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14. ABSTRACT

15. SUBJECT TERMS

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UU	UU	UU	UU		19b. TELEPHONE NUMBER 850-645-0149

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RPPR Final Report
as of 27-Apr-2020

Agency Code:

Proposal Number: 68081EGH | **Agreement Number: W911NF-15-1-0583**

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DUNS Number: 623751831 EIN: 590977035
Report Date: 31-Dec-2019 Date Received: 26-Apr-2020
Final Report for Period Beginning 15-Sep-2015 and Ending 30-Sep-2019

Title: Asymmetric Vortex Control on Slender Bodies at High Angles of Incidence

Begin Performance Period: 15-Sep-2015 **End Performance Period:** 30-Sep-2019
Report Term: 0-Other

Submitted By: Rajan Kumar Email: rkumar@fsu.edu
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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4 **STEM Participants:** 4

Major Goals: The phenomenon of vortex asymmetry has been observed over pointed forebodies at high angles of incidence. This problem is essentially predominant at low to moderate subsonic speeds, a regime in which high-alpha maneuvers normally occur. At a small incidence angle (typically less than the semi-apex angle of the conical body), the crossflow boundary layer remains attached to the surface. When the angle of incidence is increased (while still below the cone apex angle), a steady symmetric vortex pair appears in the wake region of a slender conical body. Further increasing the incidence angle (greater than the nose apex angle) results in vortex asymmetry and large magnitude of side forces and yaw moments. The yaw moments are too large to be controlled using a rudder in military aircraft and control surfaces in the case of a missile. The flow over a long slender body is very complex in nature and involve the evolution of multiple vortex pairs. The development of the flow-field can vary between studies due to the sensitivity to small scale surface imperfections. The ratio of imperfection height to the local boundary layer thickness is a critical parameter in determining the initiation and growth of vortices. On the other hand, if the surface imperfection size exceeds the boundary layer significantly, such as for protrusions, it can considerably affect the aerodynamic loads of the vehicle.

The main objectives of the study were to improve our understanding of the source and the nature of vortex asymmetry on slender cones at high angles of incidence. Although a few efforts have been made to understand the flow physics of asymmetric vortices and their influence on side forces, there is little understanding of the effect of surface imperfections, particularly the size and location on the development of vortices and associated length and time scales. A goal of the present investigation was to understand the effect of controlled imperfections on the initiation, growth, and interaction of crossflow vortices at high angles of incidence. Another goal of the study was to investigate the flowfield over a generic slender body consisting of a conical forebody and a cylindrical aft body and understand the role of secondary shear-layer vortices in the development of primary vortices over the length of the body and the resultant side force. In addition to the objectives mentioned above, another goal was to develop and implement new flow diagnostic techniques such as time-resolved particle image velocimetry to better understand the flow physics associated with slender bodies at high angles of incidence.

Accomplishments: The project goals were achieved through a combined systematic experimental, computational, and theoretical effort. Significant progress has been made in 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. Asymmetric vortices switch direction with roll orientation resulting in pressure imbalance and asymmetric yaw moments. Controlled imperfections near the nose tip can control the vortex size, location, and strength of the vortices. The vortex strength, peak streamwise vorticity, and vortex location can be extremely useful to connect the flow field to the generated side force.

The development of vortices was found to be very sensitive to any perturbation in the vicinity of incipient separation of the crossflow boundary layer. Increasing the controlled imperfection height amplified the asymmetry in vortices up to twice the local boundary layer thickness. The controlled imperfections when scaled and positioned judiciously can be very effective in achieving decreased asymmetry levels in the flowfield. It was evident from the time-resolved flowfield that the vortex switching is a gradual process, resulting in a change in the direction of the net side force. Simultaneous high-speed PIV and force measurements show a movement of vortices from one stable state to another.

Measurements carried out on a cone-cylinder to study the initiation, growth, and interaction of vortices. Both primary and secondary vortex pairs develop on the cone and continue to grow on the cylinder and merge along the cylindrical body. Force measurements showed that rotation of the conical forebody while keeping the cylinder roll orientation fixed, led to a periodic variation in the net side-force coefficient at high angles of incidence. PIV measurements showed that a pair of counter-rotating vortex pair initiates at the tip of the cone and grows over the length of the body through the assimilation of the separated shear layer. The development of the primary vortex pair on the highly polished cone is nearly symmetric, with little observable variation with the roll. However, the vortices become asymmetric while developing over the cylinder. The comparative strength and location of the two primary vortices with respect to the body-axis, vary as they grow along the cone-cylinder body.

The development of asymmetry starts at the cone-cylinder junction and seems to vary with the roll orientation of the test model. The separated shear layer from the cylinder forms secondary shear-layer vortices at several locations along the length of the body, including the cone-cylinder junction. The characteristics and number of secondary vortices formed differs on the two sides of the cylinder. These secondary shear-layer vortices generated due to surface imperfections and joints, merge with the primary vortex pair originated from the cone-tip leading to asymmetry. The greatest extent of asymmetry was observed for the roll position corresponding to the highest side-force coefficient indicating that side forces observed at high angles of incidence are due to vortex asymmetry of the flow field. At this roll position, the vortex trajectories were also highly asymmetric with respect to the axis of the body. Near the trailing edge, one of the vortices encompassed most of the region over the cylinder while the other had moved far away from the body. These results suggest that cone-cylinder junction and surface imperfections on the cylinder play an essential role in addition to the surface roughness of the conical tip towards the development of vortex asymmetry.

Training Opportunities: 1. Joseph Rodriguez, worked as a graduate student on this project and completed his M. S. Thesis and graduated in summer 2017. He is currently working for Orbital ATK (Northrop Grumman).

2. Kevin Powell, worked as a graduate student on this project and completed his M.S. Thesis and graduated in Fall 2017. He is currently working for SpaceX.

3. Srikrishna Mahadevan worked as a post-doctoral associate on the experimental aspect of this project. He is currently working for Siemens Energy.

4. Adam Edstrand also worked as a post-doctoral associate on this project on the simulations aspects and is currently working for Sandia National Labs.

5. Tufan Guha worked as a post-doctoral associate on this project and is currently working as a post-doctoral associate at the Rensselaer Polytechnic Institute.

6. Roopesh Kumar is a current graduate student working on this project. He is pursuing his Ph.D.

7. Michenell Louis-Charles is an undergraduate student getting trained on various experimental techniques on this project.

Results Dissemination: 1. Kumar, R., Guha, T. K., and 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", Submitted to Experiments in Fluids, 2020.

2. Kumar, R., Guha, T. K., Kumar, R., DeSpirito, J. (2020), "Experimental and Numerical Study of Forebody Vortex Interactions on a Generic Axisymmetric Finned Configuration", AIAA Scitech 2020 Forum, AIAA SciTech Forum, (AIAA 2020-1991) https://doi.org/10.2514/6.2020-1991

3. Kumar, R., Guha, T. K., and Kumar, R., (2019) "Experimental Investigation on the Development of Asymmetric Vortices on a Long Slender Body at High Incidence", AIAA Scitech 2019 Forum, AIAA SciTech Forum, (AIAA 2019-0844) https://doi.org/10.2514/6.2019-0844

4. Mahadevan, S., Rodriguez, J., & Kumar, R. (2018) Effect of Controlled Imperfections on the Vortex Asymmetry of a Conical Body. AIAA Journal, Vol. 56, No. 9, PP3460-3477, https://doi.org/10.2514/1.J057074

5. Mahadevan, S., Rodriguez, J. & 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

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: A Cooperative Research and Development Agreement (CRADA) established between Army Research Lab and FAMU-FSU College of Engineering to study the ‘Lateral Aerodynamic Characteristics of Basic Finner Configuration at High Angles of Incidence’

Collaborators:
Rajan Kumar (FAMU-FSU College of Engineering)
Sidra Silton (Army Research Lab.)
James DeSpirto (Army Research Lab.)

PARTICIPANTS:

Participant Type: PD/PI
Participant: Rajan Kumar
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:

International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Tufan Kumar Guha
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Roopesh Kumar
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Michenell Charles
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

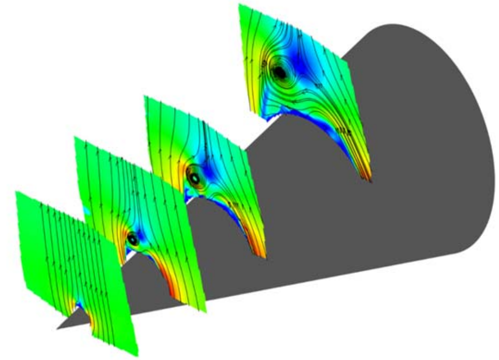
CONFERENCE PAPERS:

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: 35th AIAA Applied Aerodynamics Conference
Date Received: 10-Aug-2017 Conference Date: 05-Jun-2017 Date Published: 09-Jun-2017
Conference Location: Denver, Colorado
Paper Title: Effect of Controlled Imperfections on the Vortex Asymmetry of a Conical Body at High Incidence
Authors: Srikrishna Mahadevan, Joseph Rodriguez, Rajan Kumar
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AIAA Scitech 2019 Forum
Date Received: 26-Apr-2020 Conference Date: 07-Jan-2019 Date Published: 07-Jan-2019
Conference Location: San Diego, California
Paper Title: Experimental Investigation on the Development of Asymmetric Vortices on a Long Slender Body at High Incidence
Authors: Roopesh Kumar, Tufan Guha, Rajan Kumar
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 27-Apr-2020

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: AIAA Scitech 2020 Forum
Date Received: 26-Apr-2020 Conference Date: 06-Jan-2020 Date Published: 06-Jan-2020
Conference Location: Orlando, FL
Paper Title: Experimental and Numerical Study of Forebody Vortex Interactions on a Generic Axisymmetric Finned Configuration
Authors: Roopesh Kumar, Tufan Guha, Rajan Kumar, James DeSpirito
Acknowledged Federal Support: **Y**

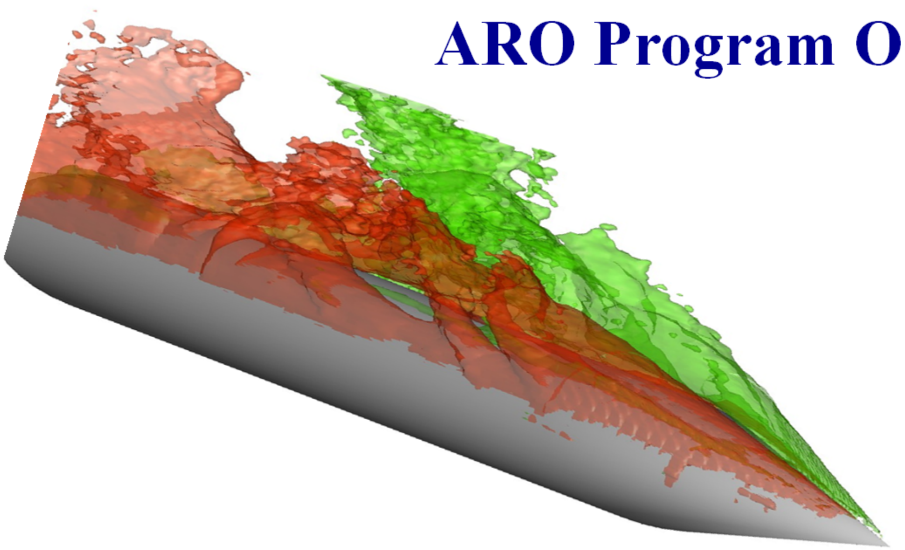


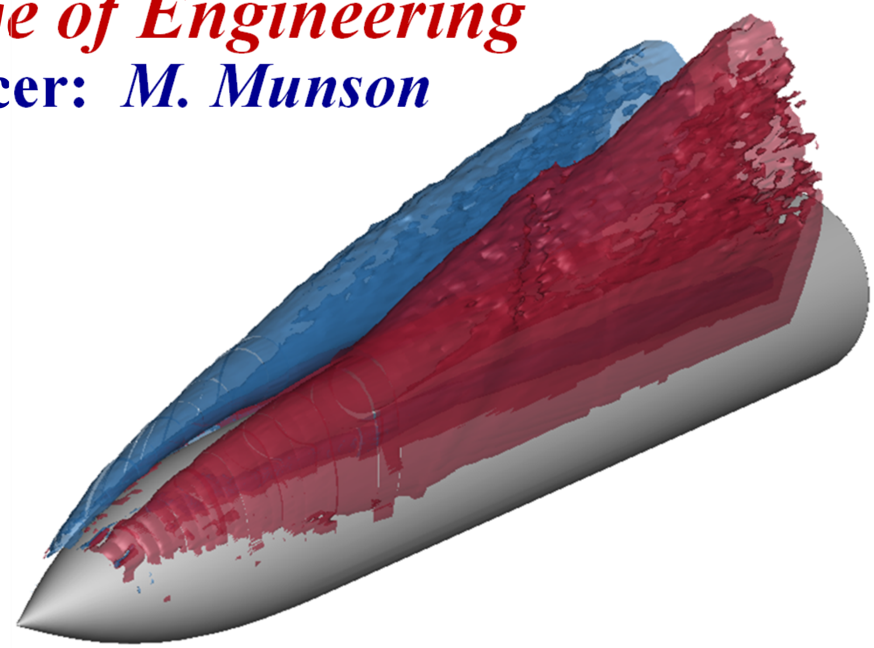
Asymmetric Vortex Control on Slender Bodies at High Angles of Incidence

Rajan Kumar et al.

FAMU-FSU College of Engineering

ARO Program Officer: *M. Munson*





Vortex Asymmetry at High Angles of Incidence

Students and Post Doctoral Associates

Joseph Rodriguez: **Graduated Summer 2017 – Orbital ATK (Northrop Grumman)**

Kevin Powell: **Graduated Fall 2017 - SpaceX**

Srikrishna Mahadevan: Post Doctoral Associate – **Siemens**

Adam Edstrand: Post Doctoral Associate – **Sandia National Labs**

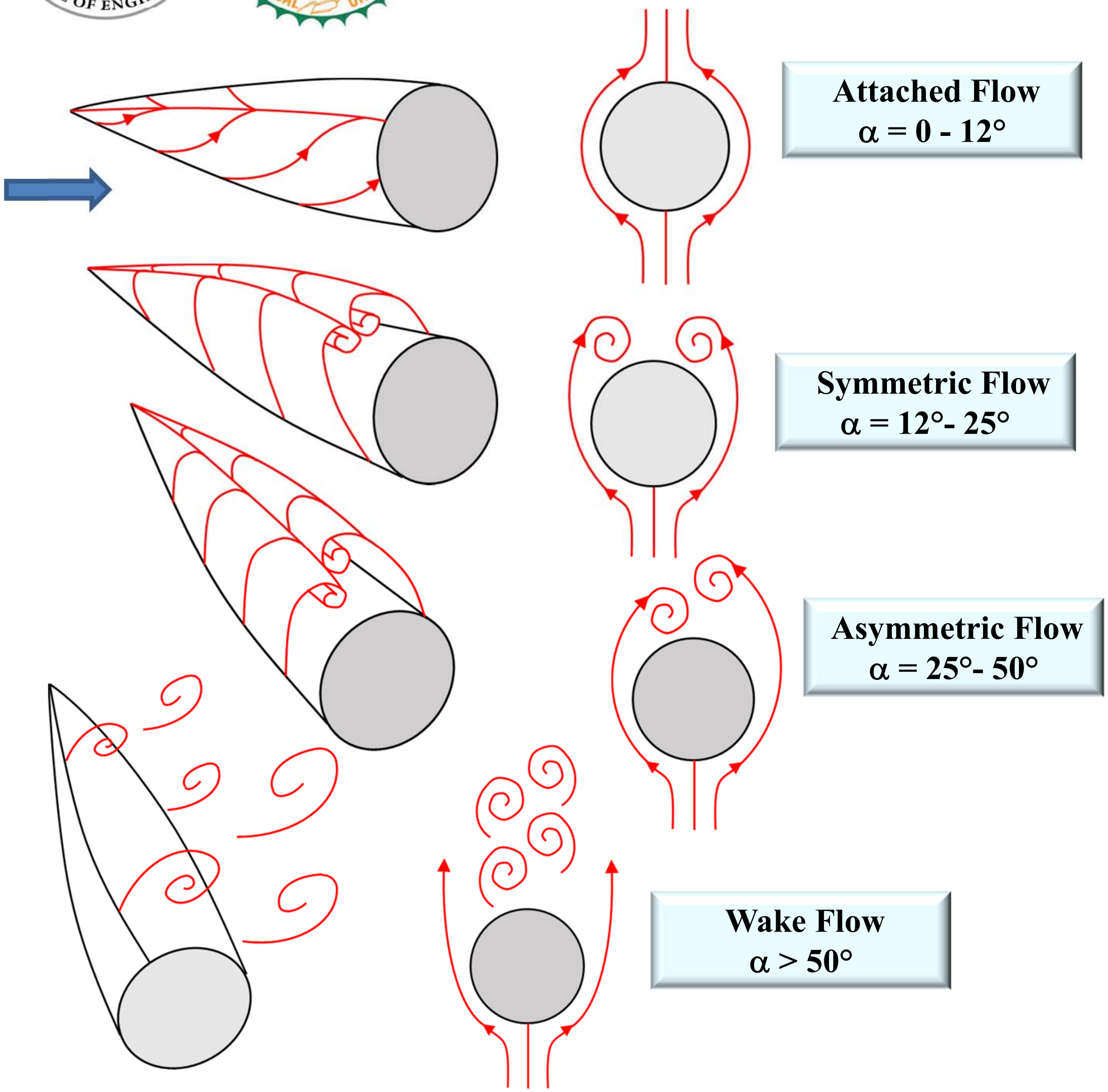
Roopesh Kumar: Graduate Research Assistant

