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Interaction of a Crossflowing Jet with a Downstream Fin on a Full-Scale Flight Vehicle Configuration

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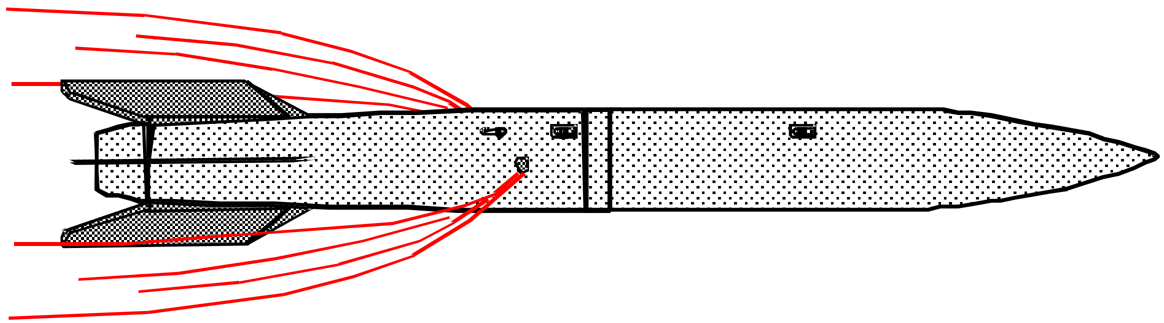
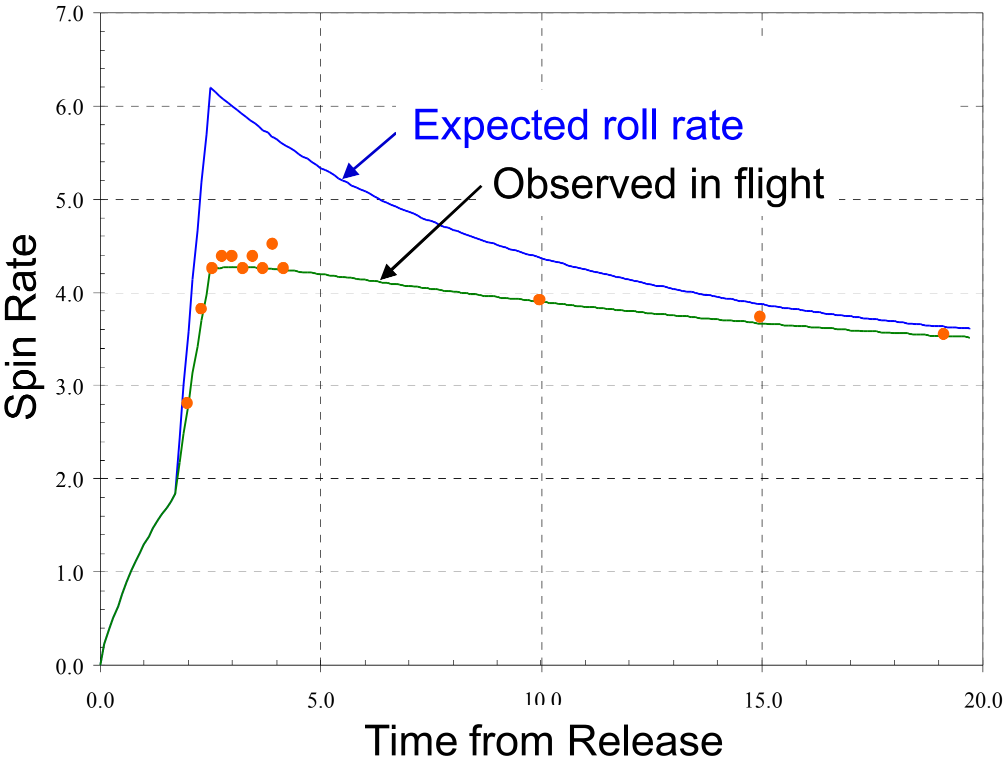
Motivation



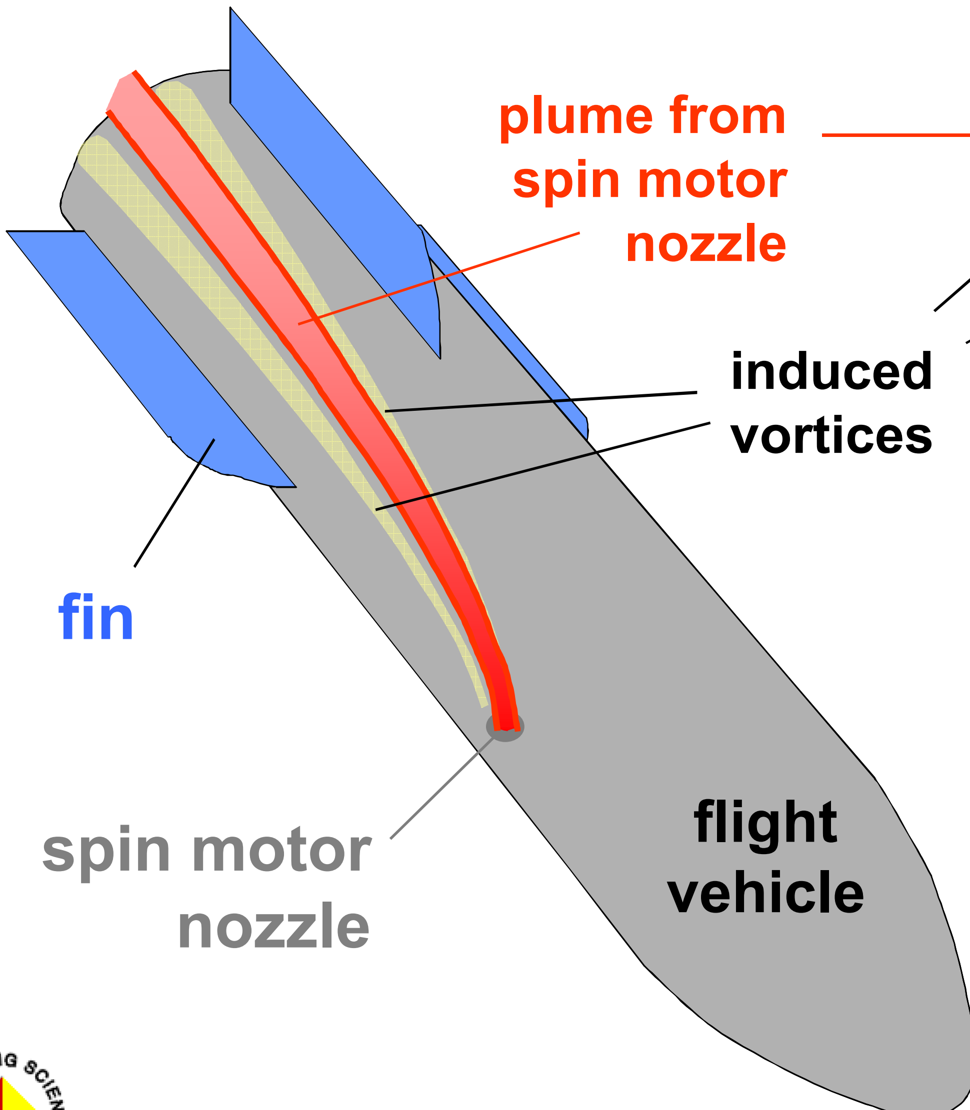
Some vehicles employ both fins and thruster rockets for roll and attitude control.

