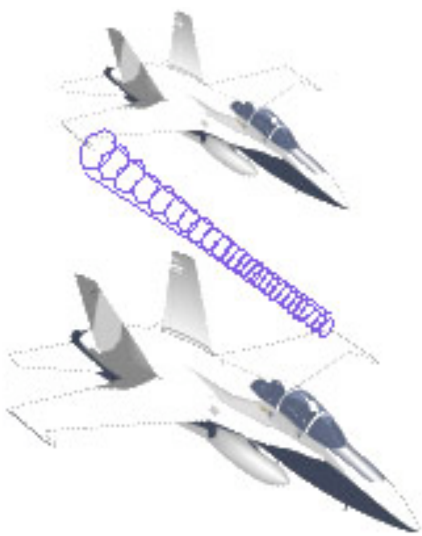
Autonomous Formation Flight

Project Overview



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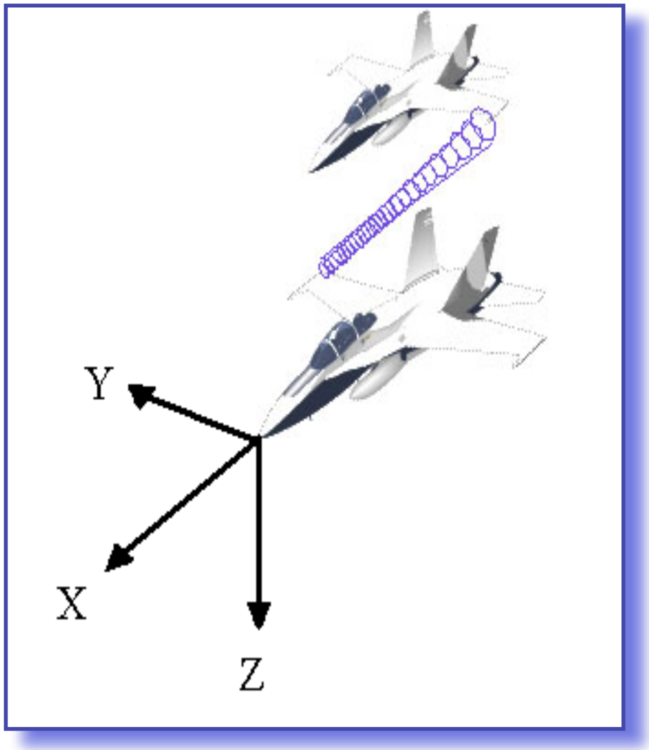
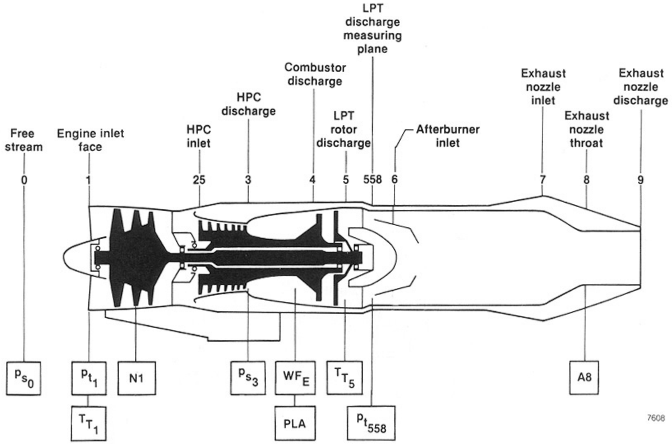
Overview of Experiment

- 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



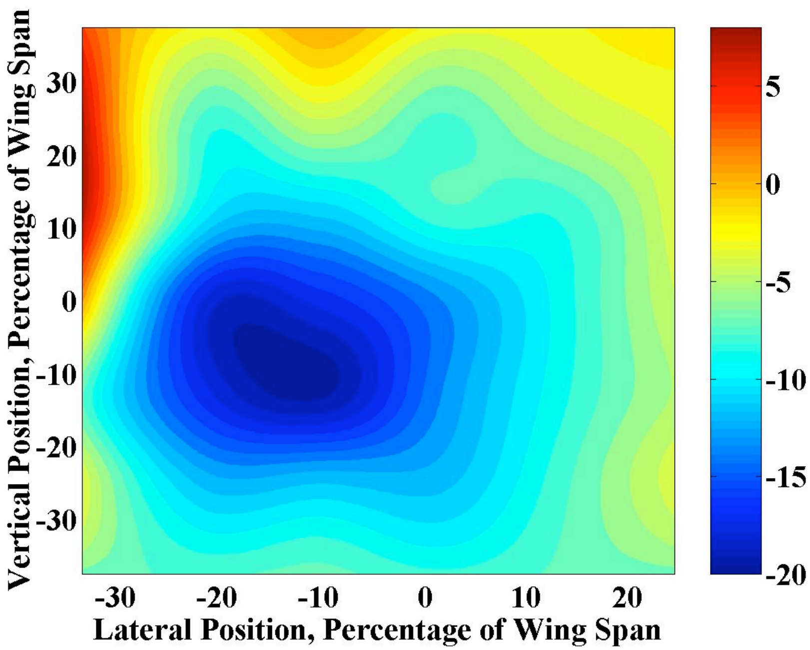
Test Point Procedure and Flight Data

- 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

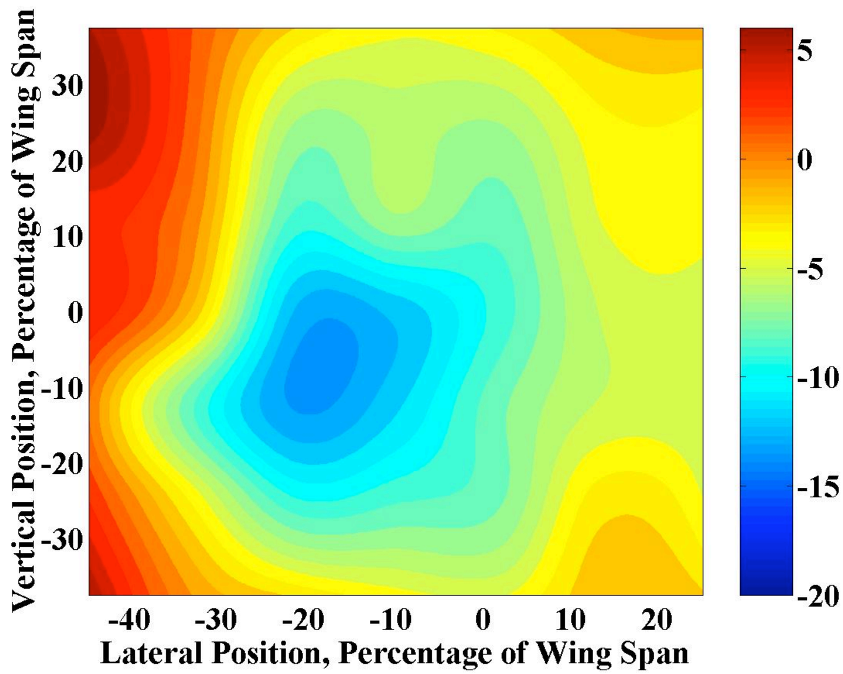


- F404 Engine In-Flight Thrust Instrumentation
  - Flight-test, volumetric fuel-flow meter installed (WF_E)
- Manufacturer's In-Flight Thrust Model used to calculate thrust

