Prediction of Coaxial Rotor Hub Flow Using Mercury Framework

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Outline

- **Introduction**
- **Computational Methodology**
  - Mercury framework
  - Mesh generation
  - Simulation setup
- **Results and Discussion**
  - Hub drag and harmonics
  - Mean wake profiles at SPIV plane, x/R_{hub} = 3 and 7
- **Concluding Remarks**

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Introduction

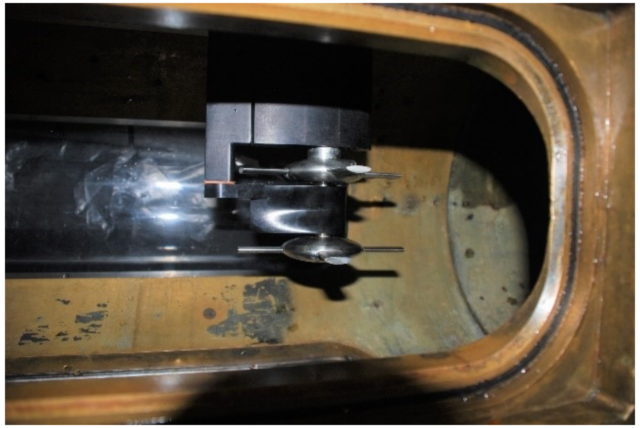
- **Rotor hub is one of main sources of the adverse interactional aerodynamics**
  - Hub wake flow remains in long wake ages and aerodynamically interacts with downstream components
  - Often results in costly redesign of tail or empennage
    - Ex) RAH-66, UH-60, AH-64, and EH-101
- **Rotor hub accounts for 25 ~ 33% of the total vehicle drag for a single main rotor and up to 50% with a coaxial rotor**
  - Drag reduction of the hub is necessary to develop next generation high speed helicopters or urban air mobility vehicles with multi-rotors
- **Three Rotor Hub Flow Prediction Workshops were held at the PSU in 2016, 2018, and 2020**
  - Water tunnel tests of defeatured rotor hub configurations
  - Measured hub drag and near- and far-wake profiles using stereoscopic particle-image velocimetry (SPIV) and laser doppler velocimetry (LDV)

Redesign of RAH-66 tail.
Images from Sikorsky Archive.

Sikorsky X-2.
Image from Lockheed Martin.

4th PSU Hub Flow Prediction Workshop

- **Phase IV VLRCOE Scaled Model Testing of Coaxial Rotor Hub Flows**
  - 12-inch-Diameter Water Tunnel at the PSU
  - Hub load data at multiple flow speeds and advance ratios for four hub shapes: 3.25:1 Rectangle, **DBLN**, 4:1 Ellipse, and OCS
  - Wake measurements at multiple downstream locations using SPIV
- **CFD simulation conditions**
  - Hub and sail fairing drag for **DBLN hub**: mean & harmonics
  - Mean wake profiles at SPIV plane, x/R_{hub} = 3 and 7



Installed hub in the test section

Hub radius, R_{hub}	0.0635 m (2.5 in)
Ratio of R_{hub}/R_{rotor}	0.15
Freestream velocity	9 m/s
Advance ratio	0.25, 0.6
Re_{hub} (based on D_{hub})	1.13 X 10^6

Experimental conditions

DBLN rotor hub

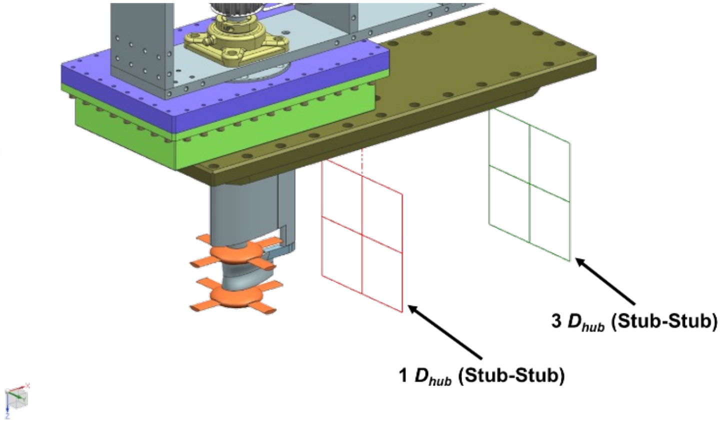
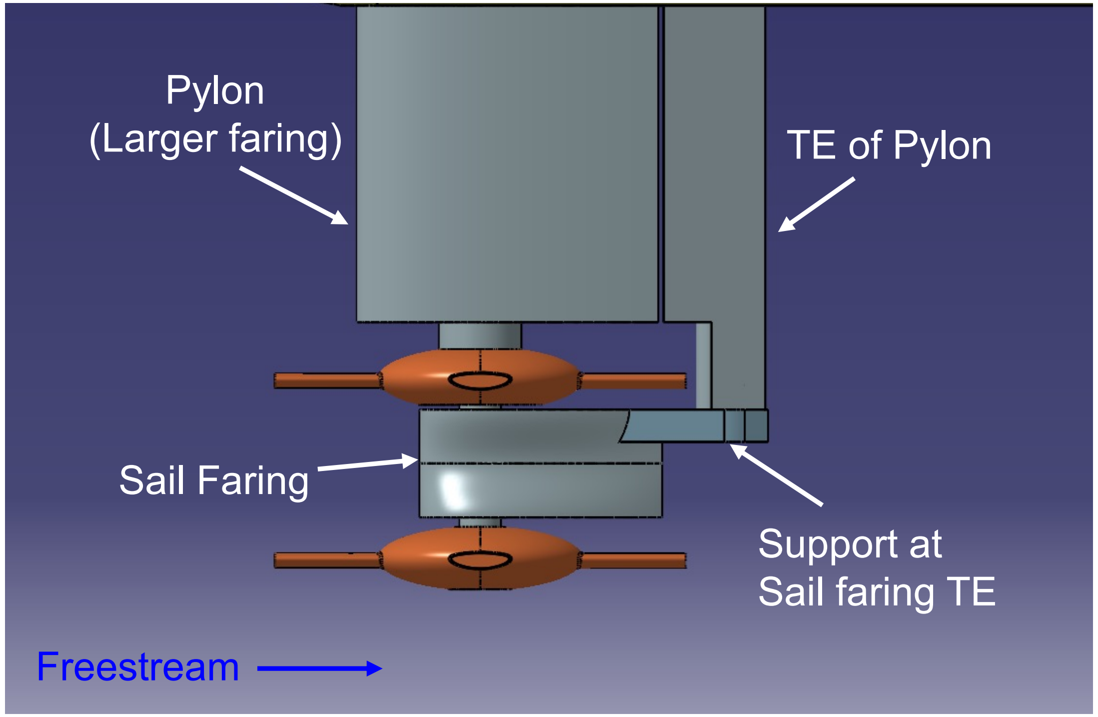
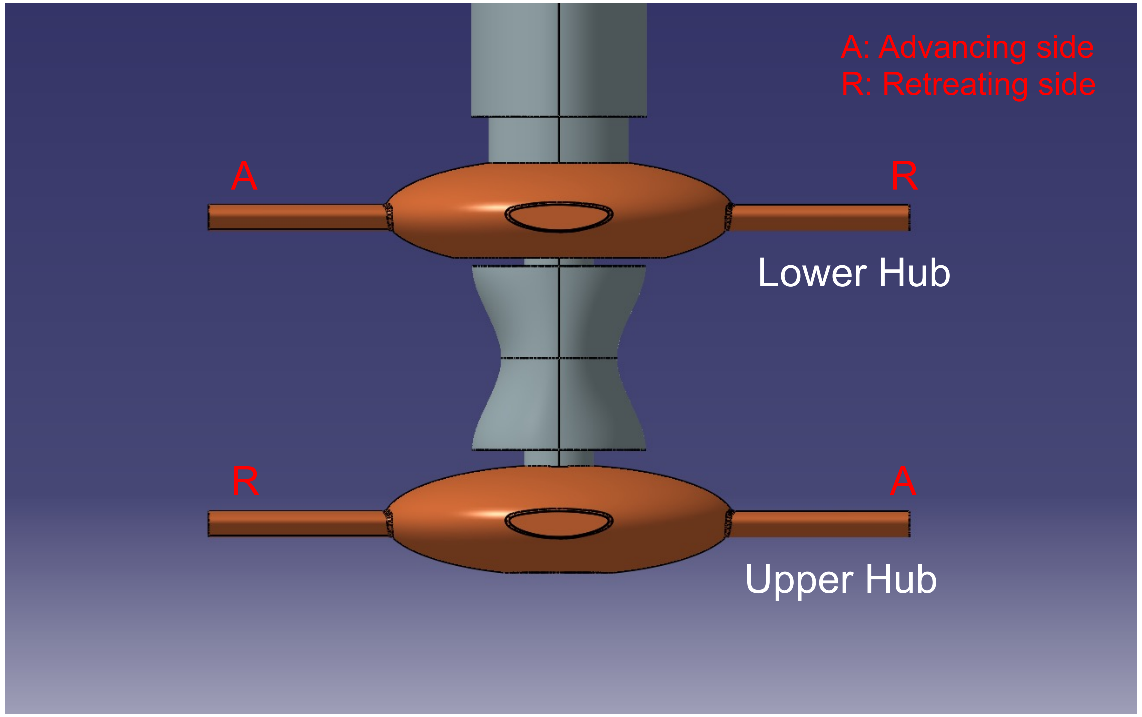