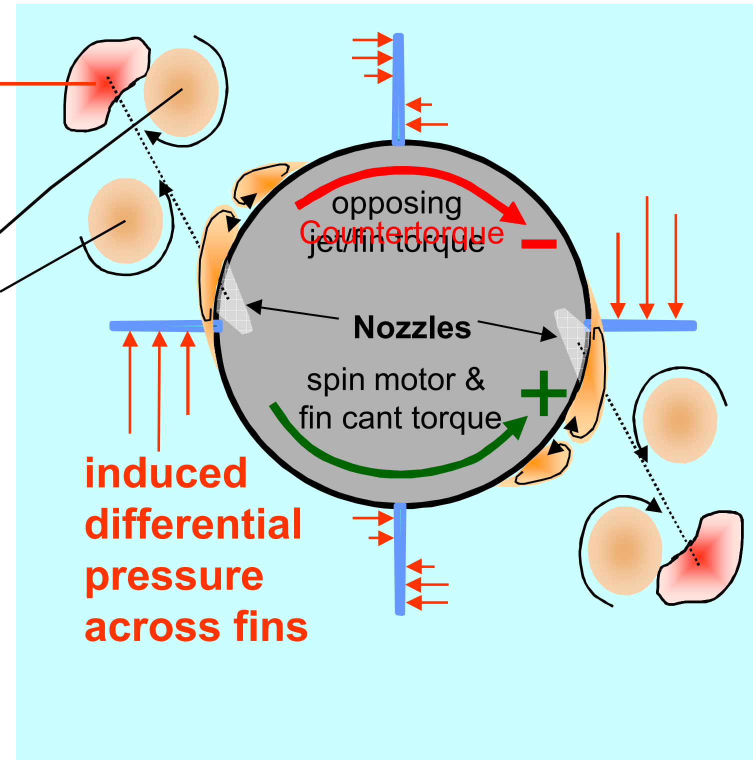
In flight, vehicle spin rates are found to be lower than expected when the spin rockets are fired.

- Due to an interaction between the jet plume from the spin motor and the fins



Jet/Fin Interaction





cross section view
at fin quarter chord
(looking from the nose)

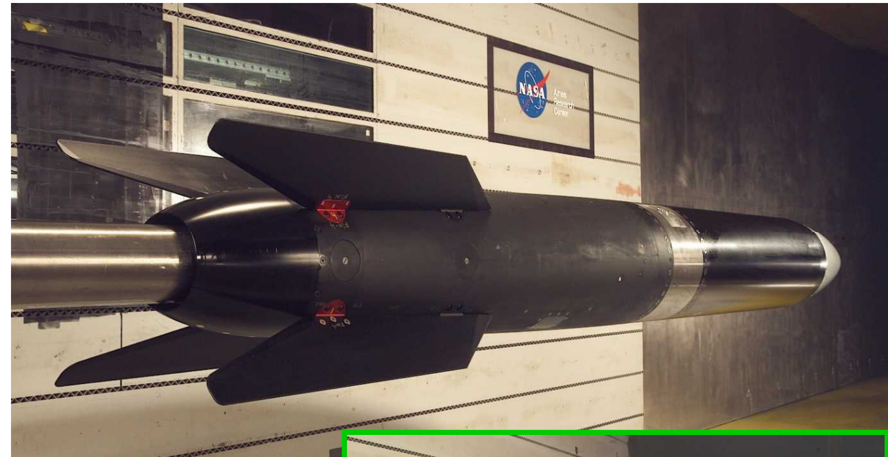
Full-Scale Wind Tunnel Test

A test was performed in the 11-Foot Transonic Tunnel at NASA Ames

- **Use an internal balance to measure the "countertorque" over a range of flow conditions**

Net roll torque = torque from canted fins
+ torque from spin rockets
– countertorque due to jet-fin interaction

- **Acquire crossplane velocity data to provide physical insight into jet/fin interaction**



Our mission: Acquire PIV data of the vortices simultaneous with countertorque measurements from the aerodynamic balance