Vortex Influence on Drag

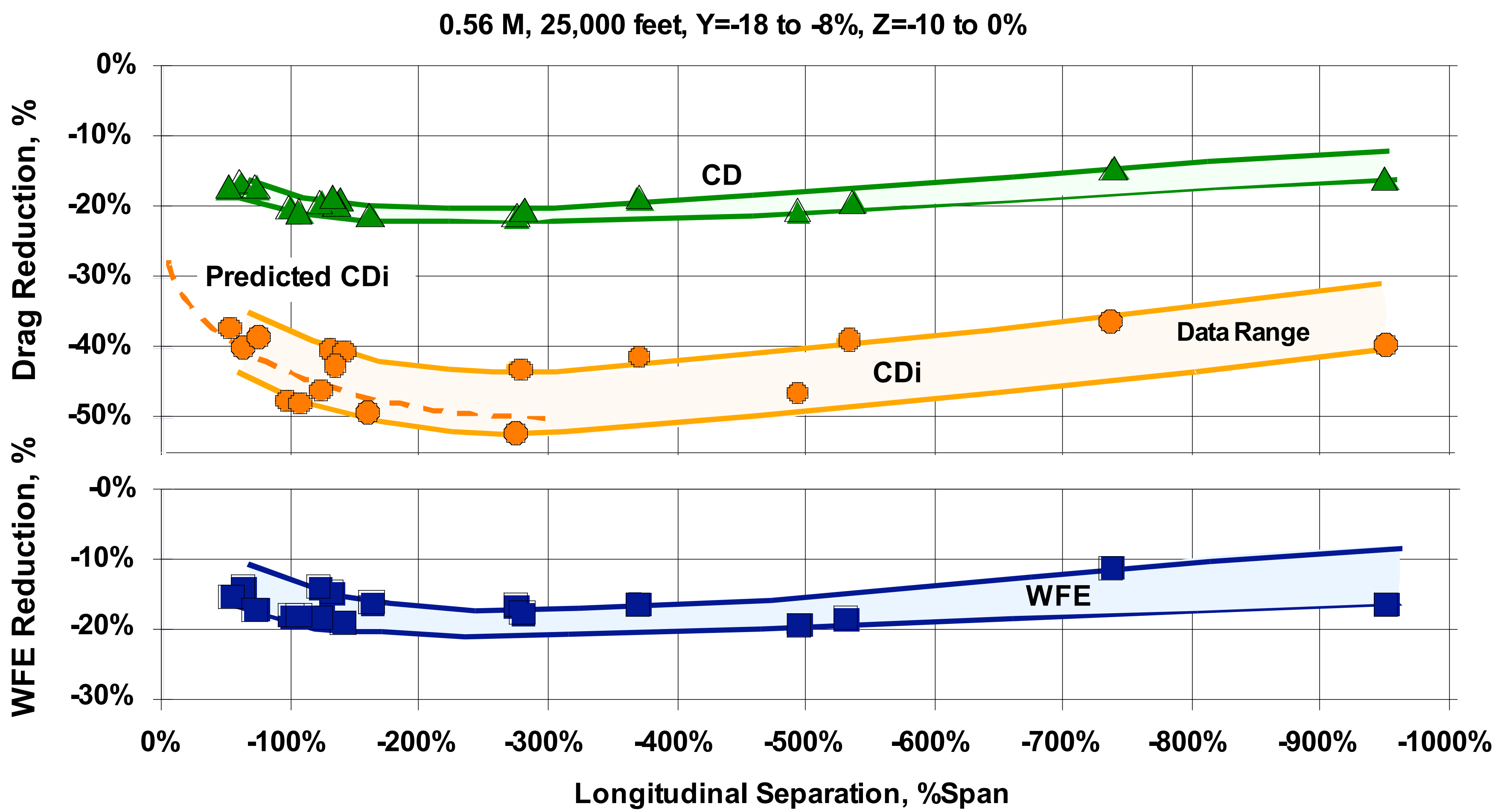


M=0.56, 25,000ft 55' N2T

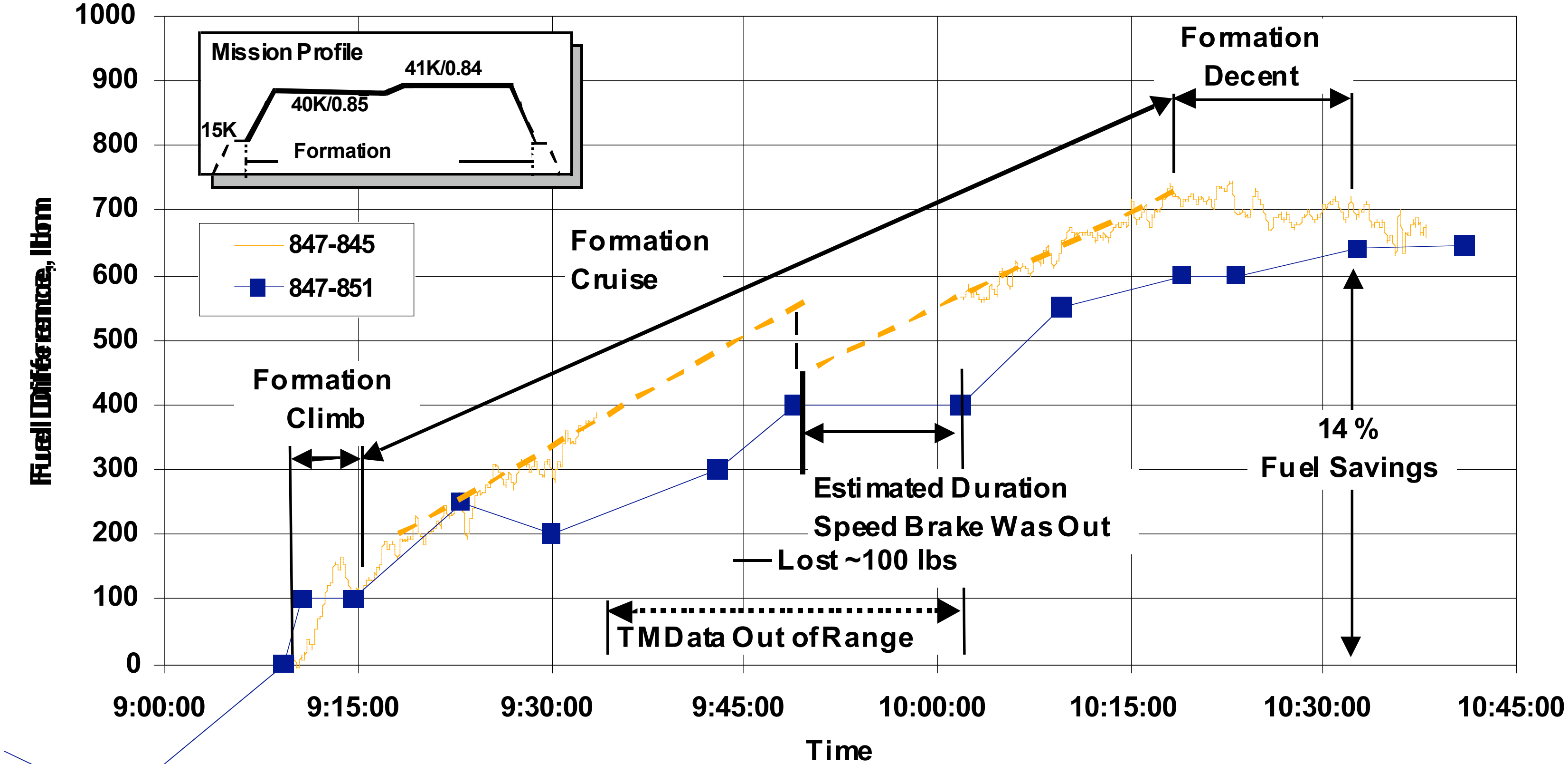


M=0.86, 36,000ft 55' N2T

Drag and Fuel-Flow Change with Longitudinal Spacing



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

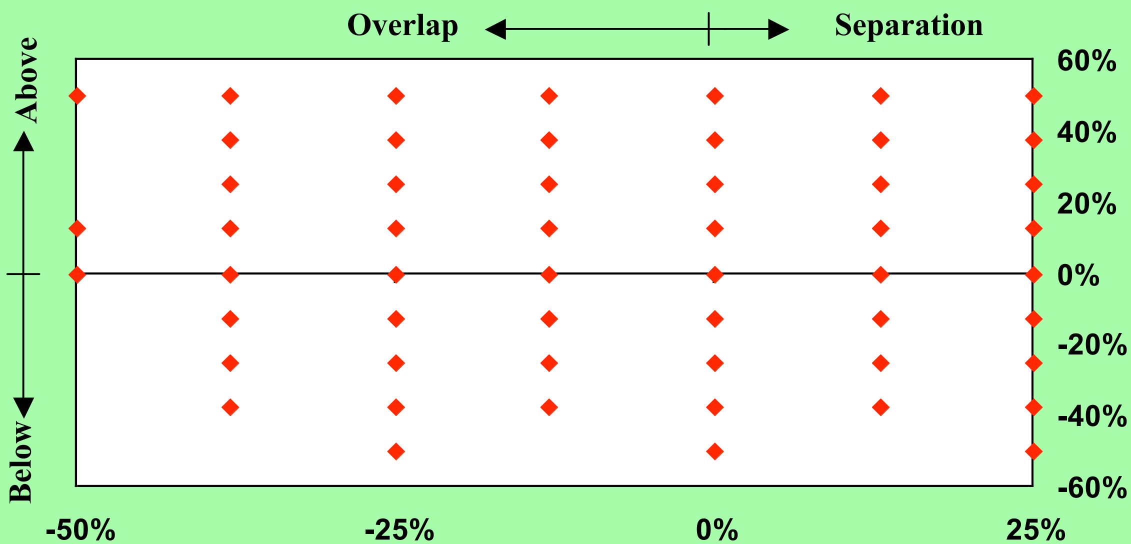
Lessons Learned

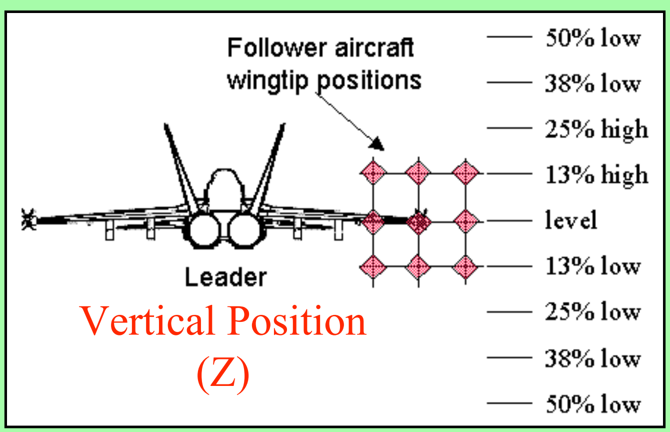
- Controllable flight in vortex is possible with pilot feedback (displays)
- Position hold at best $C_{D,}$ is attainable
- Best drag location is close to max rolling moment
  - Drag reductions demonstrated up to 22% (WF_E up to 20%)
