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Interaction of a Fin Trailing Vortex with a Downstream Control Surface

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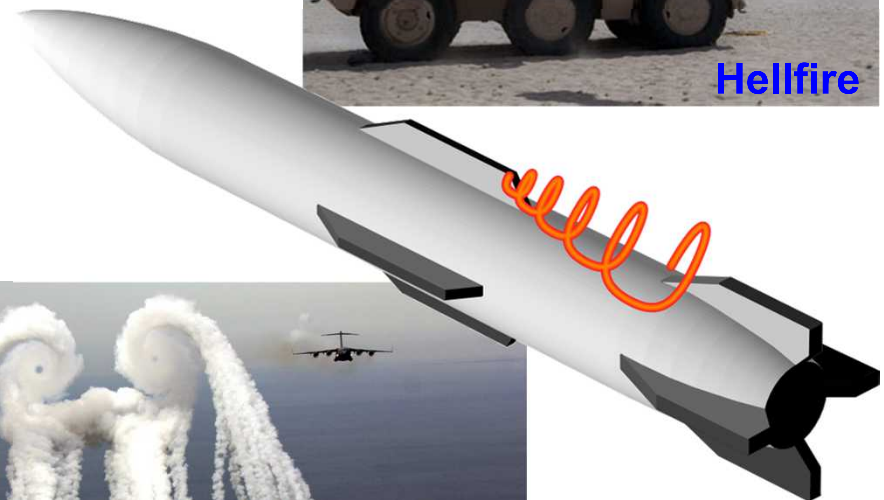
Fin Wake Interactions

- Many modern precision guided weapons use two sets of fins.
- They may experience an interaction that can dramatically alter aerodynamic control.
  - Results from upstream fin tip vortex impinging on downstream fin
  - Analogous to wingtip vortices
- Sandia is developing vehicles where this is relevant.
- We have neither the knowledge base nor the modeling capability to predict these effects to the desired fidelity.


Paveway


Harpoon


Hellfire



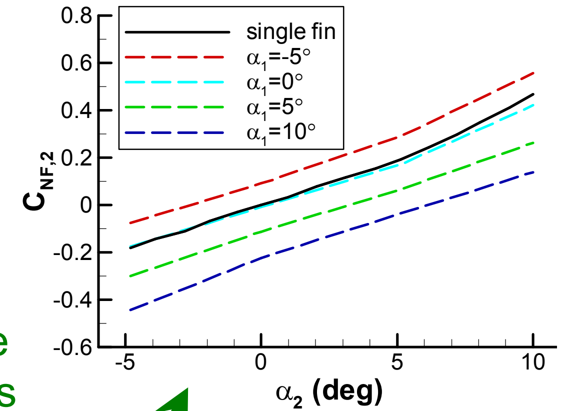

C-17 trailing vortices

Overview of Experimental Approach

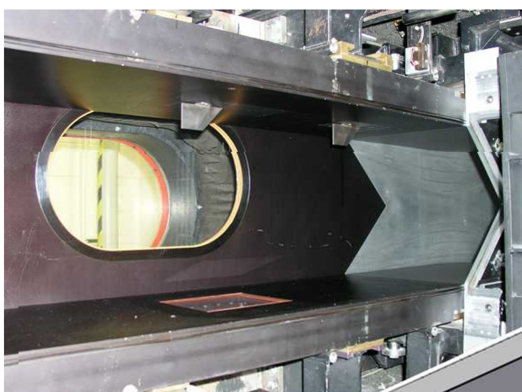
Conduct a sub-scale experiment in which one wall of the wind tunnel represents the vehicle surface.

We want to measure the aerodynamic forces on the downstream fin due to the interaction…

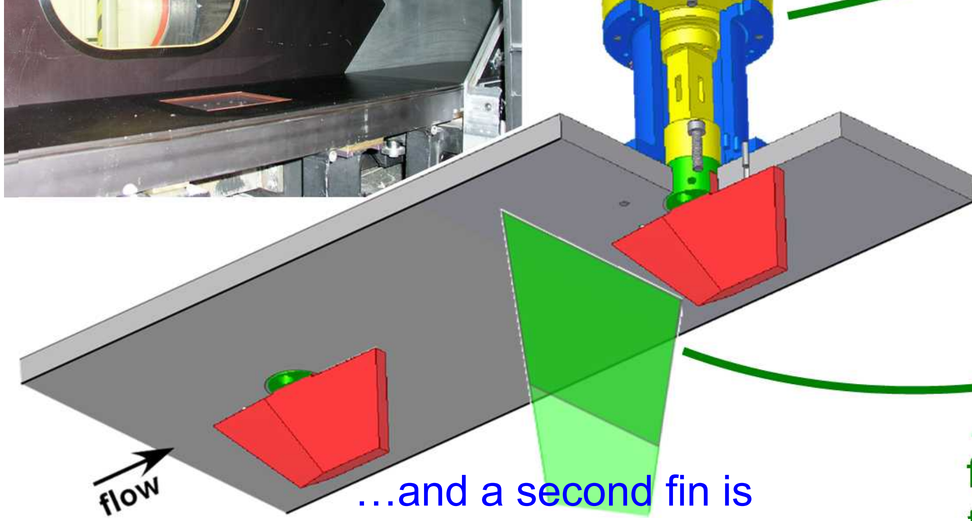
…and the vortex generated from the upstream fin to understand the underlying fluid dynamics.



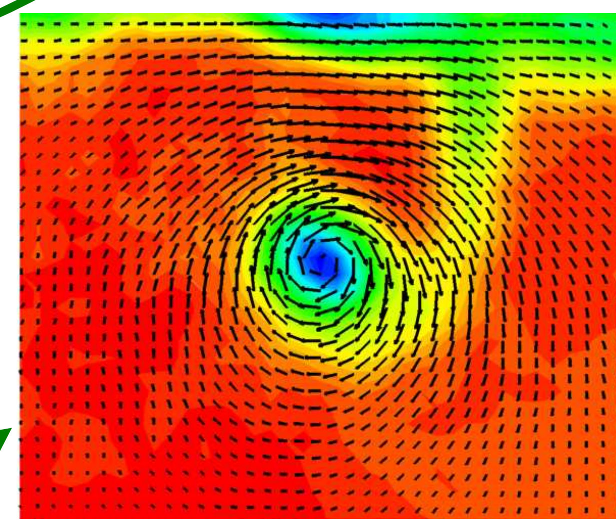
The balance measures the aerodynamics of the interaction…



A fin balance is behind one test section wall…



…and a second fin is mounted upstream.