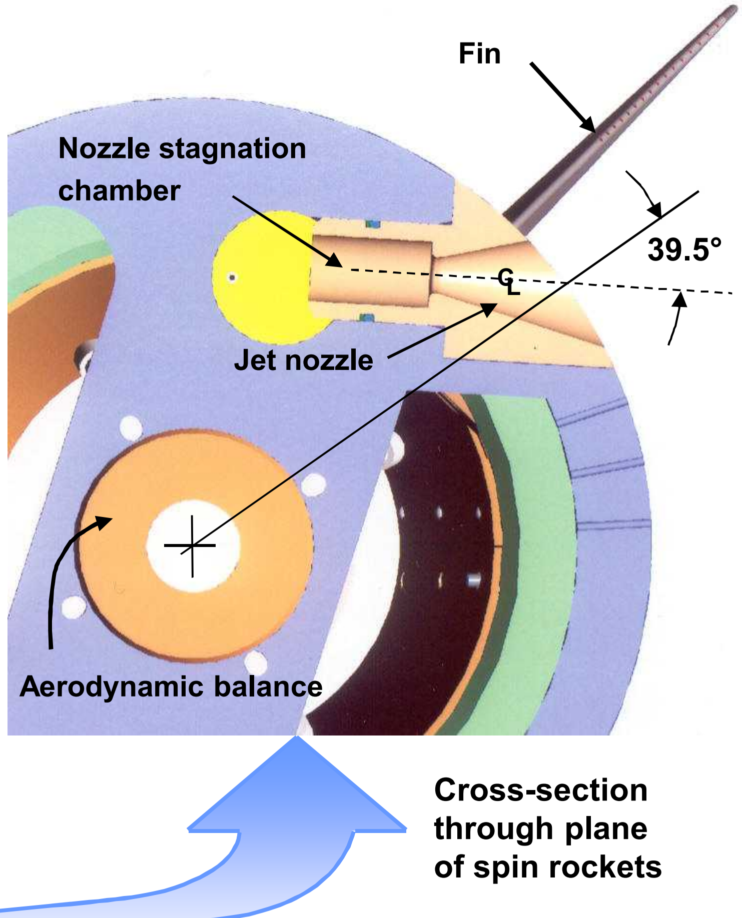
Wind Tunnel Model

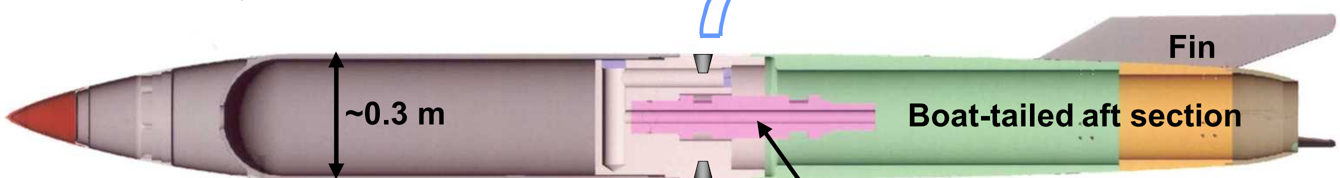
Vehicle Geometry

- Finned body of revolution
- Four equally spaced fins
  - Canted to generate steady spin rate
- Two spin rockets at center body
  - Achieve steady-state spin rate faster
- Model does not spin
  - Spin rates are low enough that the effect on jet/fin interaction is negligible

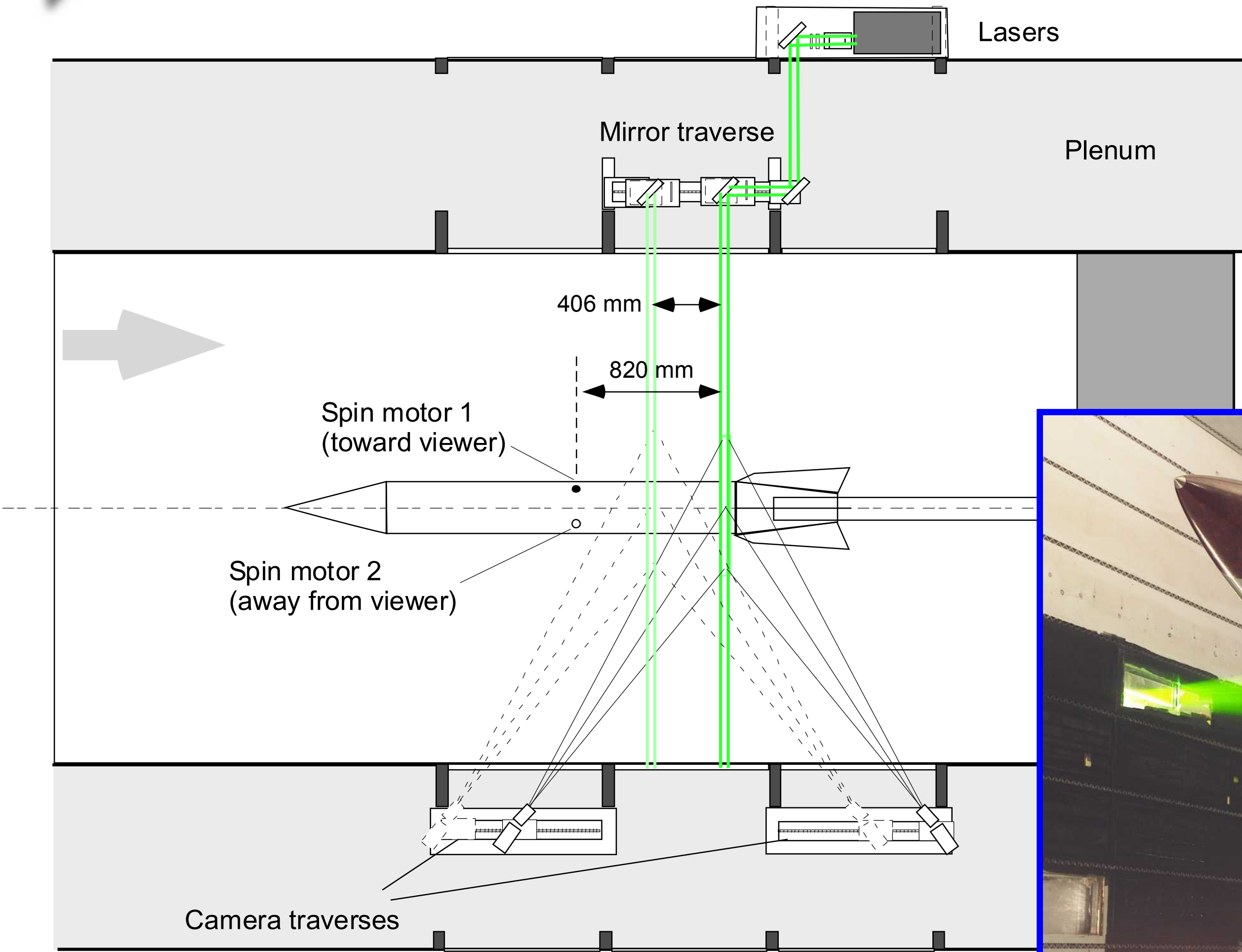
Spin Rocket Nozzles

- Simulated using high-pressure air
  - Passed through a five-component flow-through balance
- Asymmetric nozzle due to scarfing by cylindrical body