- Induced drag results compare favorably with simple prediction model
  - '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

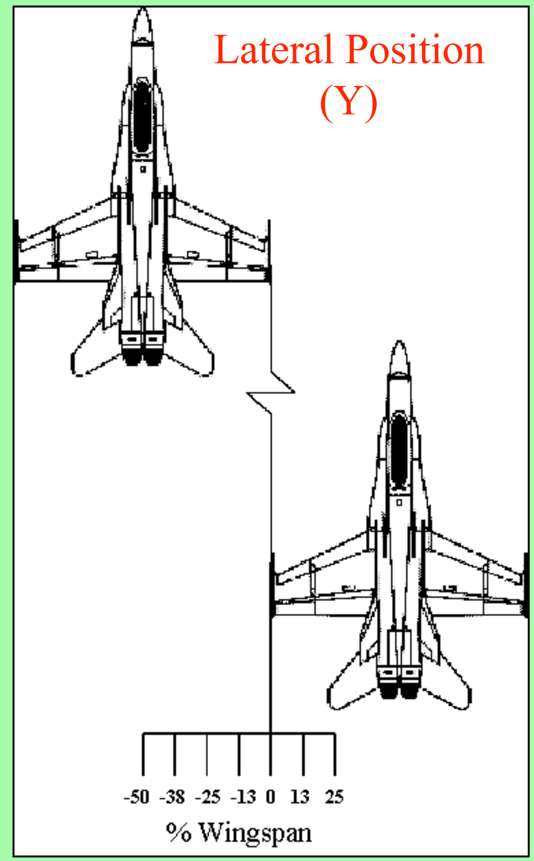
Presentation Outline

- 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







Vortex Influence on Lift and Drag

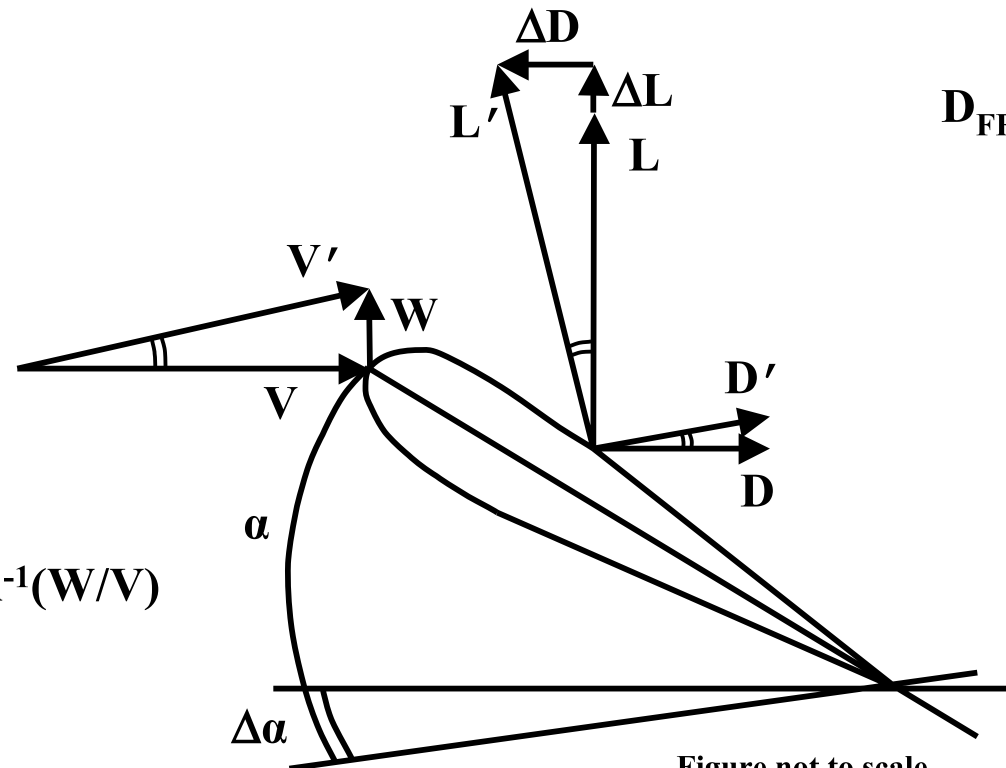


Figure not to scale

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

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

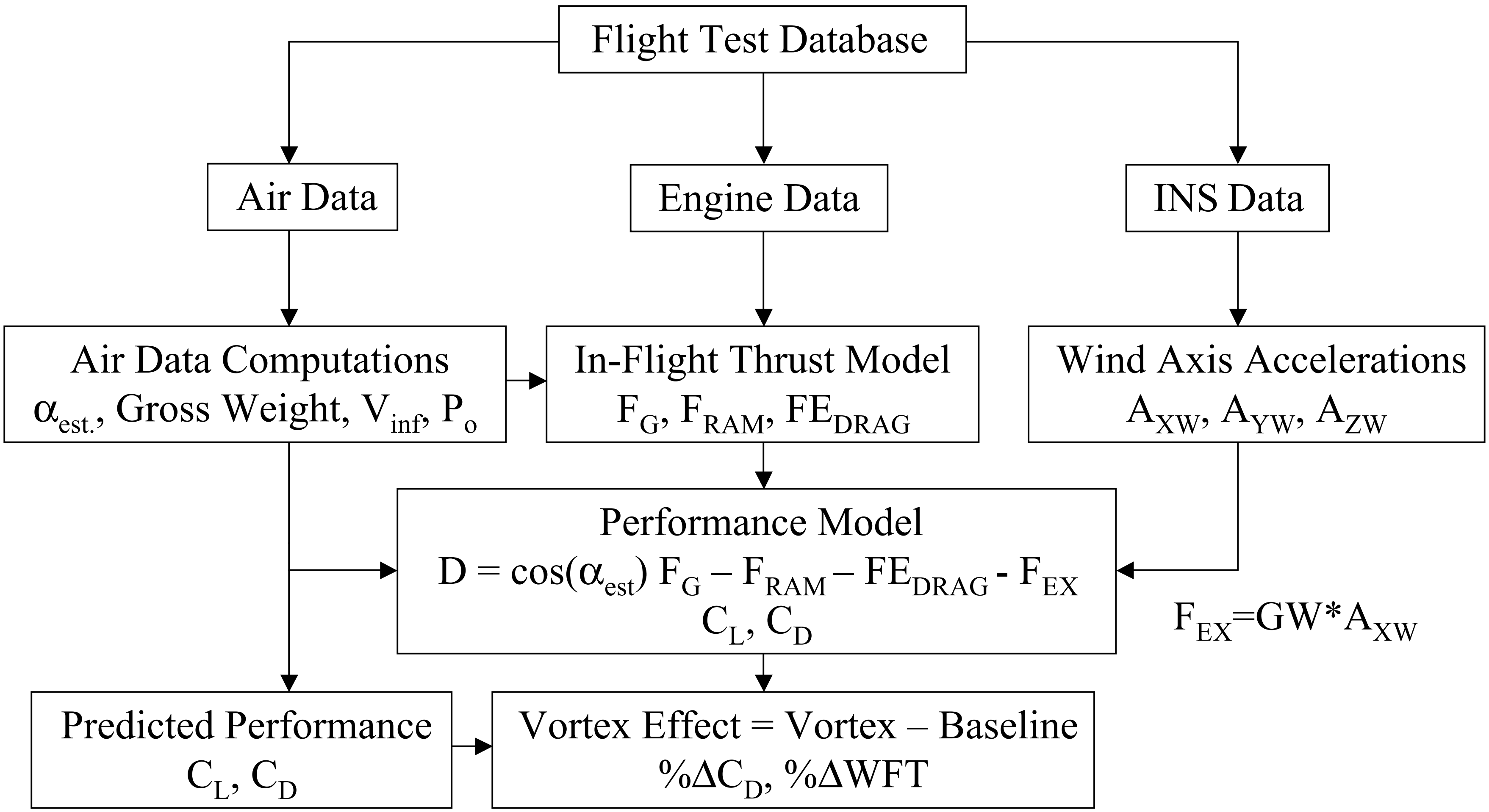
$$L_{FF} = \cos(\Delta\alpha)\, L' + \Delta L$$
$$\Delta L = \sin(\Delta\alpha)\, D$$
$$L' \sim L$$

