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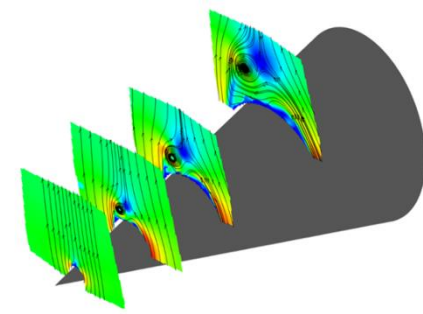
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A Comprehensive Study of Forebody Vortex Interactions with Control Surfaces of Generic Axisymmetric Configurations

Rajan Kumar and Kourosch Shoele

Roopesh Kumar, Al Shahriar, Joseph Rodriguez, Adrienne Brown, S. Mahadevan, Tufan Guha

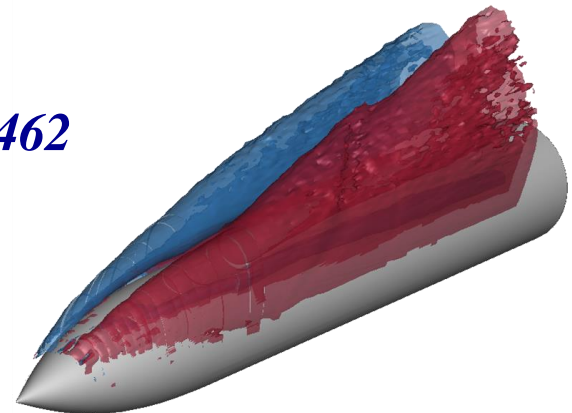
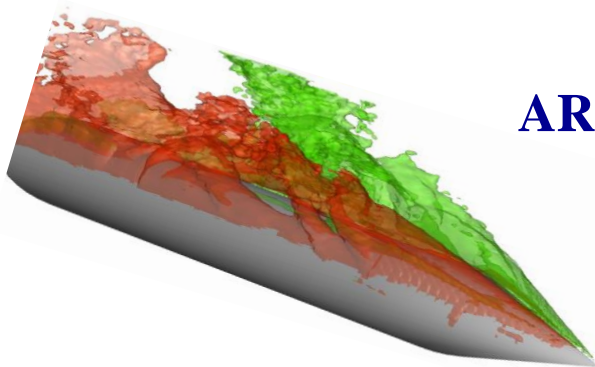
FAMU-FSU College of Engineering

In Collaboration with

James DeSpirito

Army Research Laboratory

ARO Contract # W911NF1810462

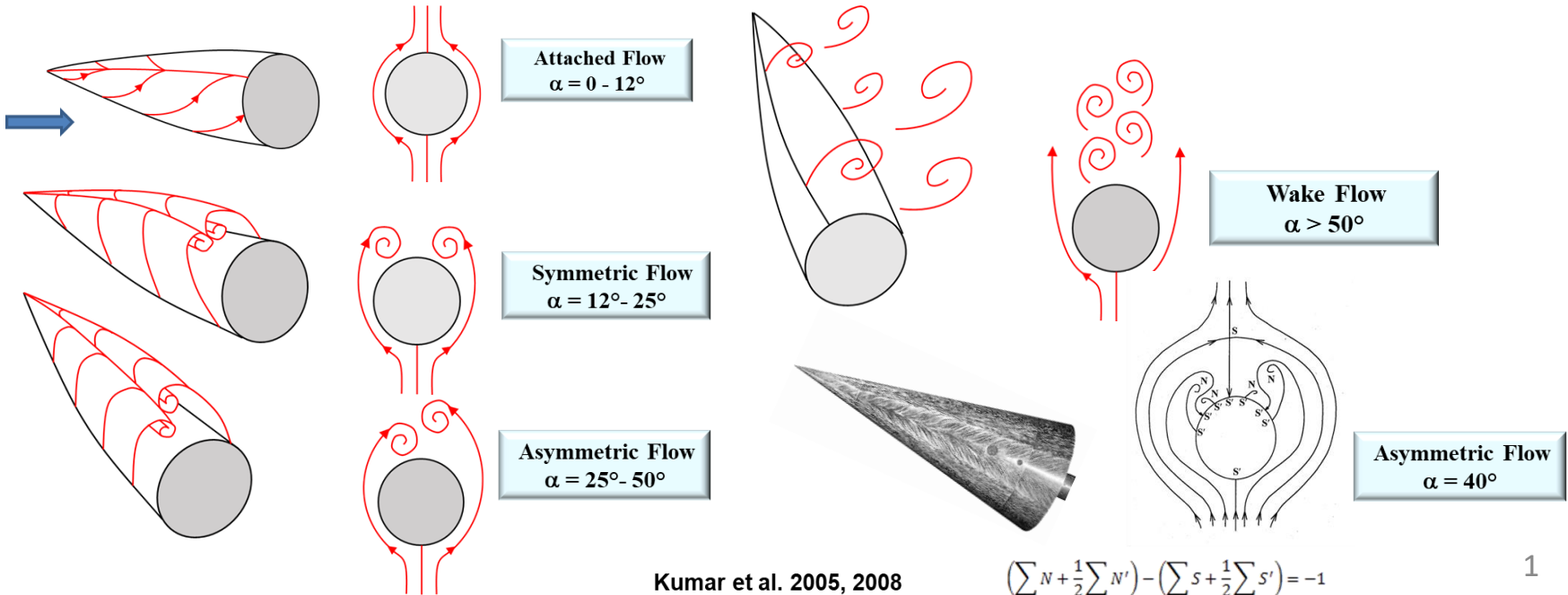
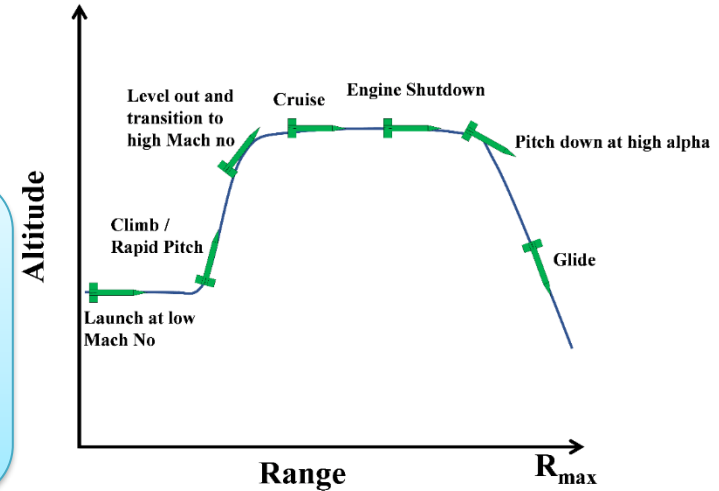


Slender Bodies at High AoA

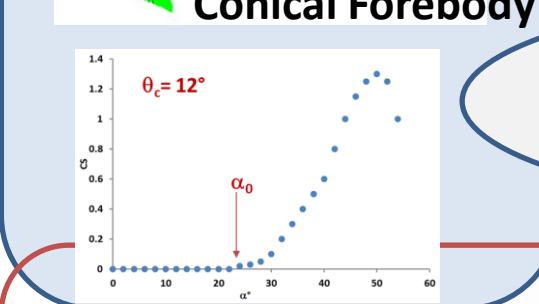
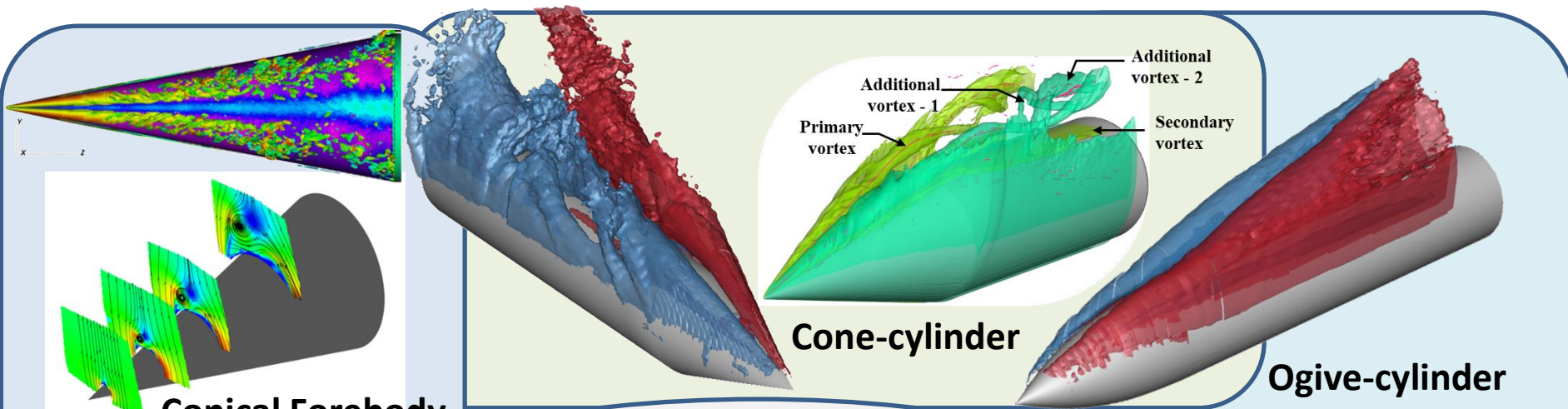
Flight vehicles are expected to perform high alpha maneuvers to achieve tactical advantages