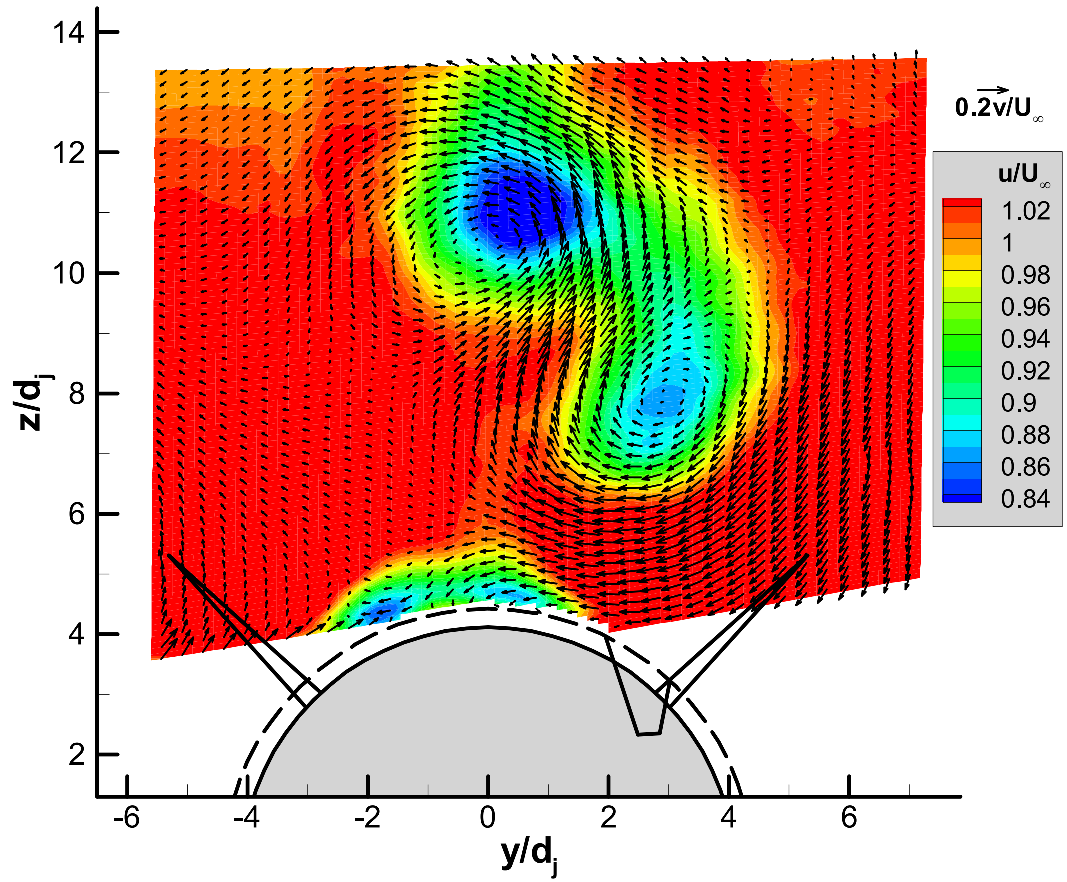
PIV Configuration



- Laser sheet introduced from one side of the test section; the cameras located on the opposite side.
- Laser sheet positioned just upstream of the leading edge of the fin root.

PIV Mean Velocity Fields

- Vectors are sub-sampled 2 × 2
- Counter-rotating vortex pair is clearly visible
  - Asymmetric due to scarfed nozzle
  - Twisted with respect to the model surface
- Remnant of horseshoe vortex visible near surface
  - Displaced laterally from nozzle exit position
- One fin is principally affected
  - Consistent with prior fin pressure measurements



We have similar data at various combinations of M_∞, J, and α to identify changes in the vortices for varied flight conditions.

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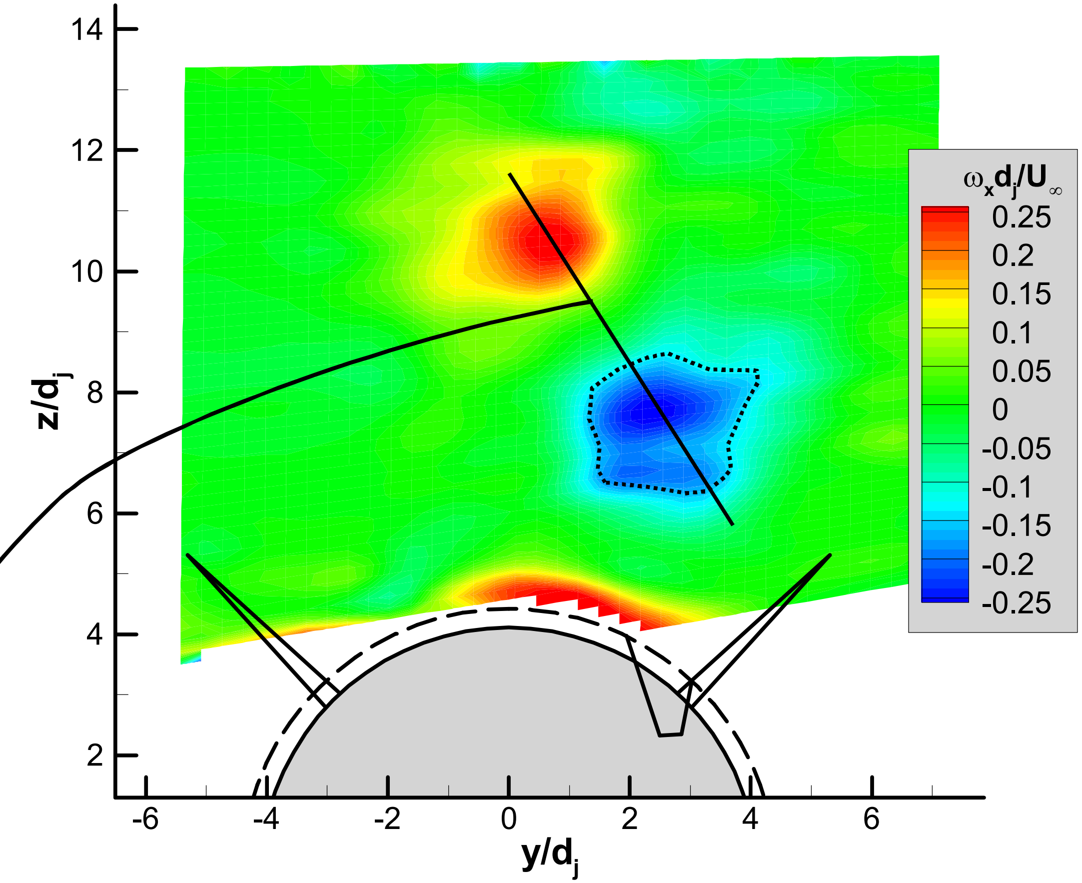
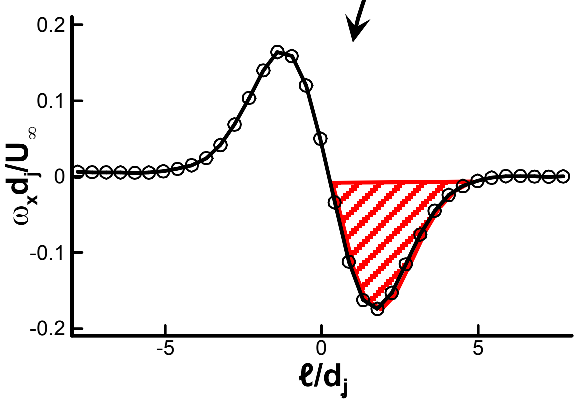
Data Analysis