…and PIV measures the fin tip vortex responsible for the altered aerodynamics.

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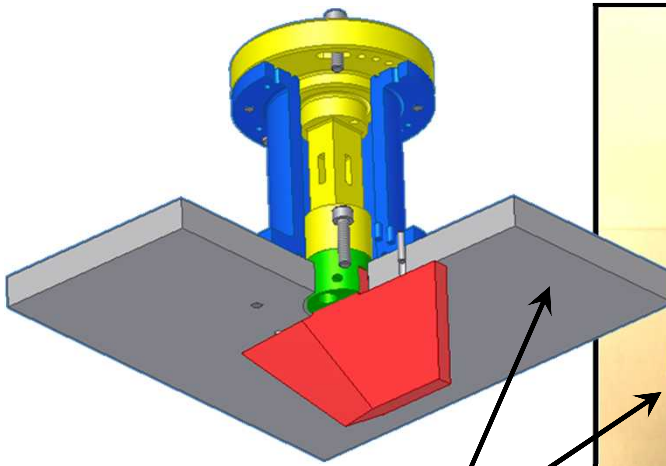
Fin Balance

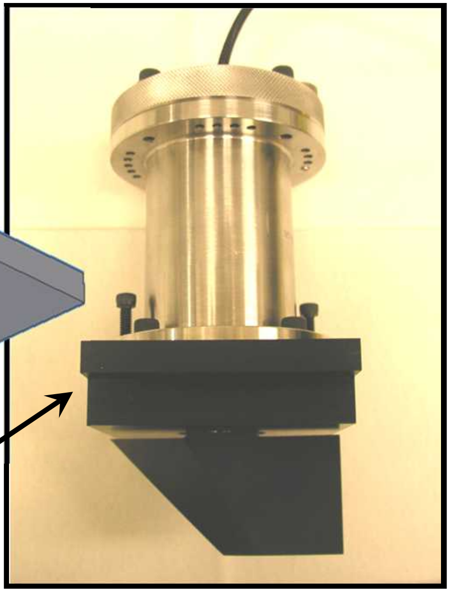
Use a customized fin balance.

- Three components: normal force, bending moment, and hinge moment.
- Neglect axial force for thin fins.
- Calibrated on a 3 × 9 matrix with uncertainties of about 0.1 - 0.2% of full-scale loading.

The balance attaches along the fin axis of rotation and sits behind the wind tunnel wall.

- Balances rotate with the fin for different angles of attack.
- Fin angles set at discrete, repeatable values by a pin arrangement.
- Range of -5 to +10 deg in 1 deg increments.





wind tunnel wall

balance calibration

Experimental Hardware

Sandia's Trisonic Wind Tunnel (TWT)

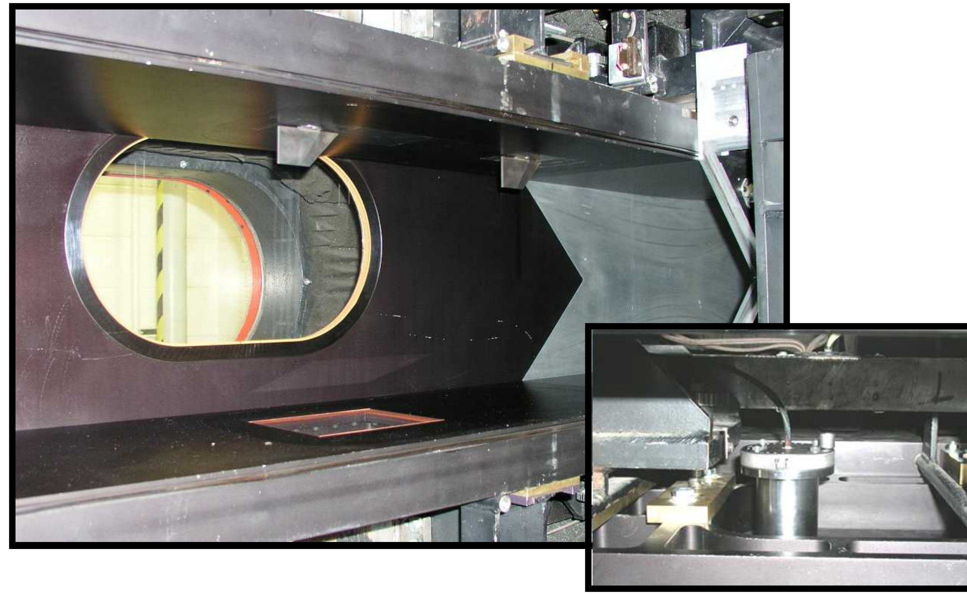
- Blowdown to atmosphere
- 305 × 305 mm test section
- Solid-wall transonic test section for the present work ($M_\infty \leq 0.8$)