At high angles of attack:

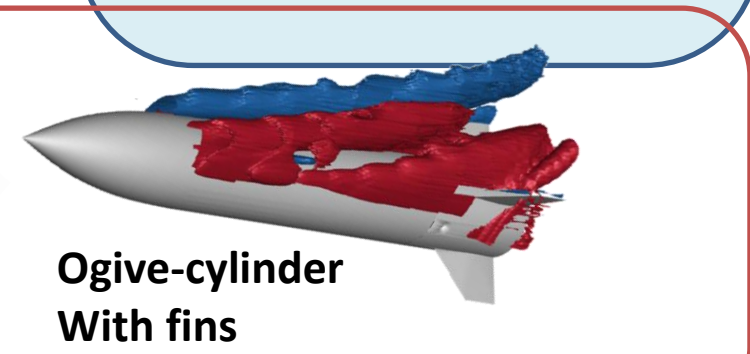
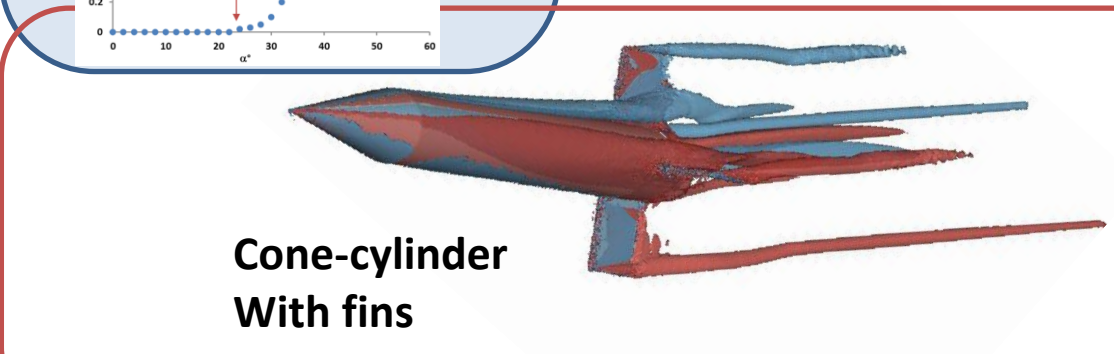
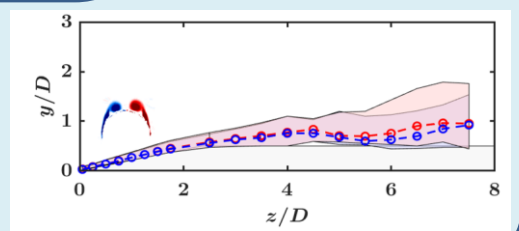
- Slender bodies at high AoA results in large side forces and yawing moments (Phantom Yaw)
- Control surfaces are relatively less effective – in the body wake
- At certain conditions side forces switch sign result in oscillatory rolling motion – **a serious consequences to mission and safety**



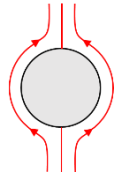
$$\left(\sum N + \frac{1}{2} \sum N'\right) - \left(\sum S + \frac{1}{2} \sum S'\right) = -1$$



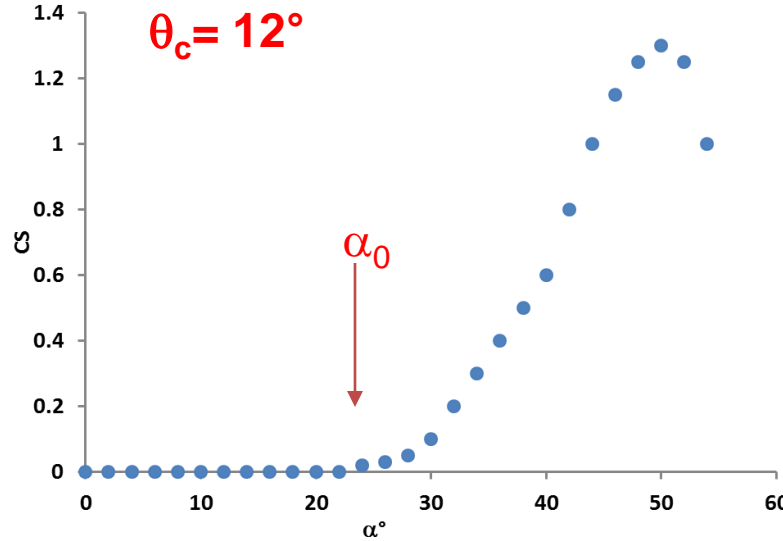
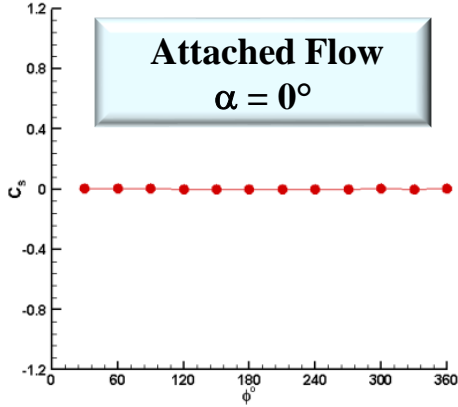
Vortex Asymmetry on Slender Bodies at High Angles of Incidence



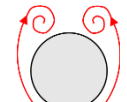
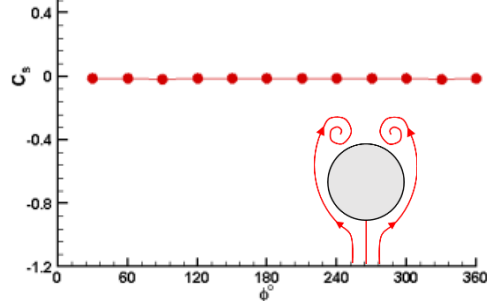
Side Force / Yaw Moment Characteristics



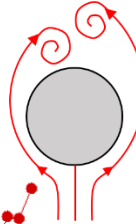
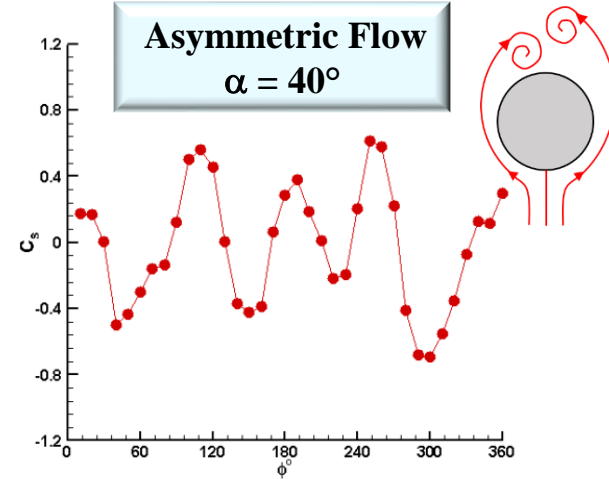
Attached Flow
 $\alpha = 0^\circ$