- **Basic theory states drag reduction, ΔD, 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**

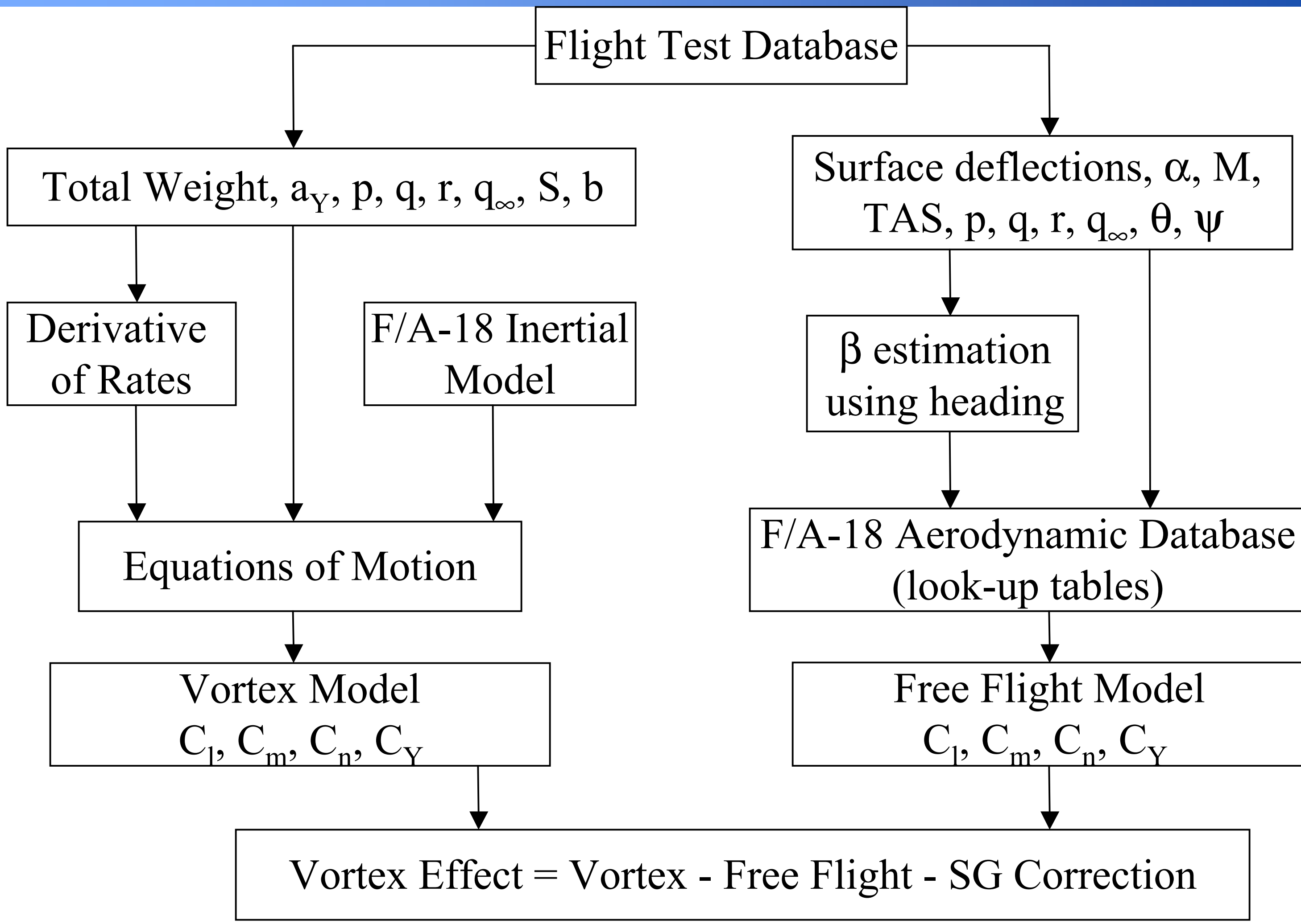
Test Point Procedure, Continued

- 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

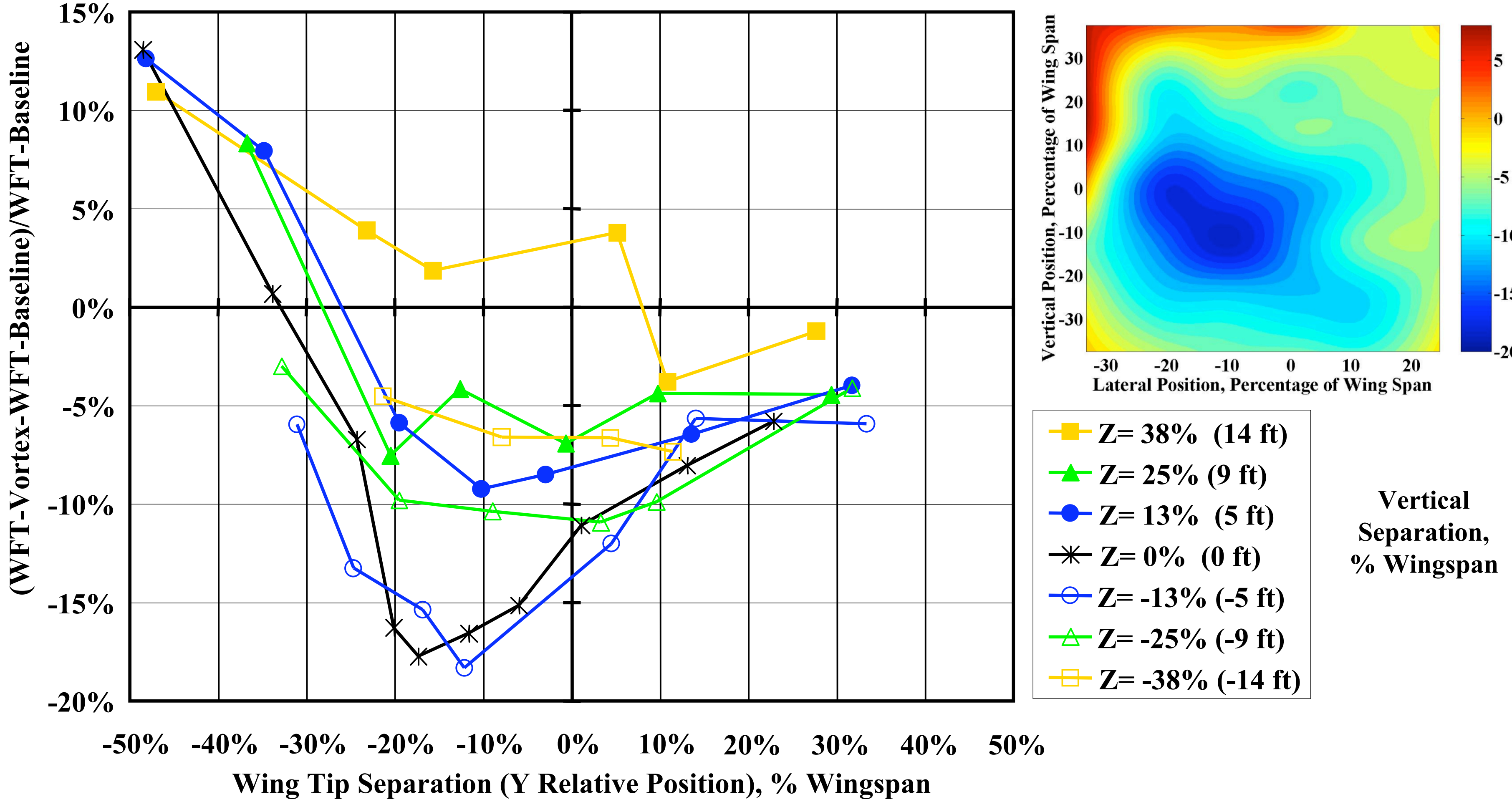
Lift and Drag Analysis



Moment Analysis



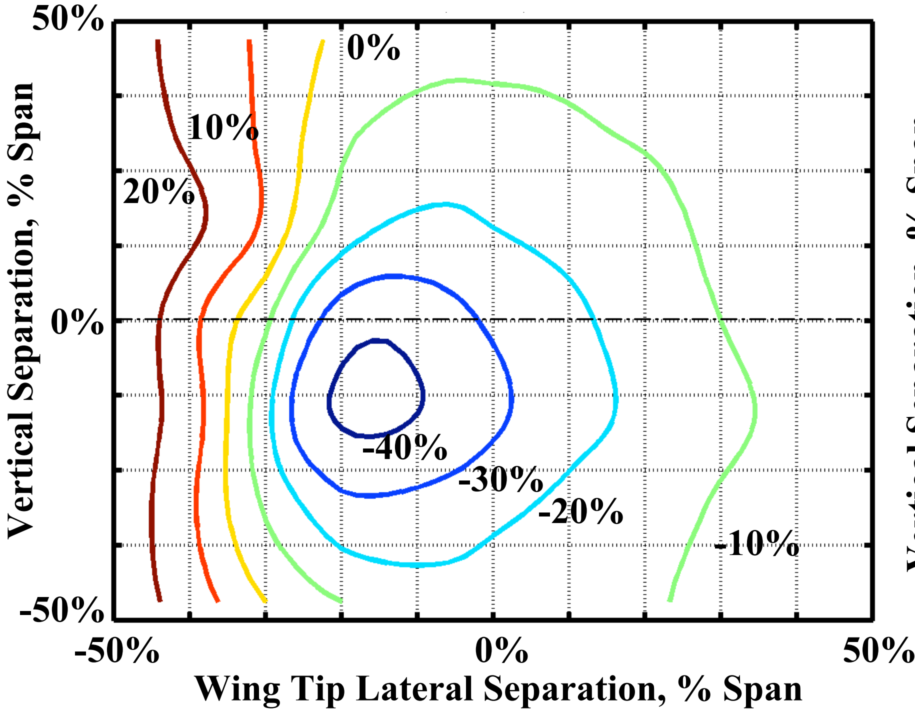
Vortex Influence on Fuel-Flow