Image of SPIV planes

Geometry of the coaxial rotor hub



Sideview of coaxial hubs in the water tunnel

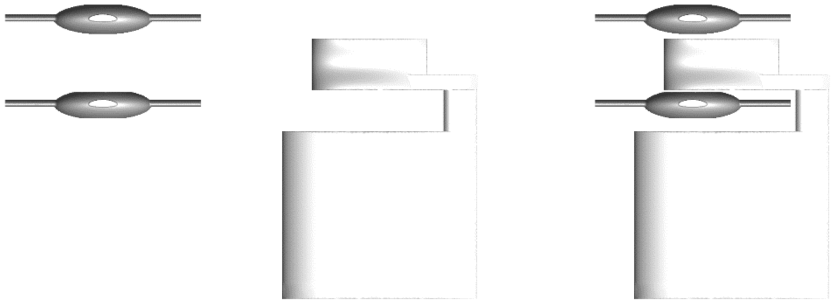


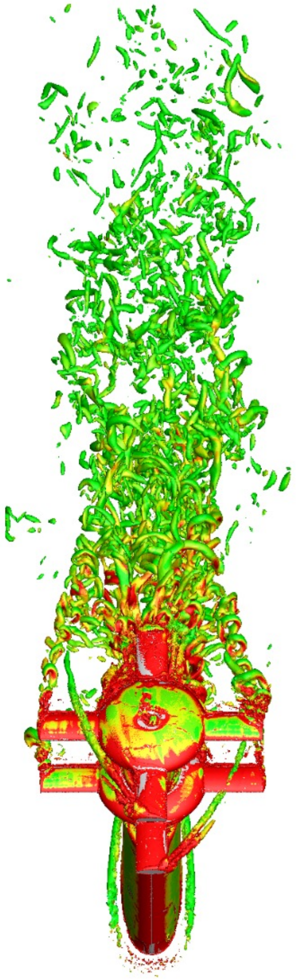
Near the hub. View from fore looking backward

- **Load measurement**
  - Hub drag: upper/lower hub and any exposed rotating shaft
  - Sail fairing: sail fairing, support at the sail fairing T.E. and T.E. of Pylon

Research Objective

- **Predict coaxial rotor hub drag and wake flow using an overset CFD framework, Mercury**
  - Multi-mesh paradigm, heterogeneous CPU-GPU framework
    - Unstructured mesh for complex geometries
    - Structured / Cartesian mesh for simpler geometries and wake capturing
- **Investigate the effects of each hub component on the drag and wake structures**
  - Perform component build-up analysis
    - Hub alone
    - Sail fairing and pylon alone
    - Hub with the sail fairing and pylon





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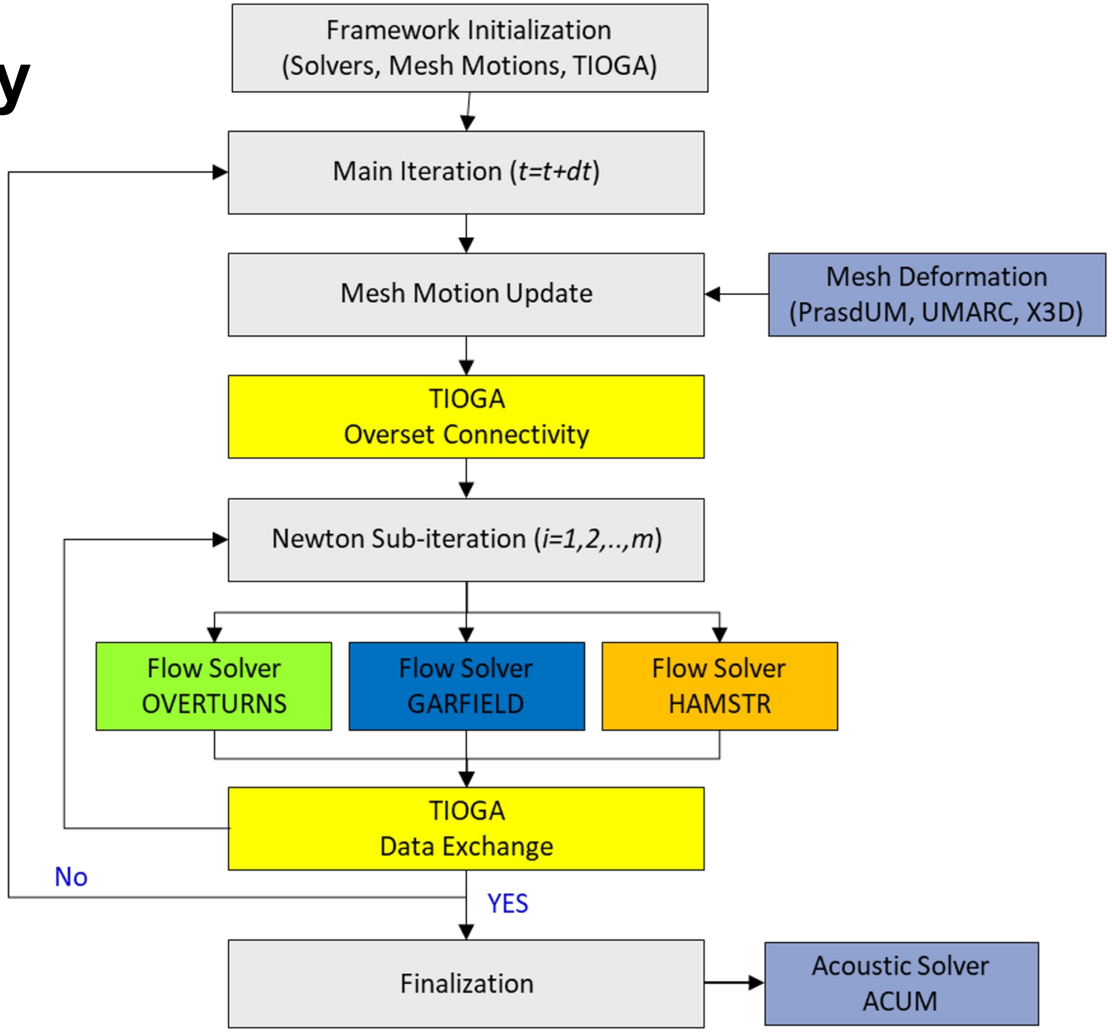
Computational Methodology