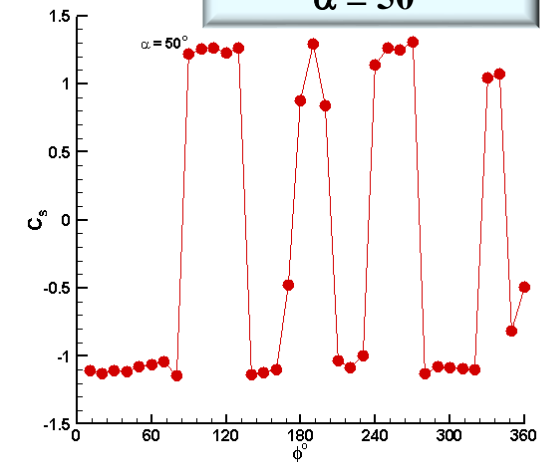
Symmetric Flow
 $\alpha = 15^\circ$



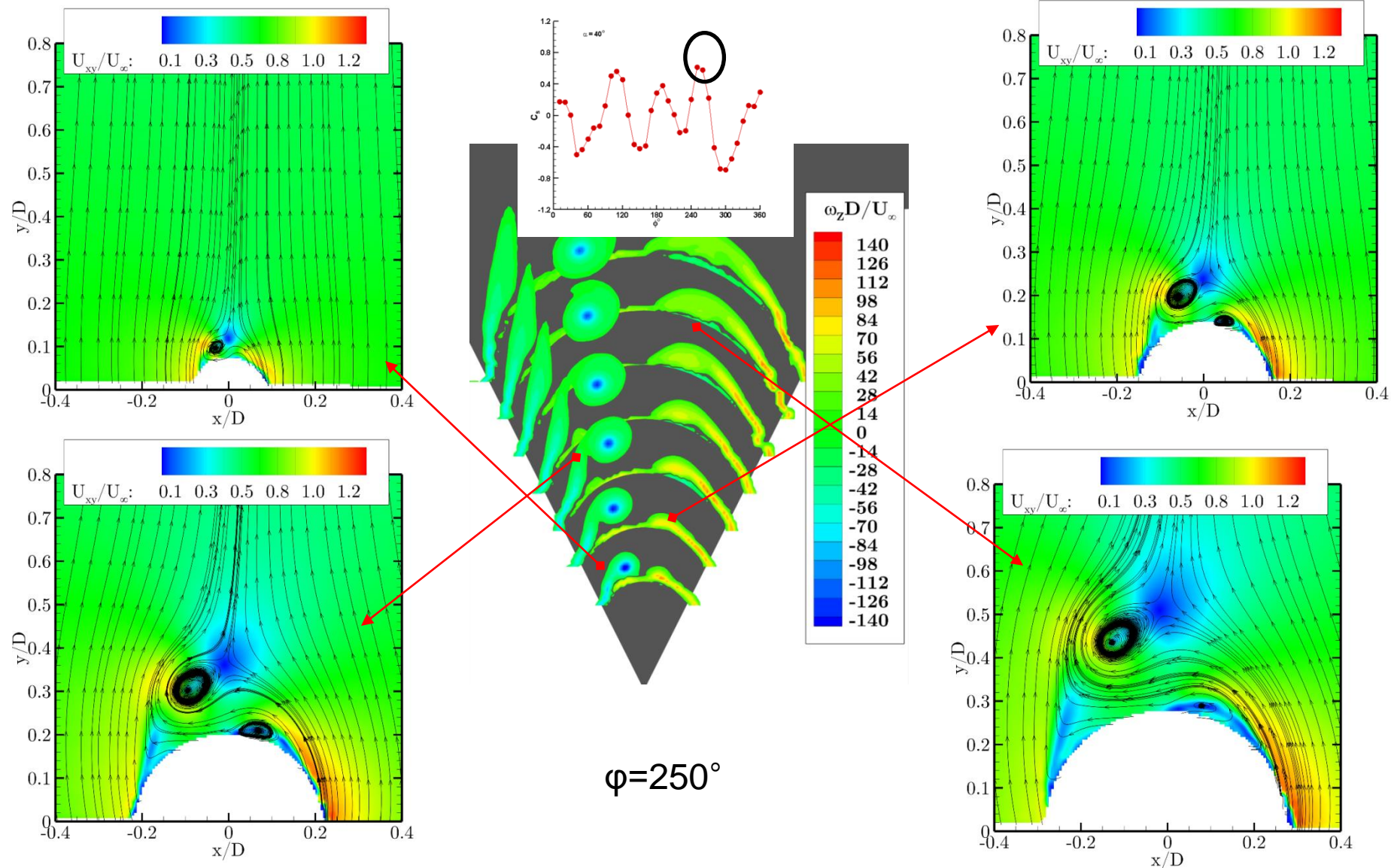
- Onset of vortex asymmetry is $2\theta_c$
- Side force a periodic function of roll orientation



Bi-stable flow
 $\alpha = 50^\circ$

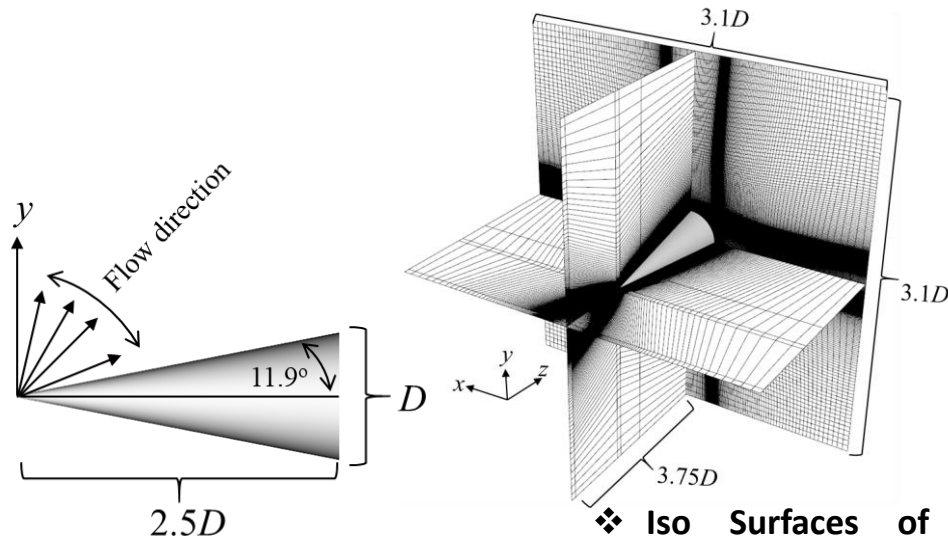


Asymmetric Flow Features, $\alpha=40^\circ$



$\phi=250^\circ$

Numerical Simulations

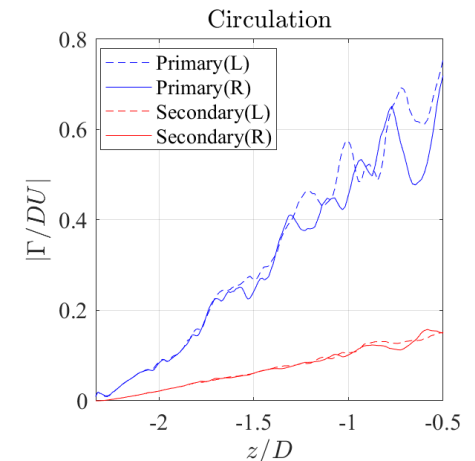
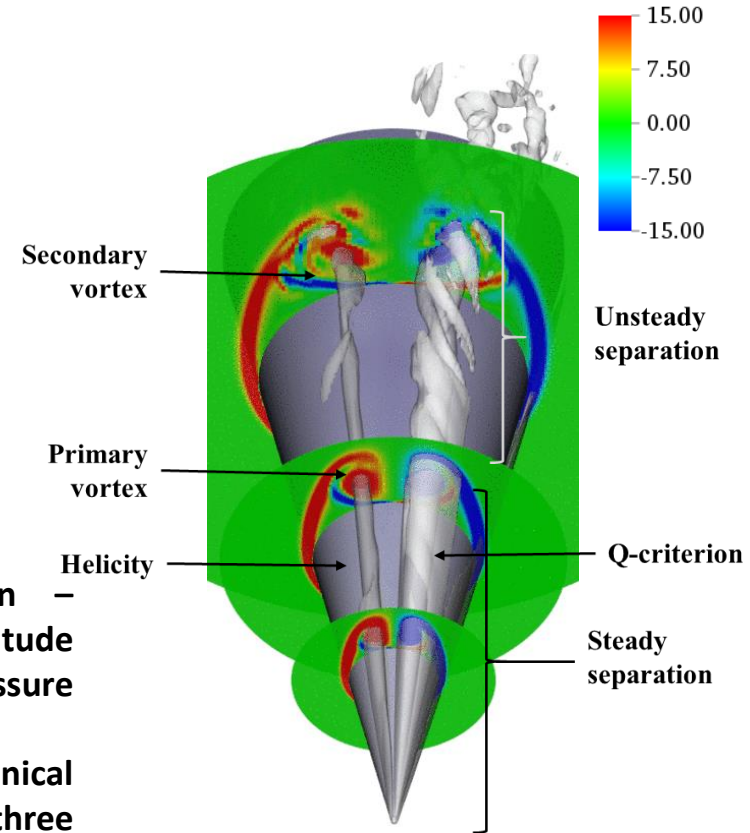


- ❖ Iso Surfaces of Q-Criterion – Colored with Velocity Magnitude and corresponding surface pressure is shown.