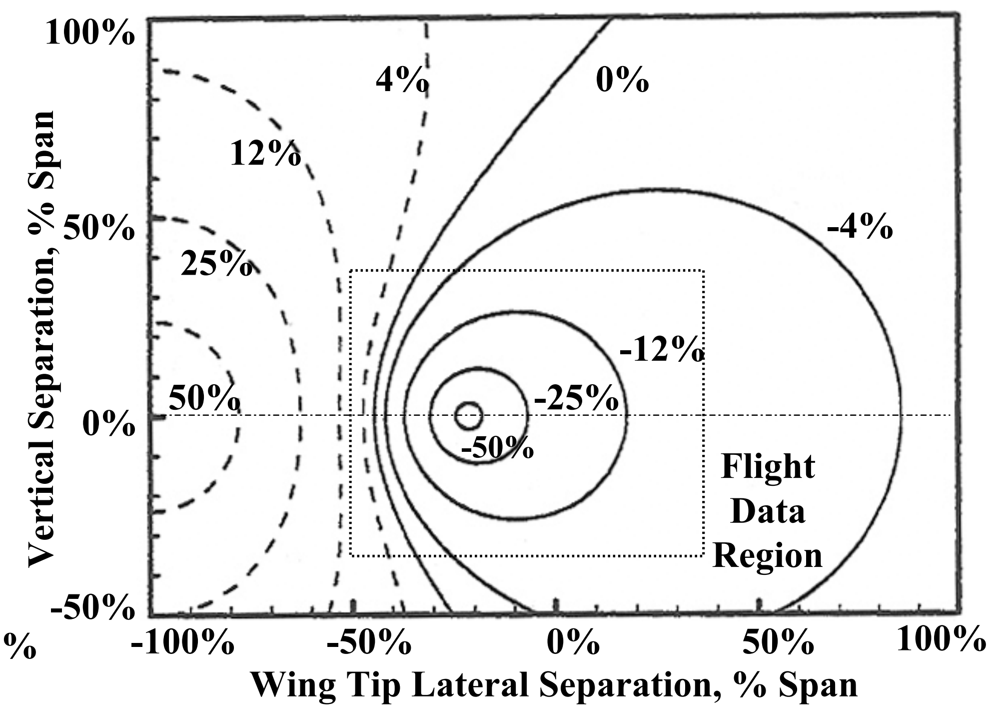
Percent change in Fuel-Flow versus position at M=0.56, 25,000ft 55' N2T

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

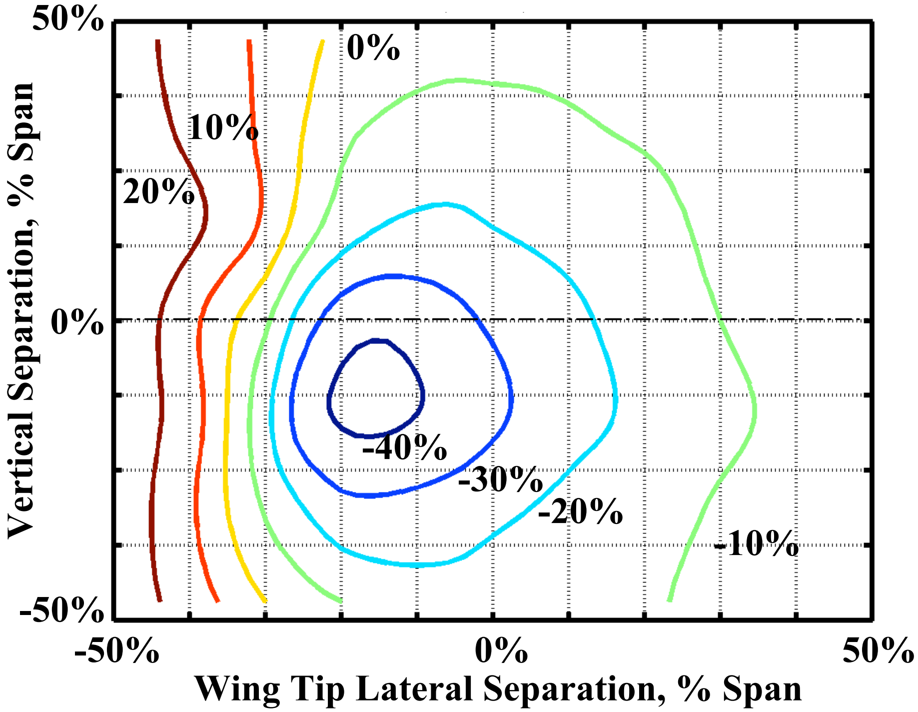


Predicted induced drag change using horseshoe vortex model*

*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



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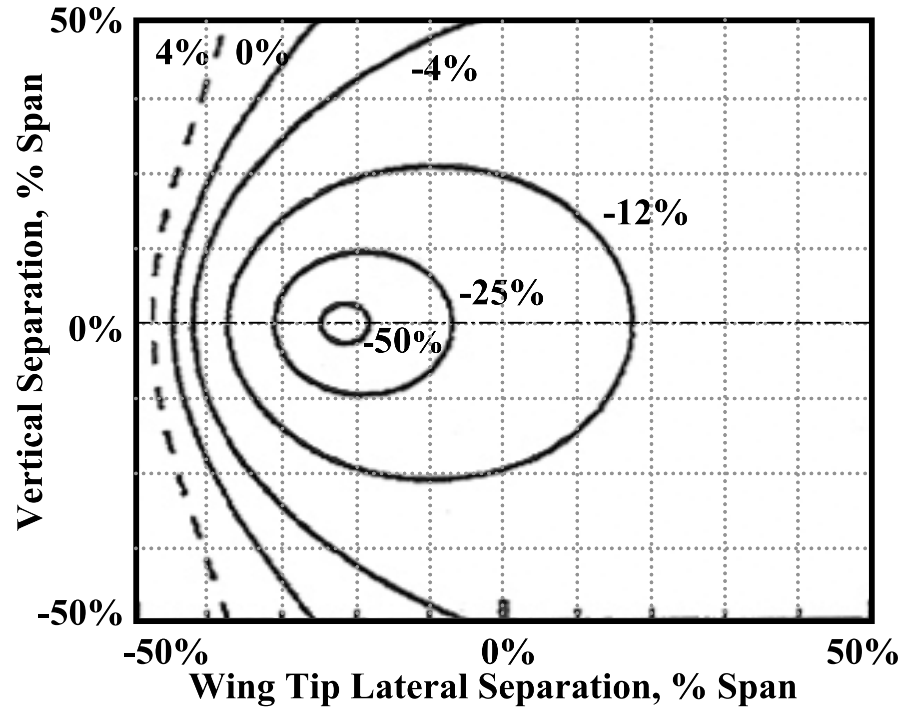