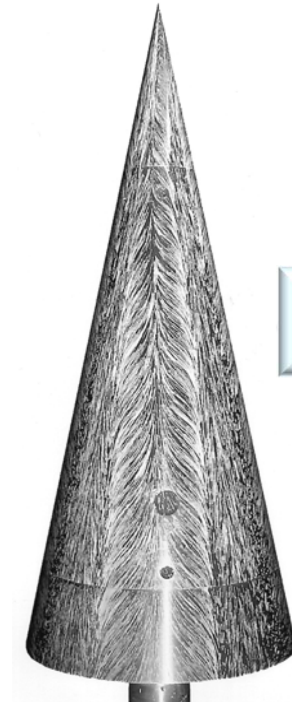
Al Shariar: Graduate Research Assistant

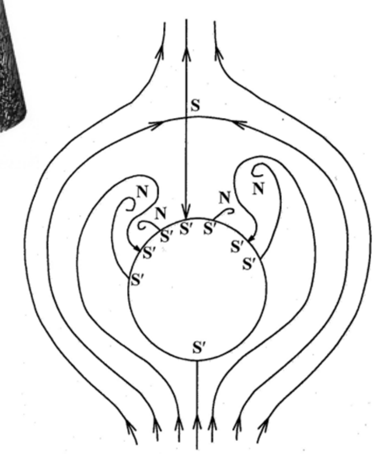
Michenell Louis-Charles: Undergraduate Research Assistant

Tufan Guha: Post Doctoral Associate

Conical Bodies at High AoA





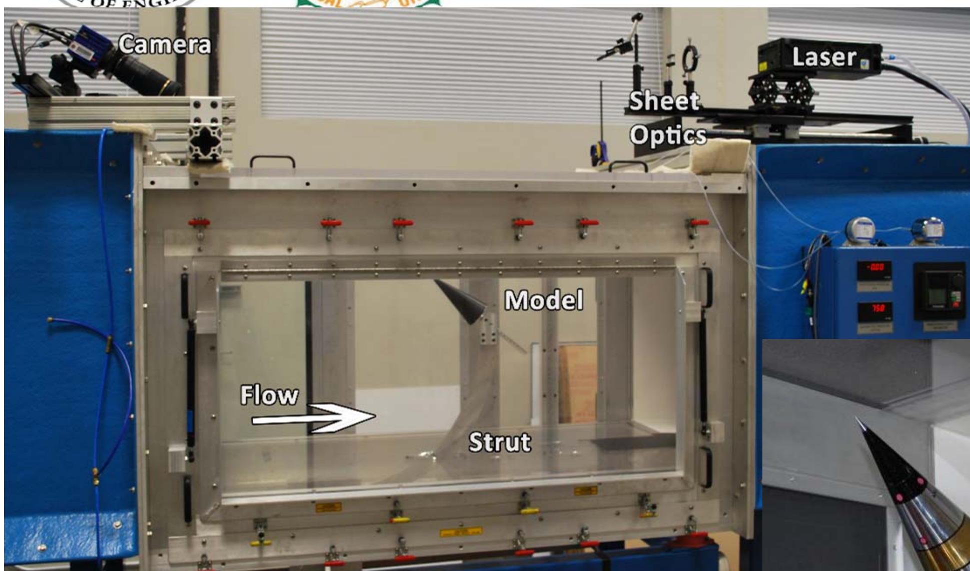


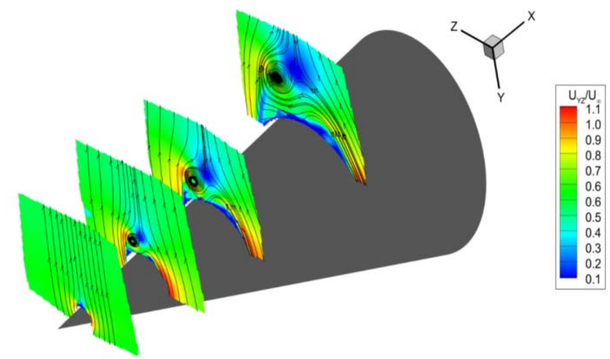
$$\left(\sum N + \frac{1}{2}\sum N'\right) - \left(\sum S + \frac{1}{2}\sum S'\right) = -1$$

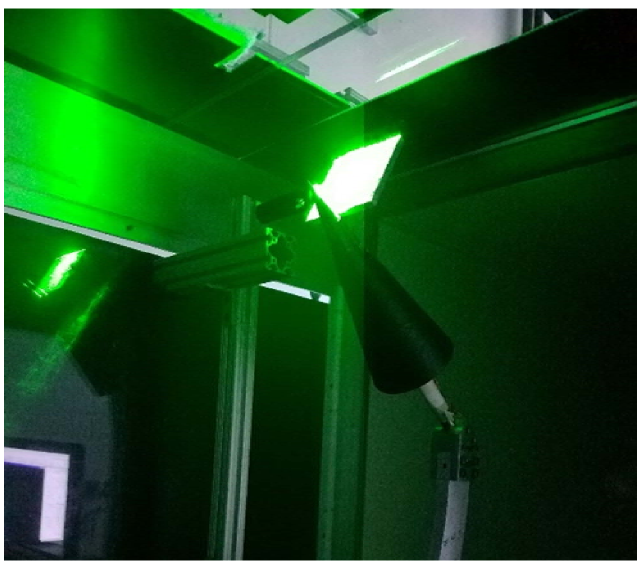
Kumar et al. 2005, 2008

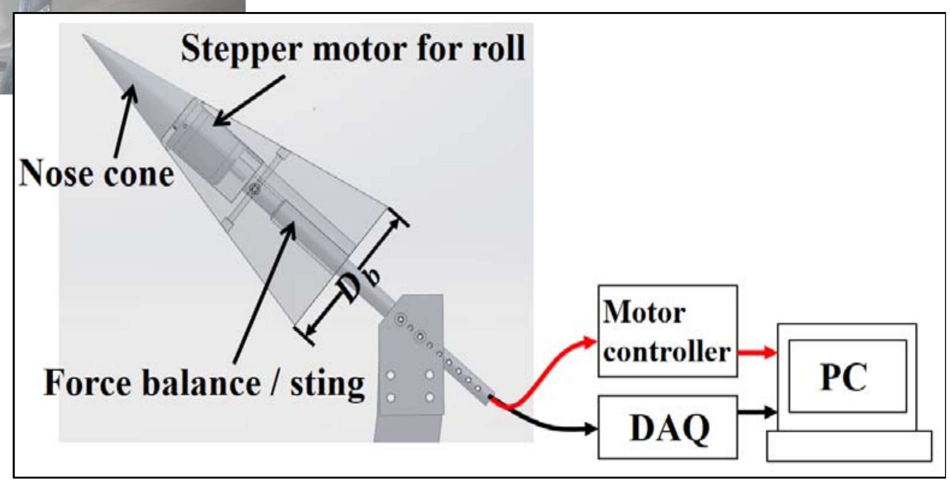
Experiments on a Cone

- *12° semi-apex cone*
- *Angle of Incidence = 0° - 50°*
- *Roll orientation = 0 - 360°*
- *Re/ft = 0.2 x 10^6 to 1.2 x 10^6*
- *Force & Moment measurements*
- *Particle image velocimetry*

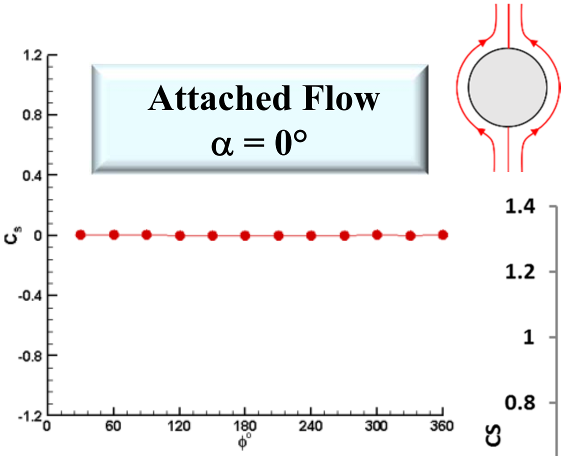


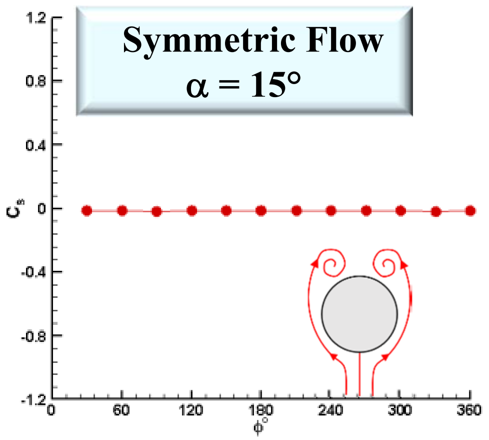


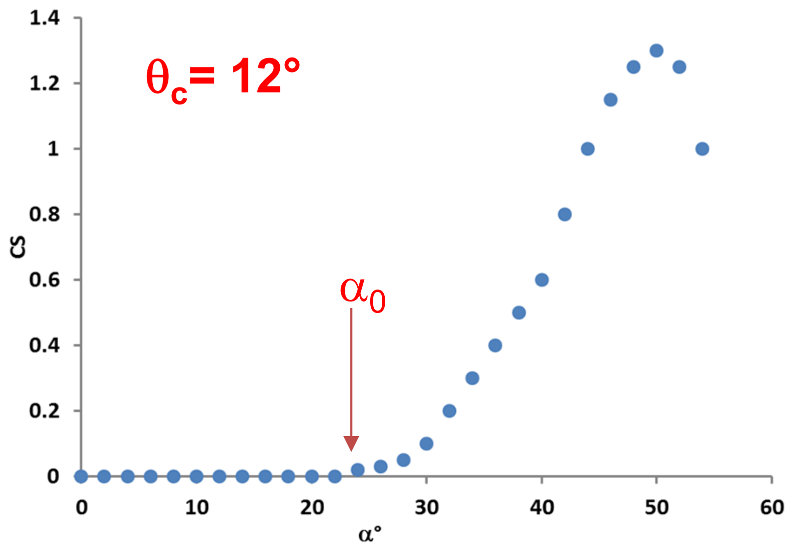


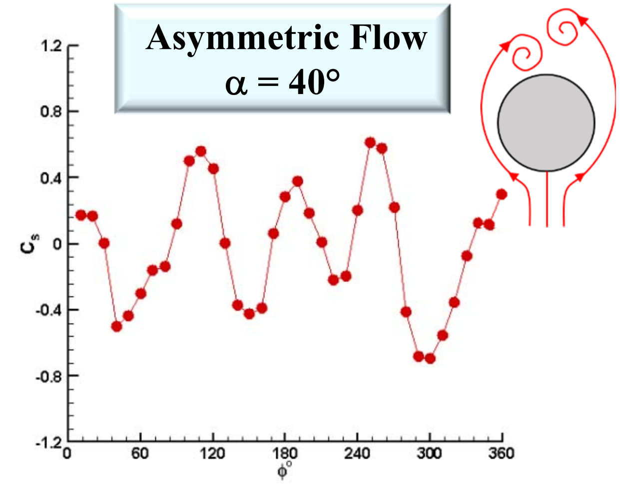


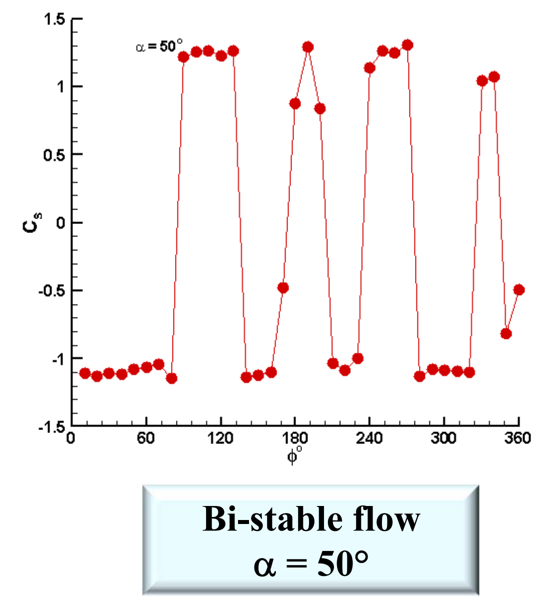
Side Force / Yaw Moment Characteristics





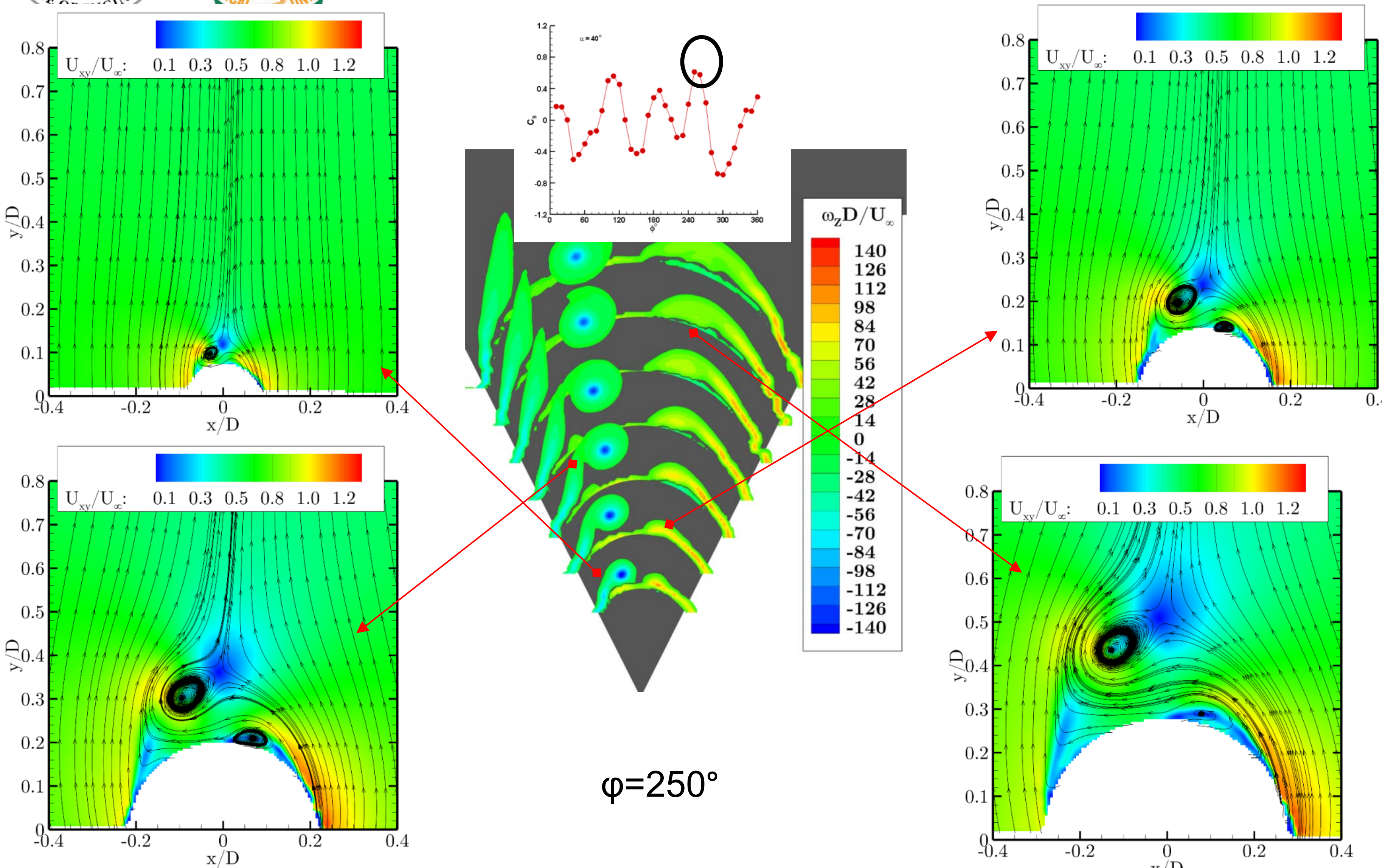




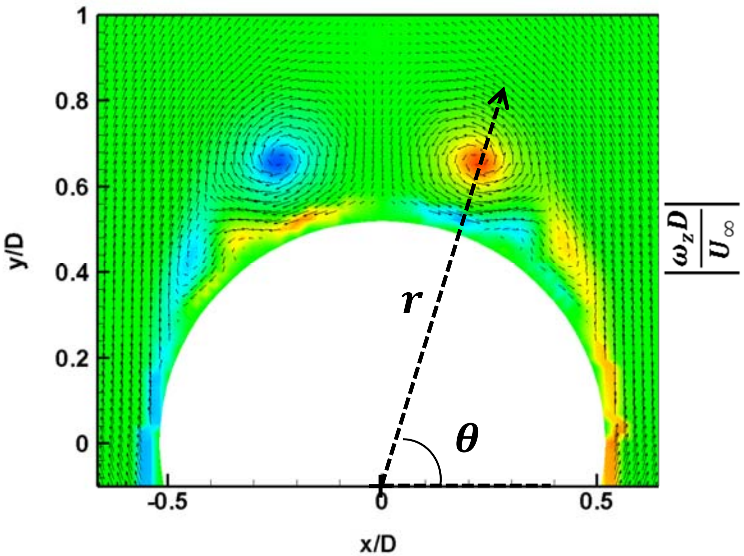


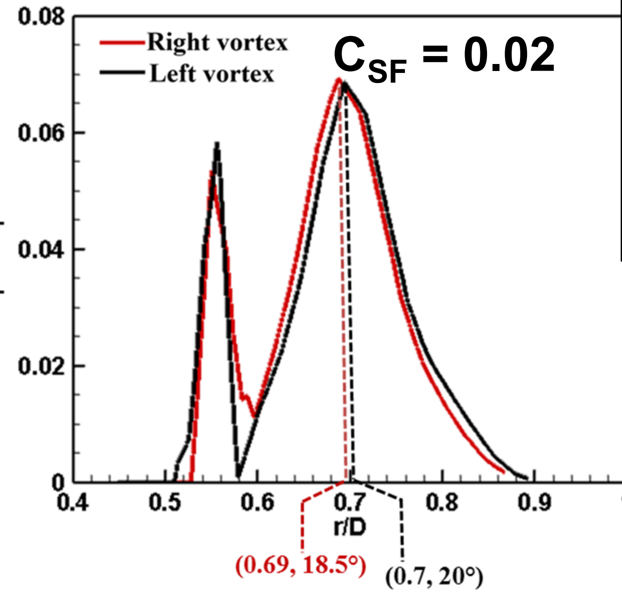
- Onset of vortex asymmetry is $2\theta_c$
- Side force a periodic function of roll orientation