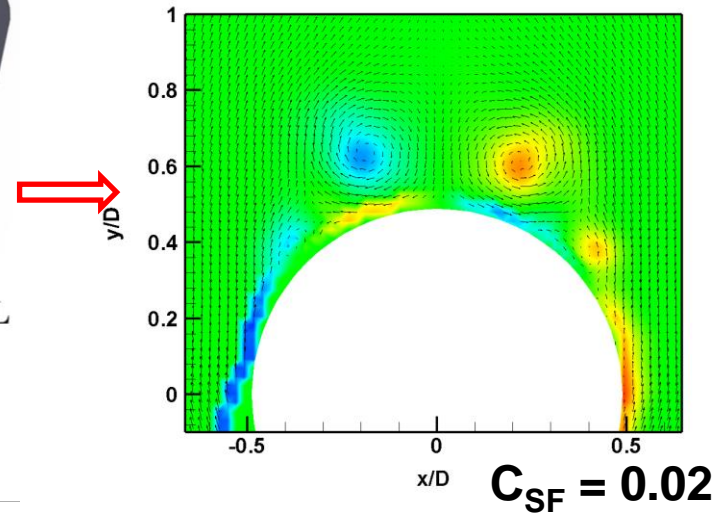
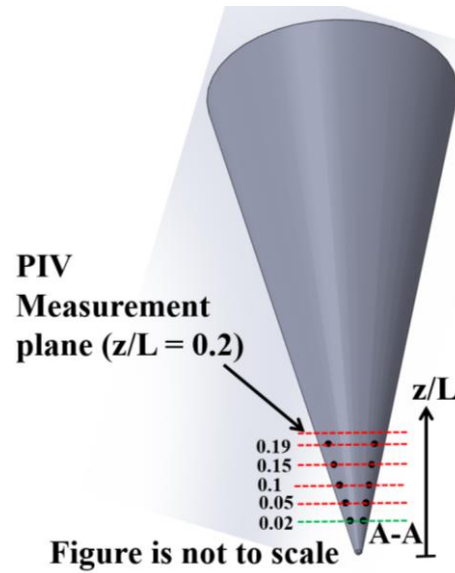
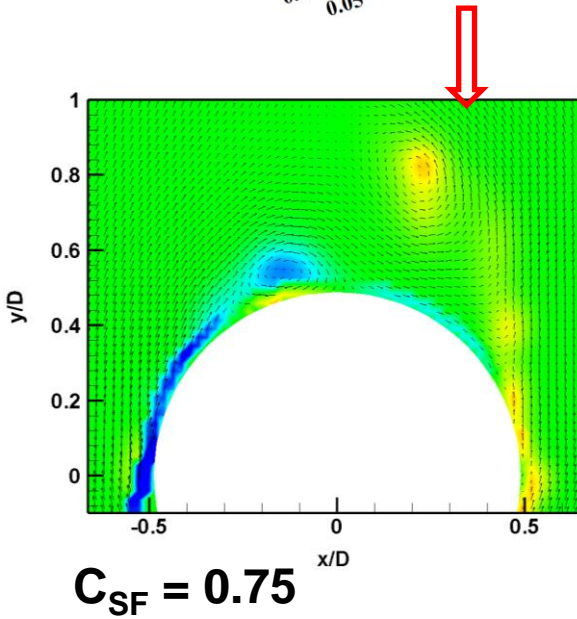
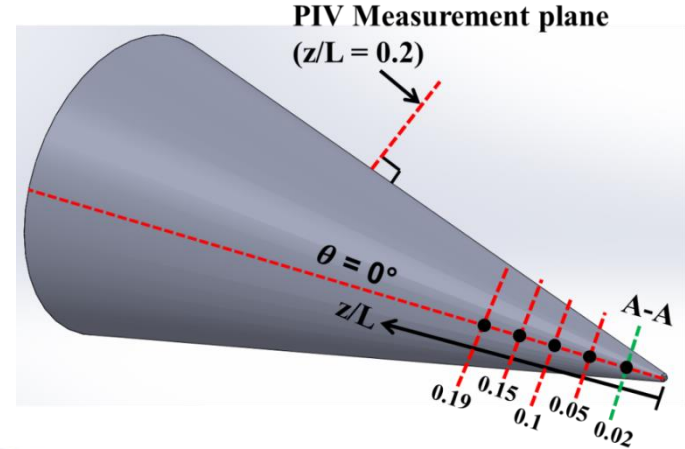
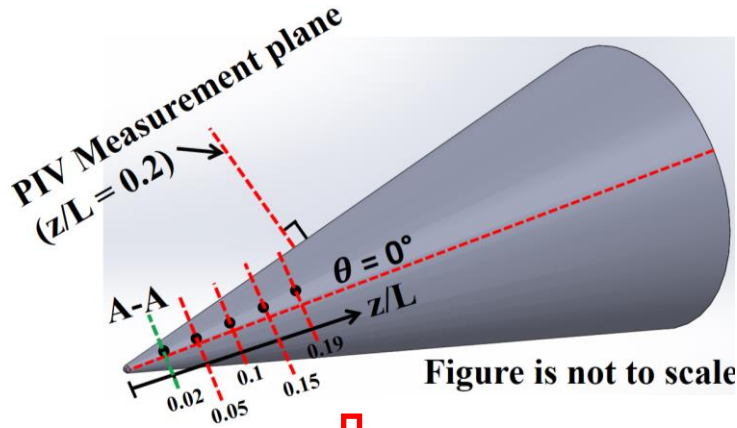
- ❖ Flow development over the conical body can be classified into three regions:

- A) Steady
- B) Intermediate
- C) Unsteady

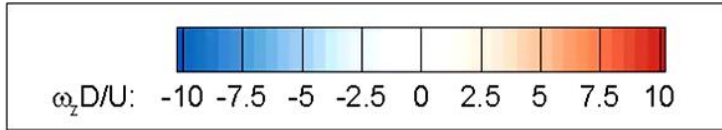
- ❖ Unsteadiness of the vortex induces an unsteady pressure distribution over the cone surface



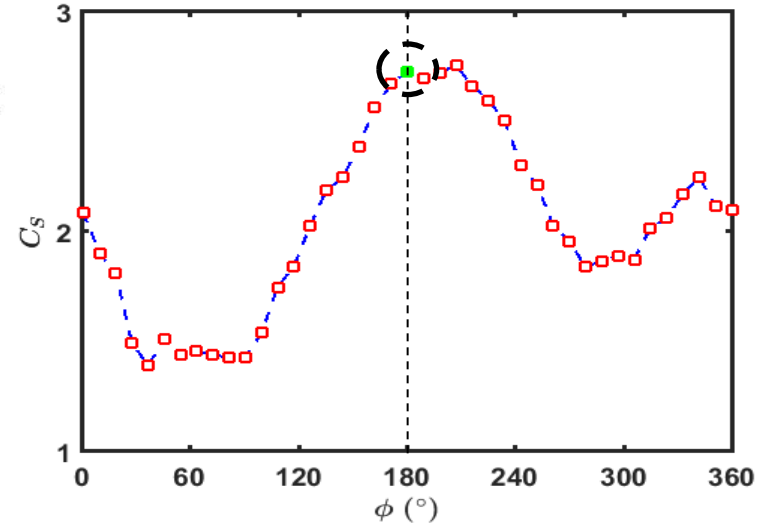
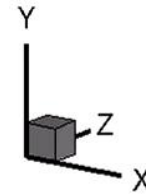
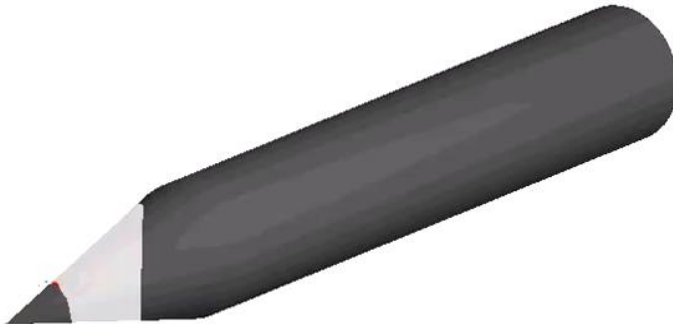
Effect of **Multiple Controlled Surface Perturbations**



Vortex Development on a Cone Cylinder Body



- **12° semi-apex cone**
- **L/D = 8**
- **Angle of Incidence = 40°**
- **Re/ft = 0.6 x 10⁶**

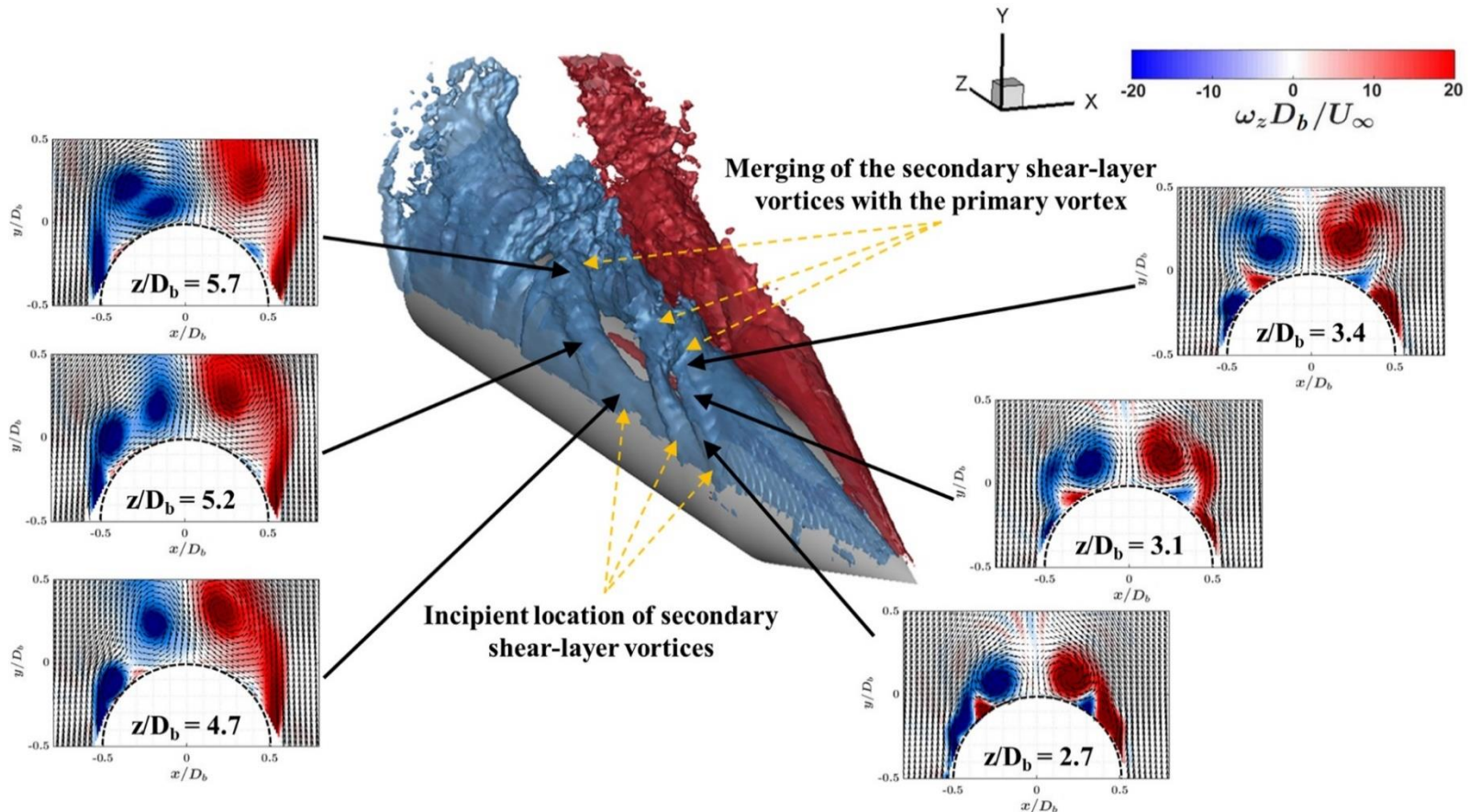


C_s vs. α , $\alpha = 40^\circ$, $\Phi = 180^\circ$

Normalized mean z-vorticity fields, $\alpha = 40^\circ$, $\Phi = 180^\circ$

- ❖ **Symmetric vortices (counter-rotating) on the cone can develop asymmetry over the cylinder.**
- ❖ **Secondary vortices (co-rotating) develop and merge with the respective primary vortices.**
- ❖ **Surface imperfections on aftbody generate secondary vortices and dictate the asymmetry.**