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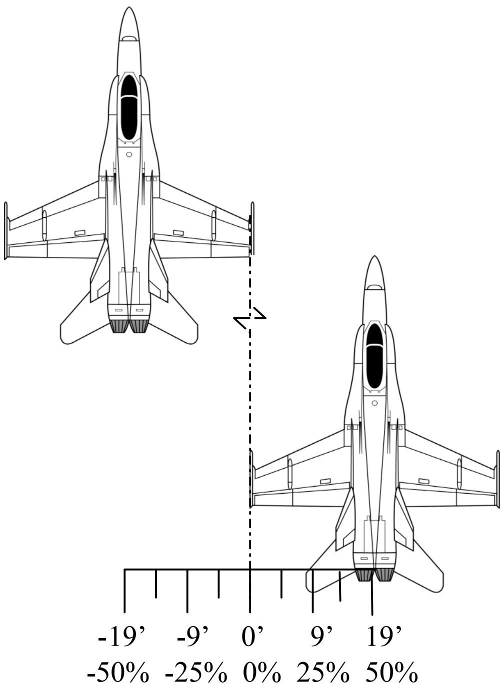
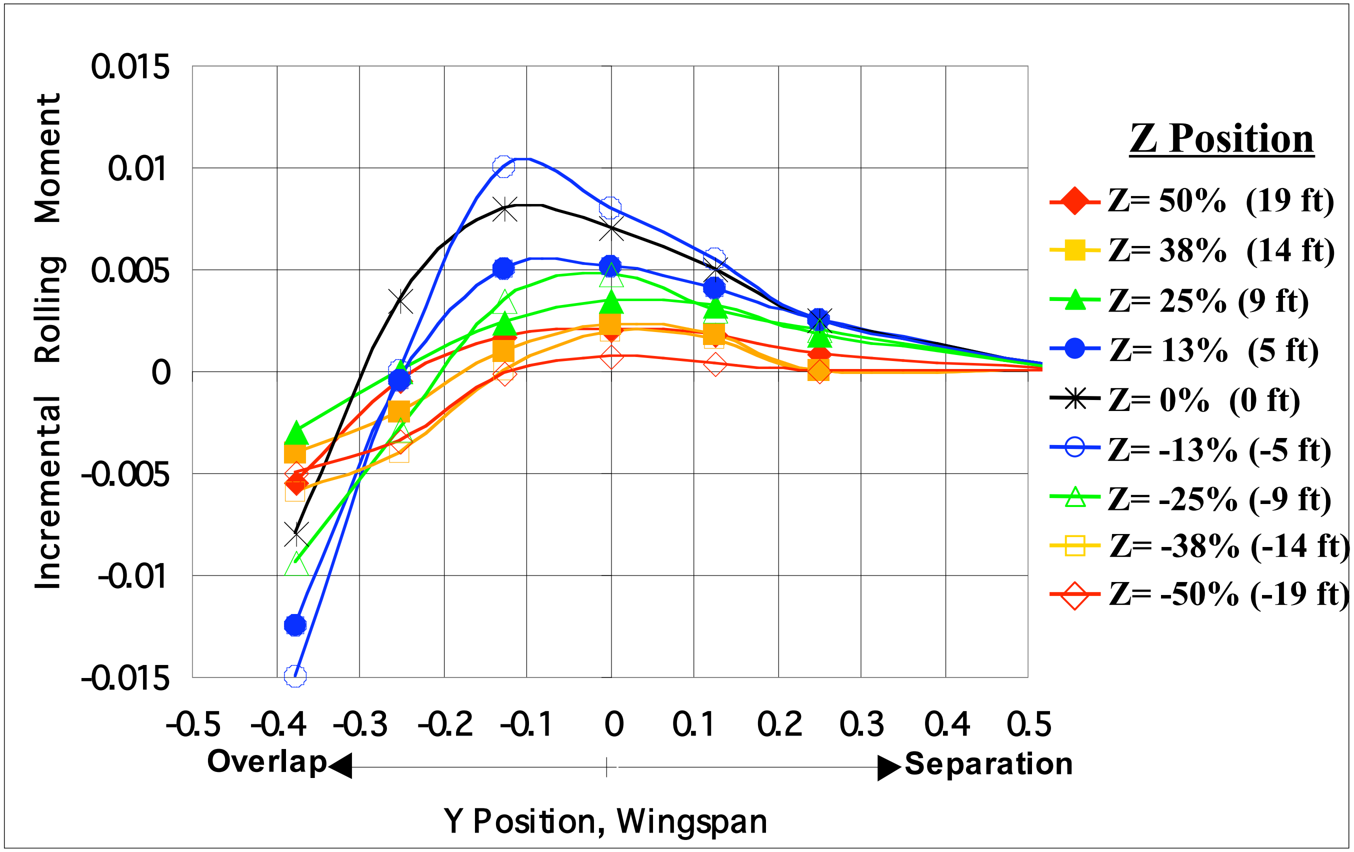
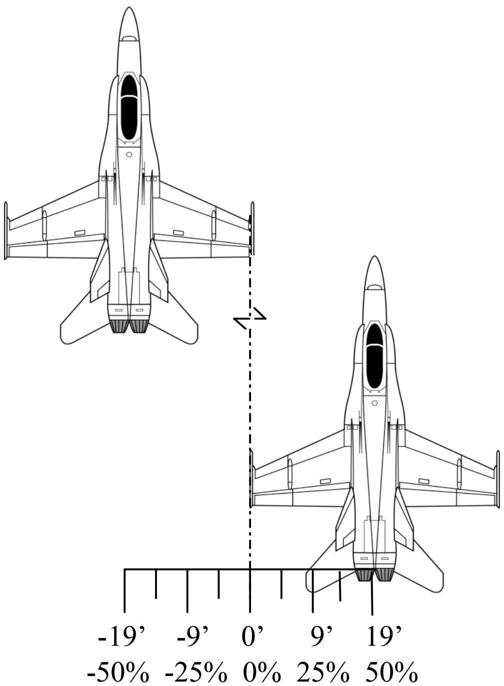
Vortex Influence on C_l