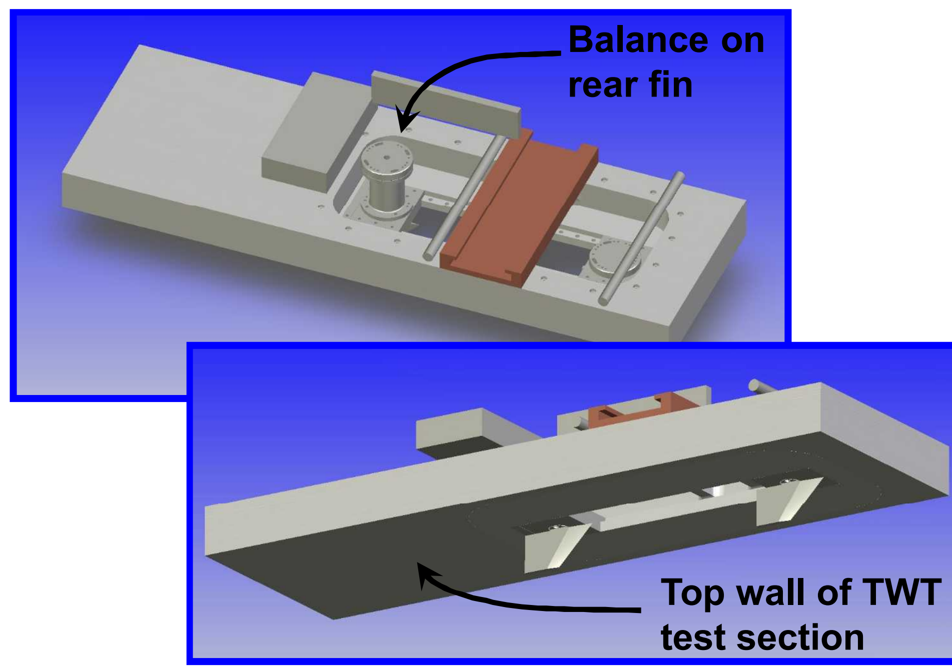
Hardware was built to configure an experiment on the top wall of the wind tunnel.

- The wall simulates the body of a flight vehicle.
- Allows a reasonably sized flowfield.

Shift fin positions by rearranging insert blocks on a rail.

- Some limits to the balance position.
- Lots of tunnel infrastructure to get in the way.





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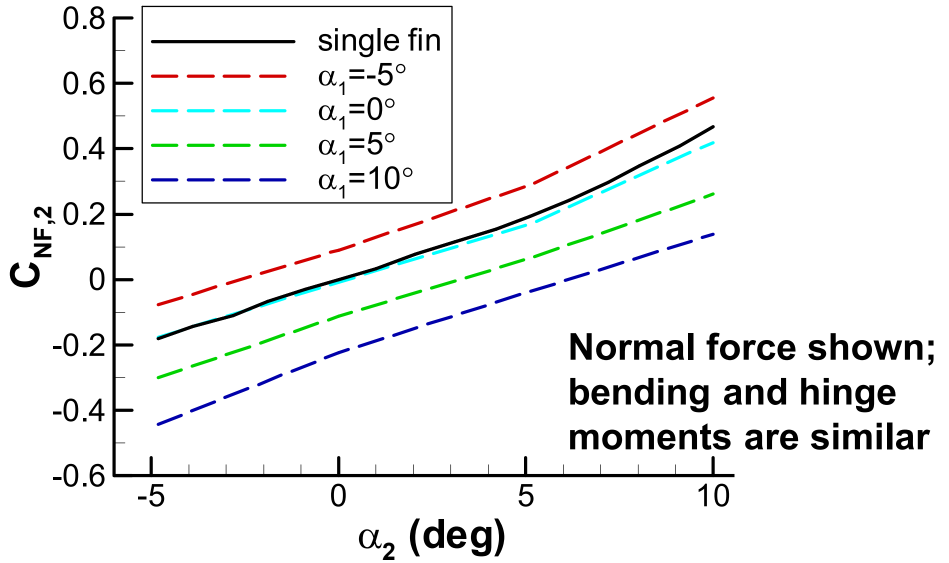
Fin Aerodynamic Data

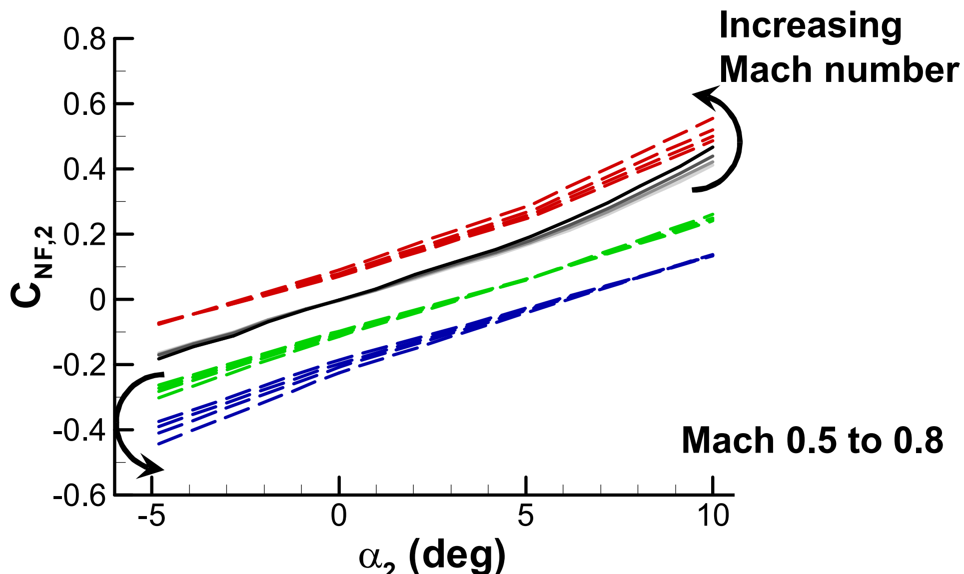
An extensive aerodynamic data set has been acquired.

- This provides a direct measurement of the aerodynamics of the interaction.
- Enables a parametric study of the effects of changing conditions.

Altering the angle of the upstream fin changes the force on the downstream fin.

- We theorize this is due to an induced angle of attack upon the fin.
  - Similar to findings for jet/fin interaction in a previous study.
- Increasing the Mach number appears to enhance the effect.
- Also have data on influence of fin spacing, fin geometry, etc.