Merging Process of **Secondary Shear Layer Vortices**

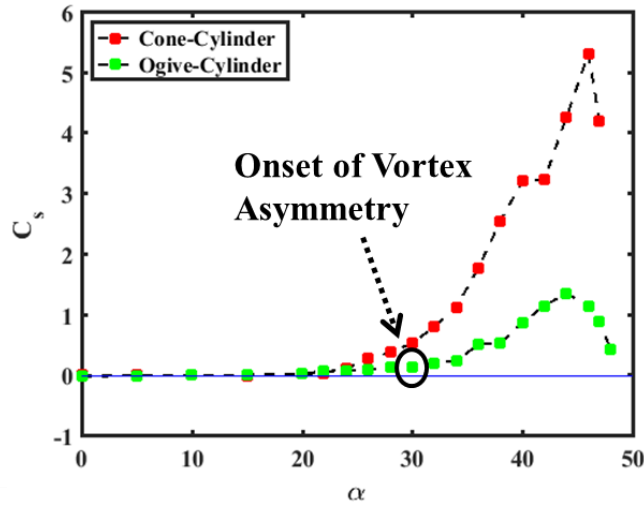


- ❖ Co-rotating vortices beyond a critical inter-core spacing develop vortex filaments.
- ❖ The filaments lead to an increase in angular momentum.
- ❖ This forces the vortex cores to move rapidly closer to conserve total momentum and complete the merging process.

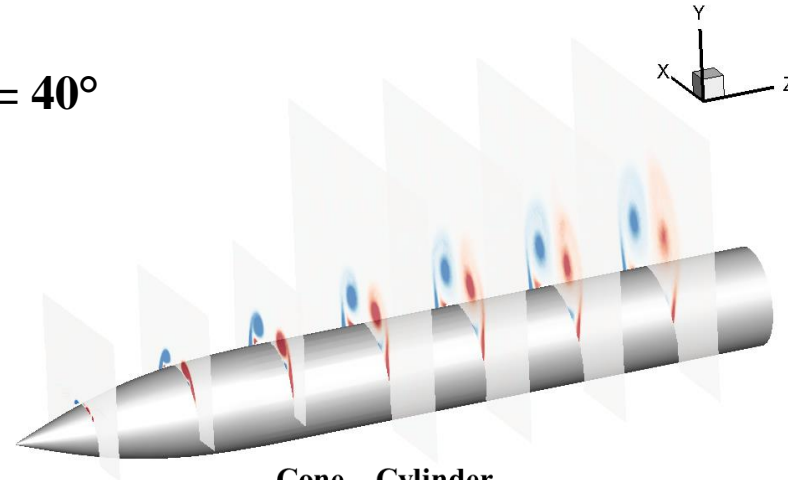
Kumar, R., Guha, T. K., Kumar, R. (2020) Role of Secondary Shear-Layer Vortices in the Development of Flow Asymmetry on a Cone Cylinder Body at High Angles of Incidence. *Experiments in Fluids*, 61:215 (2020).

<https://doi.org/10.1007/s00348-020-03045-y>.

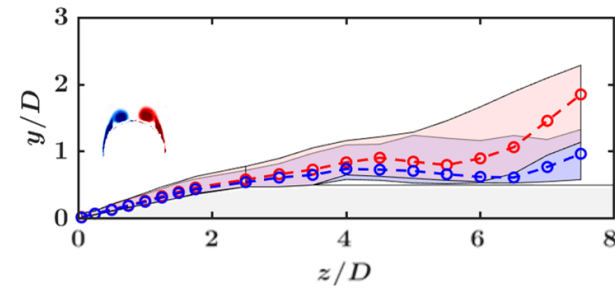
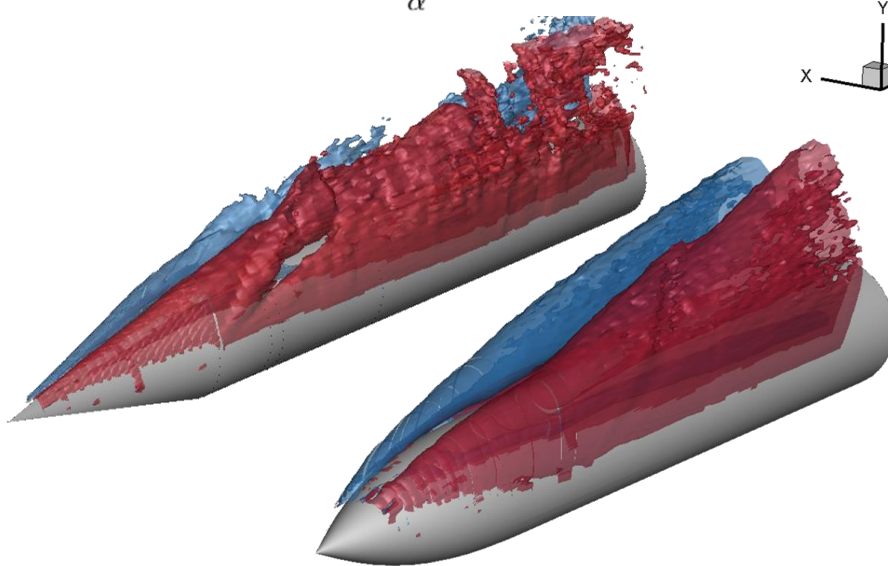
Vortex Development on a Ogive Cylinder Body