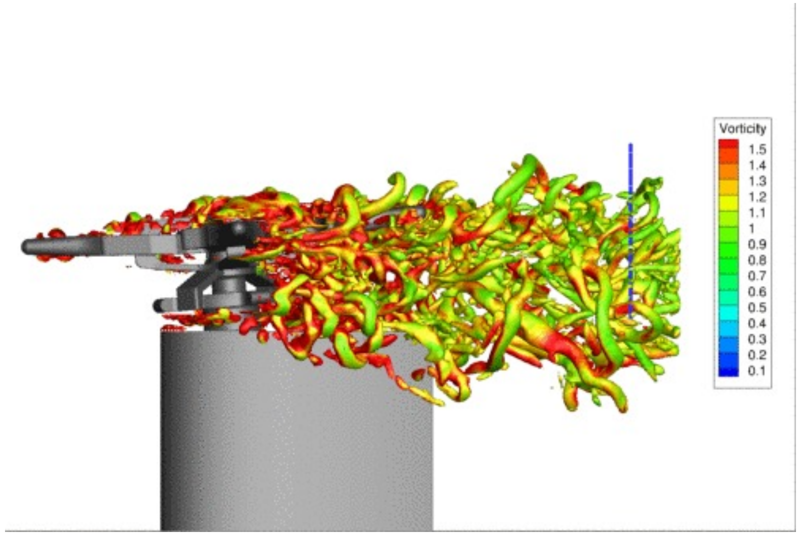
- **UMD Overset CFD Framework: Mercury**
  - Multi-mesh paradigm, heterogeneous CPU-GPU framework based on Python
  - Incorporates three flow solvers at UMD
    - OVERTURNS, HAMSTR, GARFIELD
  - TIOGA used to exchange data without file-IO, sharing CPU memory between codes
  - Light-weight and flexible
    - No expensive operations performed in Python, only function calls



Flowchart of Mercury framework

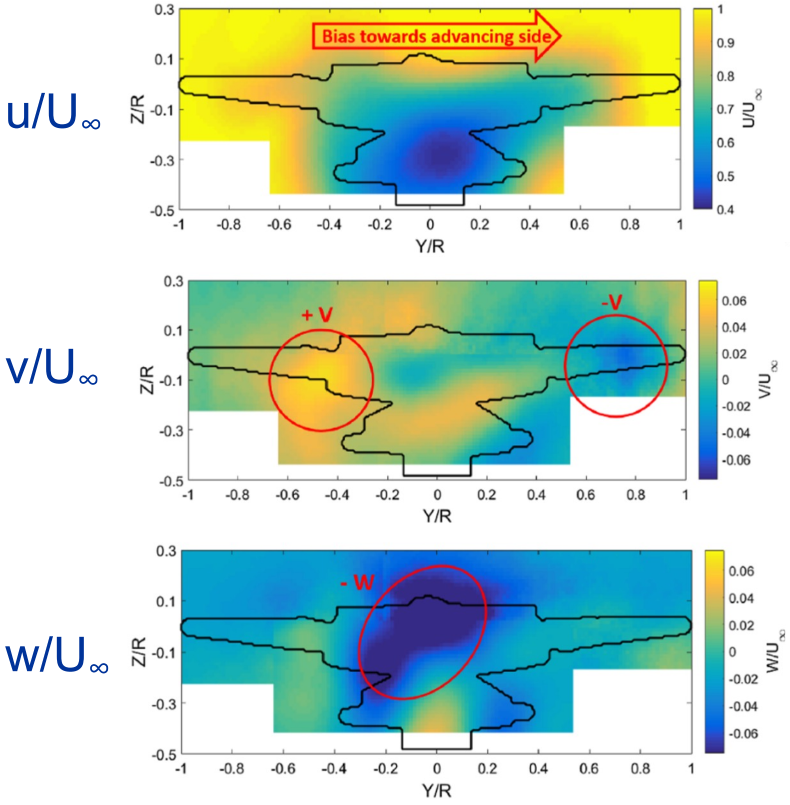
Hub Flow Prediction using Mercury Framework

- **3rd PSU Hub Flow Prediction Workshop: Test Case2**
  - Near-wake mean velocities at x/R_{hub}=2