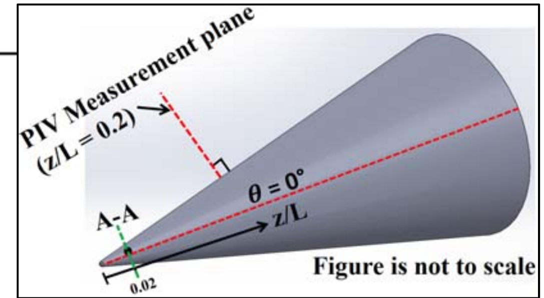
Asymmetric Flow Features, α=40°

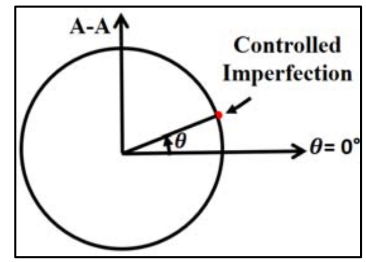


Effect of Controlled Surface Perturbations

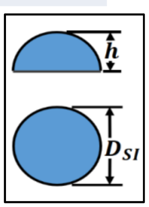


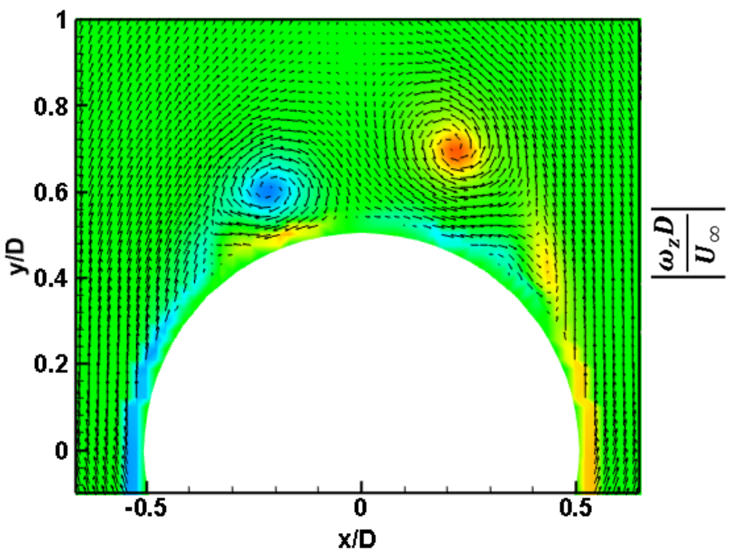


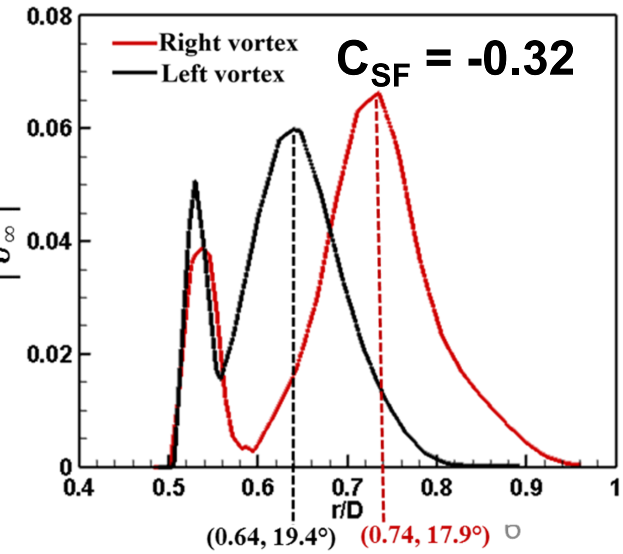




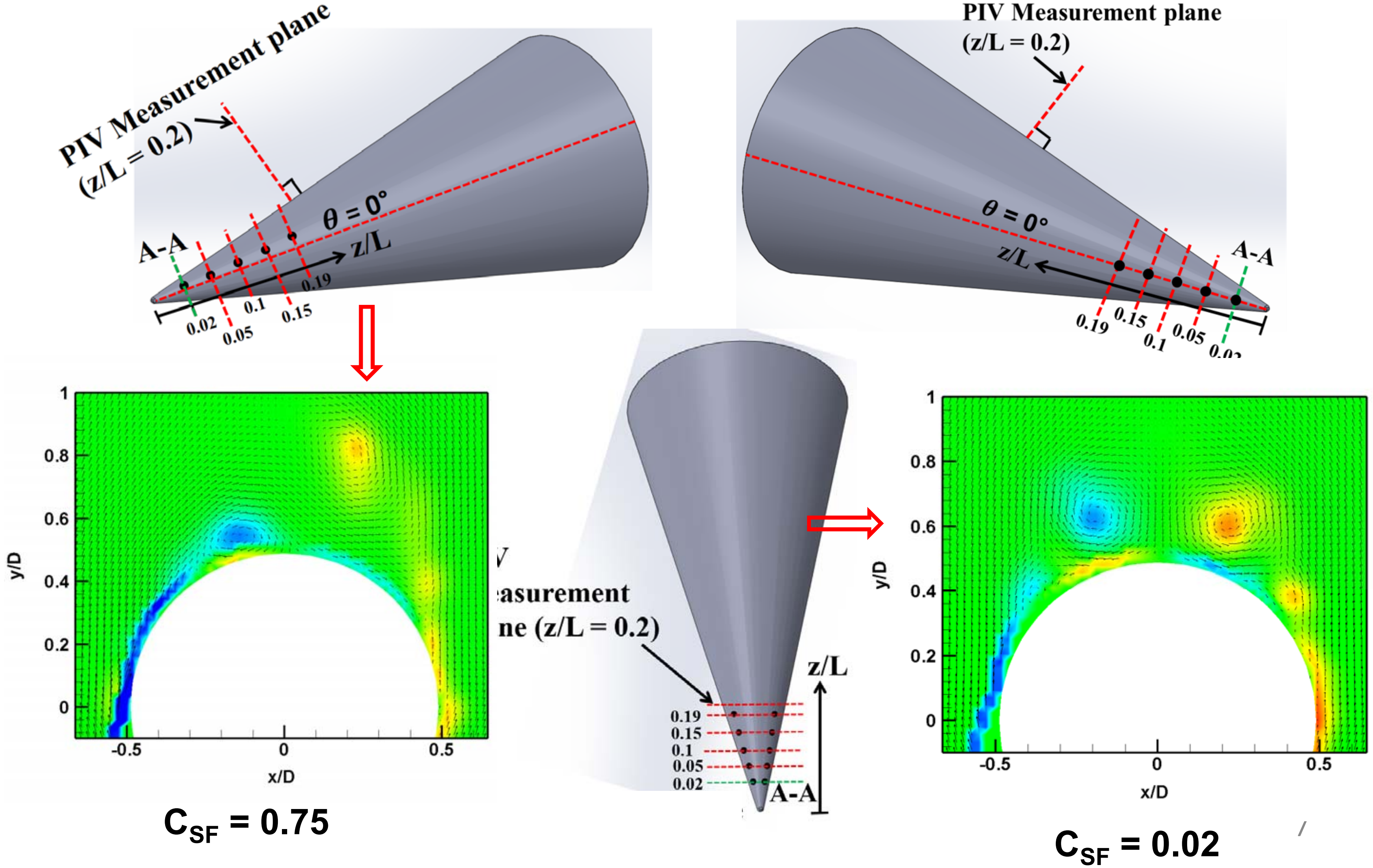
Case	Surface Imperfection (SI) height (h/δ)
1	0.5
2	1
3	2
4	3







Effect of Multiple Controlled Surface Perturbations

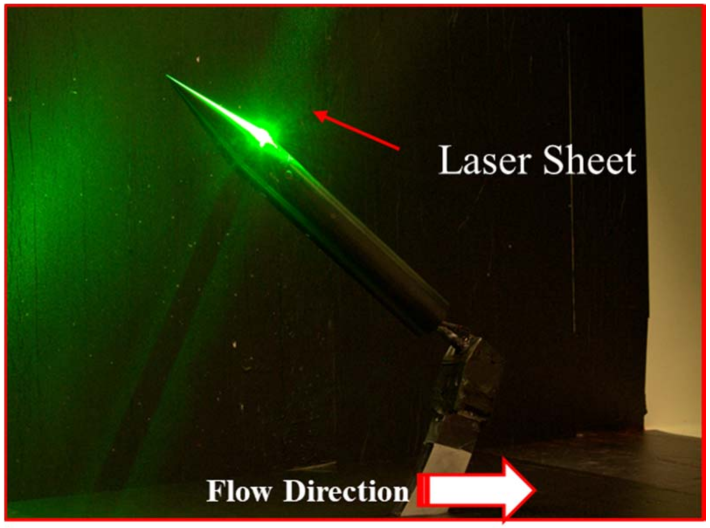


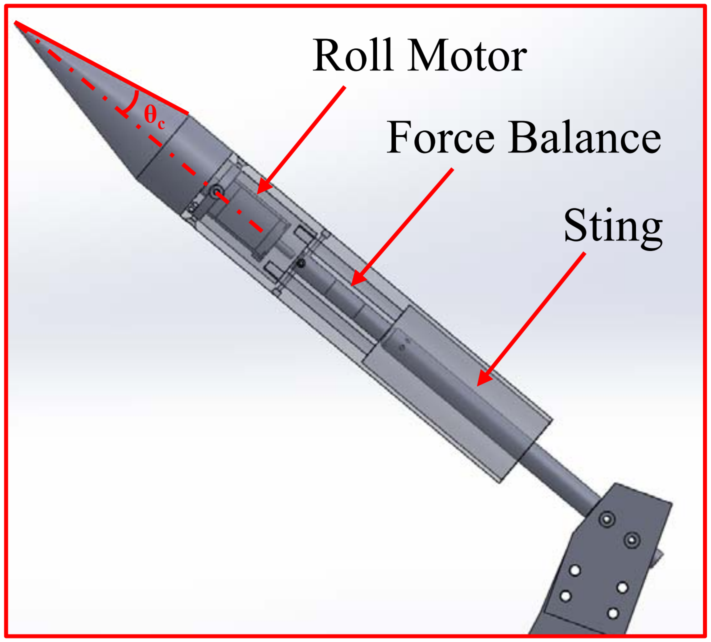
$C_{SF} = 0.75$

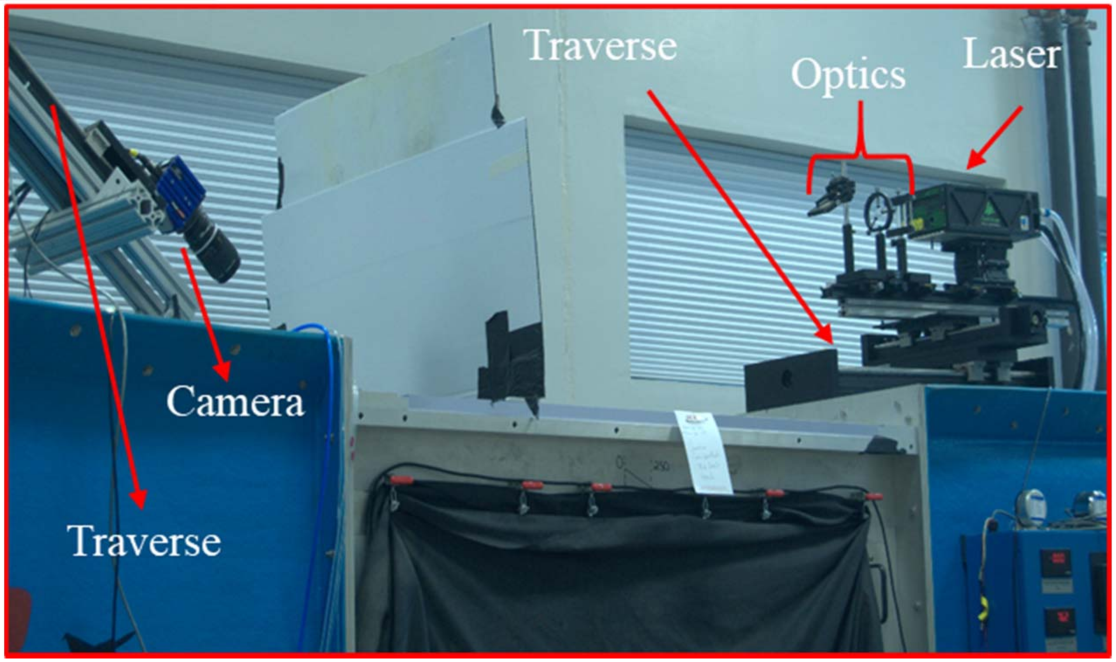
$C_{SF} = 0.02$

Experiments on a long Slender body

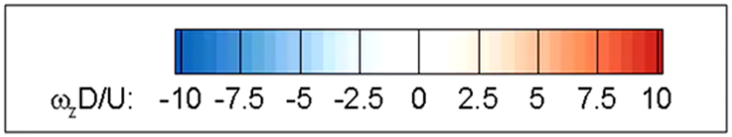
- 12° semi apex cone
- Slenderness ratio (L/D) = 8
- Angle of Incidence = 0°- 50°
- Roll Orientation = 0°-360°
- Re = 1.3×10^5
- Force and Moment Measurements
- Particle Image velocimetry



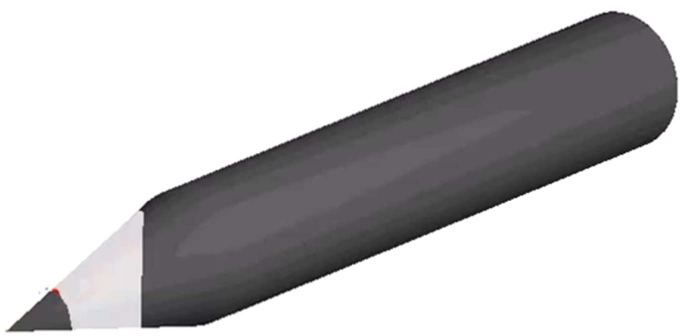


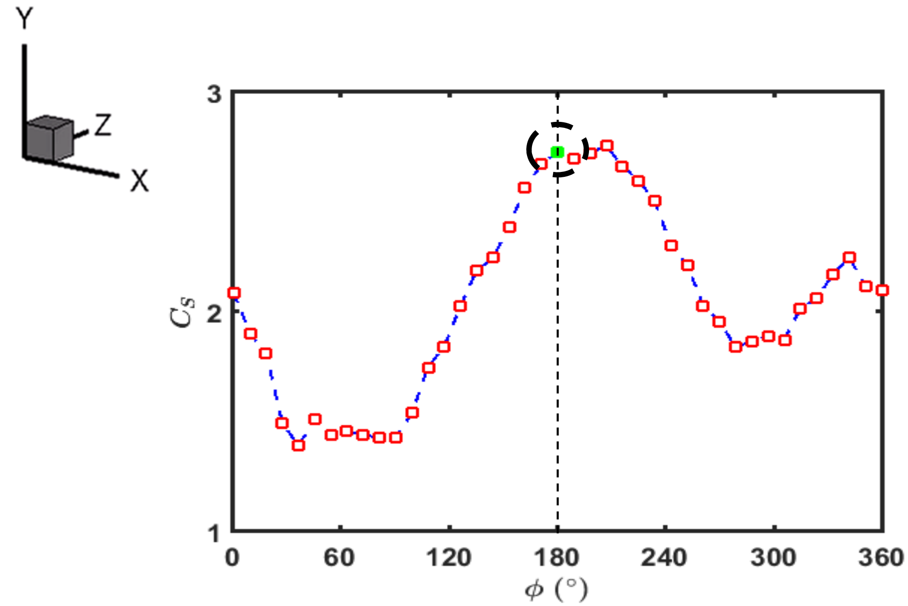


Vortex Development along the Body



- *12° semi-apex cone*
- *L/D = 8*
- *Angle of Incidence = 40°*
- *Re/ft = 0.6 x 10^6*