Fin spacing is 4 root chords

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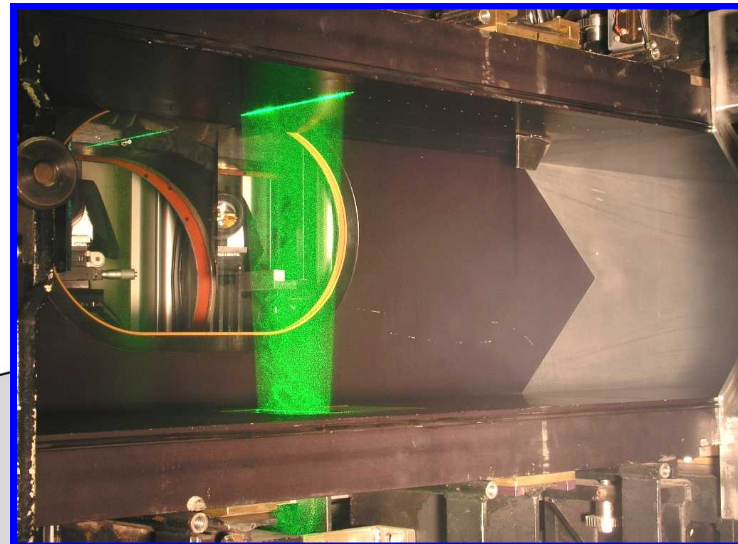
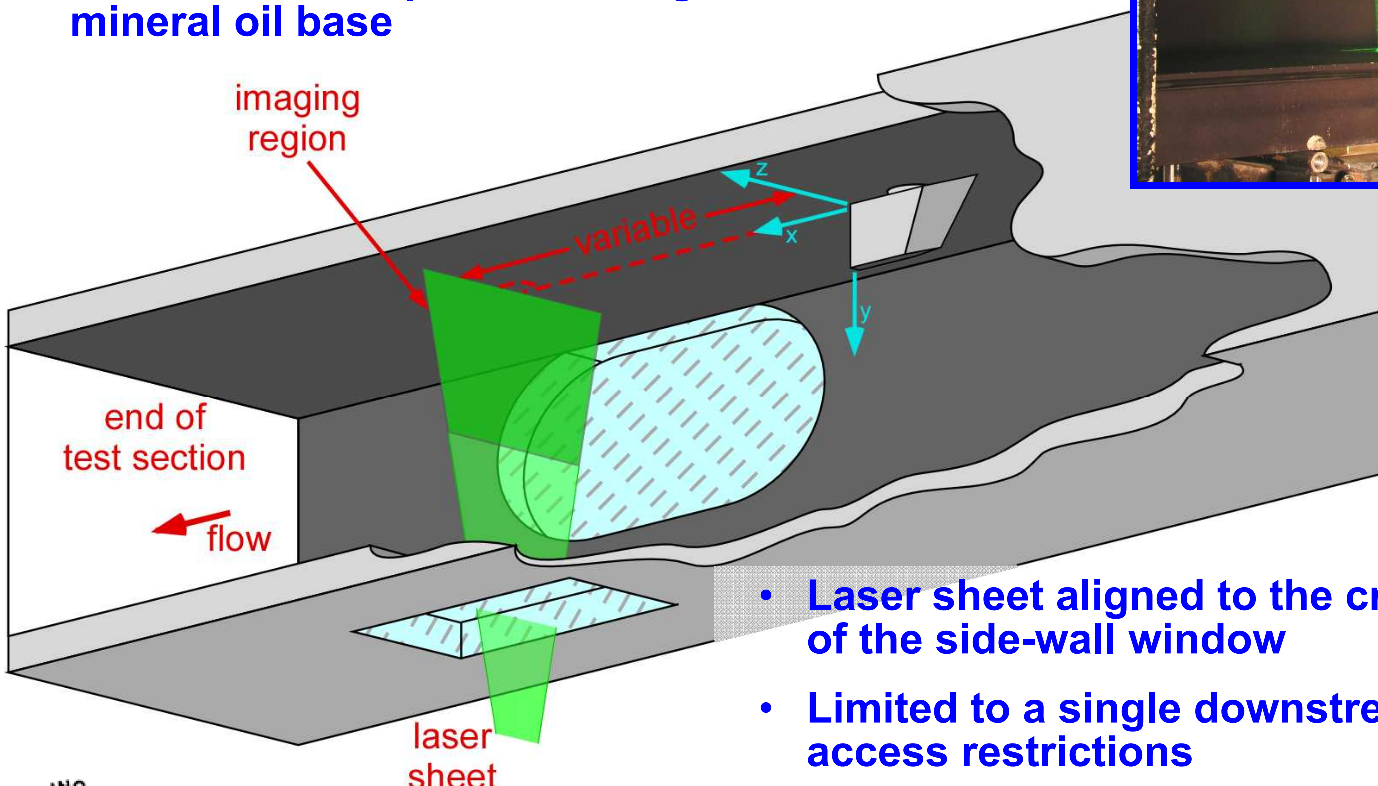
Particle Image Velocimetry (PIV) System

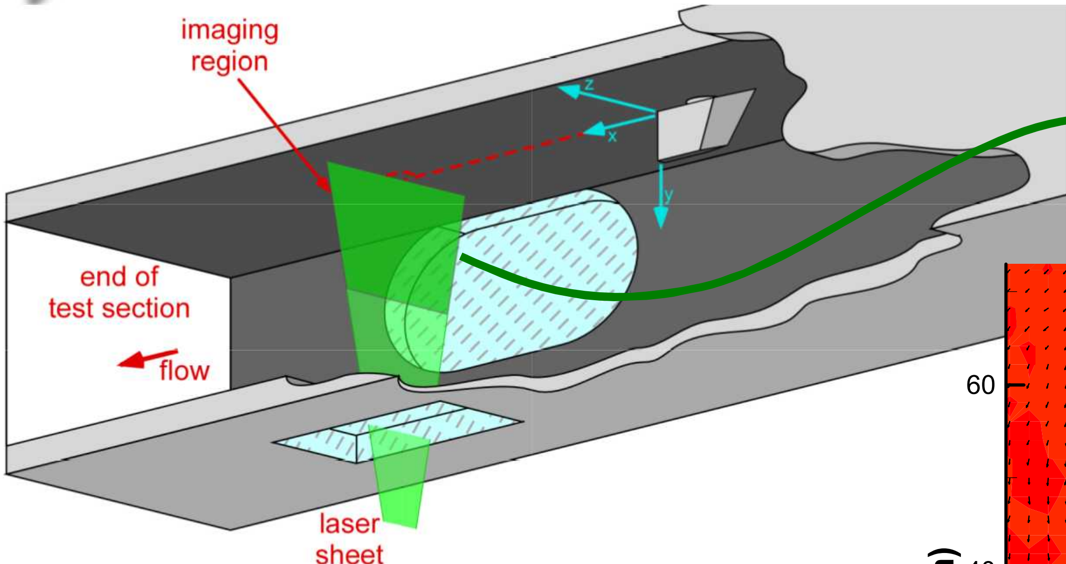
- **Illuminate with two Nd:YAG lasers, with 2 mm sheet thickness and Δt=1.4 μs**
- **Images captured using 2k×2k pixel interline-transfer CCD cameras**
- **Data processed using LaVision DaVis v7.1**
- **Particles 0.2-0.3 μm diameter generated from a mineral oil base**