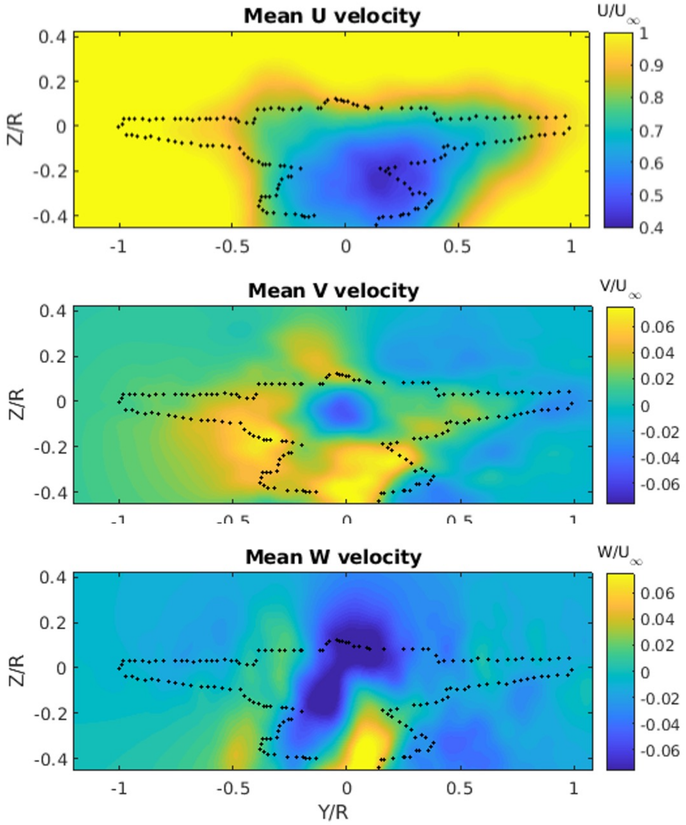


Iso-surface of Q criterion colored by vorticity

PSU SPIV Measurement



Mercury Framework

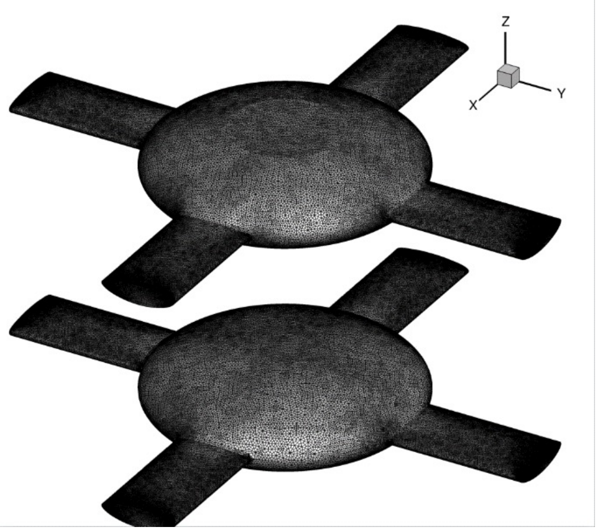


Mesh Generation for building up tests

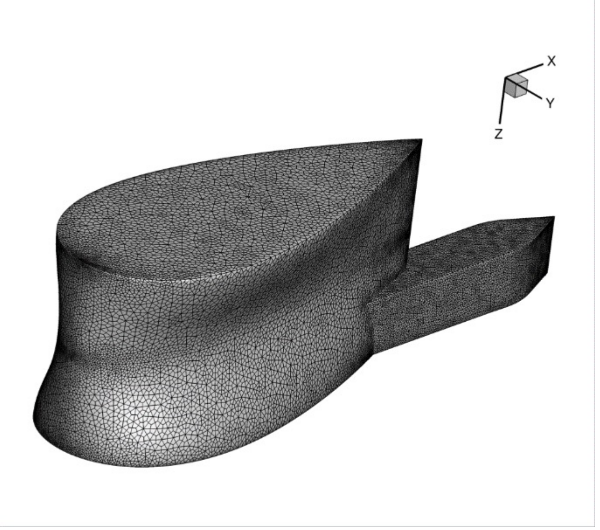
- **Hub and fairing: unstructured surface / volume grid generation from CAD in Pointwise**
- **Surface node points are flushed using RBF**
- **Coaxial hub shafts are not modelled**
- **Gaps and holes on the hubs and fairings are filled**
- **Viscous wall BC at the hubs and fairings**

Geometry	Node	Element	Topology
Upper Hub	10.2M	8.1M	Unstructured
Lower Hub	10.1M	8.1M	Unstructured
Sail Fairing	3.3M	2.6M	Unstructured
Total Fairing	7.2M	5.7M	Unstructured

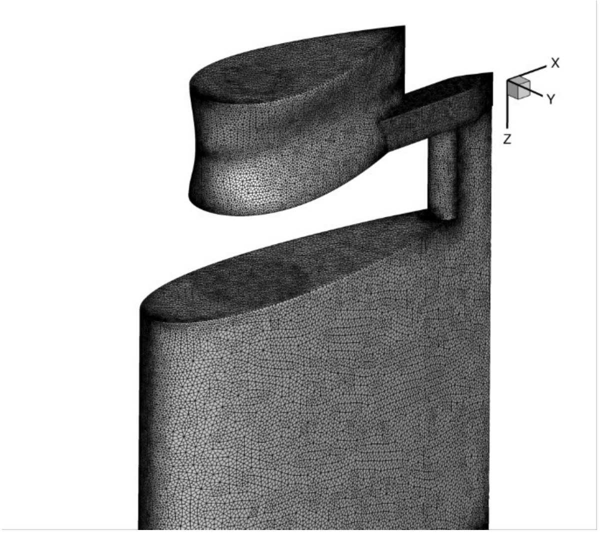
Number of grid points: near-body meshes



Surface mesh of isolated hubs



Surface mesh of Sail Fairing

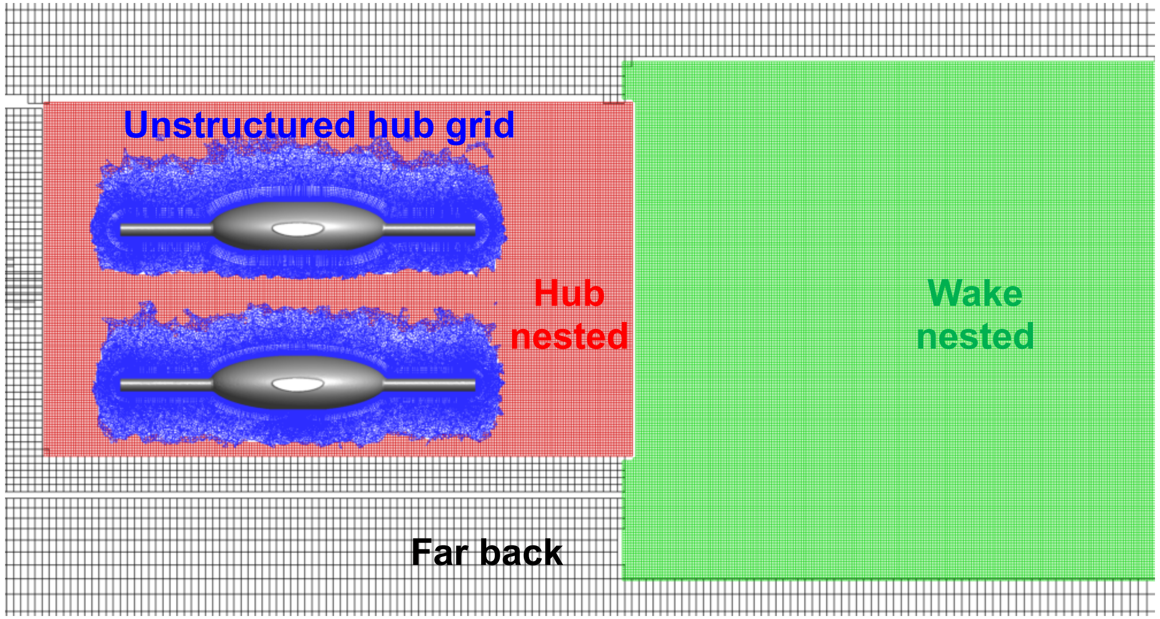


Surface mesh of Total Fairing

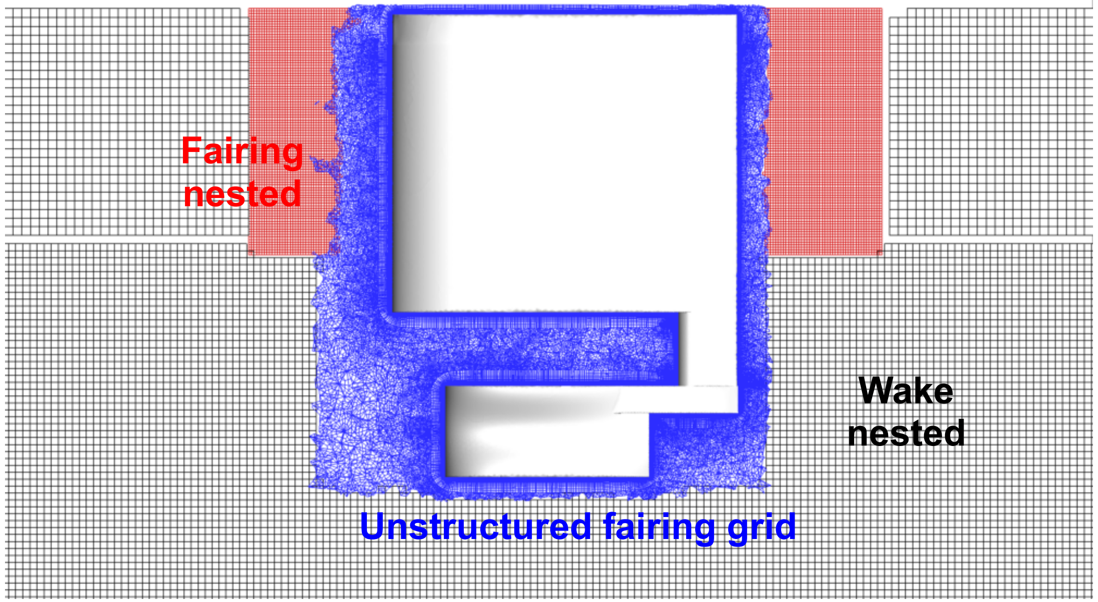
Mesh Generation for building up tests

- **Unstructured volume grid generations**
  - Initial wall normal spacing 1×10^{-4} inches from surface ($\approx y^+ = 1$)
  - Wall normal stretching ratio of 1.17 for 38 viscous grid layers
- **Overset setting of near-body and Cartesian Wake meshes**
  - Equal spaced grid at Hub nested and Wake nested meshes as $0.015R_{hub}$
  - Overset connectivity is only required between unstructured hub grid and Hub nested domains