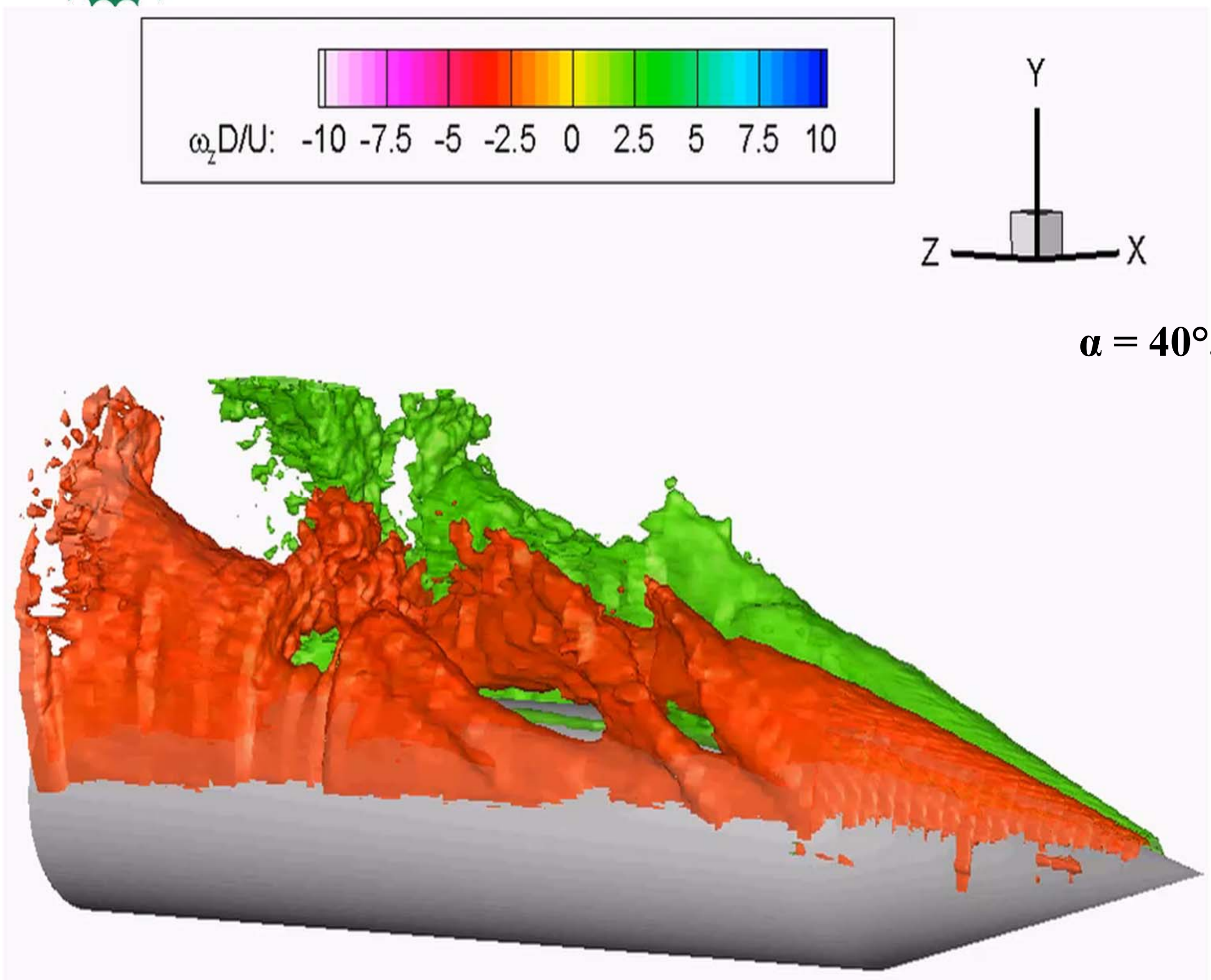


C_s vs. α, α = 40°, Φ = 180°

Normalized mean z-vorticity fields, α = 40°, Φ = 180°

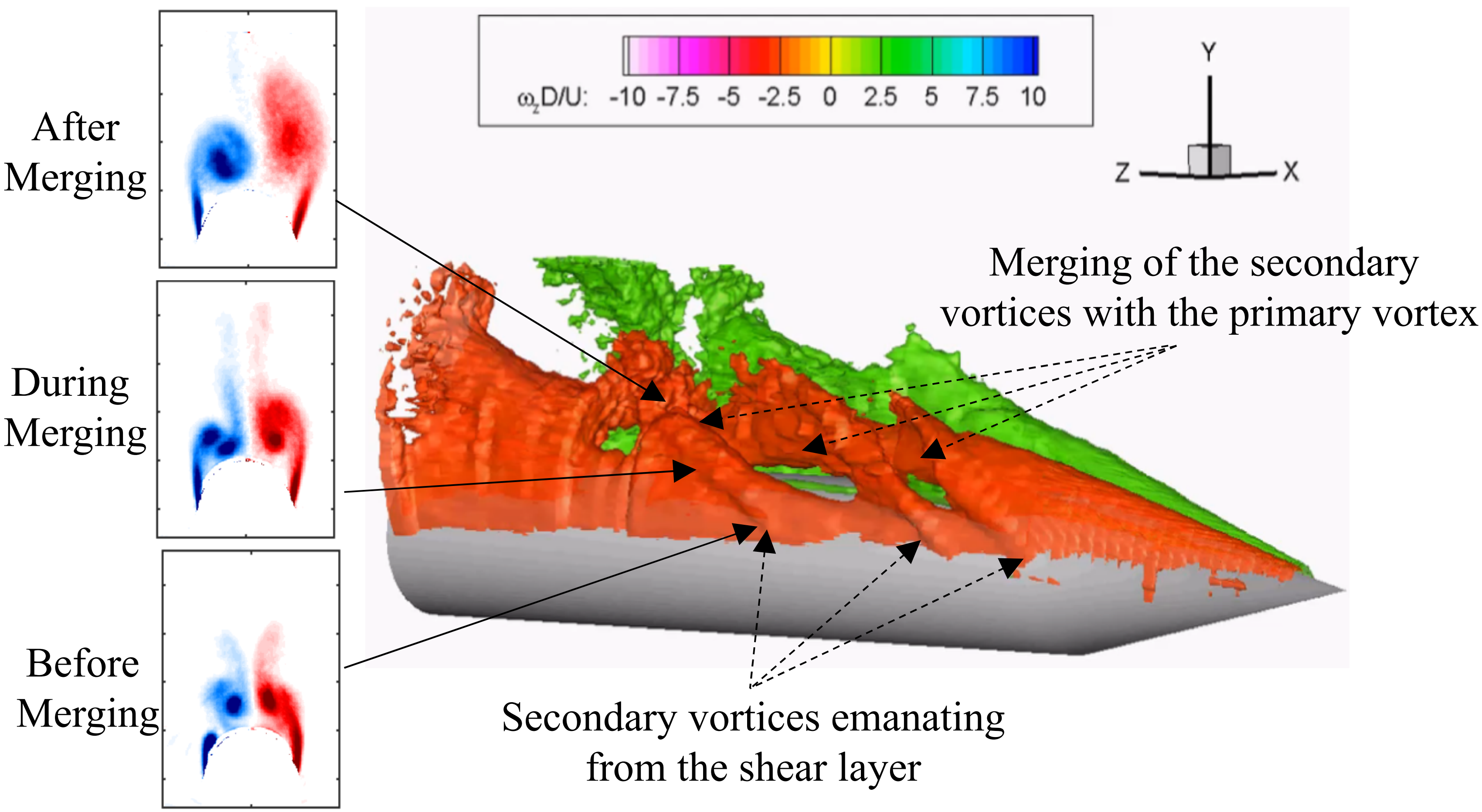
- **Symmetric vortices (counter-rotating) on the cone can develop asymmetry over the cylinder.**
- **Secondary vortices (co-rotating) develop and merge with the respective primary vortices.**
- **Surface imperfections on cylinder may affect the secondary vortices and dictate the asymmetry.**

Vorticity Iso-Surfaces



α = 40°, Φ = 180°

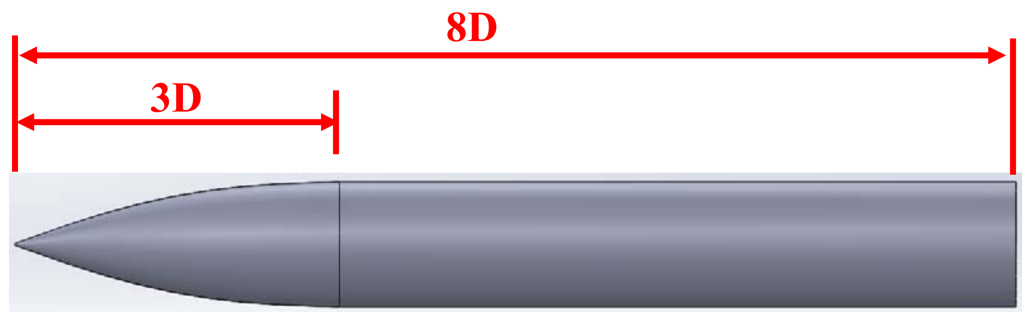
Development and Merging of Secondary Vortices

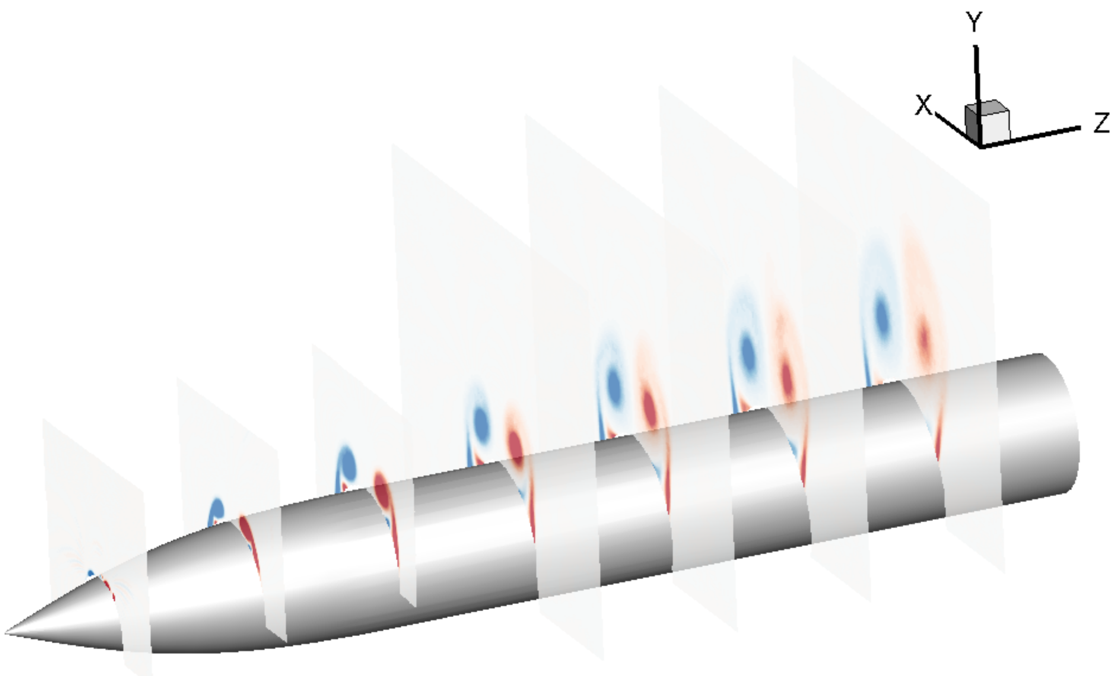


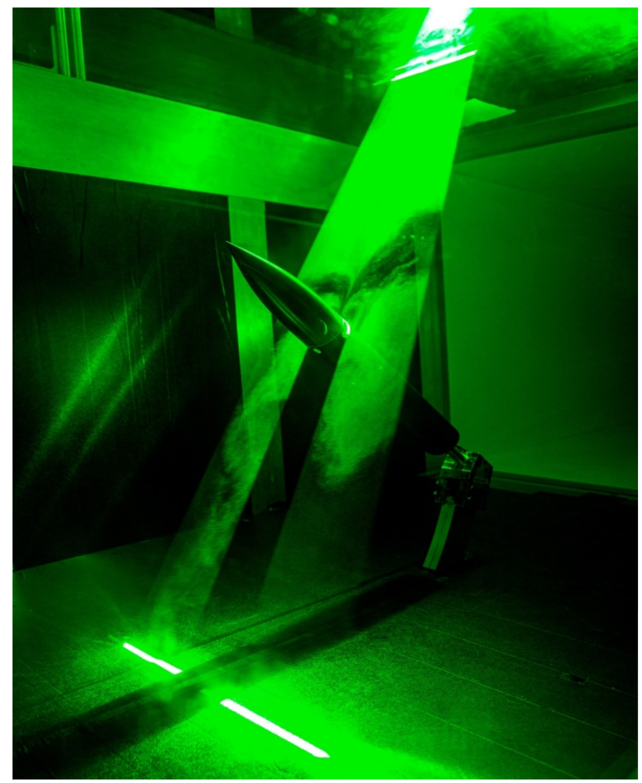
- **Co-rotating vortices beyond a critical inter-core spacing develop vortex filaments.**
- **The filaments lead to an increase in angular momentum.**
- **This forces the vortex cores to move rapidly closer to conserve total momentum and complete the merging process.**

Experiments on a Tangent Ogive Cylinder

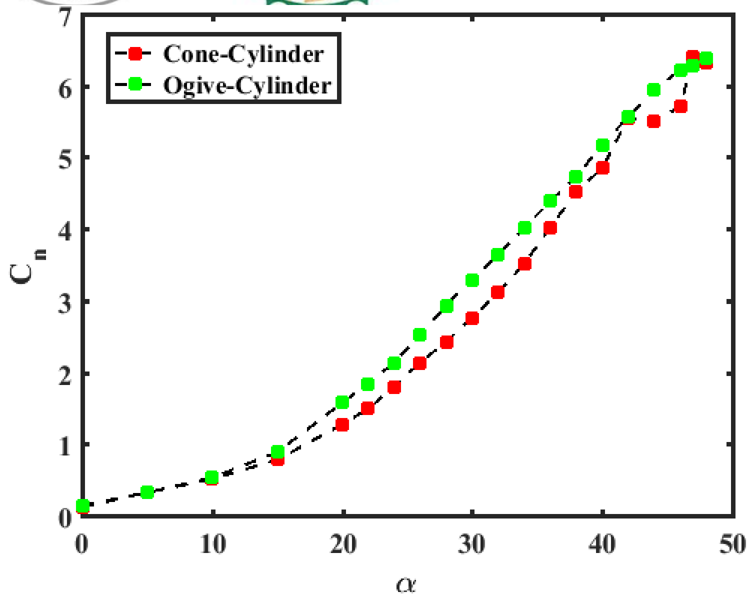
- Tangent Ogive model (Dia_{Base} = 2 inch)
- Angle of Incidence = 0°- 50°
- Roll Orientation = 0°-360°
- $Re_d = 1.3 \times 10^5$
- Force and Moment Measurements
- Oil Flow Visualization
- Particle Image velocimetry

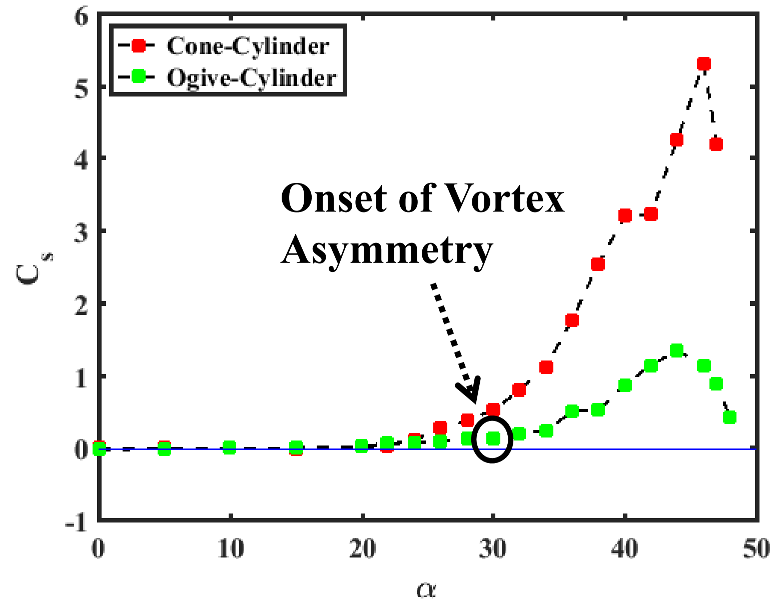


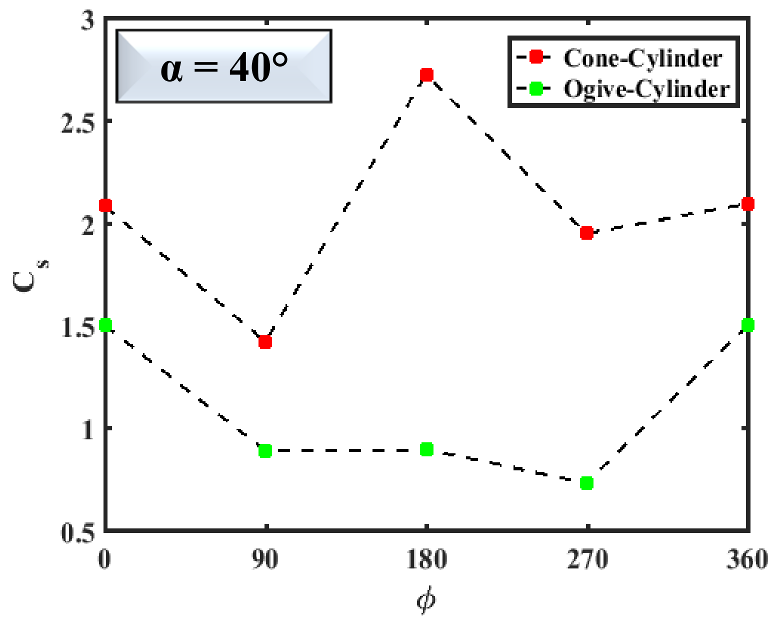




Aerodynamic Characteristics





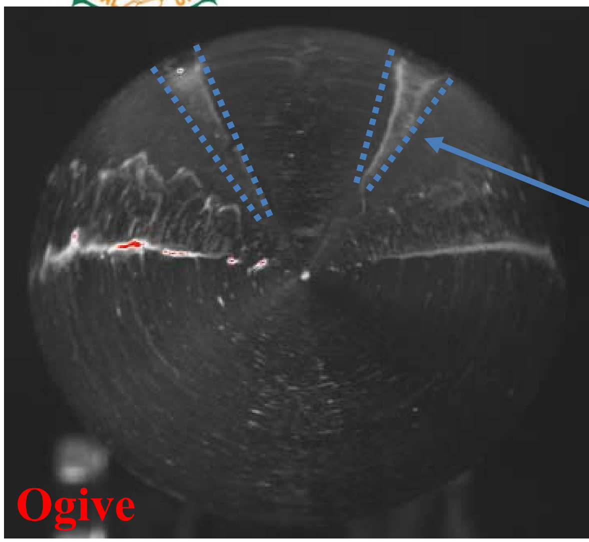


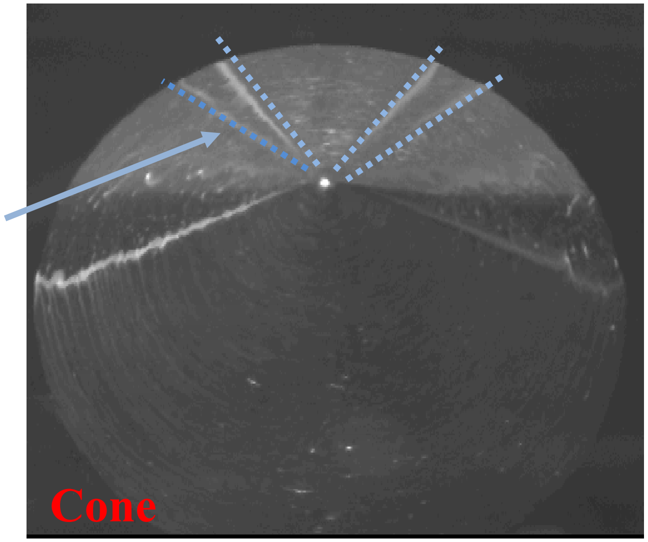
$$C_N = \frac{NF}{\rho_\infty \frac{(U_\infty)^2}{2} * \frac{\pi}{4} D_b^2} \qquad C_{SF} = \frac{SF}{\rho_\infty \frac{(U_\infty)^2}{2} * \frac{\pi}{4} D_b^2}$$

- **Normal force characteristics of ogive cylinder similar to cone-cylinder but significantly lower side force magnitude.**
- **Delayed onset of vortex asymmetry compared to cone-cylinder.**