Use the vorticity field to characterize the vortices.

The vortex pair can be characterized by the position, size, and strength of each vortex.

Restrict our analysis to α=0° for brevity.





$$\Gamma_x = \int \omega_x dA$$

$$(\bar{y}, \bar{z}) = \frac{1}{\Gamma_x} \int (y,z)\,\omega_x dA$$

$$d_\Gamma^2 = \frac{4}{\pi} \int dA$$

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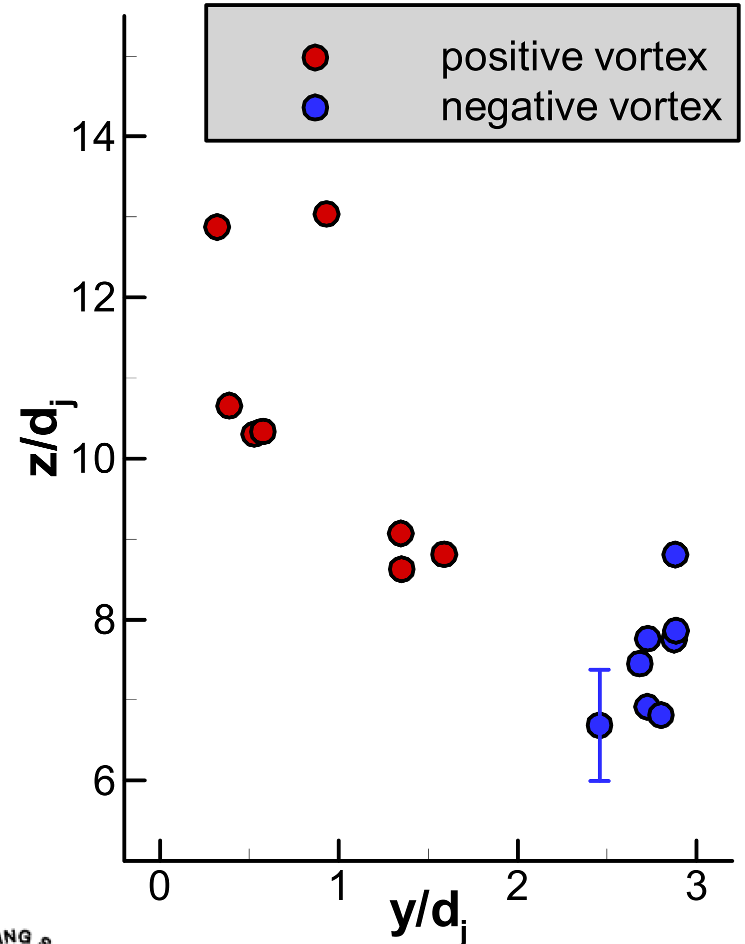
Vortex Positions

Find the vortex positions by centroiding the vorticity field:



We observe that:

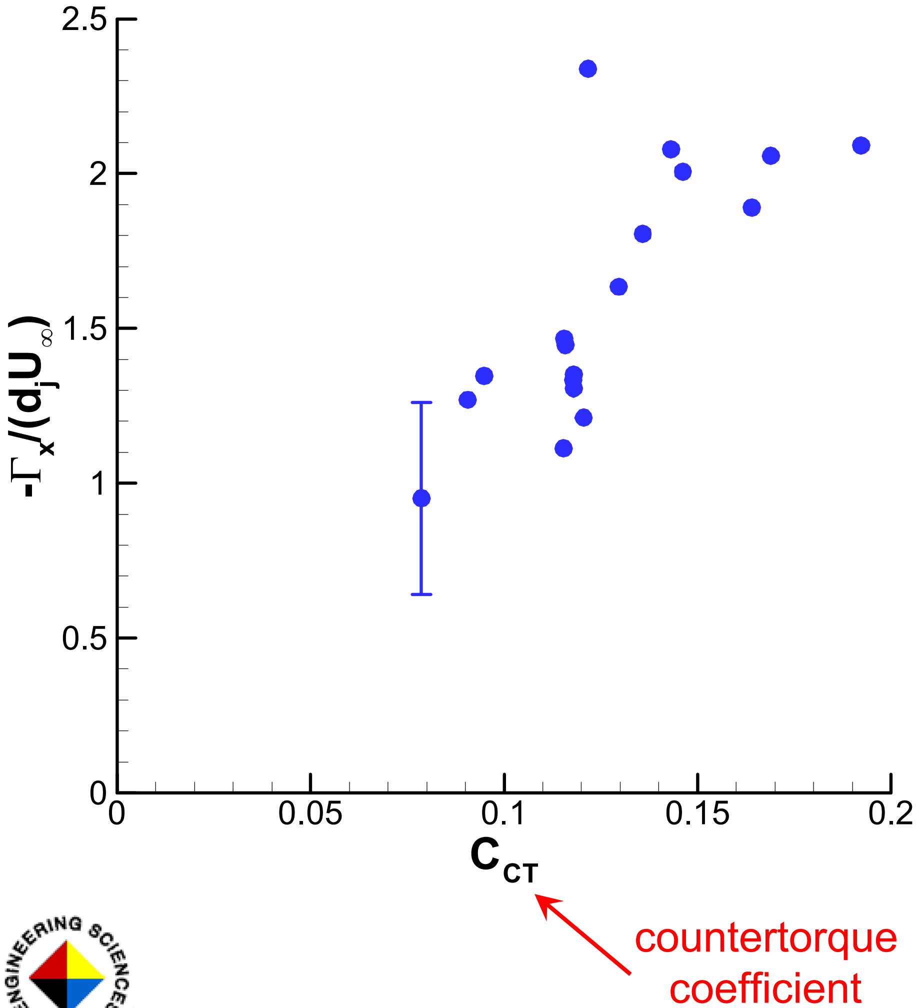
- In all cases, negative vortex is closer than the positive vortex to the fin where the interaction is strongest.
- The position of the negative vortex is not a strong function of flight conditions.