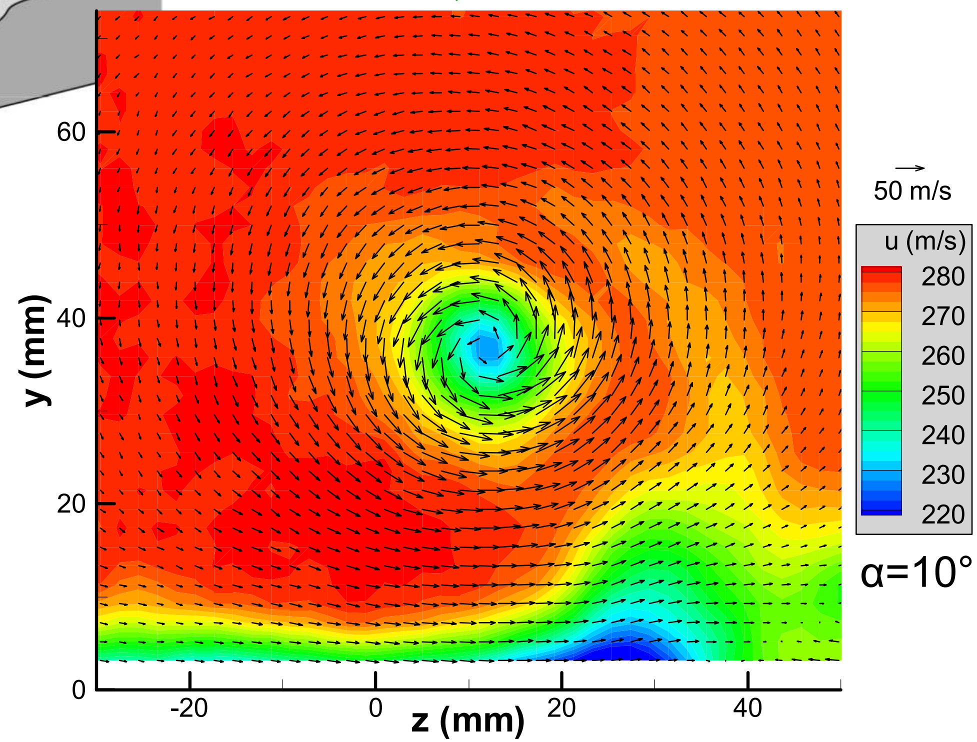


- **Laser sheet aligned to the crossplane at the center of the side-wall window**
- **Limited to a single downstream plane due to optical access restrictions**
- **Stereoscopic camera arrangement using scheimpflug mounts and a multi-plane calibration**

PIV Results



y-axis flipped so tunnel wall is at the bottom of the image

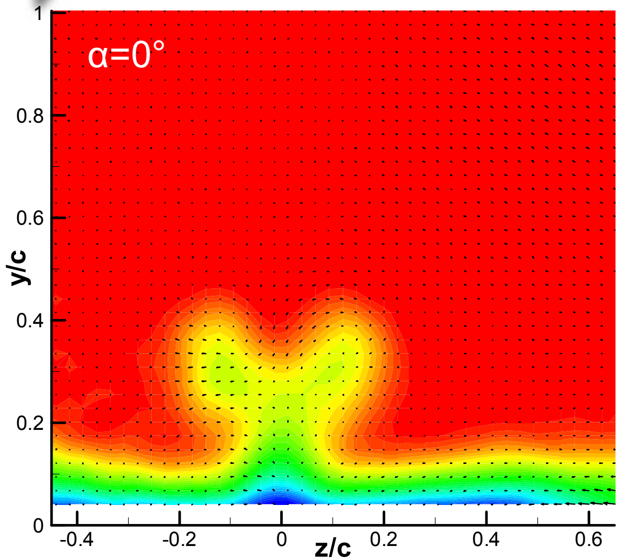


Perform the PIV experiment with a single upstream fin.

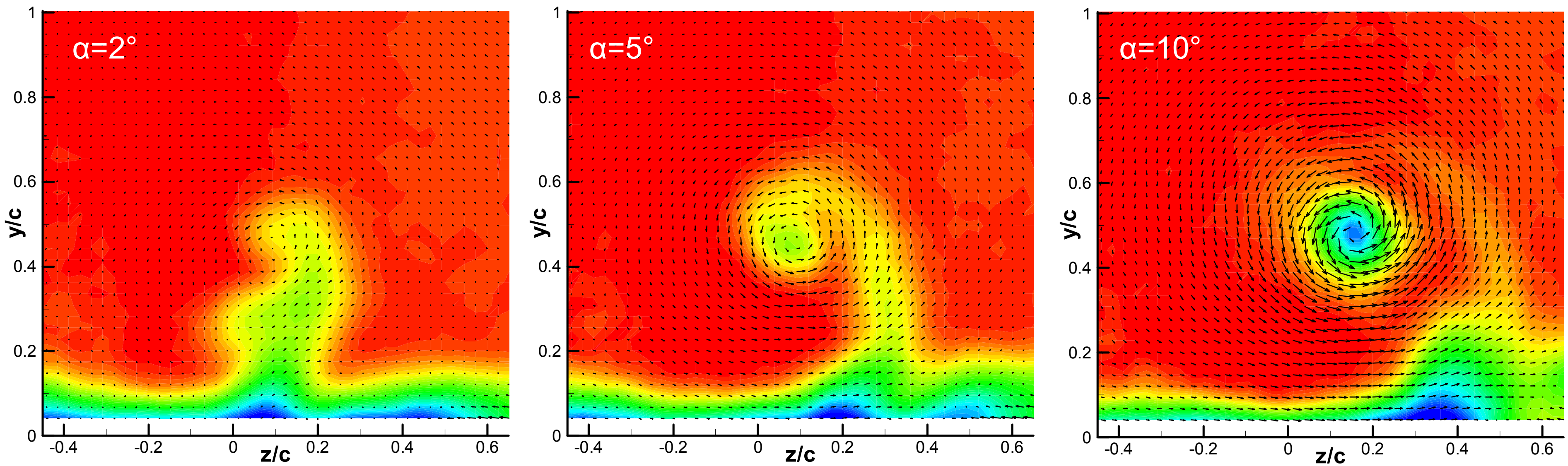
- Presence of a downstream fin would occlude the PIV images.
- Assume that the same fin tip vortex would impinge upon downstream fin
  - i.e., no upstream influence
  - balance measurements highly repeatable