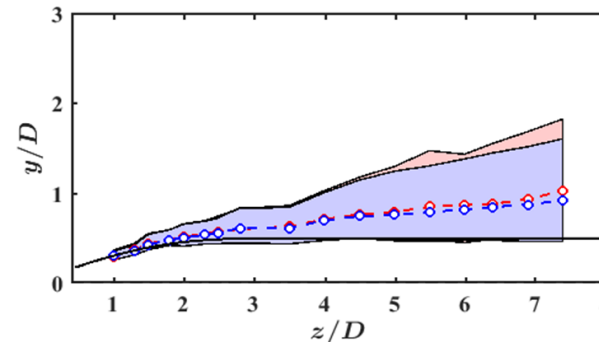
$\alpha = 40^\circ$



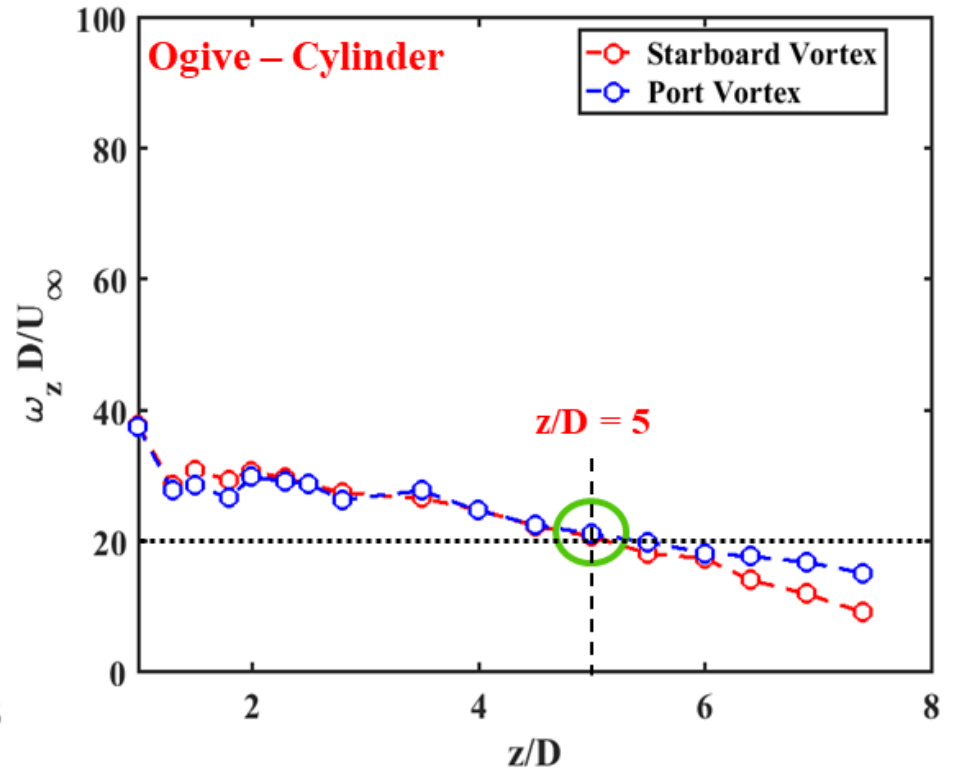
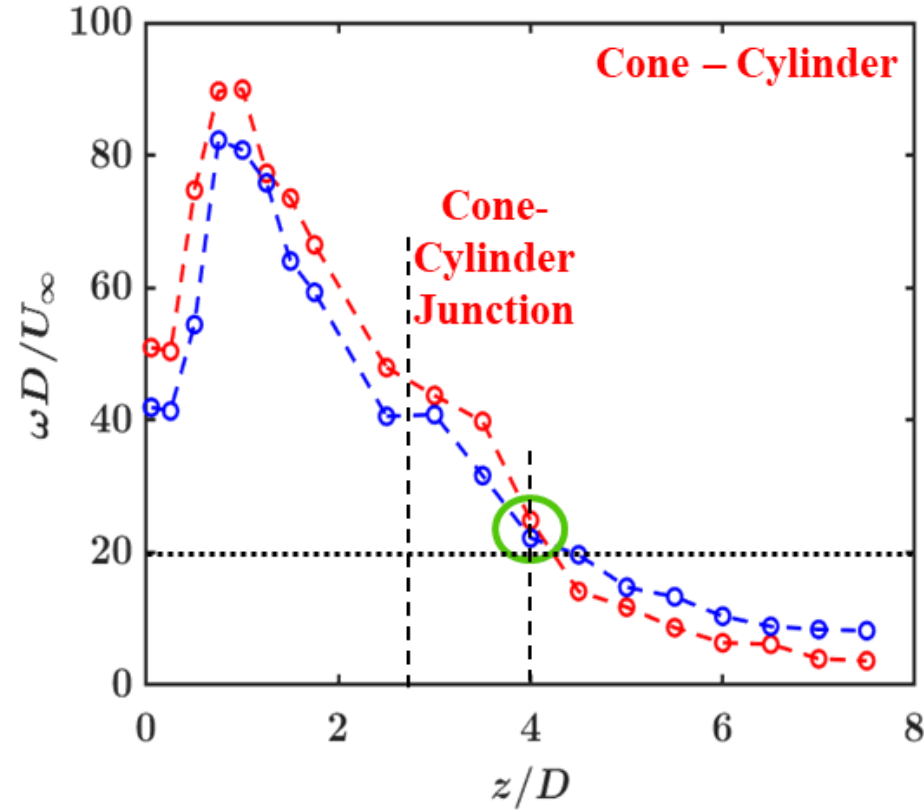
Cone - Cylinder



Ogive - Cylinder



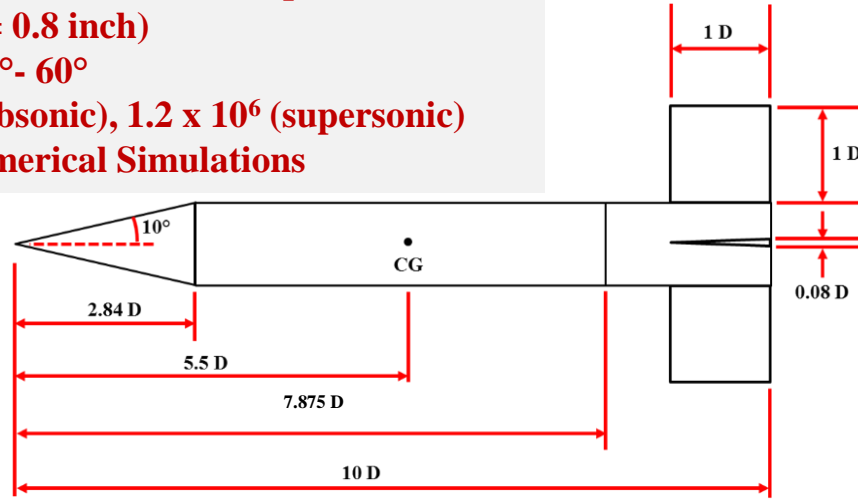
- ❖ Absence of secondary vortex due to the elimination of sudden change in geometry (Cone-Cylinder junction)



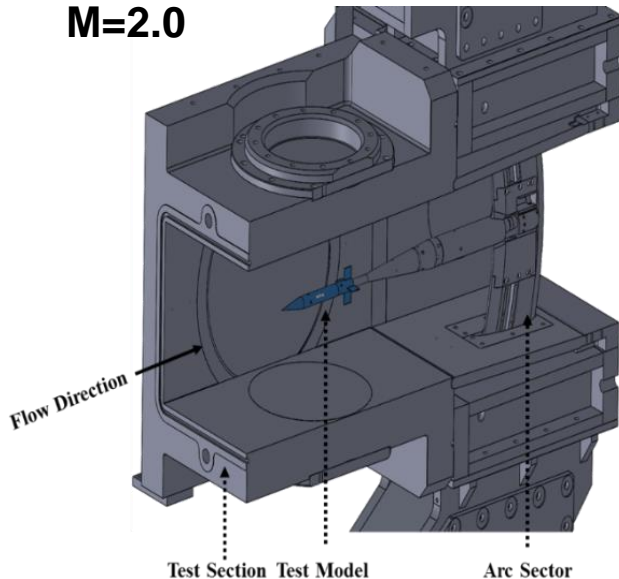
- ❖ Sharp decline in peak vorticity level for cone-cylinder. Whereas it is distributed along the slender body for the ogive-cylinder

Forebody Vortex Interactions with Control Surfaces

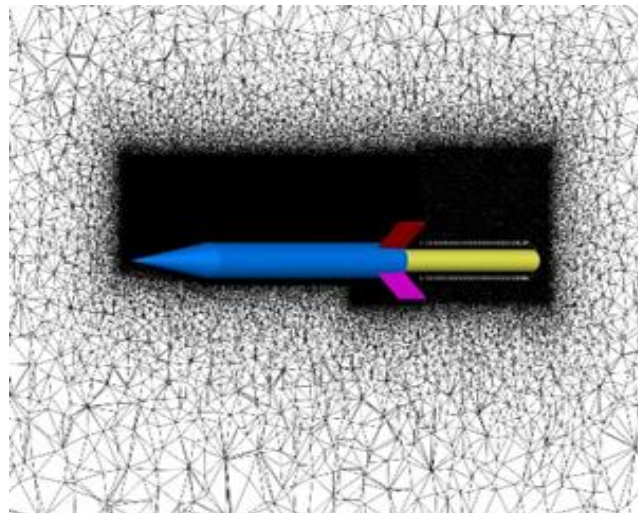
- Collaboration with ARL (Dr. James DeSpirito)
- Basic Finner ($\text{Dia}_{\text{Base}} = 0.8$ inch)
- Angle of Incidence = $0^\circ - 60^\circ$
- $\text{Re}_d = .3 \sim 0.7 \times 10^5$ (Subsonic), 1.2×10^6 (supersonic)
- Experimental and Numerical Simulations



M=2.0

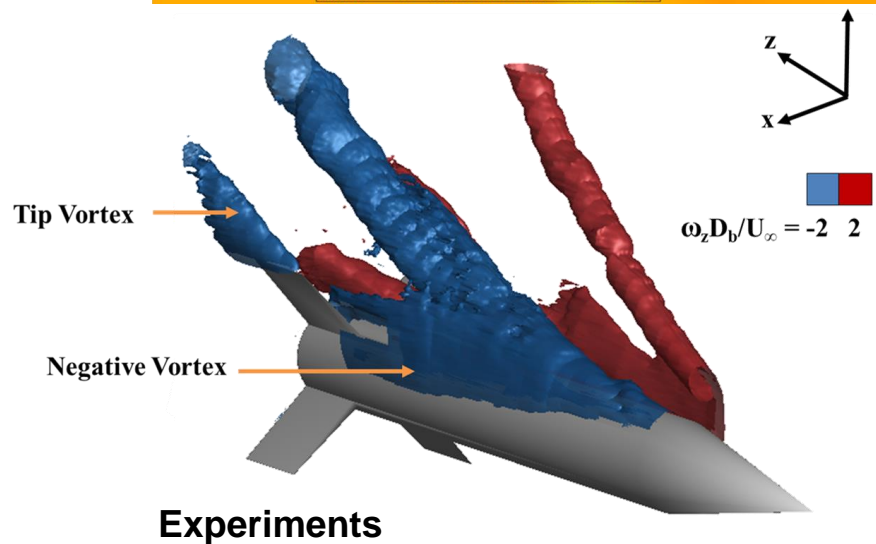
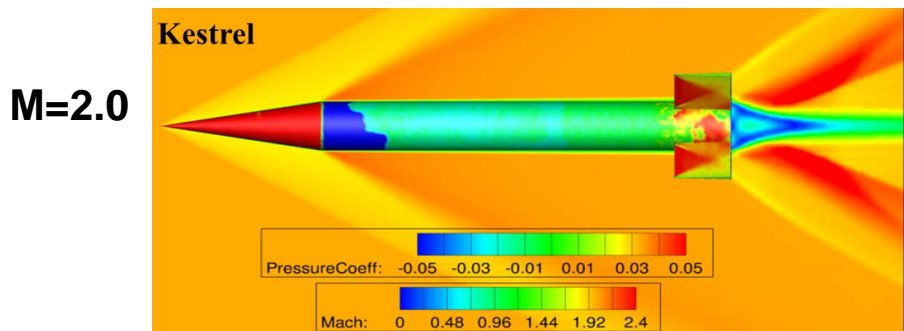
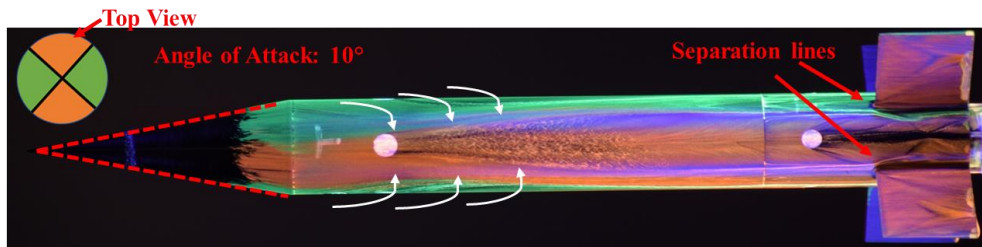