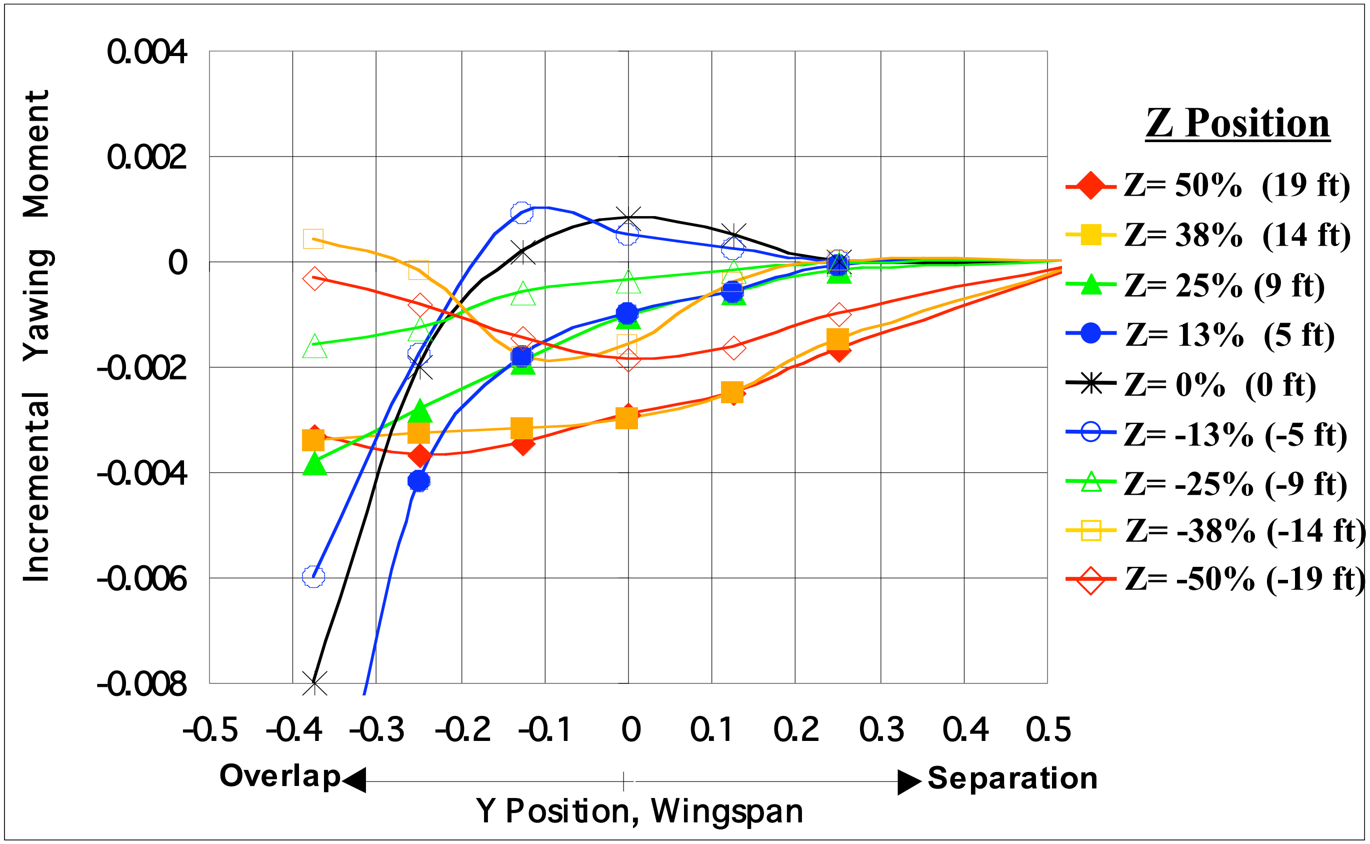




Incremental Rolling Moment at M=0.56, 25000 feet, 55’ N2T

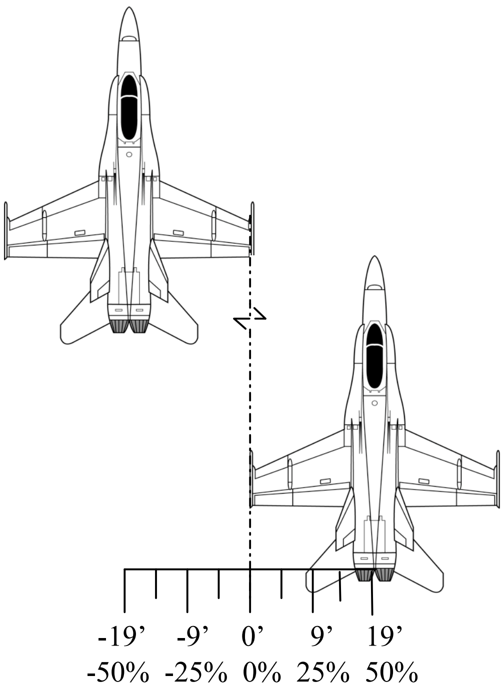
Vortex Influence on C_n

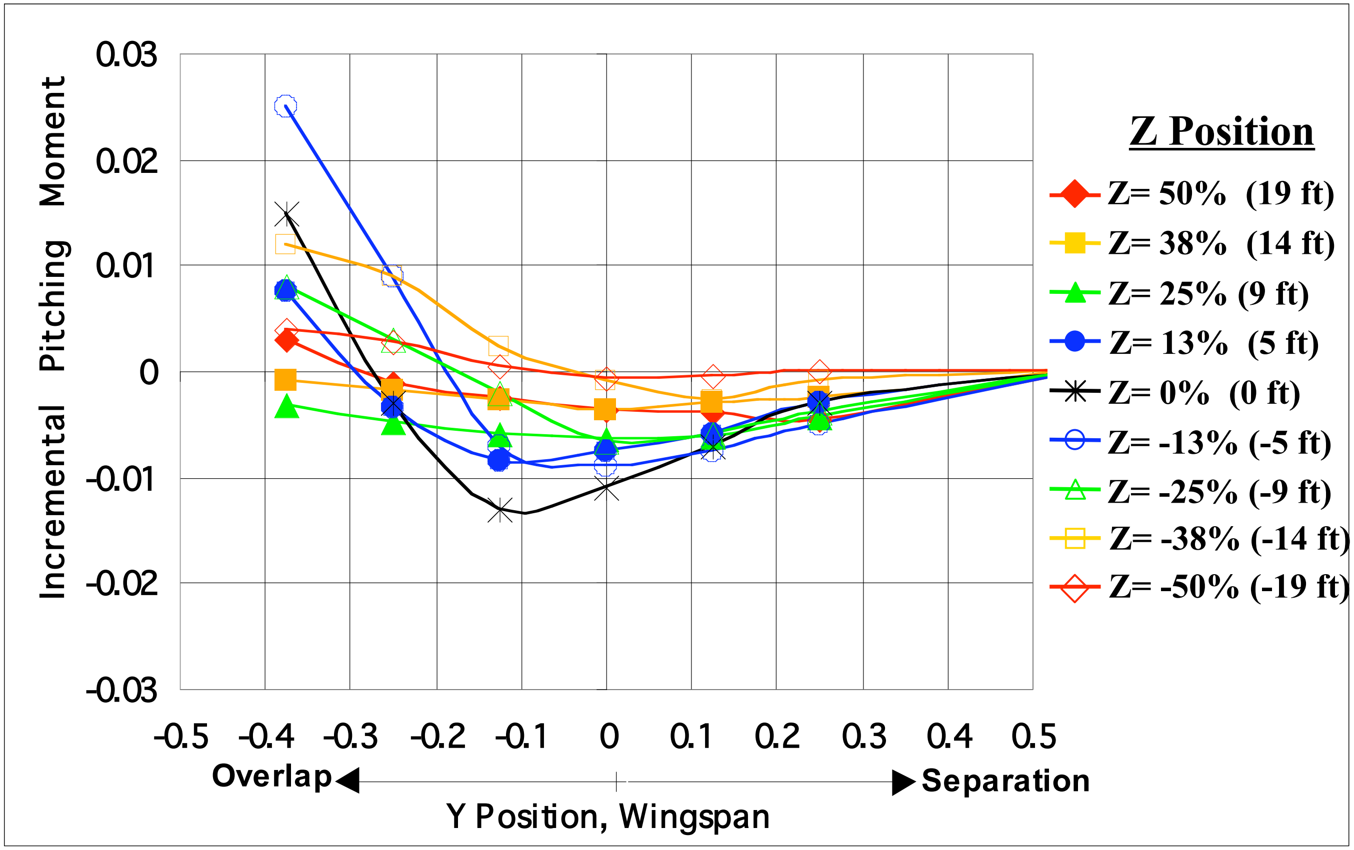




Incremental Yawing Moment at M=0.56, 25000 feet, 55’ N2T

Vortex Influence on C_m

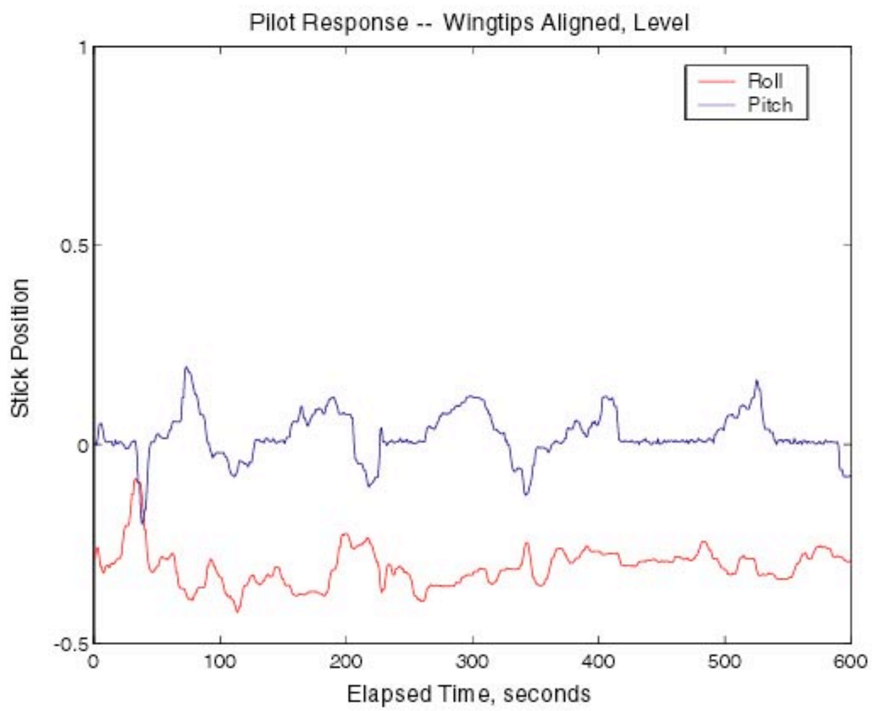