The vortex shed from the fin tip is clearly visualized, as is the streamwise velocity wake.

Vortex Structure at Different Angles of Attack



- The fin tip vortices are shown at four different angles of attack, normalized by freestream velocity and fin root chord.
- Data were acquired about four fin lengths downstream of the fin trailing edge.
- As expected, vortex strength increases with alpha, and its position further from the tunnel centerline.
- A wake is seen even at α=0° where no vortex is shed.

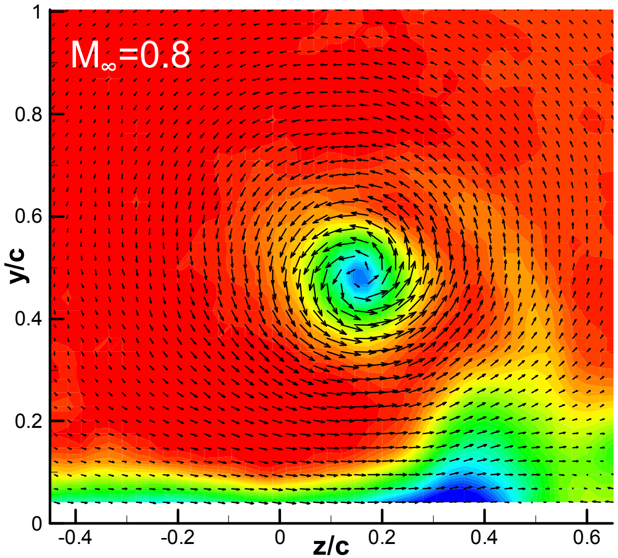


M_∞=0.8, x/c=4.18

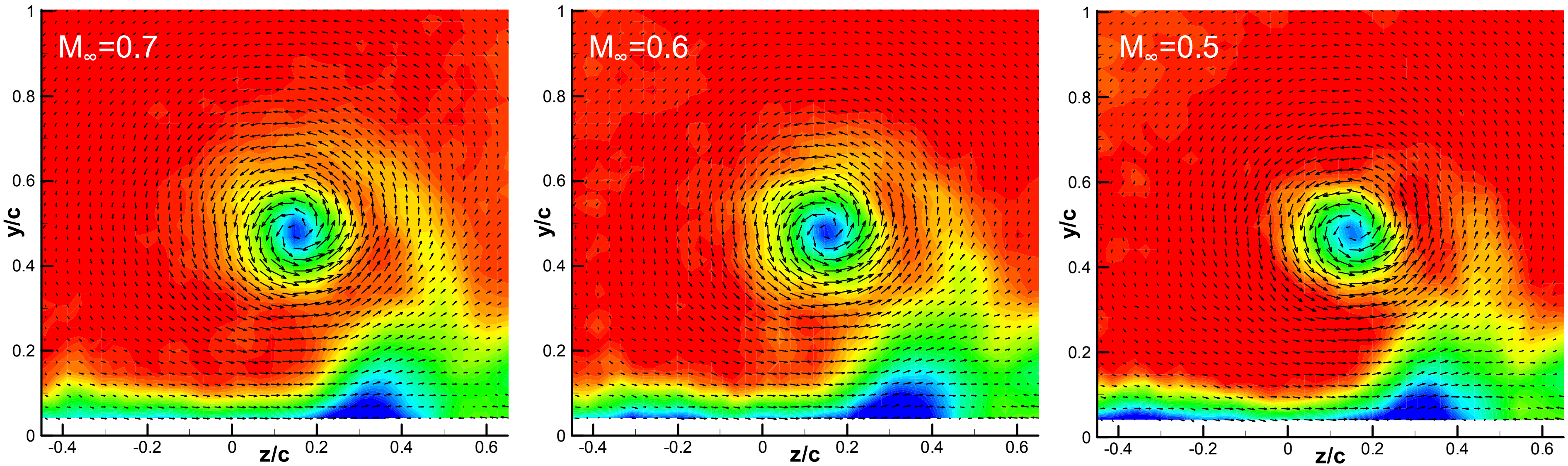
u/U_∞: 0.8 0.85 0.9 0.95 1

$0.2U_\infty$

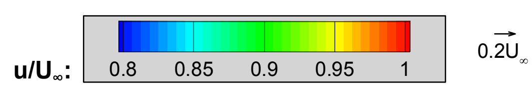
Vortex Structure at Different Mach Numbers



- **When normalized, no appreciable effect due to Mach number variation.**
  - Vortex size, strength, and position are constant
- **The Mach number effect on the interaction as measured by the downstream fin balance is subtle but detectable.**
- **Vortex breakdown on the downstream fin may be significant.**