M=0.2

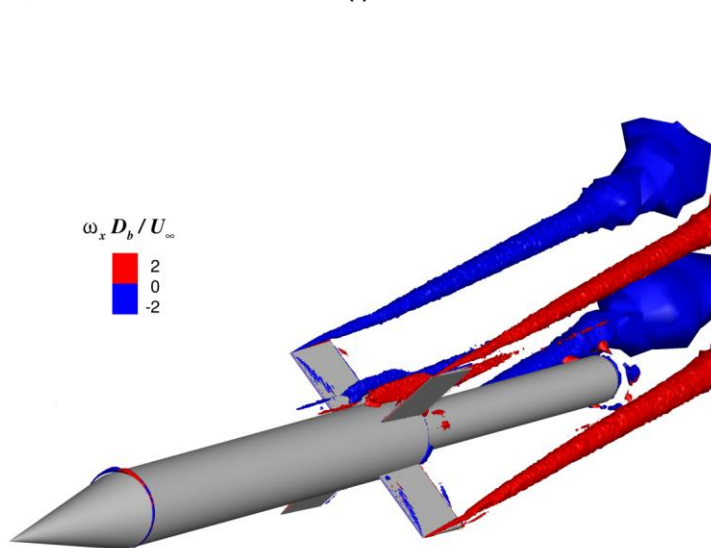
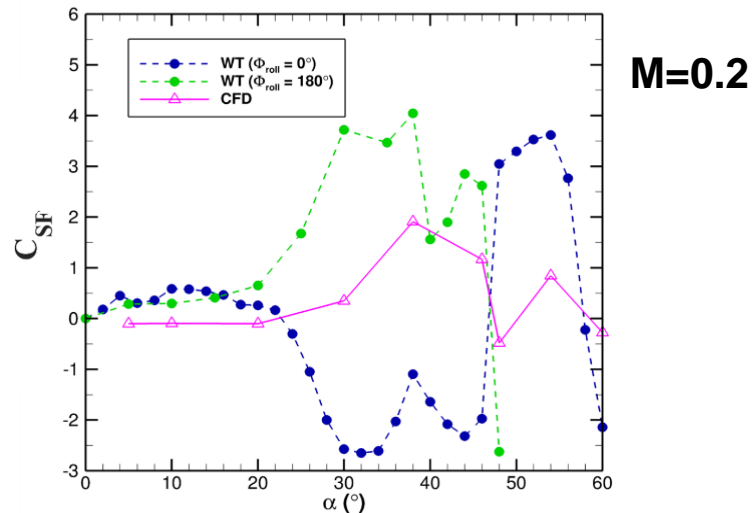


- ❖ *Kestrel Computational Fluid Dynamics Solver (KCFD) – Unsteady RANS ($\alpha = 0^\circ$ to 60° range)*
- ❖ *Spalart-Allmaras one-equation model*

Forebody Vortex Interactions with Control Surfaces

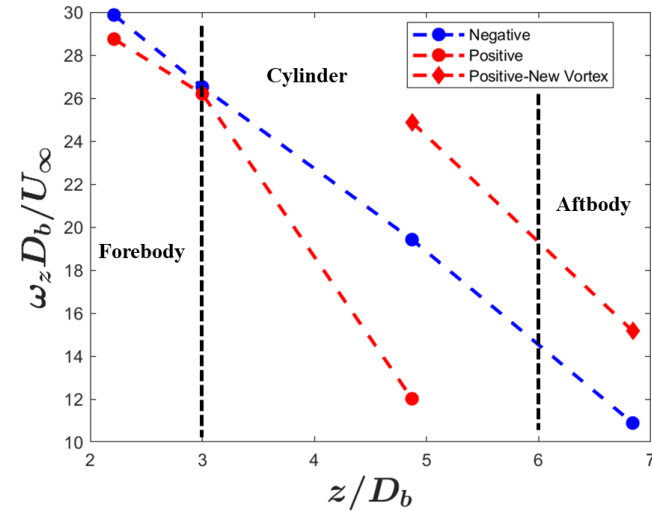
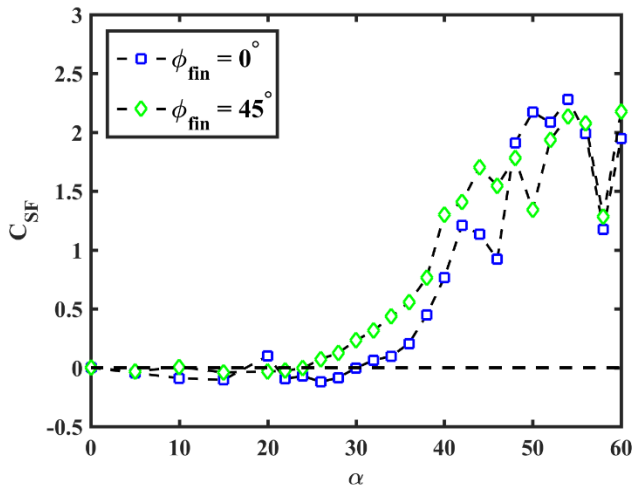
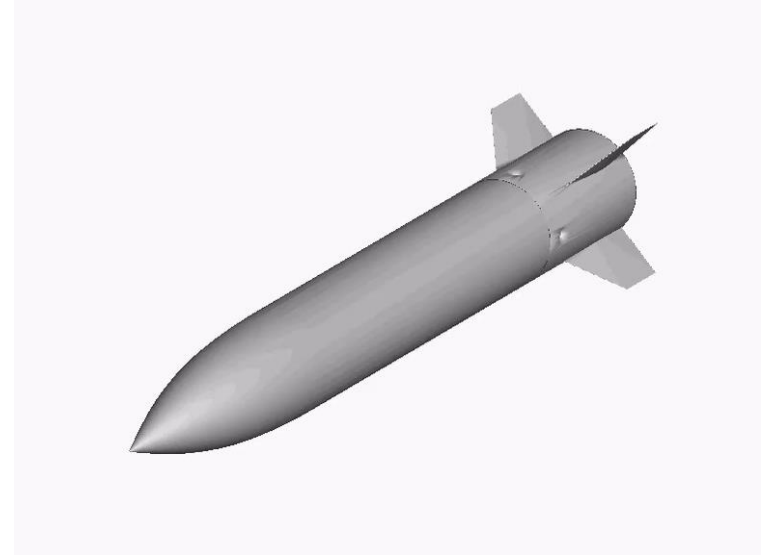
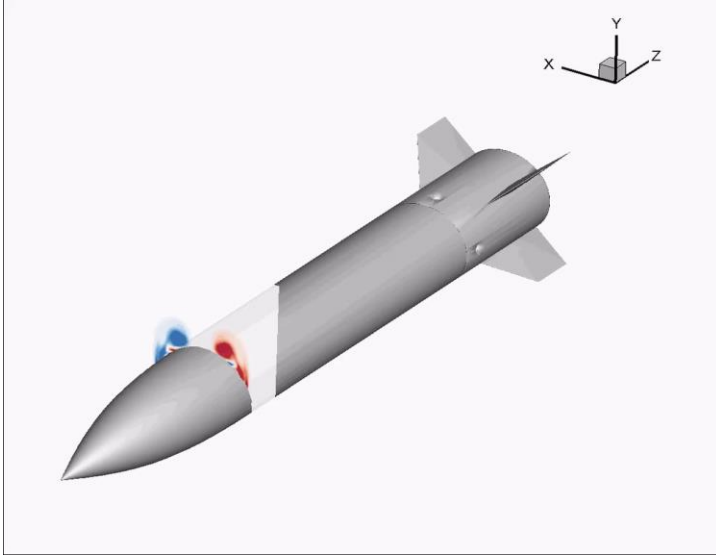