Therefore we theorize that the countertorque is influenced by the circulation of the negative vortex.

Can we find a correlation between these two values?

Correlations with Countertorque

A clear correlation is evident between circulation and countertorque.



This suggests that jet/fin interaction arises from an induced angle of attack on the fins, α_{fin}.

- Created by the lateral motion from the CVP vorticity.

Extract the mean velocity vector near the affected fin and compute the fin angle of attack, α_{fin}.

Can we find a correlation between α_{fin} and countertorque?

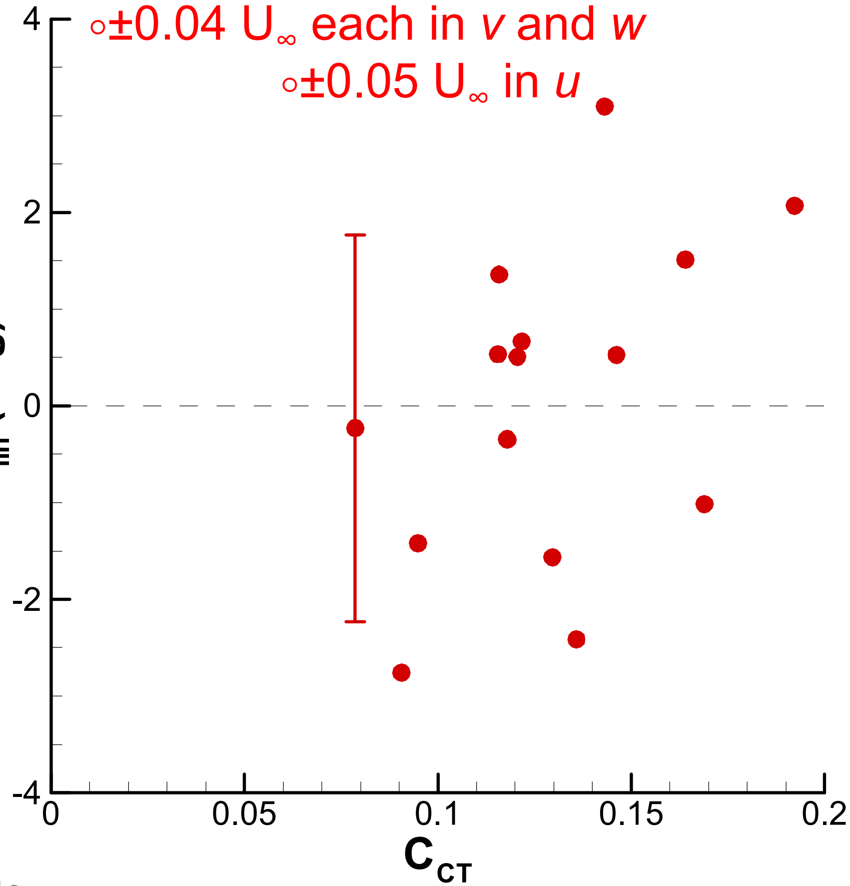
Correlations with Countertorque

No correlation is evident between induced fin angle of attack and countertorque.

Estimate error as:

◦±0.04 U_∞ each in *v* and *w*

◦±0.05 U_∞ in *u*



We found a strong correlation between C_{CT} and circulation…

…but not between C_{CT} and induced fin angle of attack.

Bias errors in the velocity field near the vortex pair are of low spatial frequency.

Thus the error does not greatly influence calculation of vorticity.

Result: the vorticity field is more trustworthy than the velocity field for subtle correlations.

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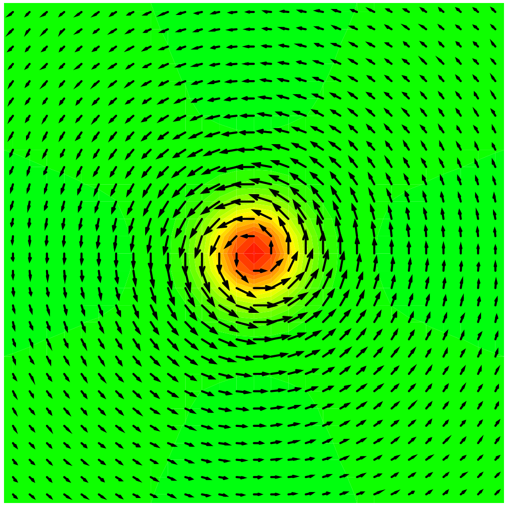
Vortex Modeling

