NATO AVT-279 Formation Flying for Improved Efficiency
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AVT-279 Pillar 1A: Vehicle Impacts

OVERVIEW / STATE OF THE ART

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AVT-279 Pillar 1A: Vehicle Impacts

Overview

The impacts of Formation Flying for Improved Efficiency on trailing airplanes within the formation fall into the following three categories:

1. Structures
   local loads / fatigue / resonance / aeroelastic effects on performance
   areas of concern: winglets / engine nacelles / empenage

2. Actuation and Engines
   increased duty cycle / reduced life (MTBF / accelerated maintenance)
   areas of concern: engines / ailerons / auto-throttle servos

3. Ride Quality
   vibration / noise / nausea / wake upsets / crew fatigue
   areas of concern: passengers / crew / sensitive cargo

The fuel savings of formation flight must outweight its consequences on maintenance costs, airframe life, mission availability, and safety.

Structures

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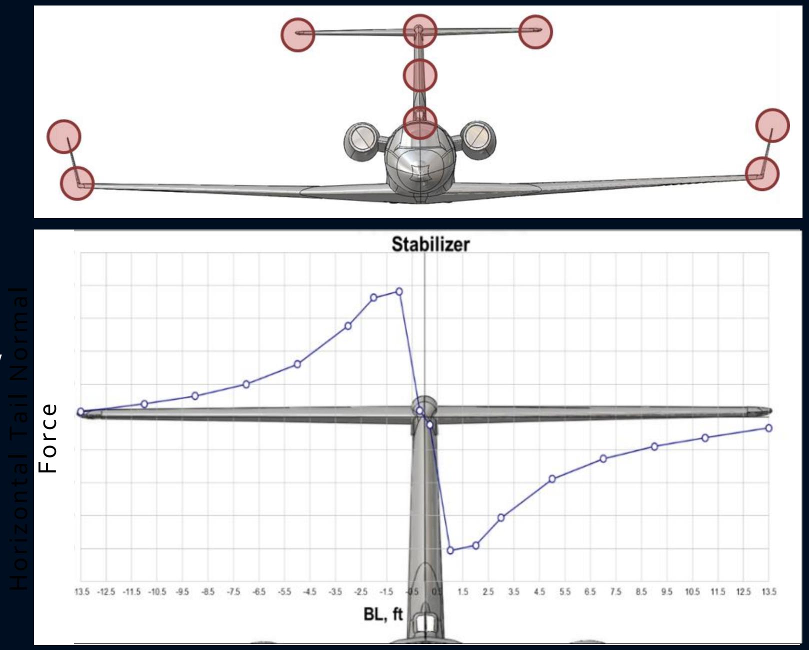
Structures - Local Loads Considerations

- Outer Region of the Wake
  - Normal area of operations during formation flight for operational efficiency.
  - How do worst-case local loads compare to moderate turbulence?
- Inadvertent Wake Crossings
  - Vortex core might impinge on winglets, engine nacelles, or empennage.
  - Steep velocity gradients produce short-term, high-intensity shear and bending.
  - Possibly exacerbated by pilot recovery attempts, especially involving rudder inputs (e.g. 2001 American Airlines Flight 587 crash).
- Key Technology Gaps
  - Modeling techniques, guidance on allowable limits, validation through flight test



from 2014 NASA loads analysis of two G-III jets in formation flight

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Structures - Fatigue and Resonance

- Dynamic Wake Excitation
  - Variations in vortex tangential velocity profile.
  - Low-level variations could produce structural fatigue over extended periods of time.
  - Regularly-spaced periodic variations could excite a structural resonance mode.
  - These effects could worsen with increasing nose-to-tail separation distance and/or atmospheric turbulence (for example Crow instability).
- Control Oscillations
  - Nonlinearities in the control path, coupled with steep trim gradients, can lead to persistent control cycling.
  - If these variations are large enough they can increase structural fatigue.
- Key Technology Gaps
  - Validated dynamic wake models in the near far-field