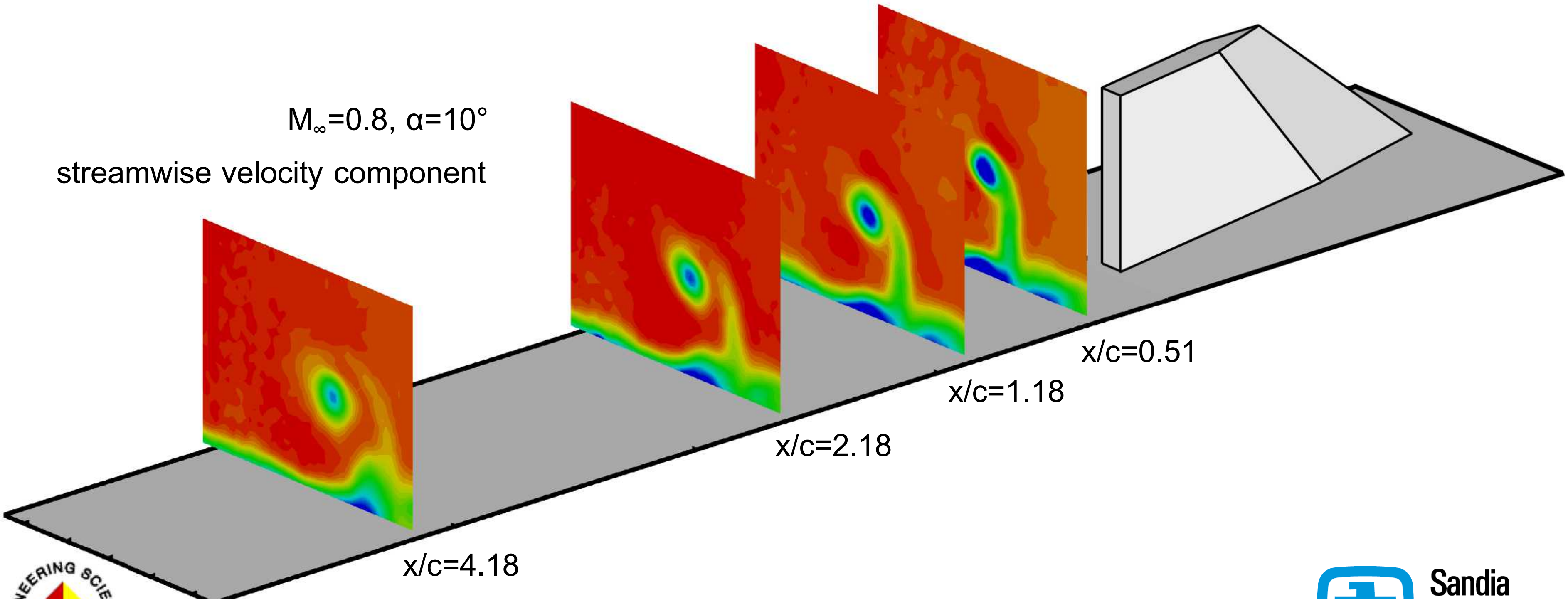


α=10°, x/c=4.17



Vortex Downstream Evolution

- **We also have data at multiple stations downstream of the fin to examine how the vortices shed and evolve.**
- **This allows us to better understand the physics and model them in our computational simulations…**
- **…and it is relevant to different fin positions on flight hardware.**



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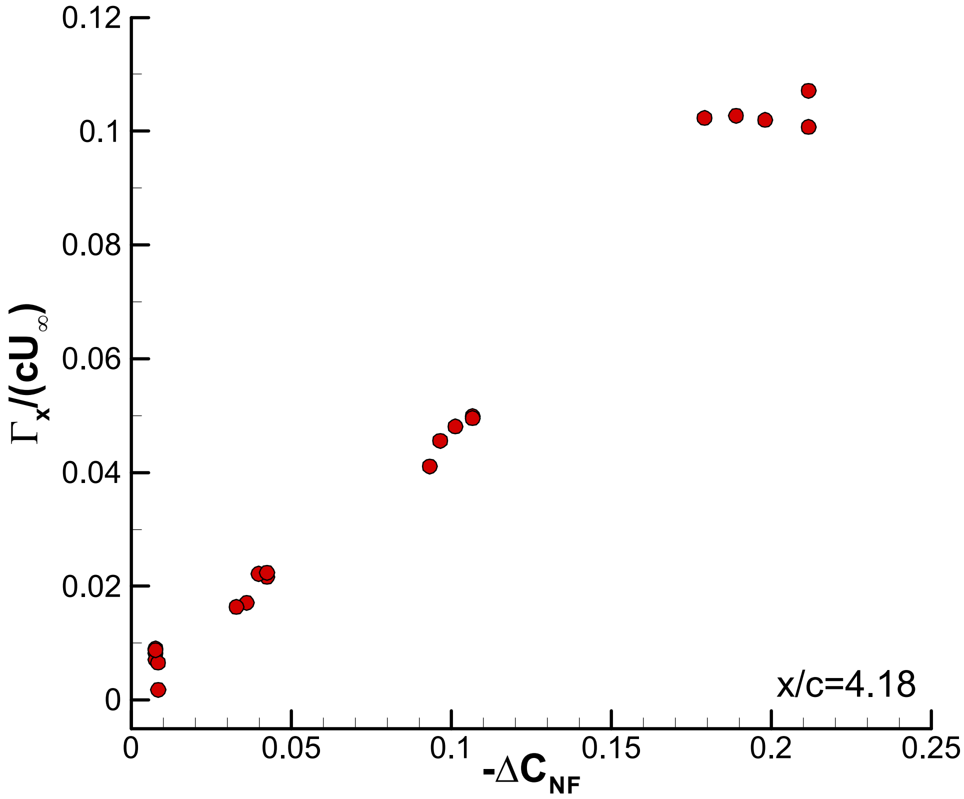
Correlation with Fin Balance Measurements

Can we find a correlation between the vortex strength and the fin aerodynamic forces?

Compute the vortex circulation and plot against ΔC_{NF}, the change in normal force due to the interaction.

We find a clear correlation.