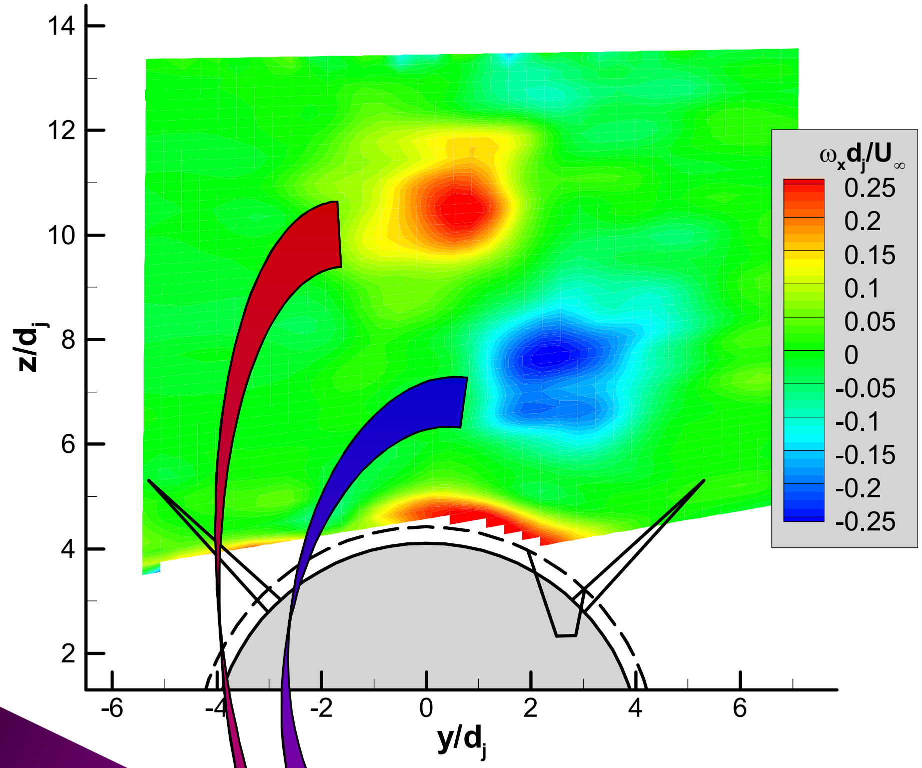
We can generate a new velocity field using key vortex parameters found from the vorticity field

Model each vortex in the vortex pair with a Gaussian velocity distribution

- *Not* a point vortex as in potential flow models

$$\vec{V} = \frac{\Gamma_x}{2\pi}\left(\frac{1-e^{-d_\Gamma^2 r^2}}{r}\right)\hat{e}_\theta$$