Surface Oil Flow Visualization

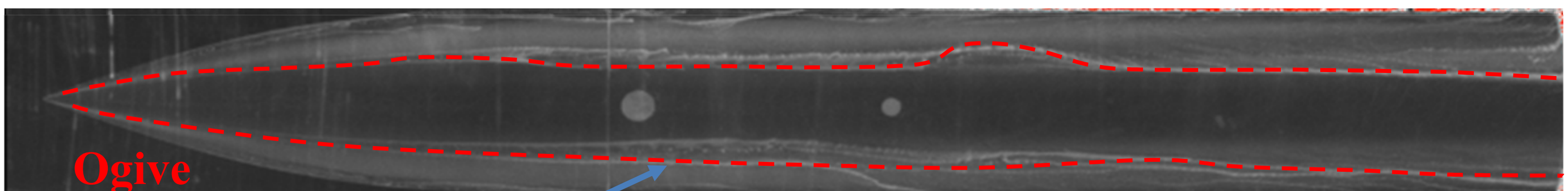
Front





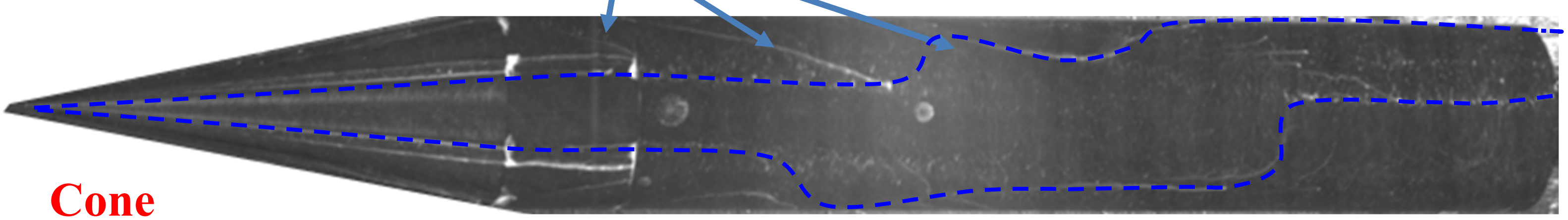
Secondary Vortices

Top



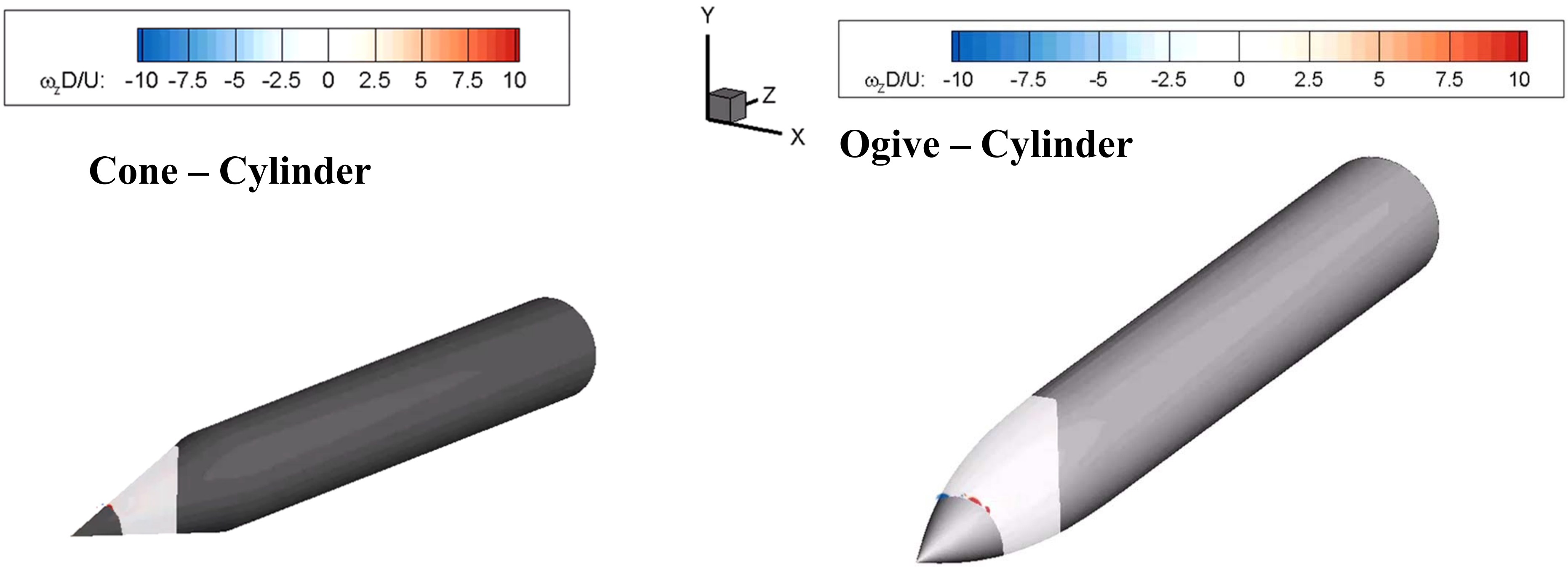
Secondary Vortices extend all the way till the afterbody end

Footprint of the tertiary vortices merging with the primary flow field.



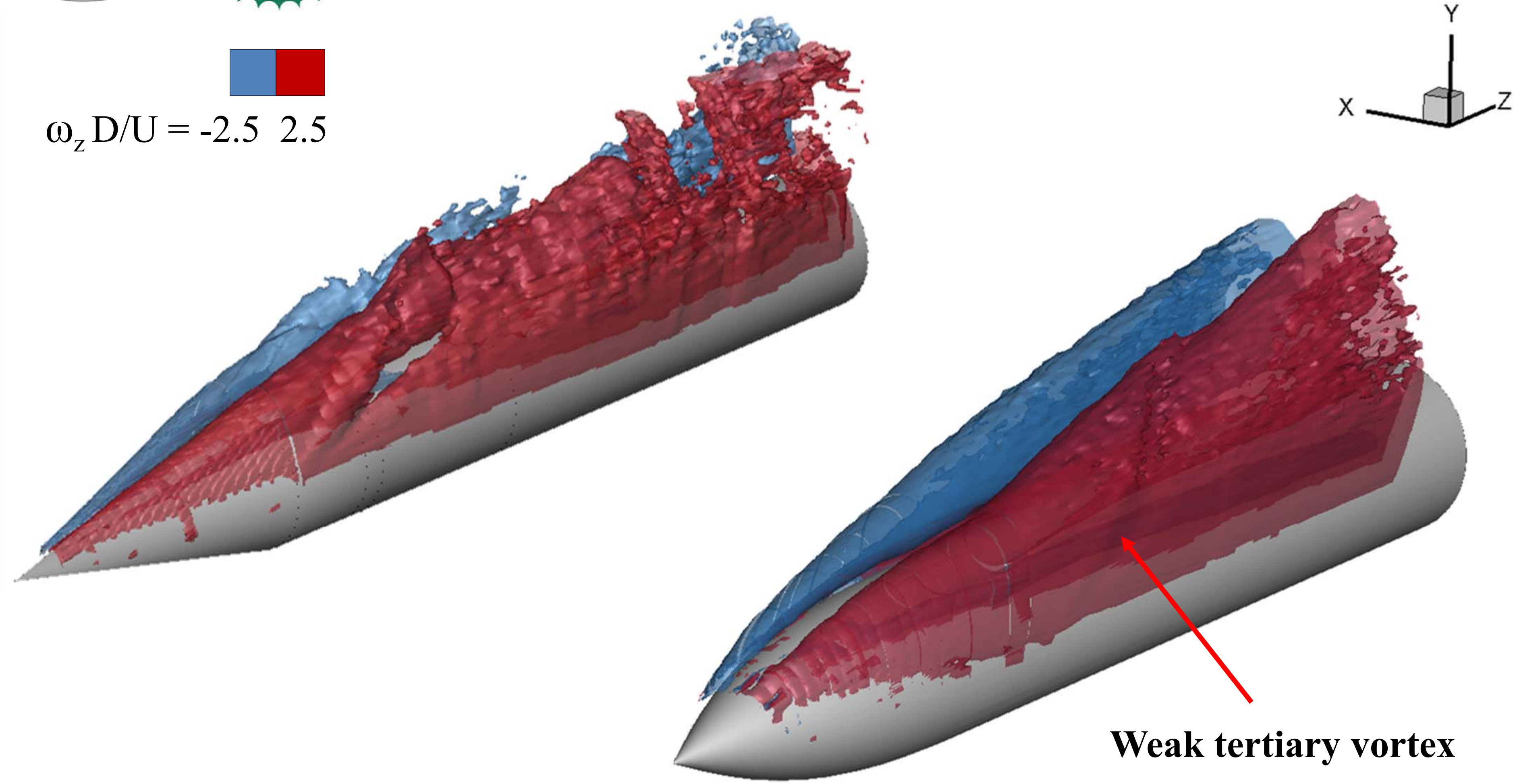
Cone

Development of Vortices Ogive Vs Cone-Cylinder



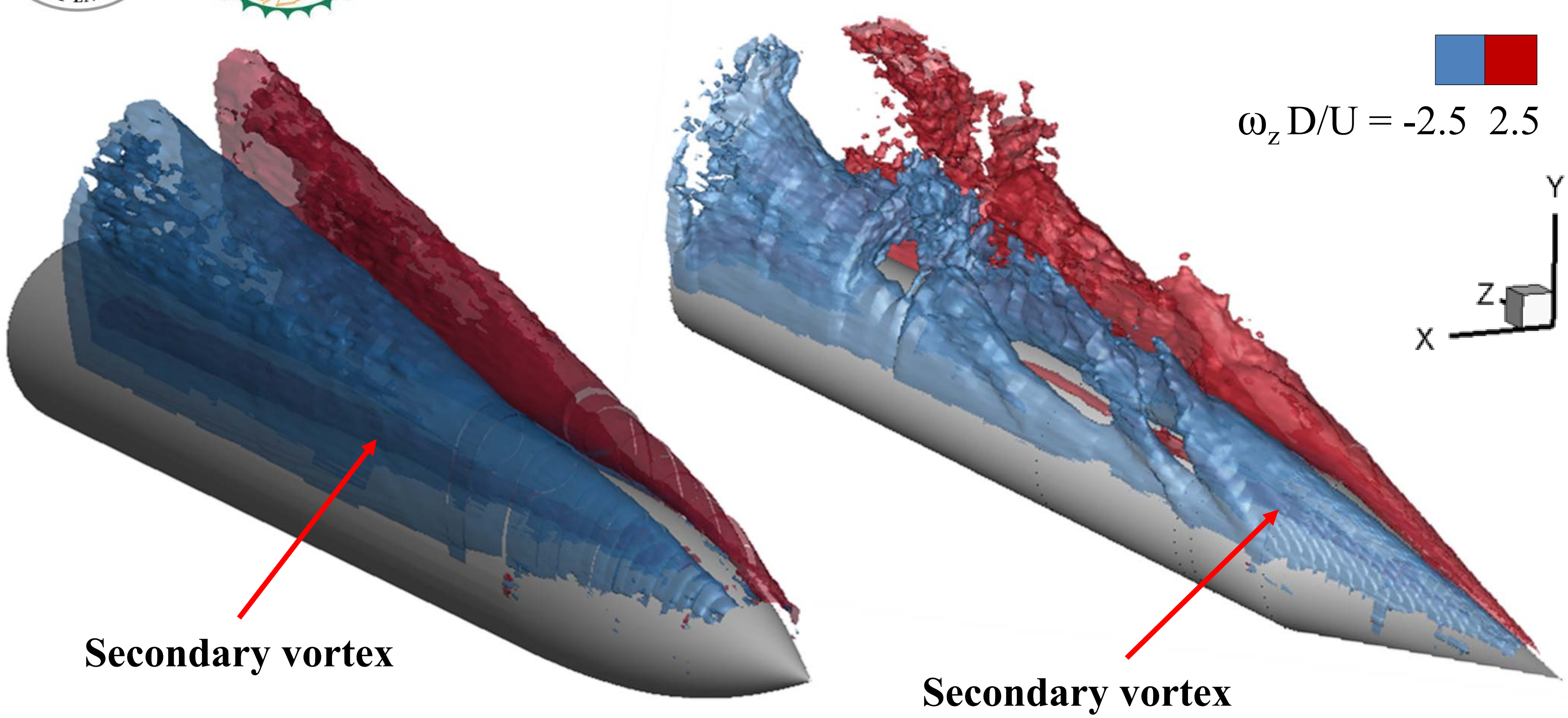
- **Cone – Cylinder: Tertiary vortices (co-rotating) develop and merge with the respective primary vortices.**
- **Ogive – Cylinder: No tertiary vortex merging on the port side. A very weak tertiary vortex merging can be observed on the starboard side.**

Vorticity Iso-surface



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

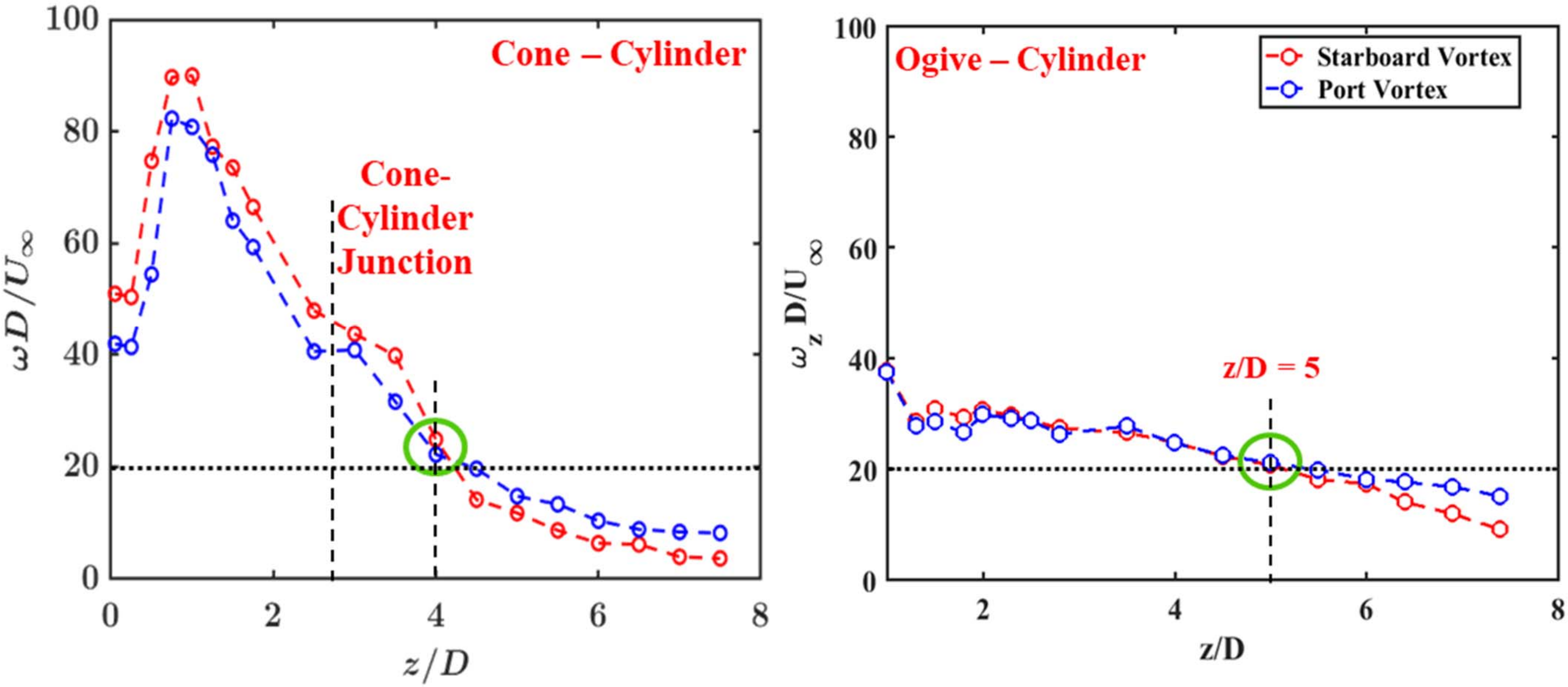
Vorticity Iso-surface



- Counter-rotating secondary line vortices beneath primary vortex extend all the way till the end of the body for the ogive-cylinder.

- These secondary vortices are closer to the surface, and they will have an important impact on the side-force development.