- Certainly, this is the expected result.
- Other fin spacings and aero coefficients are similar



Correlation with Fin Balance Measurements

We believe the interaction arises from an induced angle of attack on the fins, $\alpha_{induced}$

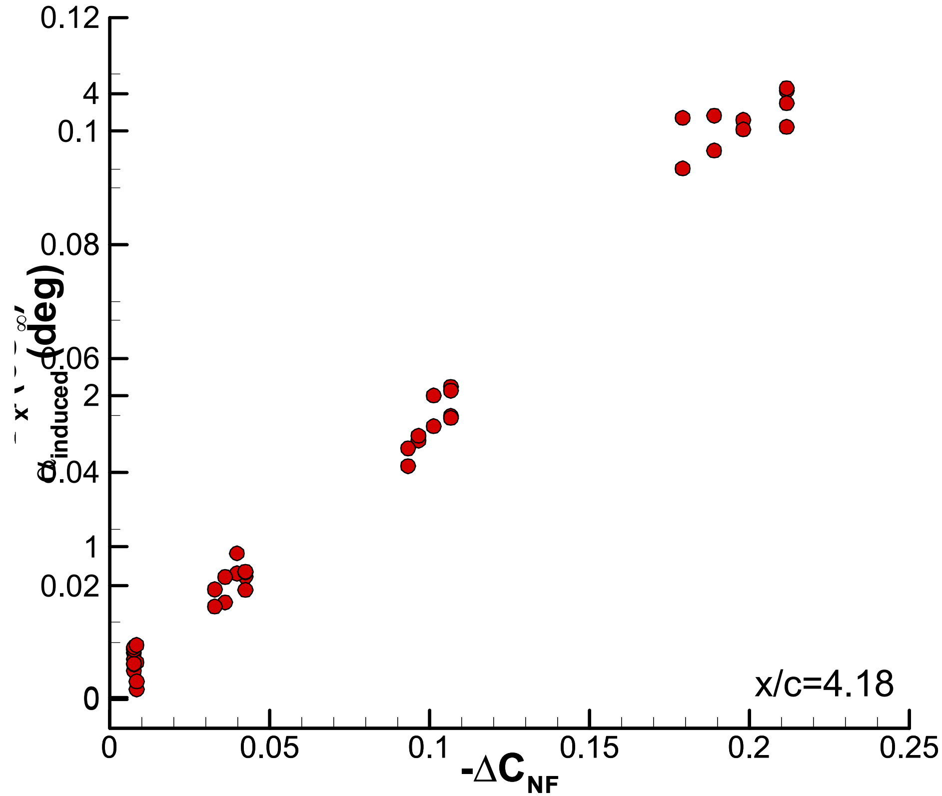
- Created by the lateral motion from the vorticity

Extract the PIV velocities along at the fin quarter-chord position (if it were there) and average.

Then compute $\alpha_{induced}$ and plot against ΔC_{NF}

We find a clear correlation.

- Other fin spacings and aero coefficients are similar



Correlation with Fin Balance Measurements

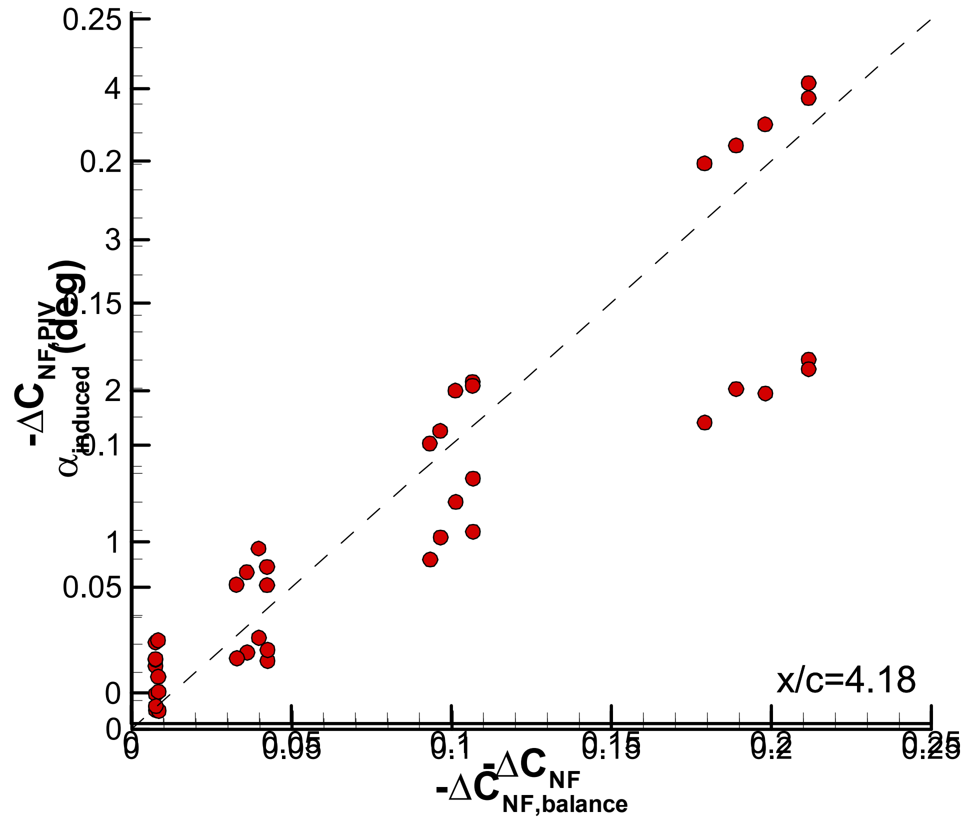
We can convert $\alpha_{induced}$ to a normal force coefficient using the single-fin balance data.

- Use the C_{NF} vs α curve

We find a strong correlation, but at less than the ideal one-to-one relationship.

Possibly a counteracting effect from additional lift as the upstream vortex interacts with the downstream fin.

Additional experiments are planned.



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Summary

- We have initiated a program to study fin tip vortices and their aerodynamic influence on downstream control surfaces.
- Sub-scale experiments utilize fins mounted on a wall of the wind tunnel.
- Data are being collected using two primary diagnostics:
  - Fin balances to measure the aerodynamic forces.
  - PIV to measure properties of the vortex responsible for the interaction.
- Future work:
  - Further analyze the PIV data to compare fin-tip vortices with better-known aircraft wing-tip vortices.
  - New experiments will be run at conditions surrounding Mach 1 to explore transonic effects.

These data will enhance our understanding of fin wake interactions to aid in the design of future flight vehicles, as well as directly providing measurements for the validation of computational models.

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