vortex position: $(\bar{y}, \bar{z})$

vortex strength: Γ_x

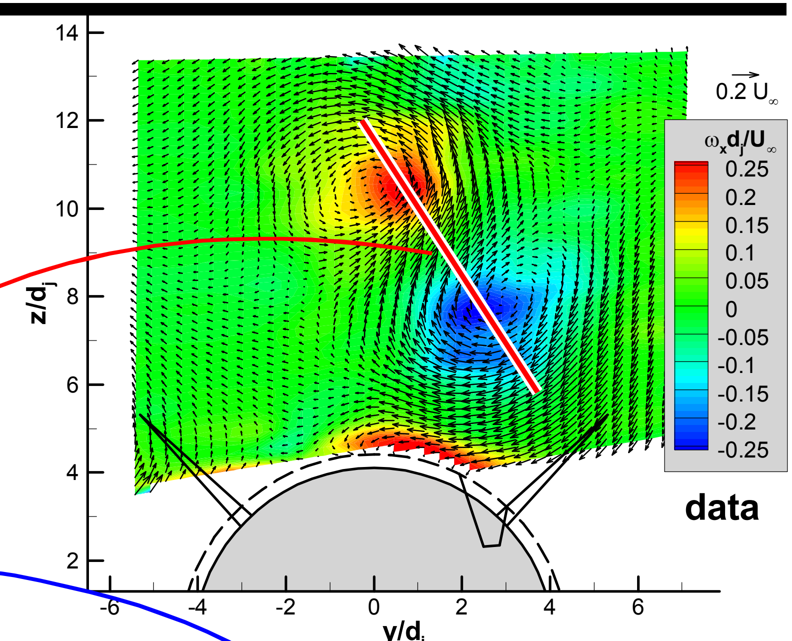
vortex size: d_Γ

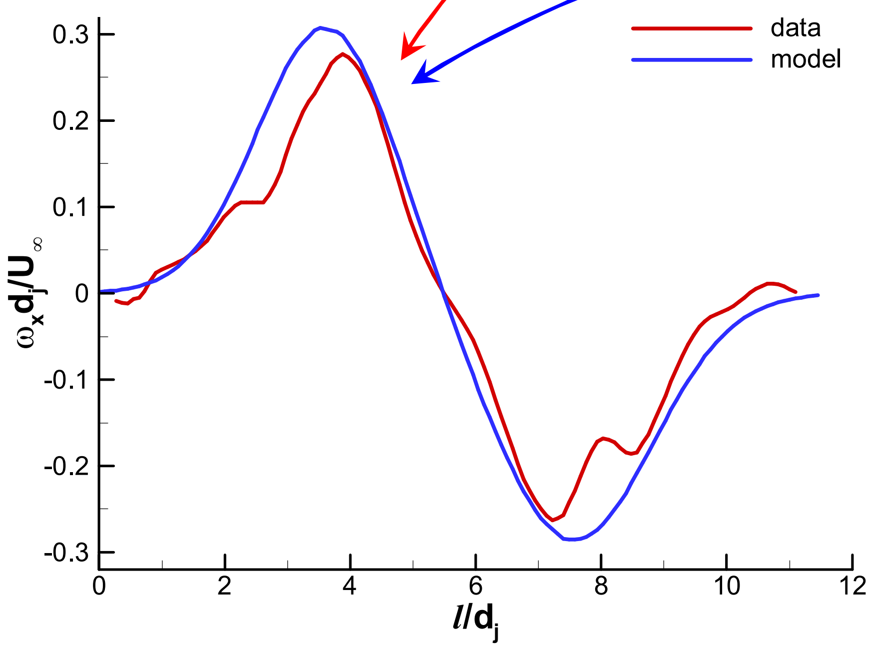
for each vortex in the CVP

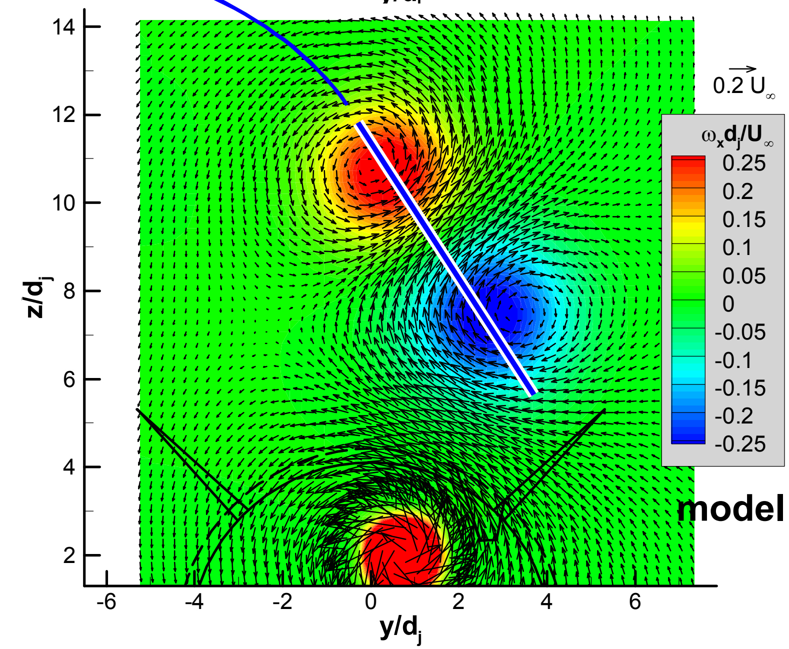
Vortex Modeling

Model the flowfield using a three-vortex approach

- One modeled vortex for each vortex in the counter-rotating vortex pair…
- …plus an image of the negative vortex inside the vehicle
    - The positive vortex is not imaged because it is far from the surface
- Neglect effects of the horseshoe vortex







Vortex Model Correlations with Countertorque

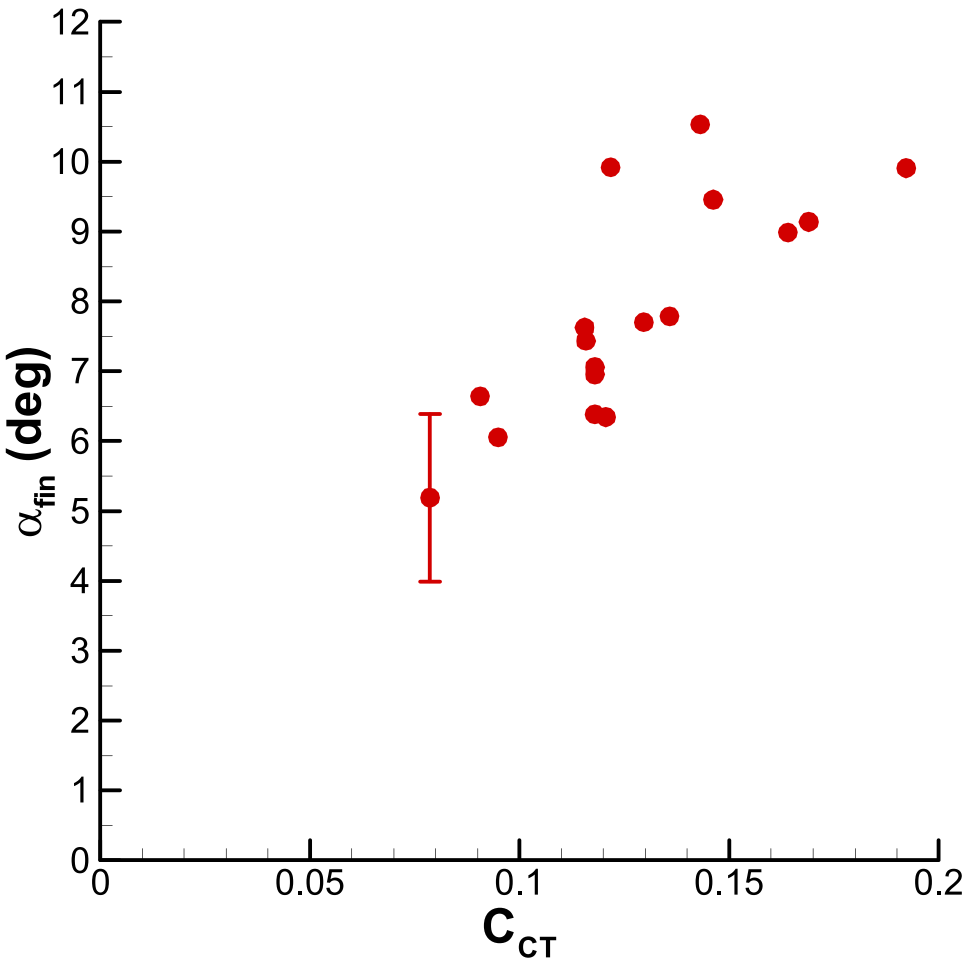
This not intended to be an accurate model of the vortex structure of the interaction.

- Merely provide more accurate velocities near the fin.

But we can use it to seek a correlation between the countertorque and the induced angle of attack on the fin.

- Extract velocity vector from vortex model at midpoint of fin length
- Find the velocity component normal to the fin and calculate α_{fin}

This correlation demonstrates that countertorque arises from an angle of attack induced on the fins by the vortex pair.



Summary

- Stereoscopic particle image velocimetry has been used to study jet/fin interaction on a full-scale flight vehicle configuration.
  - Data have been collected principally at a station just upstream of the leading edge of the fin root.
- The induced counter-rotating vortex pair is highly asymmetric due to the scarfed jet nozzle.
  - One vortex remains close to the fins regardless of flight conditions.
  - Its strength determines the severity of the jet/fin interaction.
- A model of the vortex structure was fit to the vorticity field
  - Overcomes difficulties with bias errors in the measured velocity field
  - *The angle of attack induced upon the fins by the counter-rotating vortex pair is responsible for a reduction in the vehicle roll torque*