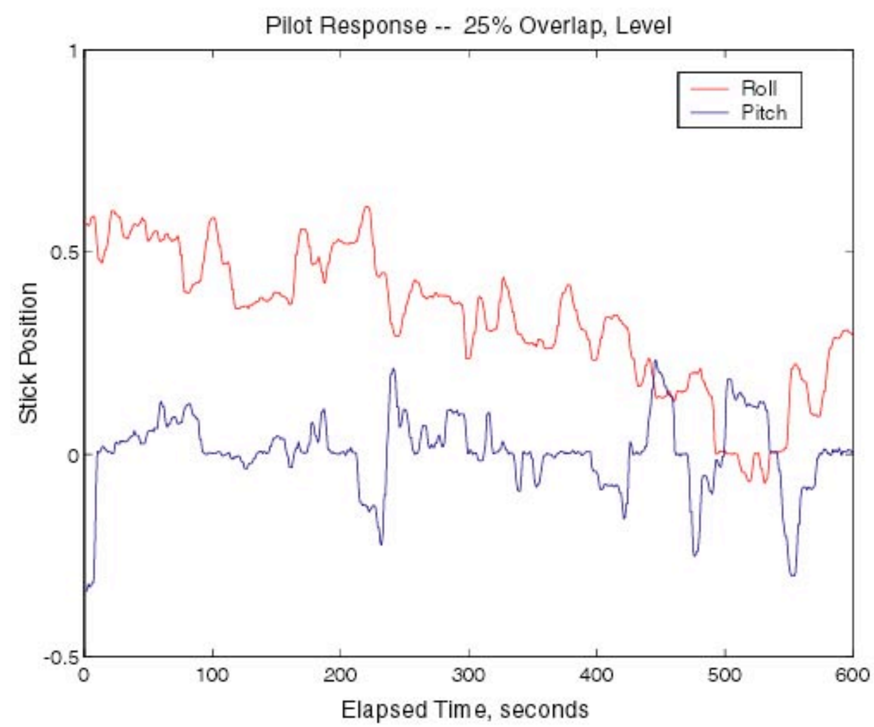
Incremental Pitching Moment at M=0.56, 25000 feet, 55’ N2T

Pilot Response - Comparison
55' N2T, Reference Condition

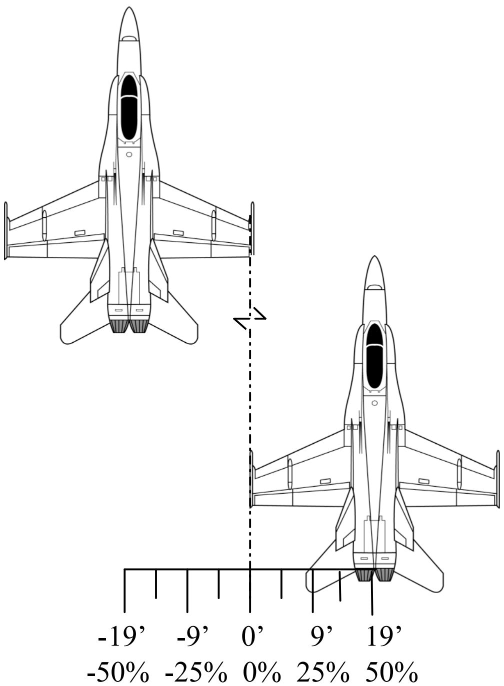
Wingtips Aligned, Level

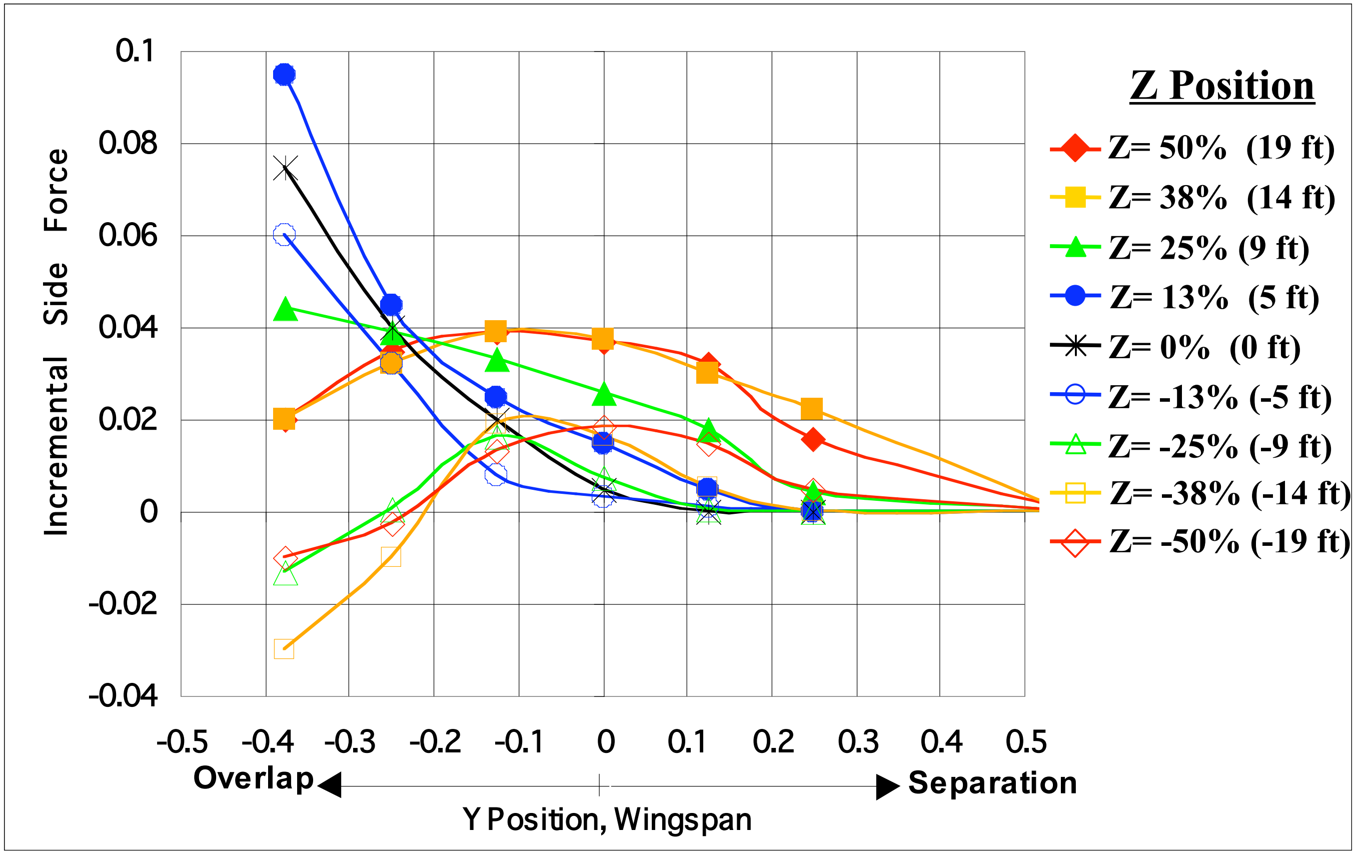


25% wing Overlap, Level



Vortex Influence on C_Y





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