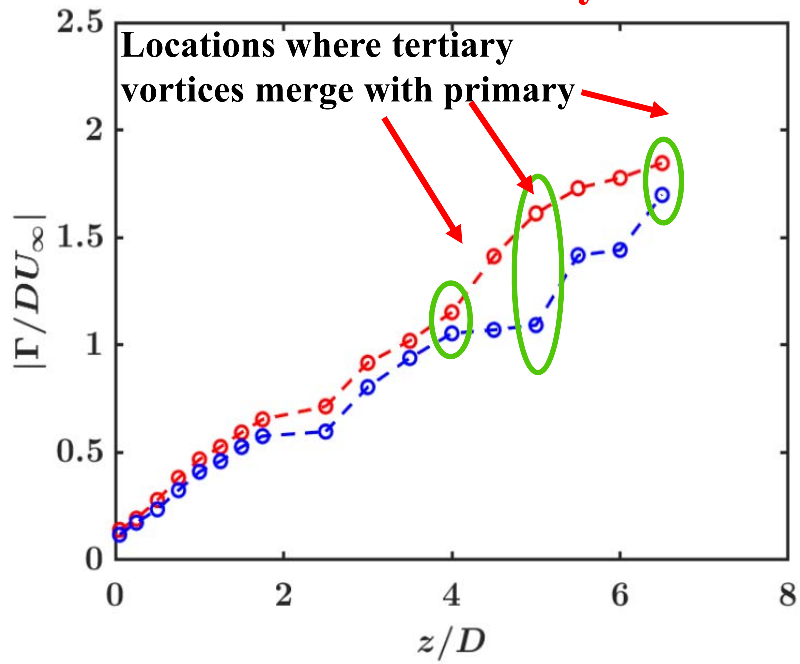
Peak Vorticity



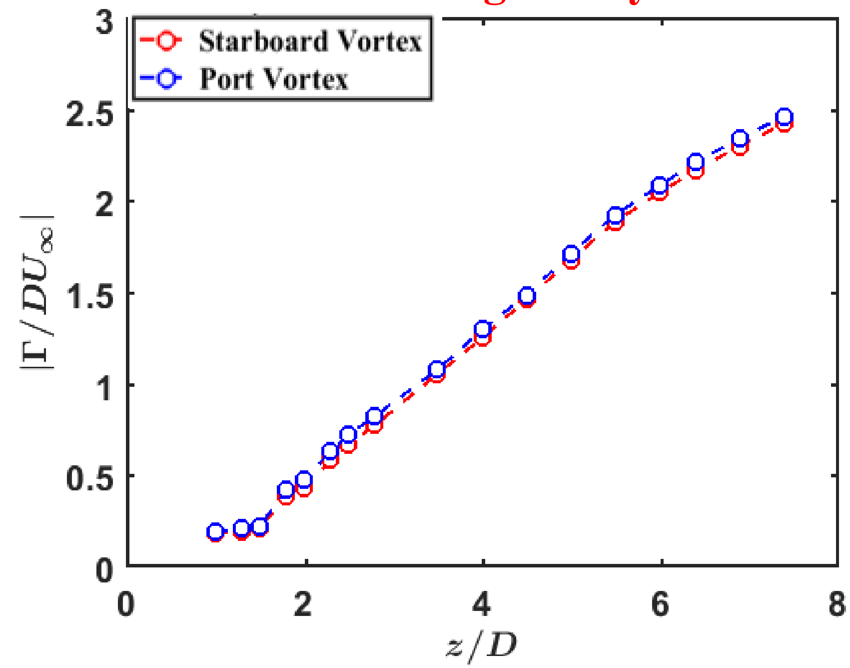
- **Sharp decline in peak vorticity level for cone-cylinder. Whereas it is distributed along the slender body for the ogive-cylinder**

Circulation

Cone- Cylinder

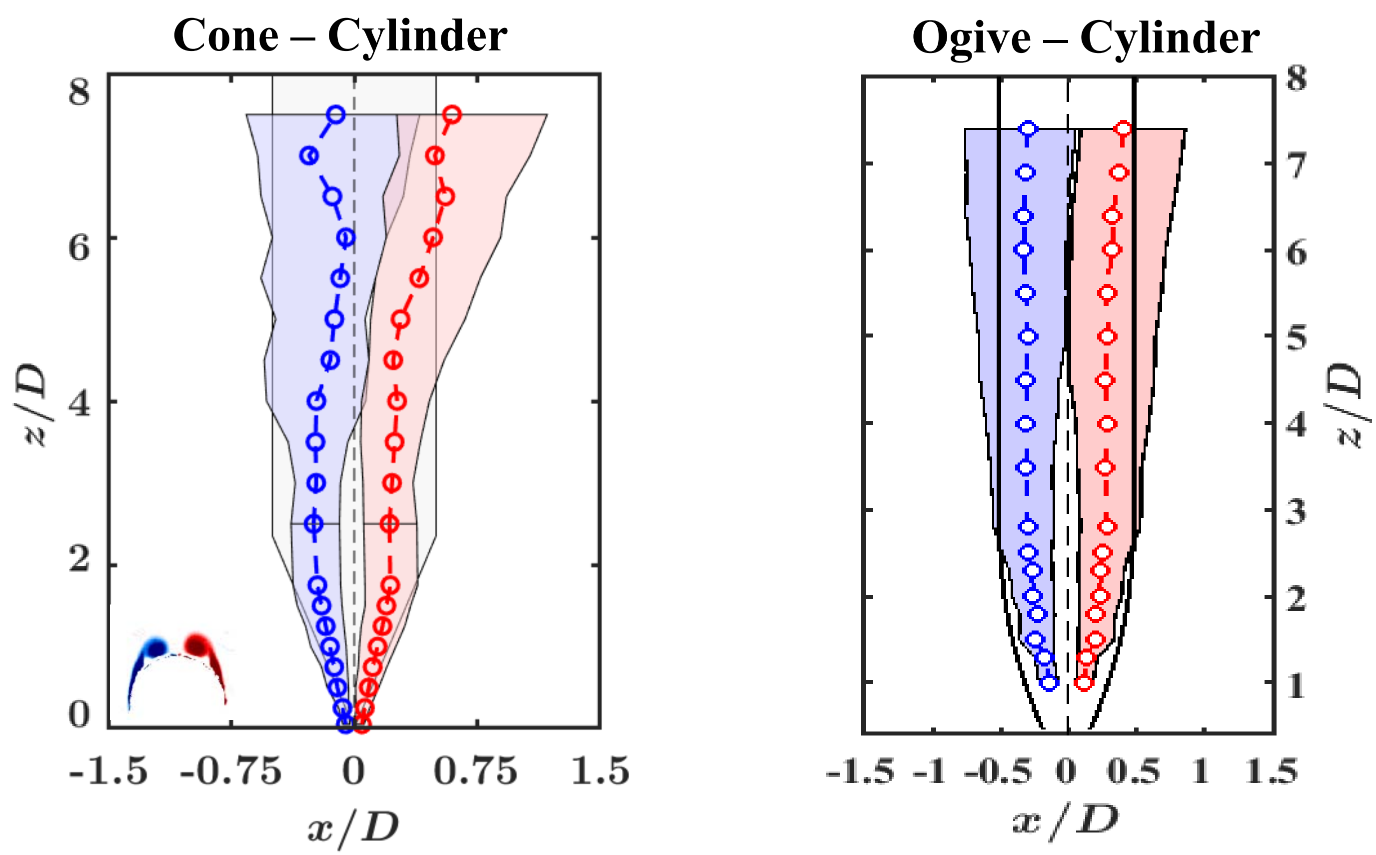


Ogive- Cylinder



- Circulation increases with z/D for both the cases.
- A considerable difference in observed between the positive and the negative circulation for cone-cylinder.
- For the ogive-cylinder, the positive and the negative circulation is almost equal.

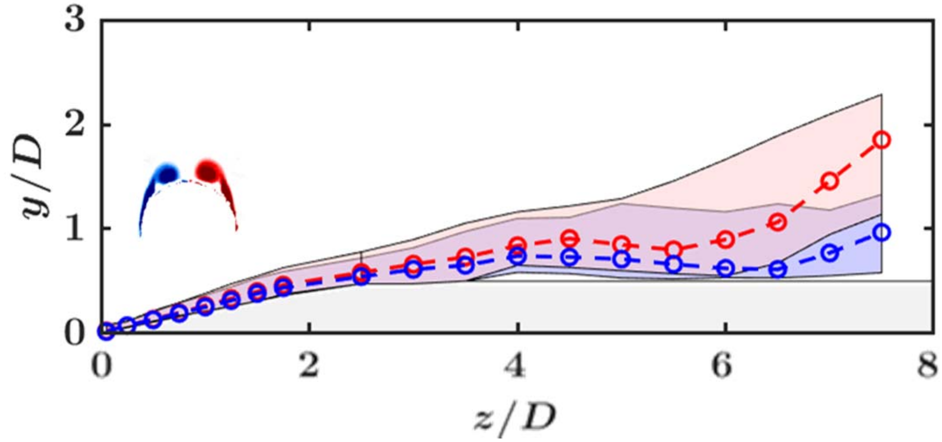
Vortex Trajectory



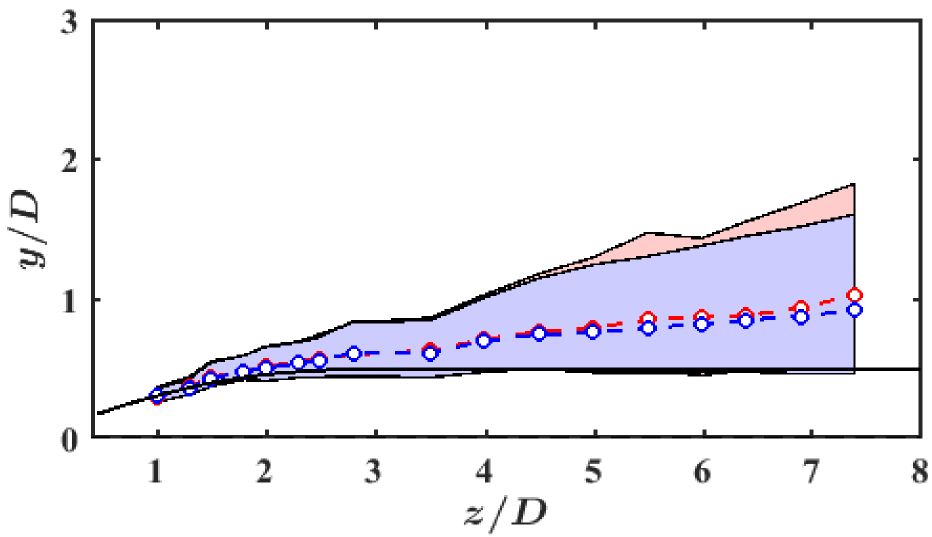
- Asymmetry in trajectory seem to develop after z/D = 4 for Cone-Cylinder.
- Trajectory is nearly symmetric for the ogive-cylinder.

Vortex Trajectory

Cone – Cylinder



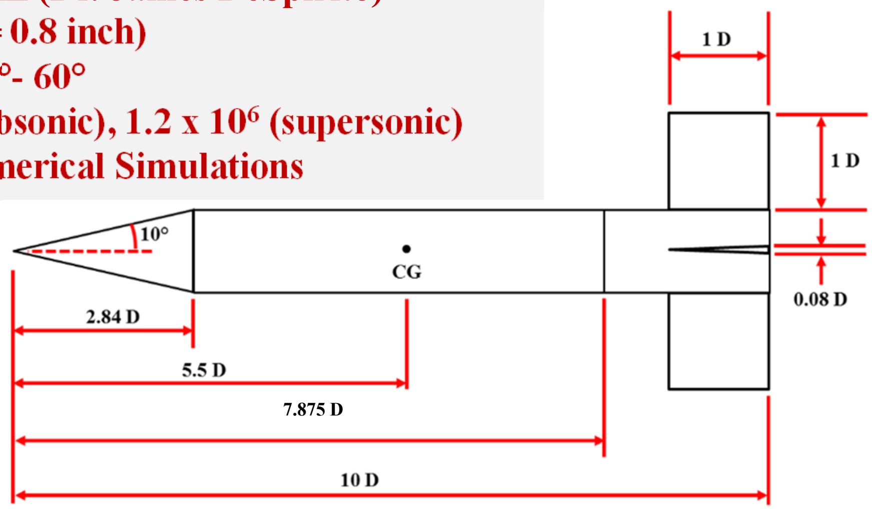
Ogive – Cylinder

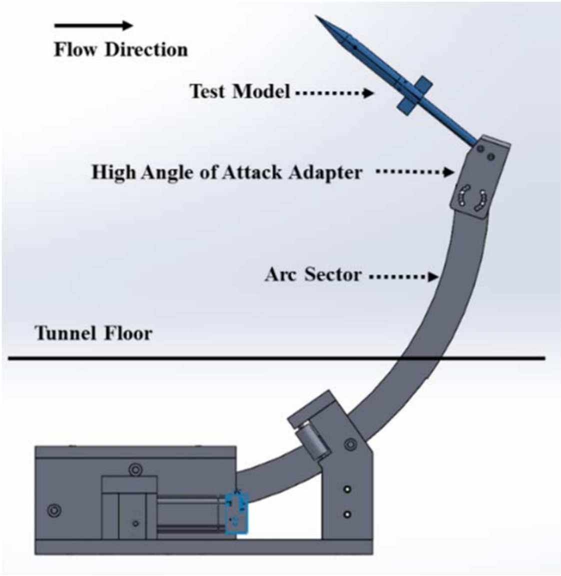


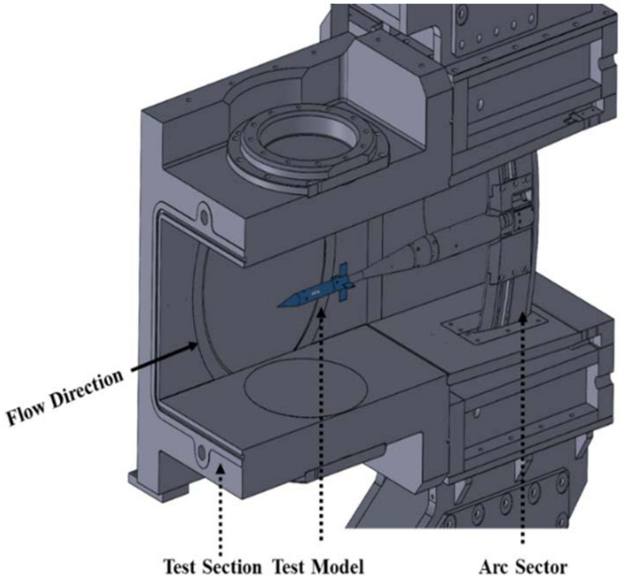
- ❖ **The positive vortex core lifts off the surface around z/D of 5 for cone-cylinder.**
- ❖ **Trajectory is nearly symmetric for the ogive-cylinder.**

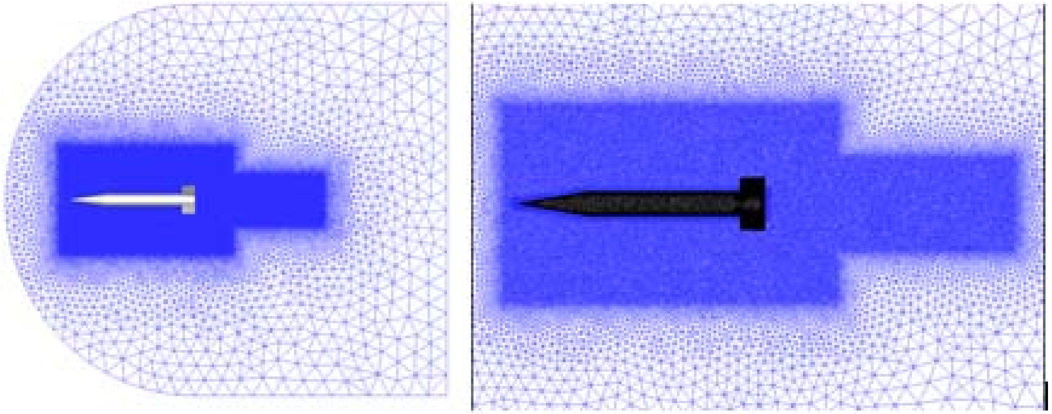
Forebody Vortex Interactions with Control Surfaces

- Collaboration with ARL (Dr. James DeSpirito)
- Basic Finner (Dia_{Base} = 0.8 inch)
- Angle of Incidence = 0°- 60°
- Re_d = .3 ~ 0.7× 10^5 (Subsonic), 1.2 x 10^6 (supersonic)
- Experimental and Numerical Simulations





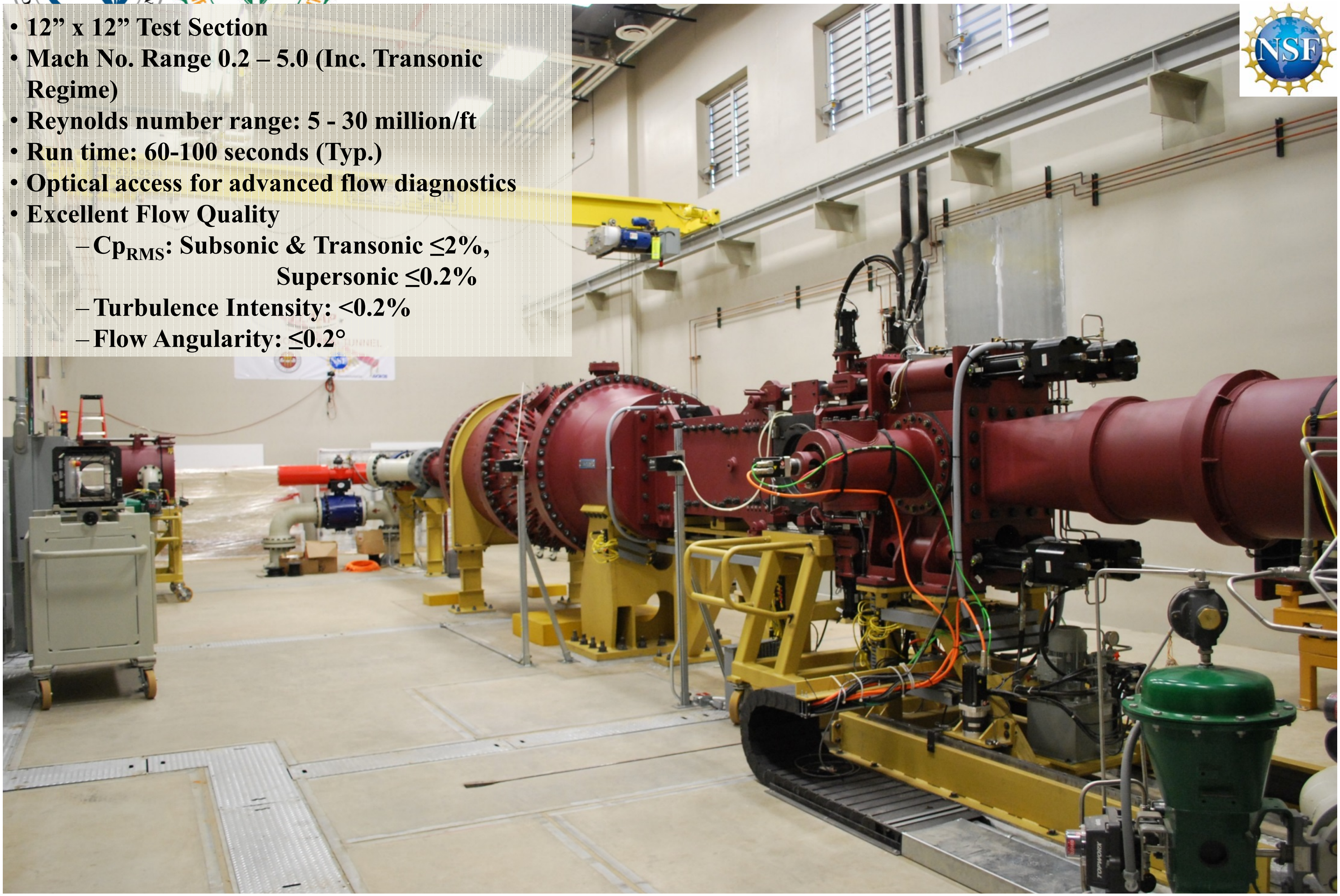




MIME mesh generator: 54.2 million cells, unstructured mesh with prismatic elements (4.2 million) in the boundary layer region and tetrahedral cells elsewhere.