Experiments



Simulations

Ogive Forebody Vortex Interactions with **Control Surfaces**

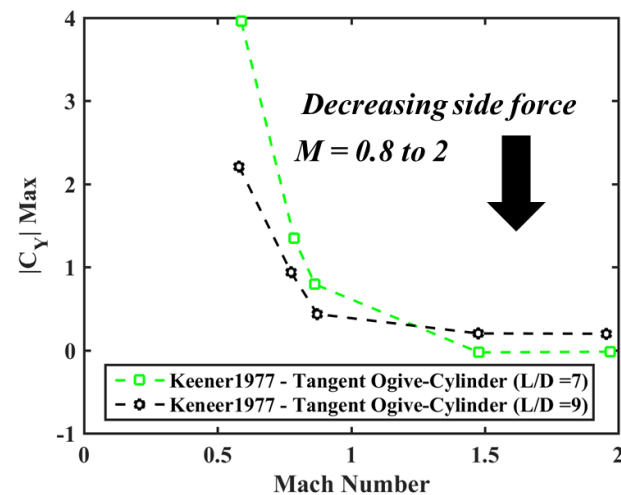
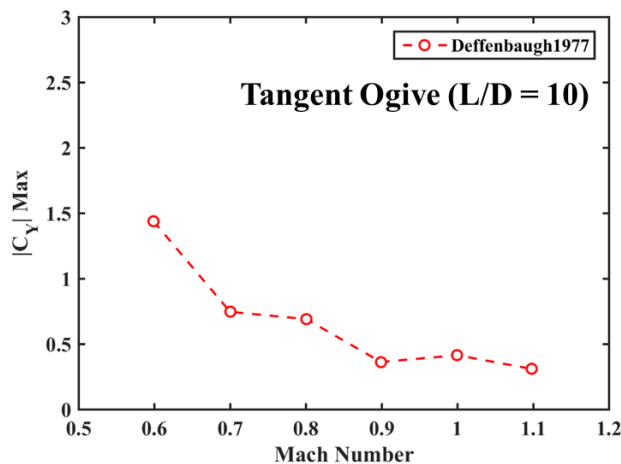
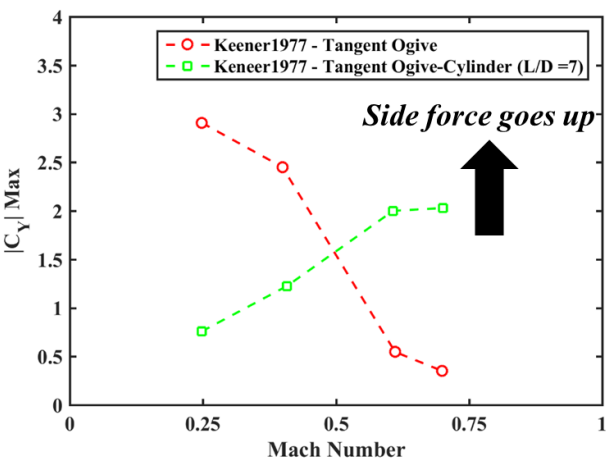
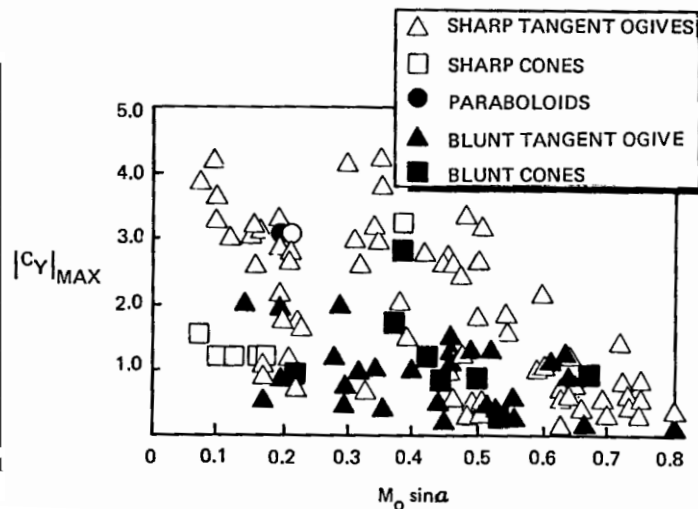
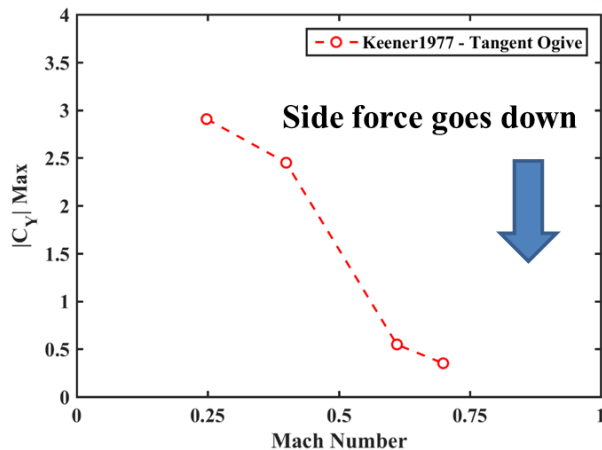
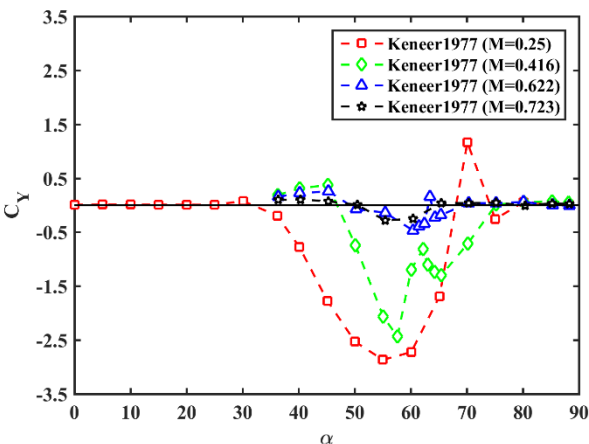


Better understanding the flow physics associated with vortex asymmetry at high angles of incidence

- Side force and yawing moment characteristics show a systematic variation with angle of incidence and roll orientation
- Controlled imperfections near the nose tip can control the vortex size, location and strength
- Both primary and secondary vortex pairs develop on the cone and continue to grow on cylinder and merge along the cylindrical body.
- Co-rotating vortices beyond a critical inter-core spacing develop vortex filaments. The filaments lead to an increase in angular momentum. This forces the vortex cores to move rapidly closer to conserve total momentum and complete the merging process.
- On cone – cylinder, secondary vortices (co-rotating) develop and merge with the respective primary vortices whereas on ogive – cylinder there is no merging. A very weak secondary vortex merging can be observed on the starboard side.
- Sharp decline in peak vorticity level for cone-cylinder, whereas it is distributed along the slender body for the ogive-cylinder.
- Vortex Interaction with control surfaces significantly alter their effectiveness.
- A good comparison of basic aerodynamic characteristics between experiments and numerical simulations using Kestrel.
- Numerical simulations of flow over cone cylinder enhance our understanding of flow physics associated with vortex asymmetry, particularly vortex lift off location on the body

What Next!!

Role of Compressibility on crossflow separation and Vortex Asymmetry



The available literature is inconclusive and contradictory.

- Kumar, R., Kumar, R., DeSpirito, J. 2021 “Experimental and Numerical Investigation of the Vortex Asymmetry on the Basic Finner Configuration”, AIAA SciTech 2021 Forum, 11-21 January 2021, Virtual Event, AIAA 2021-0025 <https://doi.org/10.2514/6.2021-0025>.
- Shahriar, A., Kumar, R., and Shoele, K. 2021 “Vortex interactions in the wake of the axisymmetric body in uniform cross-stream”, AIAA SciTech 2021 Forum, 11-21 January 2021, Virtual Event, AIAA 2021-0026 <https://doi.org/10.2514/6.2021-0026>.
- Kumar, R., Guha, T. K., Kumar, R. (2020) Role of Secondary Shear-Layer Vortices in the Development of Flow Asymmetry on a Cone Cylinder Body at High Angles of Incidence. *Experiments in Fluids*, 61:215 (2020). <https://doi.org/10.1007/s00348-020-03045-y>.
- Kumar, R., Guha, T, Kumar, R. (2020) *Experimental and Numerical study of Forebody Vortex Interactions on a generic Axisymmetric Finned Configuration*, AIAA SciTech Forum, 6-10 January 2020, AIAA 2020-1991
- Shahriar, Al, Kourosh Shoele, and Rajan Kumar. (2020) "Vortex formation at the apex of an oblique cone in uniform cross-stream." *Bulletin of the American Physical Society* 64 (2019).
- Kumar, R., Guha, T, Kumar, R. (2019) *Experimental Investigation on the Development of Asymmetric Vortices on a Long Slender Body at High Incidence*, AIAA SciTech Forum, 7-11 January 2019, AIAA 2019-0844.
- Mahadevan, S., Rodriguez, J. and Kumar, R. (2018) *Effect of Controlled Imperfections on the Vortex Asymmetry of a Conical Body*. *AIAA Journal*, Vol. 56, No. 9, pp 3460-3477
- Mahadevan, S., Rodriguez, J. and Kumar, R. (2017). *Effect of controlled imperfections on the vortex asymmetry of a conical body at high incidence*. 35th AIAA Applied Aerodynamics Conference, AIAA AVIATION Forum, AIAA 2017-3240.
- Reese, B. and Collins, E. (2017). *Learning a cost-to-goal estimate for fast model predictive optimization based on graph search*. 2017 American Control Conference, May 24-26, 2017, Seattle.
- Taligoski, J., Fernandez, E., Uzun, A., & Kumar, R. (2015). *Study of the roll orientation effects on vortex asymmetry on a conical forebody at high angles of incidence*. 53rd AIAA Aerospace Sciences Meeting, Kissimmee, FL. AIAA 2015-0547