Near-body overset setting of isolated hub simulation

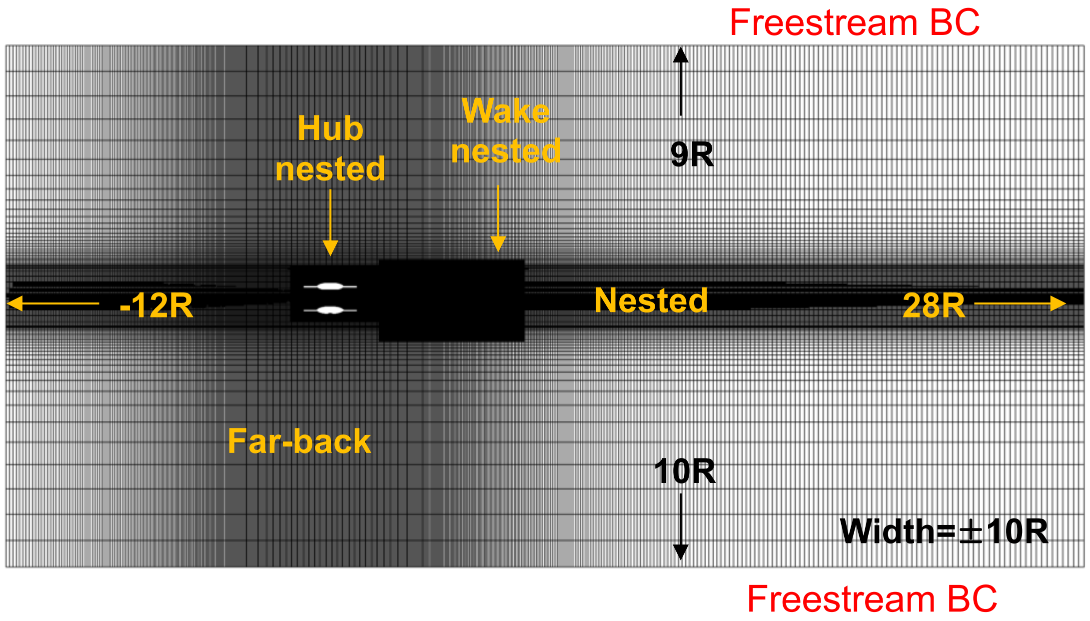


Near-body overset setting of isolated fairing simulation



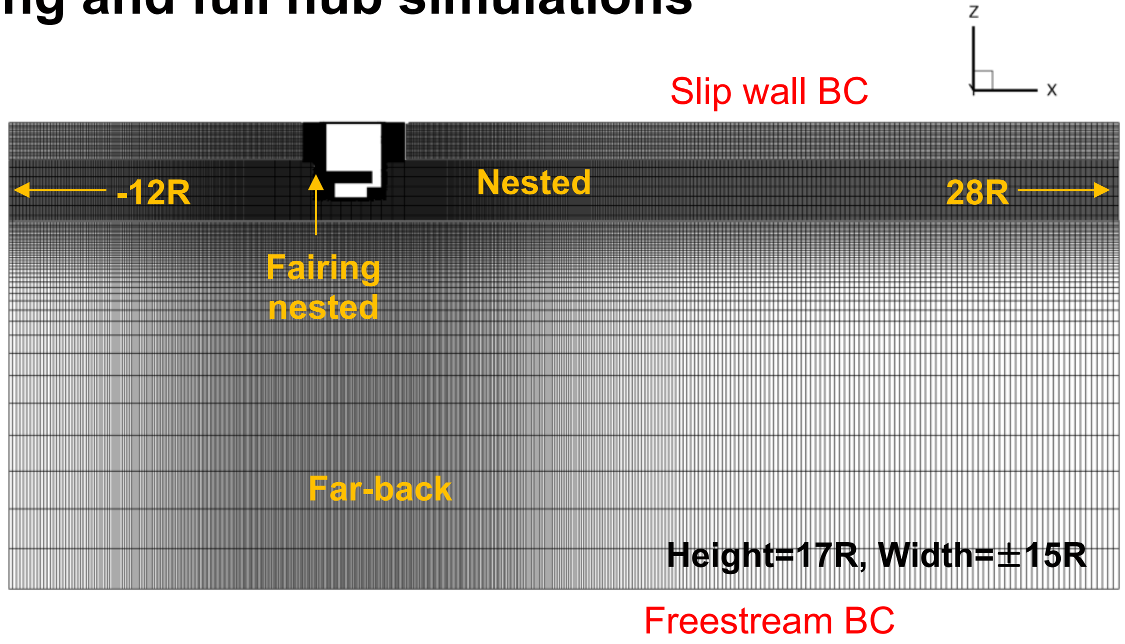
Mesh Generation for building up tests

- **Background / wake meshes: Structured / Cartesian meshes using an in-house meshgen**
- **Freestream BC at the far-field boundaries and the inlet and outlet**
- **Inviscid wall BC at the bottom plane for the fairing and full hub simulations**



	Node	Topology
Hub nested	5.7M	Cartesian
Wake nested	13.1M	Cartesian
Nested	2.3M	Cartesian
Far-back	5.9M	Cartesian

Nested and background meshes for the hub alone simulations

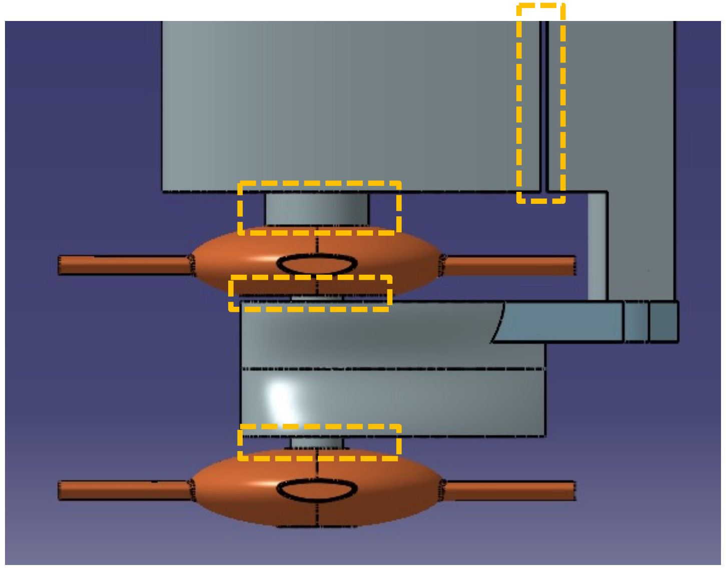


	Node	Topology
Fairing nested	2.0M	Cartesian
Nested	2.3M	Cartesian
Far-back	6.1M	Cartesian