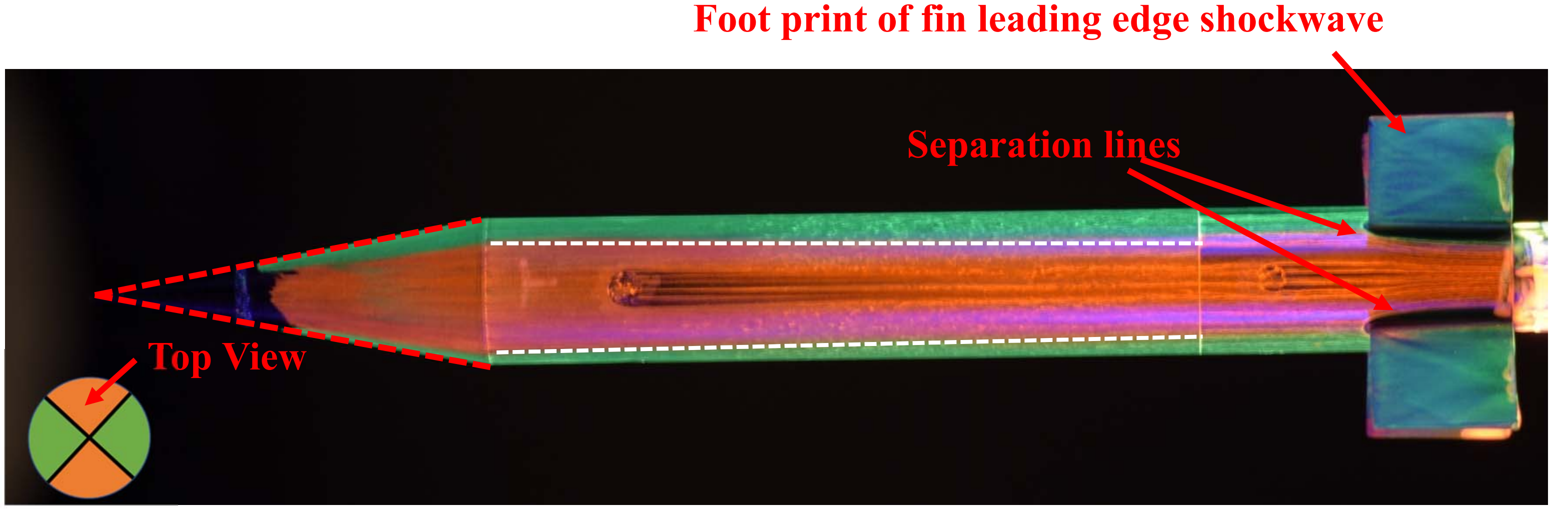
Polysonic Wind Tunnel

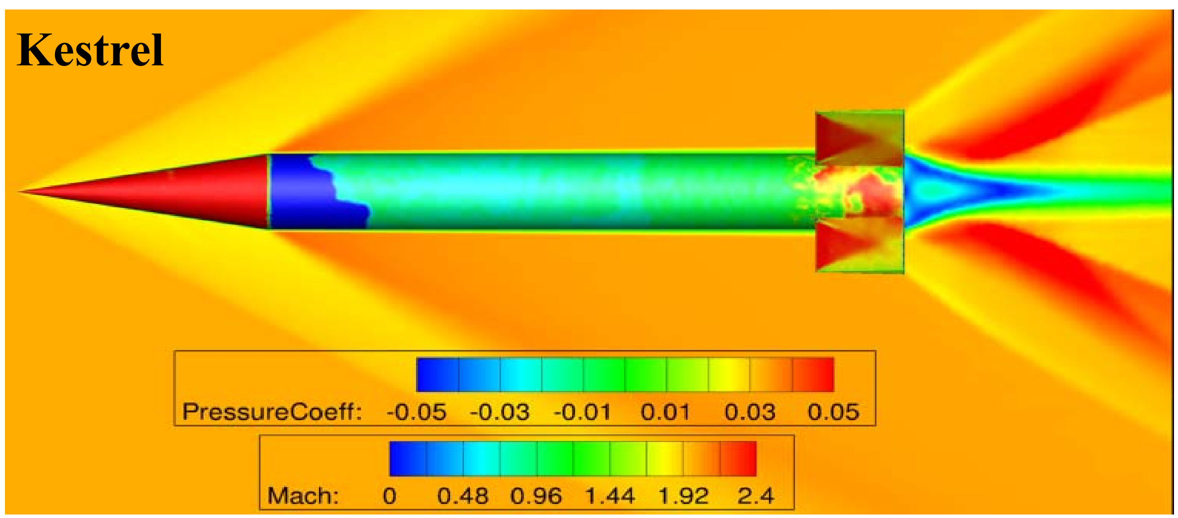
- 12” x 12” Test Section
- Mach No. Range 0.2 – 5.0 (Inc. Transonic Regime)
- Reynolds number range: 5 - 30 million/ft
- Run time: 60-100 seconds (Typ.)
- Optical access for advanced flow diagnostics
- Excellent Flow Quality
  - Cp_{RMS}: Subsonic & Transonic ≤2%, Supersonic ≤0.2%
  - Turbulence Intensity: <0.2%
  - Flow Angularity: ≤0.2°



Surface Flow Features – x Configuration

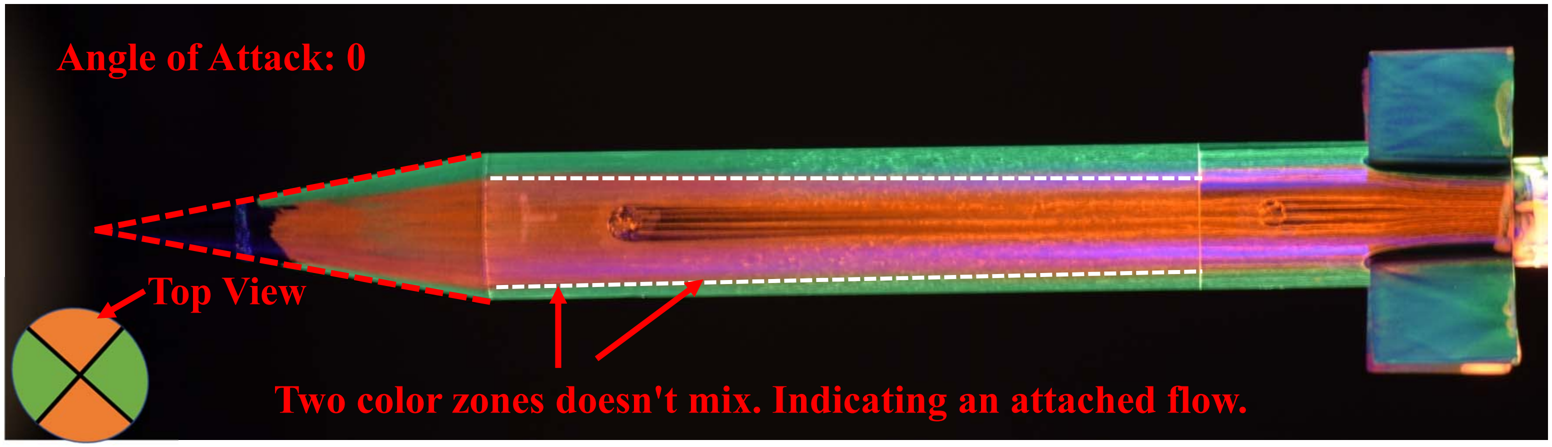
❖ **Flow conditions: - Mach # = 2, Angle of attack = 0**

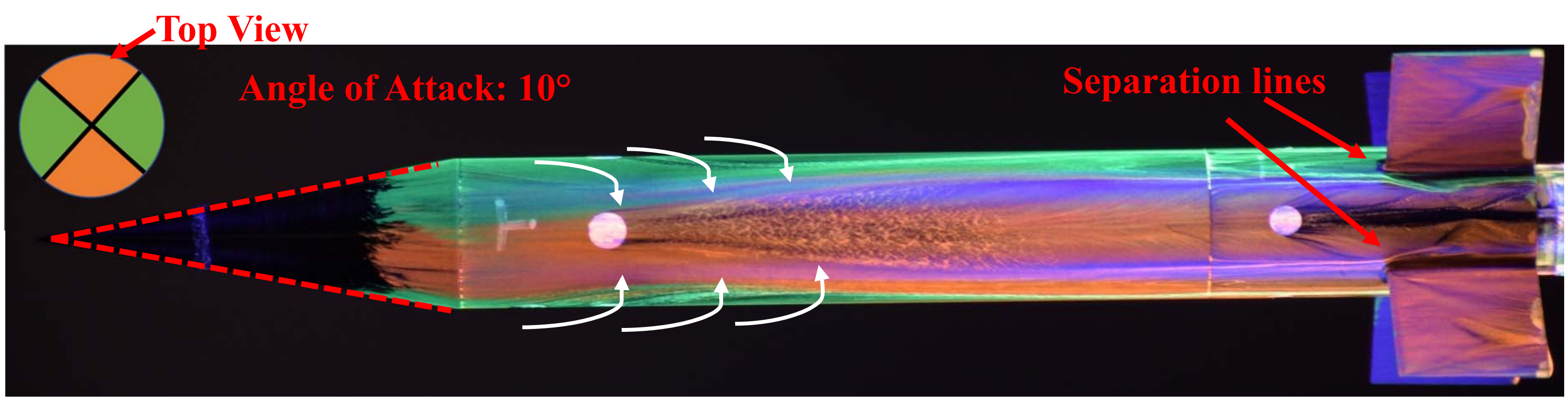




Surface Flow Features – x Configuration

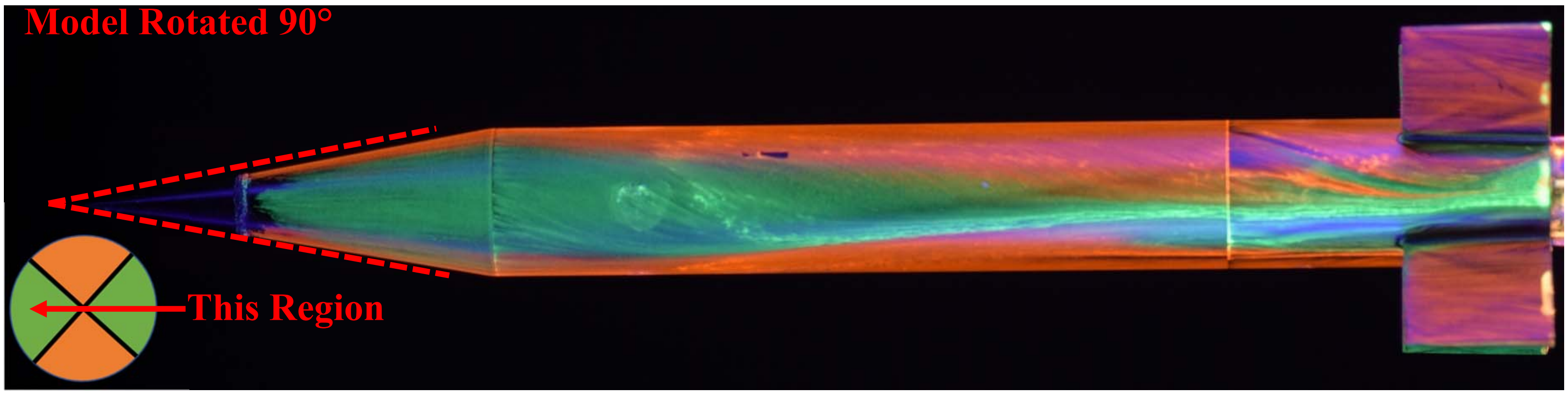
❖ **Flow conditions: Mach # = 2**

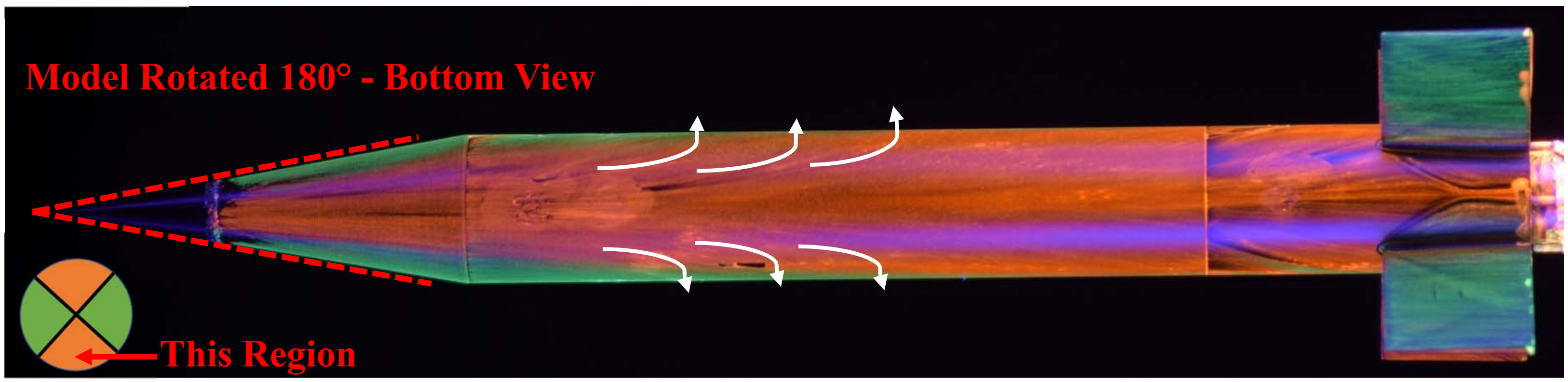




Two color zones mix. Indicates a separated cross flow rather than an axially dominated attached flow field.

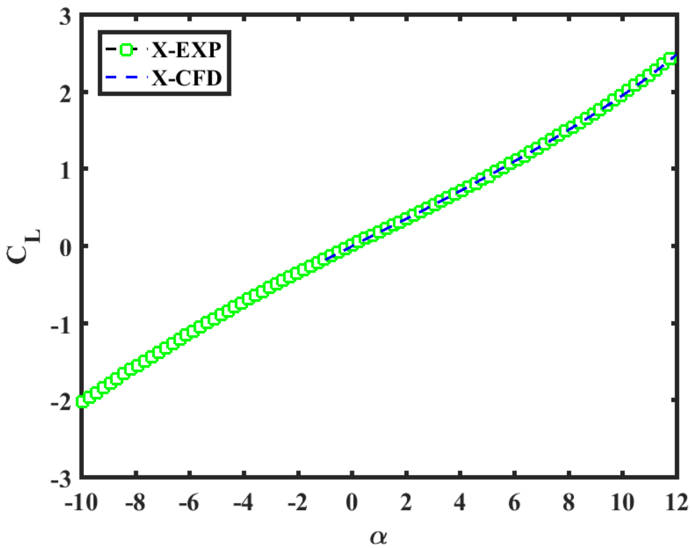
Surface Flow Features – x Configuration

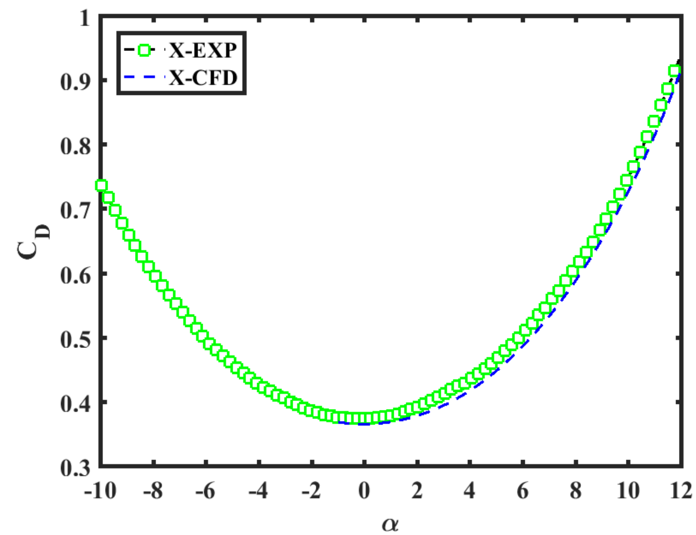


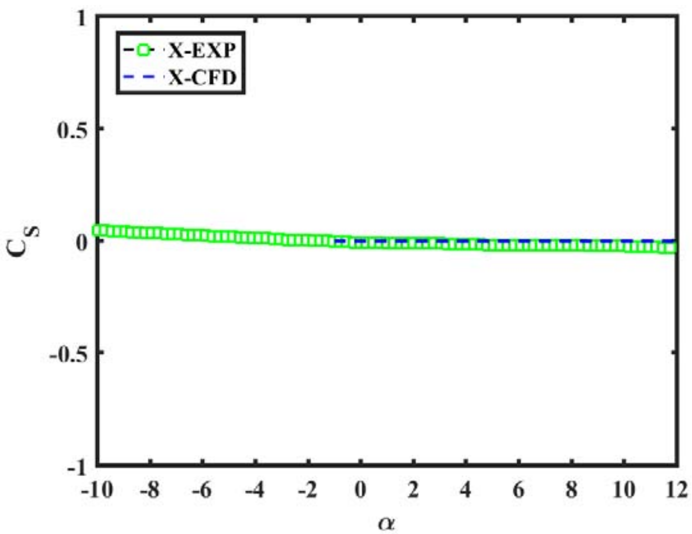


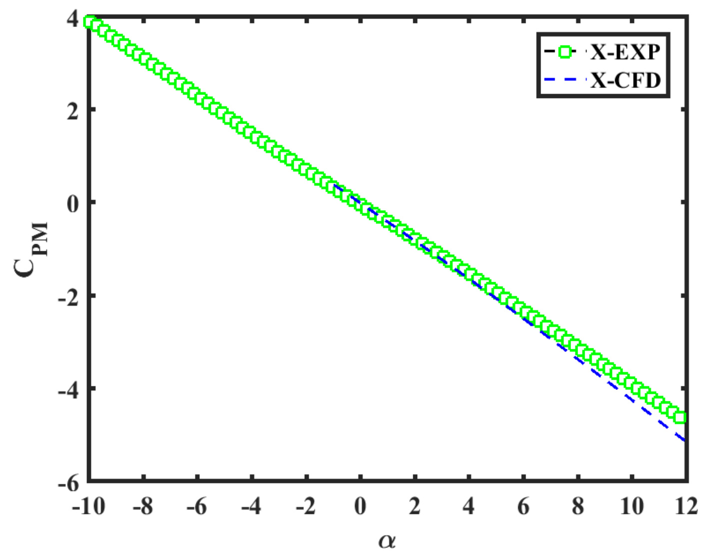
Basic Aerodynamic Characteristics at Supersonic Speeds