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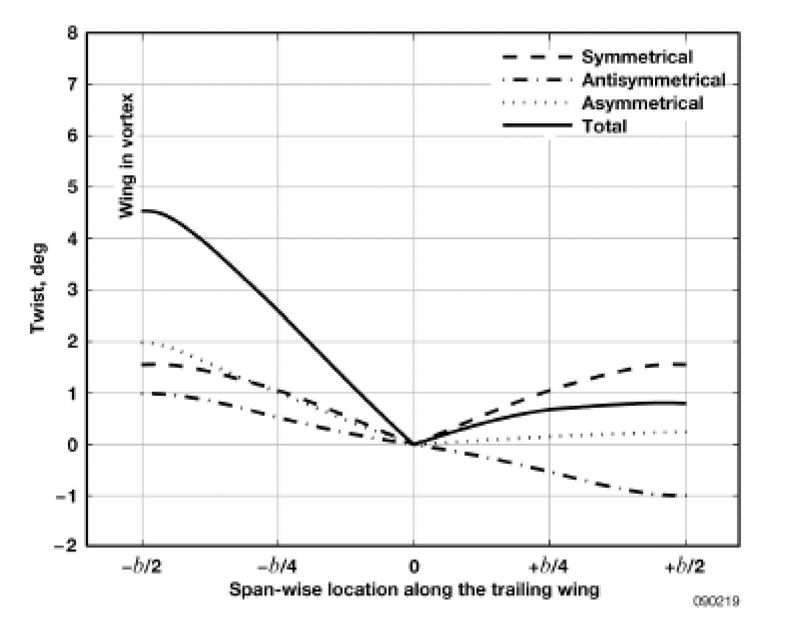
Structures - Aeroelastic Effects on Performance

- Flexible Wing Effects
  - The non-uniform upwash field of the wake vortex, along with the associated roll trim control, changes the lift distribution across the wing.
  - The modified lift distribution results in a vortex-induced change in the wing twist/bending distribution.
  - These changes in wing shape can affect the airplane's trim state, altering its position in the non-uniform upwash field.
  - Flexible wing effects can impact performance, or potentially lead to instabilities or limit-cycle oscillations.
- Wing Shape Optimization
  - Wing designs optimized for formation flight.
  - Real-time control of wing flexure.
- Key Technology Gaps
  - Validation of flexibility effects through CFD and flight test, modeling of wing bending effects including swept wings.



From Hanson, "Static Aeroelastic Effects of Formation Flight for Slender Unswept Wings," NASA TM-2009-214649

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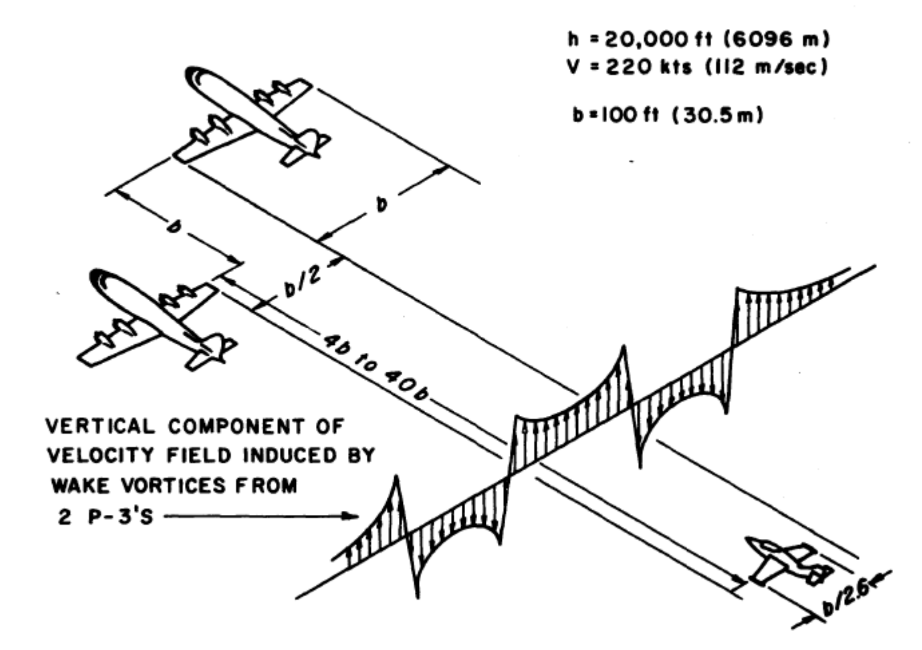
Structures - Literature Survey