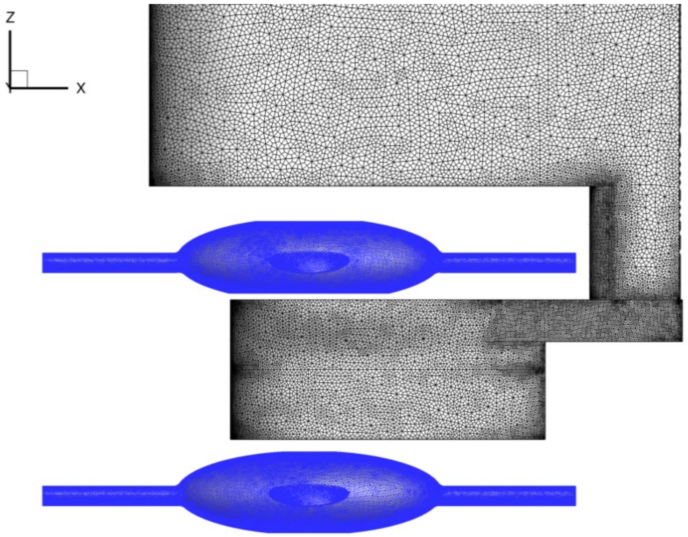
Nested and background meshes for the fairing alone simulations

Mesh Generation for complete model

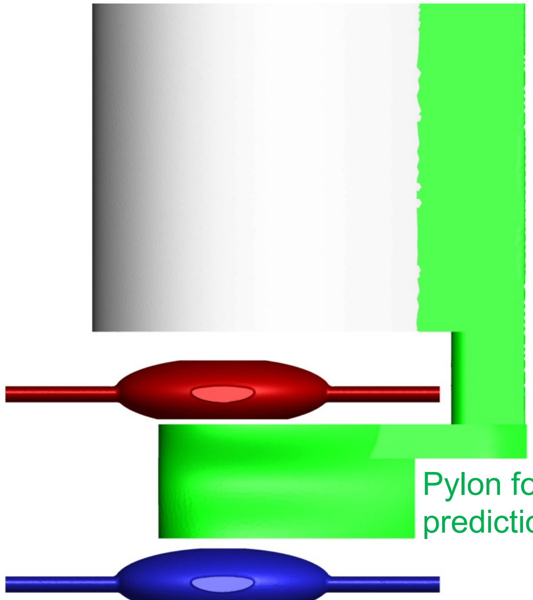
- Complete model by combining isolated hubs and fairing models in free-air condition
- Coaxial hub shafts are not modelled
- Gaps and holes on the hubs and fairings are filled
- Upper plate of the large fairing is not modelled
- Pylon for drag prediction is separated through a virtual boundaries



Original CAD file



Hub and fairing without shaft



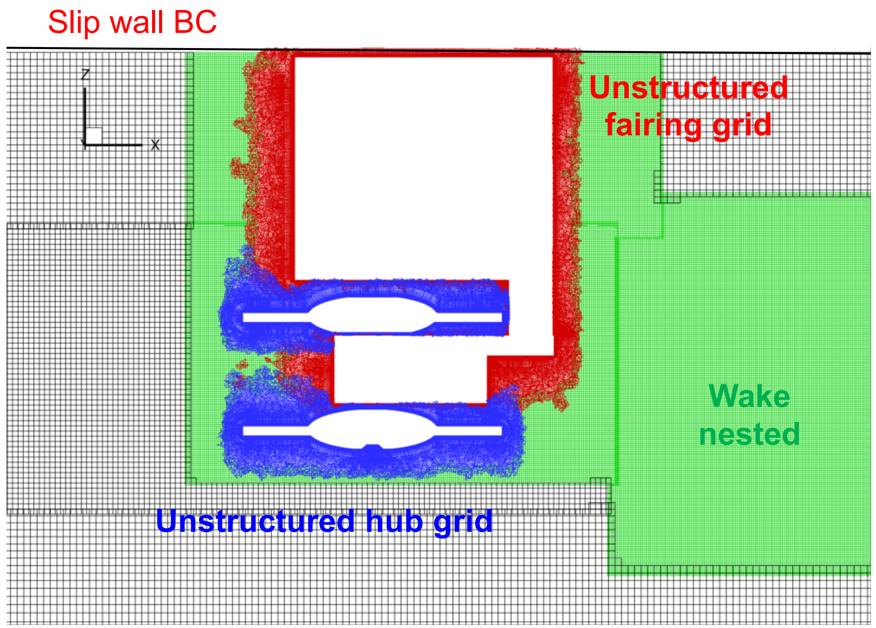
Hub and fairing without shaft

Mesh Generation for complete model

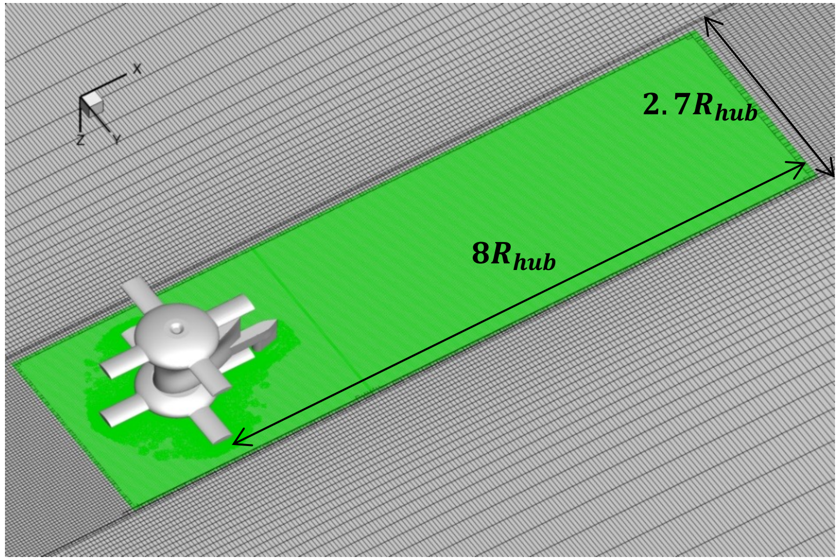
- Same far-field domain size with the isolated fairing simulation
- Added a hub nested mesh until $8R_{hub}$ for wake profile predictions at 3 and $7R_{hub}$ downstream from the hub center
- Near-body domain: 27.5 M nodes
- Off-body domain: 31.4 M nodes

	Node	Topology
Hub nested	5.7M	Cartesian
Fairing nested	2.0M	Cartesian
Wake nested	15.3M	Cartesian
Nested	2.3M	Cartesian
Far-back	6.1M	Cartesian

Nested and background meshes for complete simulations



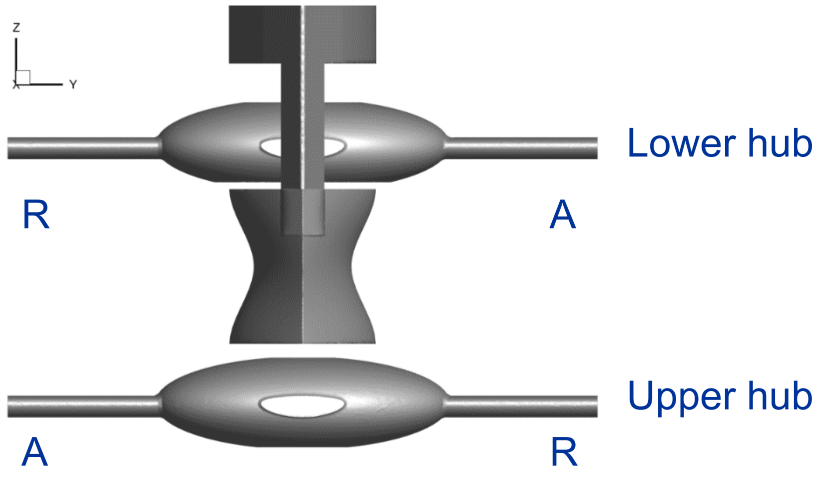
Near-body overset setting of the complete simulation