- Experiments: Polysonic Wind Tunnel Facility, Mach = 2.0
- Numerical Simulations: KESTREL

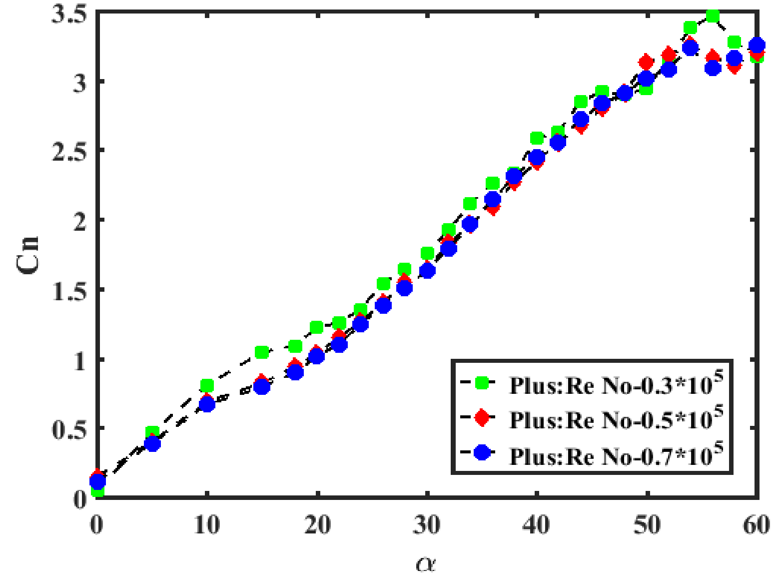


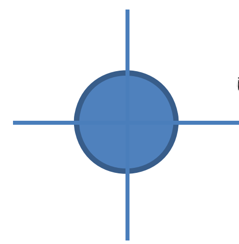


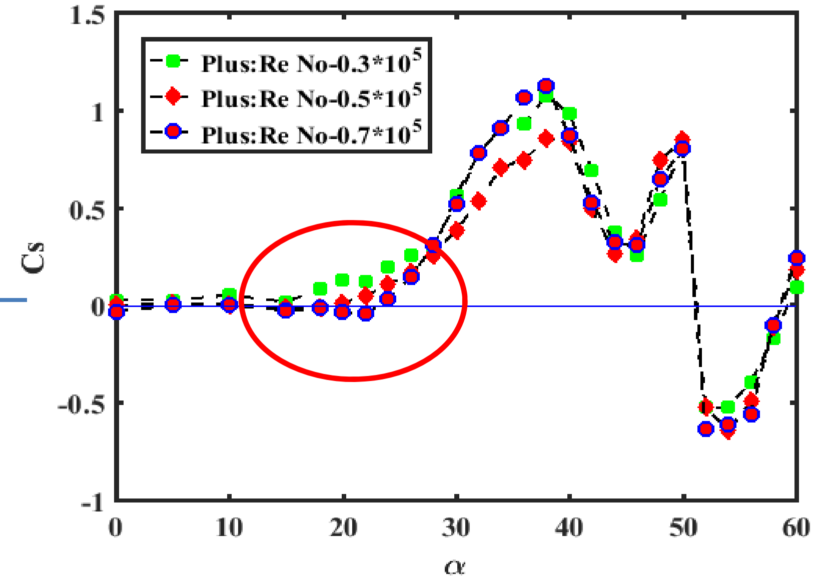


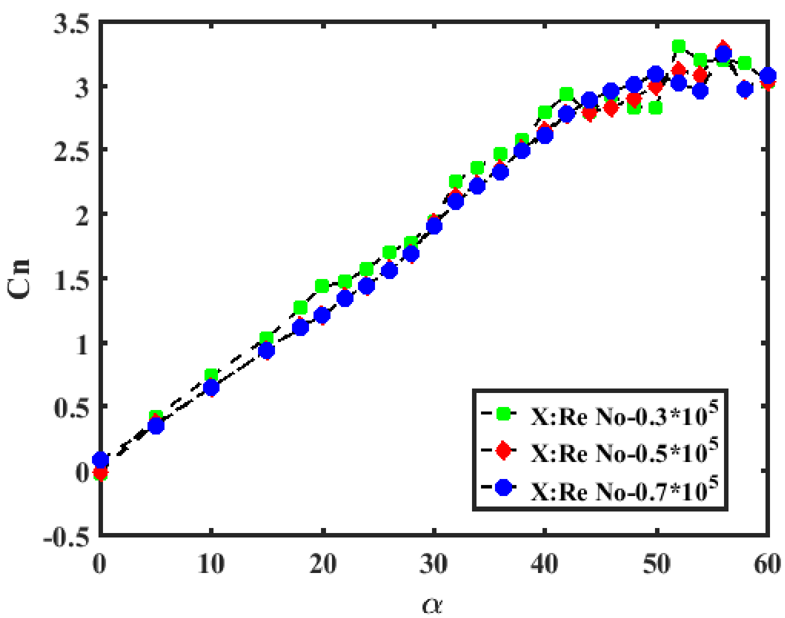


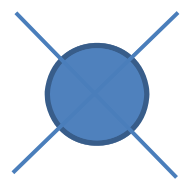
Basic Aerodynamic Characteristics at Low Speeds

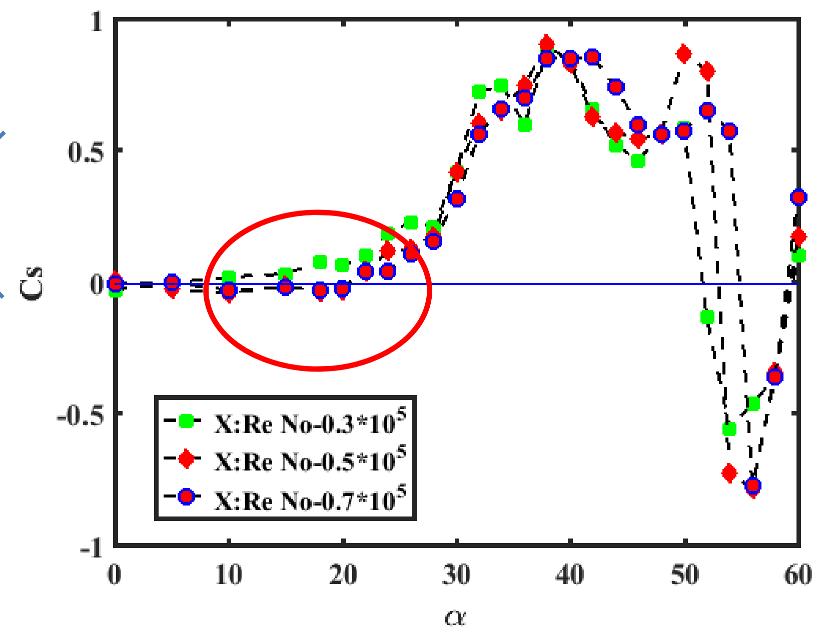




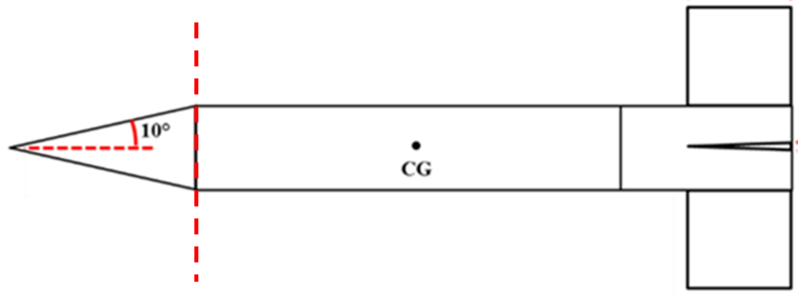


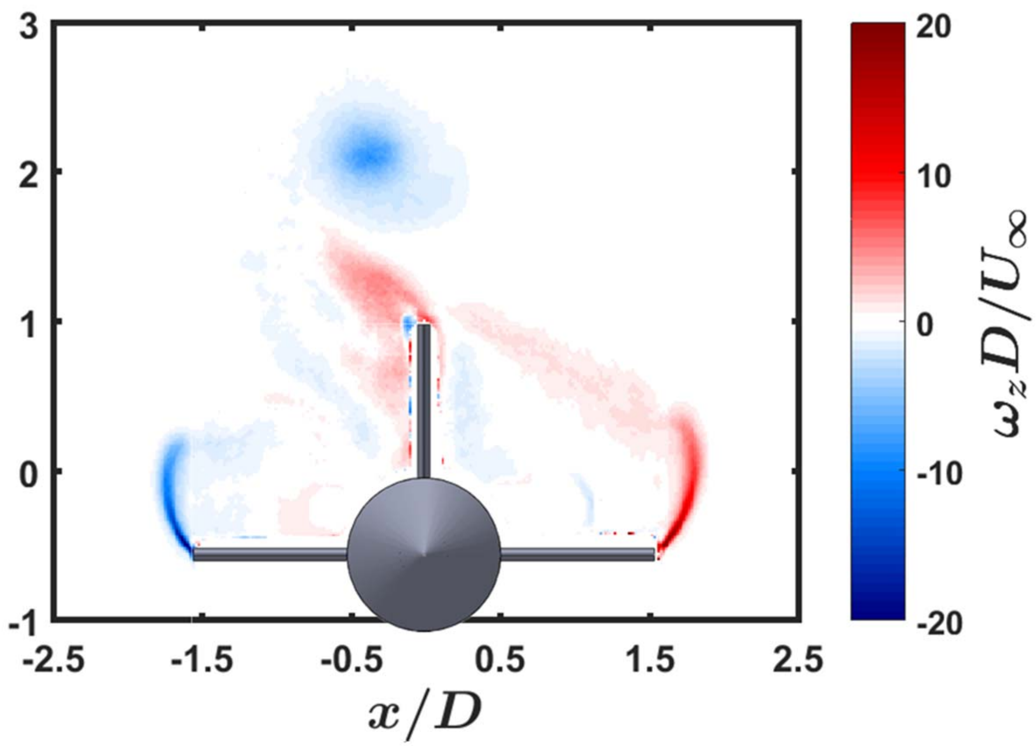


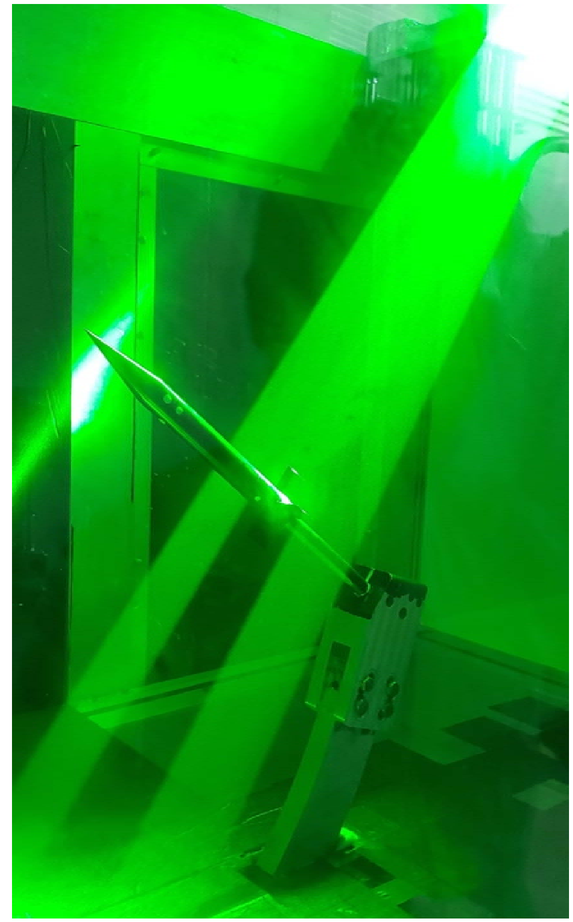




Forebody Vortex Interactions with Control Surfaces

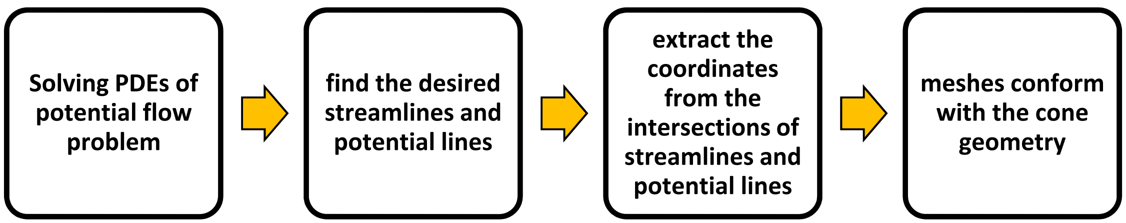


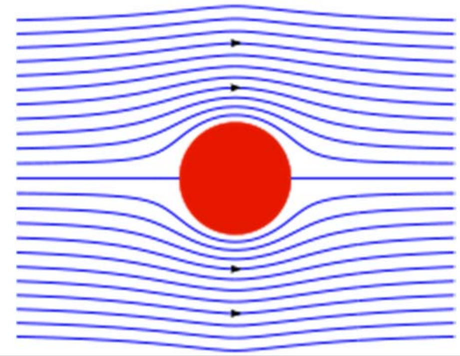


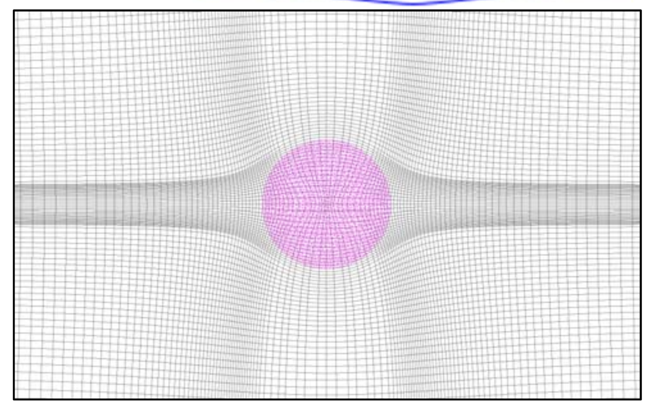


Immersed boundary method with semi-conformal mesh:

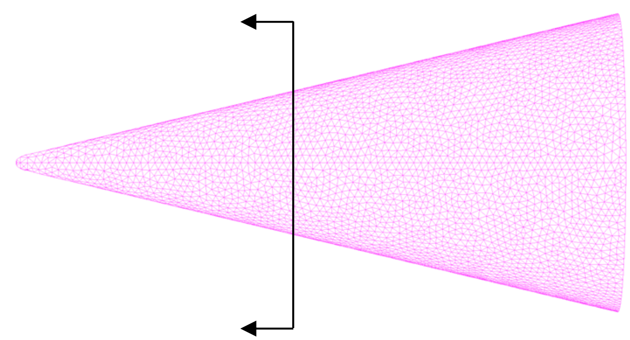
- Structured partially conformal mesh generation
  - Grids are aligned with surface







  - Faster rate of convergence
  - Higher solution accuracy near the wall, still have the benefits of IBM
  - Time efficient.
  - Highly space efficient, since the neighborhood relationships are defined by storage arrangement
  - Provides higher resolution
- Geometry: unstructured triangular surface mesh

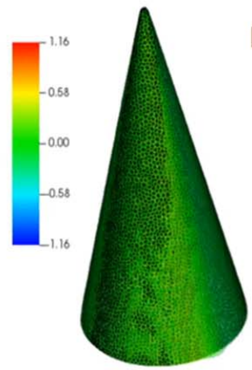


Simulations by: Kourosh Shoele

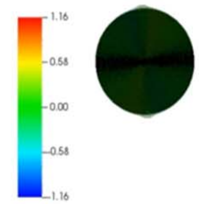
Preliminary verification and validation

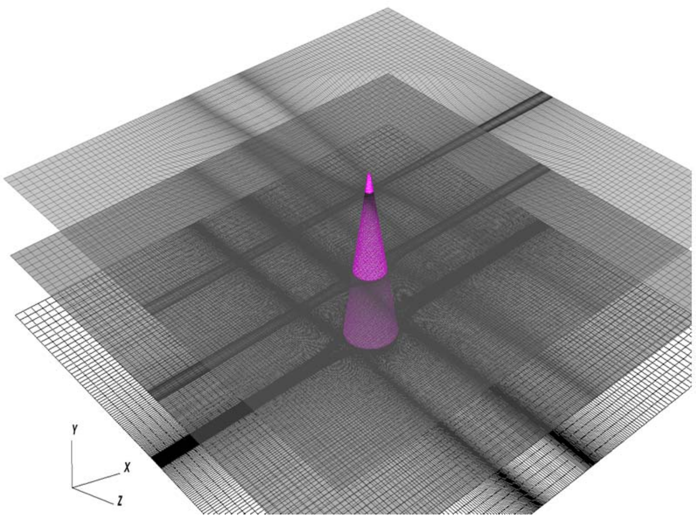
3D flow simulation over a cone

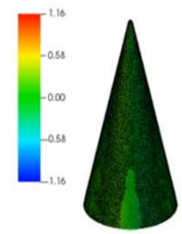
- Dynamic LES model with a equilibrium wall function
- Grids: 201×71 ×201
- Cone height=2 Diameter at the base

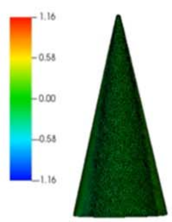


Isosurface of velocity magnitude – showing the streamwise velocity









Summary

Significant progress has been made in 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
- Asymmetric vortices switch direction with roll orientation resulting in pressure imbalance and asymmetric yawing moments
- 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, tertiary vortices (co-rotating) develop and merge with the respective primary vortices whereas on ogive – cylinder there is no tertiary vortex merging on the port side. A very weak tertiary 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.
- A good comparison of basic aerodynamic characteristics between experiments and numerical simulations using Kestrel.

Publications

- Kumar, R., Guha, T, Kumar, R. *Experimental and Numerical study of Forebody Vortex Interactions on a generic Axisymmetric Finned Configuration*, Submitted to AIAA SciTech Forum, 6-10 January 2020.
- 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*