inter-ship Communication

Wireless LAN Connection (9 GHz, 2.1 MB/sec)

FFIS

Trail Aircraft
Lead Aircraft

PBD

Cockpit Interface

ISMS

Independent Safety System

AMUX

PSFCC

FFCS
AFF Guidance Overview

Two Guidance Approaches

Trajectory Tracking

• Trajectories defined by great circle path. IC = lead aircraft initial heading, velocity and alt.
• Position errors are calculated between AC and prescribed trajectory.
• Appropriate for small and large formations with prescribed maneuvering.

Leader-Follower

• Reference frame defined by lead aircraft’s current velocity vector.
• Position errors are based on aircraft relative position.
• Appropriate for tracking arbitrary maneuvering. Potential Application To Aerial Refueling & Auto-Carrier Landing Systems.