Hub nested mesh for wake capturing

Simulation Setup

- **Compressible flow solver based on the perfect gas**
  - Match the experimental Reynolds number and advance ratio
  - Increase the freestream Mach & adjust hub RPM
- **CFD Flow conditions**
  - Reynolds number: 1.13×10^6
  - Freestream Mach number: 0.2
  - Hub tip Mach number: 0.12 ($R_{hub} / R_{rotor} = 0.15$)
  - Advance ratio: 0.25
  - Rotor tip Mach number: 0.8
- **Flow Solver Setup**
  - HAMSTR (near-body) / GARFIELD (off-body)
    - HAMSTR: 2nd order reconstruction using linear least square
    - GARFIELD: 5th order WENO
  - 0.5 ° time step, BDF2 with 15 sub-iterations
  - Spalart-Allmaras Delayed Detached Eddy Simulation



Orientation of rotation
View from aft looking forward

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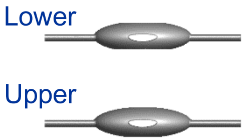
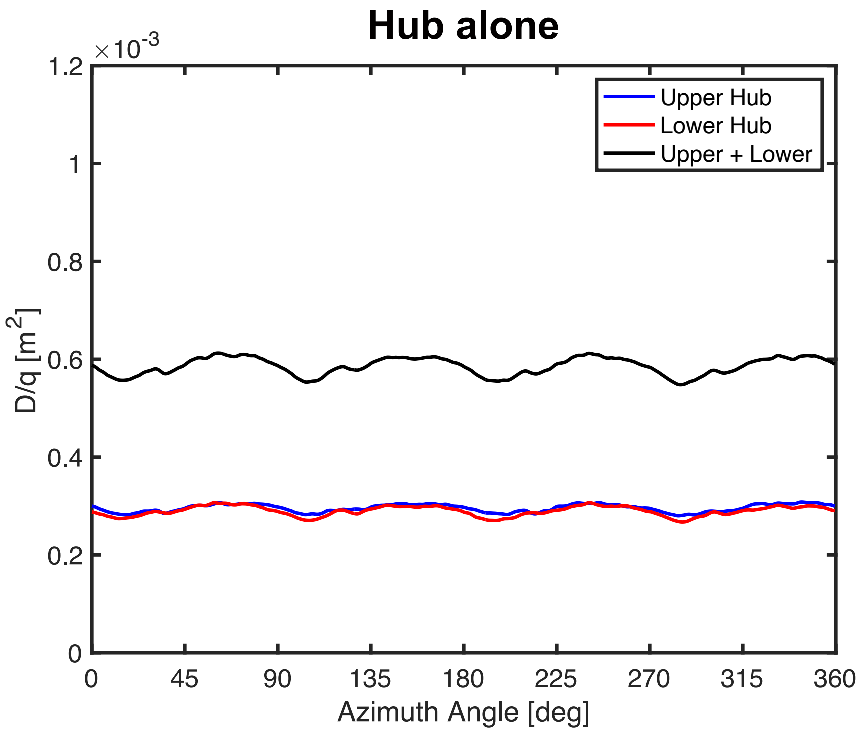
Hub drag: phase-averaged drag (6 revs)

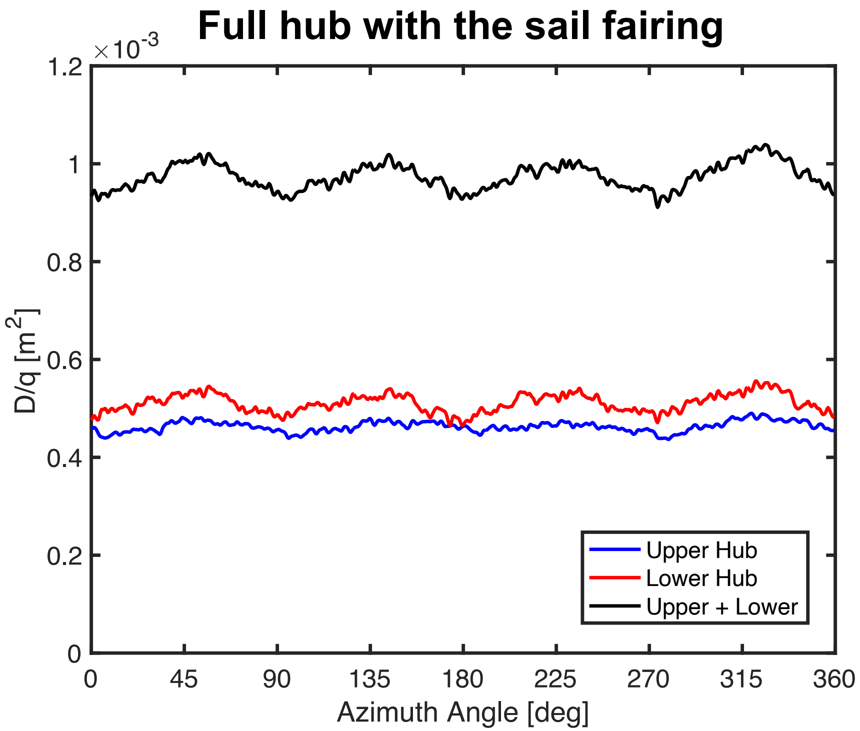
- **Hub alone: drag difference is about 2%**
- **Full hub: both hubs experience drag increase**
  - Upper hub by 56.4%, lower hub by 76.2%, total drag by 65.5%
  - Wake interaction with the sail fairing clearly affects the hub drag

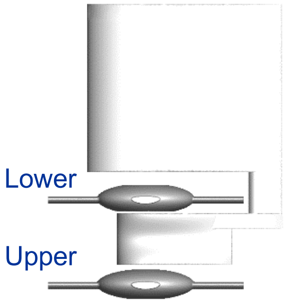
	Hub alone	Full hub	Increase [%]
Upper hub	0.000296	0.000463	56.42
Lower hub	0.000290	0.000511	76.21
Total	0.000585	0.000974	66.50

Time averaged D/q [m²]