1974 Donaldson, Bilanin, Williamson, and Snedeker (Aeronautical Research Associates of Princeton)

- *"Study of the Feasibility of Conducting a Wake-Riding Experiment Using a T-2 Aircraft Behind a P-3 Aircraft"*
- Estimated the structural loads encountered if the T-2 were to pass directly through one of the P-3's trailing vortices.
- Wind tunnel measurements of rolling moment.
- Designed an autopilot to estimate the difficulty of the piloting task.
- Incorporated aerodynamic models and a simple autopilot into a simulation.
- Vertical tail root bending was predicted to exceed design limit due to vortex impingement and pilot rudder input.



From Donaldson, "Study of the Feasibility of Conducting a Wake-Riding Experiment Using a T-2 Aircraft Behind a P-3 Aircraft"

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Structures - Literature Survey

2000 Iglesias (Virginia Polytechnic Institute and State University)

- *"Optimum Spanloads Incorporating Wing Structural Considerations And Formation Flying"*
- Investigated the optimal wing twist distribution for wings in formation flight.
- Included optimization of both leading and trailing wings.
- Also 2002 paper "*Optimal Spanloads in Formation Flight*".

2004 Nehrbass, Frommer, Garison, Loffing, and Crossley (Purdue University)

- *"Point to Point Commercial Aircraft Service Design Study Including Formation Flight and Morphing"*
- Evaluated asymmetric wing shape changes to counteract vortex-induced rolling moment.
- Also 2002 paper "*Use of Design Methods to Generate and Develop Missions for Morphing Aircraft*".

2007 Nangia and Palmer (Nangia Aero Research Associates)

- *"Formation Flying of Commercial Aircraft – Assessment using a New Approach - Wing Span Load & Camber Control"*
- Investigated changes to wing camber and twist to counter vortex-induced asymmetric spanwise lift distribution.

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Structures - Literature Survey

2009 Hanson (NASA Armstrong Flight Research Center)

- *"Static Aeroelastic Effects of Formation Flight for Slender Unswept Wings"*
- Modeled asymmetric upwash effects on wing twist and associated changes to roll trim and drag reduction.
- Analysis restricted to straight, slender wings (gliders).

2011 Dijkers, van Nunen, et al (TU Delft)

- *"Integrated Design of a Long-Haul Commercial Aircraft Optimized for Formation Flying"*
- Proposed a morphing wing to counteract vortex-induced rolling moment.

2014 Boyle (NASA Armstrong Flight Research Center)

- *"Cooperative Trajectories Gulfstream III Aerodynamic Loads Analysis"*
- Analyzed the aerodynamic loads due to wake vortex core impingement on the winglet and tail of a G-III in formation flight behind a similarly-sized aircraft.
- *Internal project document, not currently approved for public release.*

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Structures - Literature Survey

2014 Bieniawski, Clark, Rosenzweig, and Blake (Boeing / AFRL)

- *"Summary of Flight Testing and Results for the Formation Flight for Aerodynamic Benefit Progam"*
- C-17 flight tests: wake crossings (safety and wear) and dwell points (wear)
- Accelerometer and strain gage peak responses during wake crossings.
- "Airframe safety and engine operability from 40+ wake crossings reveal no concerns."
- "No significant increase in airframe wear due to SAVE."
- "Minor increases in wear, < 5% life reduction, observed close to wake and during crossings (if SAVE performed on 75% of all logistics flights over airframe life)."

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Structures - Summary

- Concerns
  - Increased fatigue or resonant mode excitation due to wake dynamics and control.
  - Excessive loads during or after (recovery) a wake crossing.
  - Effects of flexibility on performance benefits and controller stability.
- State of the Art
  - Limited flight data on structural impacts of formation flight in the wake.
  - Few published analyses of wake-induced load predictions.
  - Several methods for off-line or real-time optimization of wing shape.
- Key Technology Gaps
  - Dynamic wake models
  - Structural modeling techniques for non-uniform flow fields and trim conditions
  - Guidance on allowable predicted loads
  - Flexible wing models integrated with non-uniform flows
  - Validation through flight test

Questions?