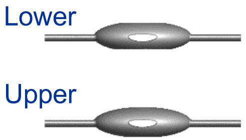


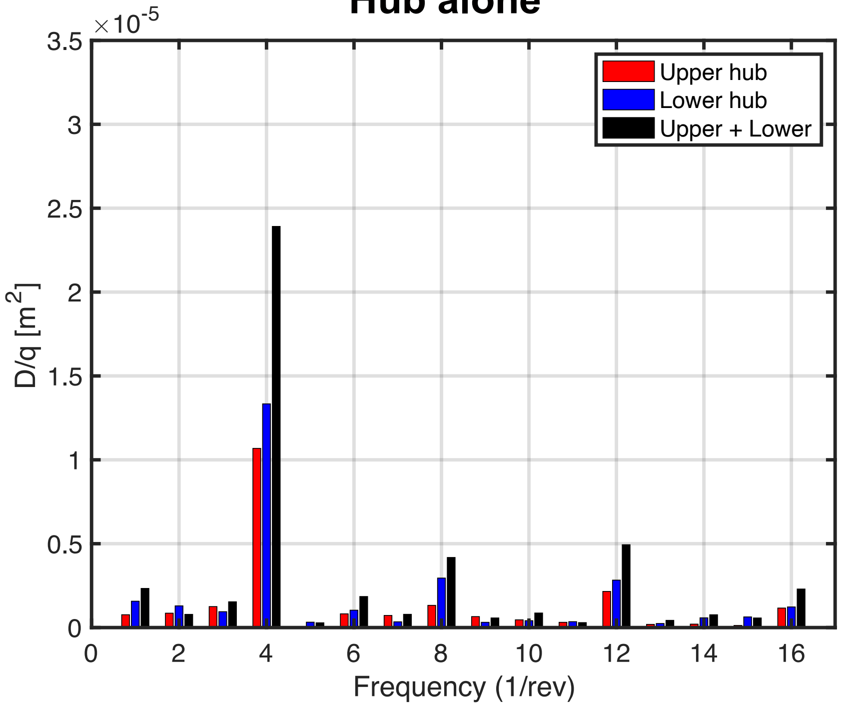


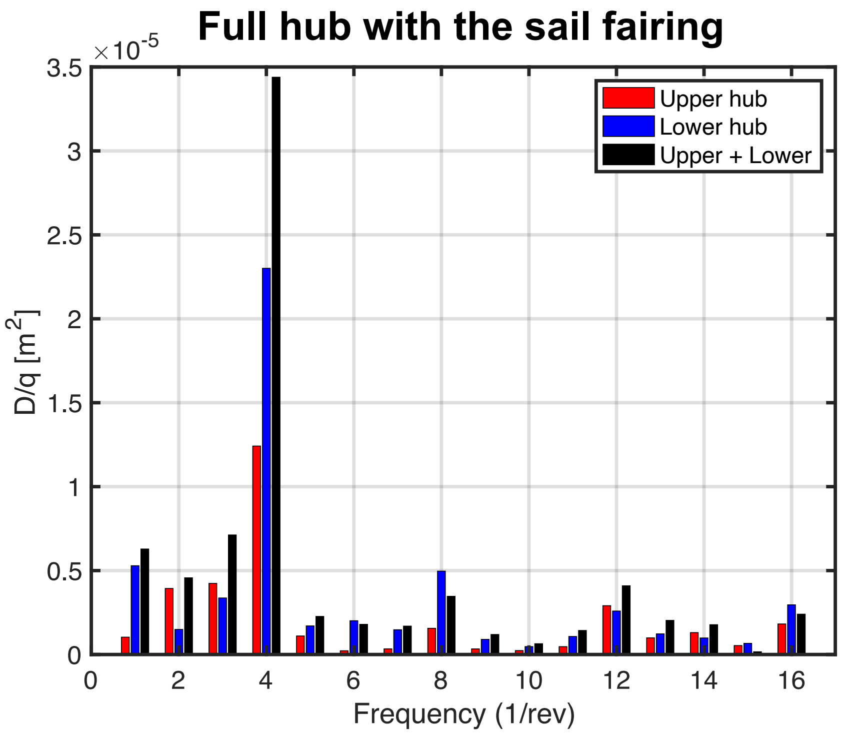


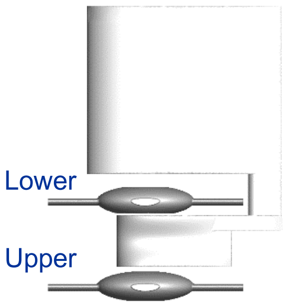
Hub drag: harmonics

- Hub alone: strong 4/rev for the both hubs with some 8/rev and 12/rev components
- Full hub: lower hub experiences more 4/rev than that in the hub alone case

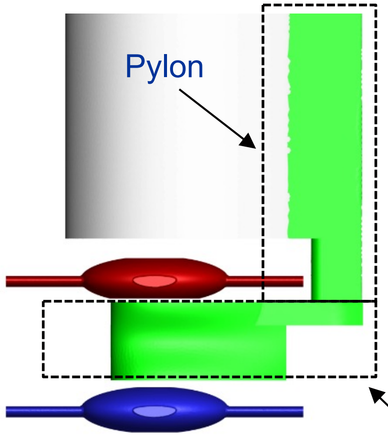




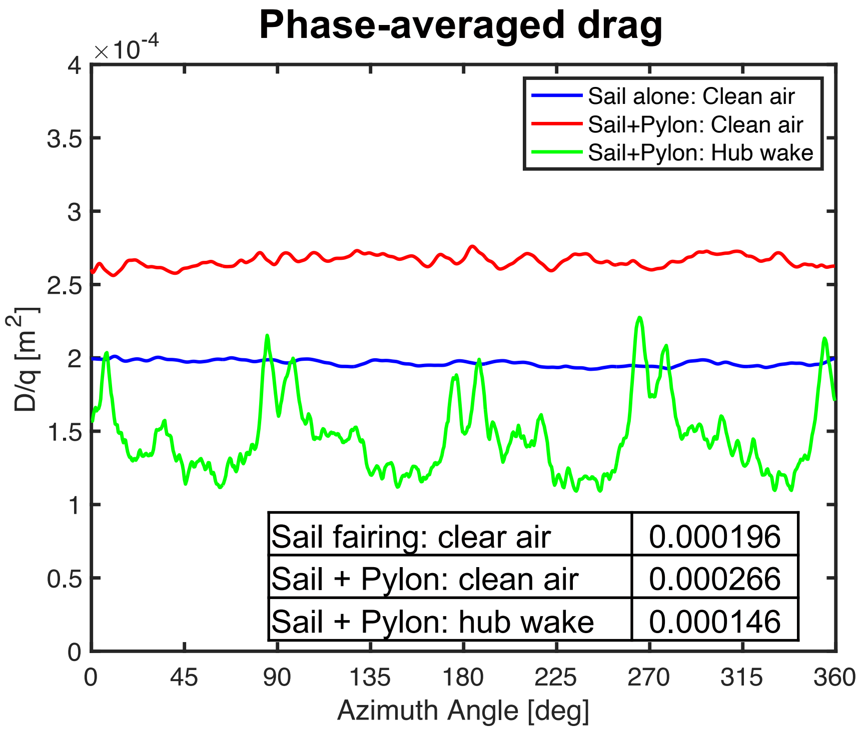


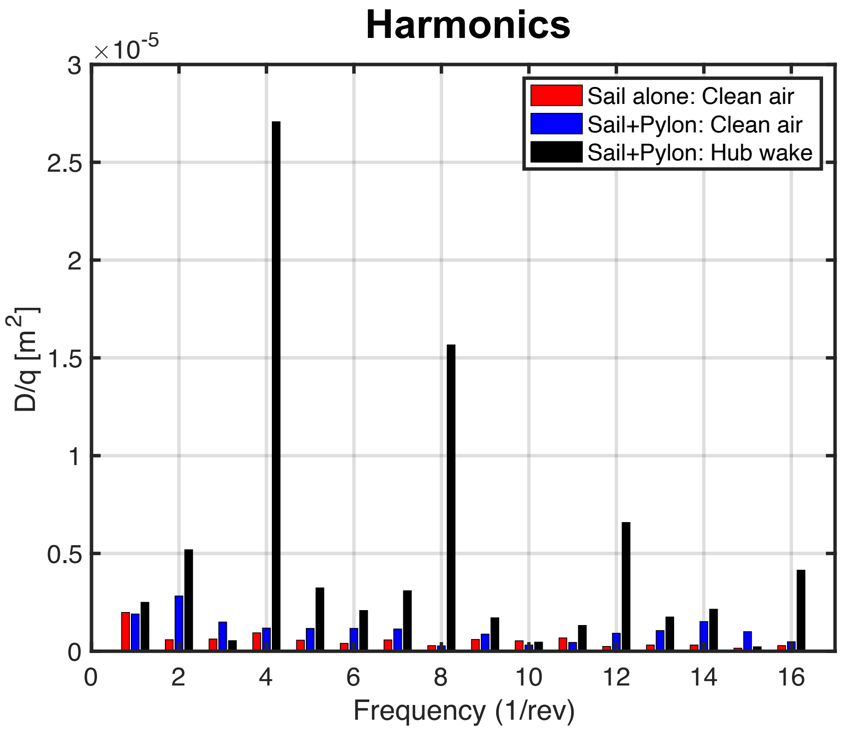


Sail fairing drag and harmonics



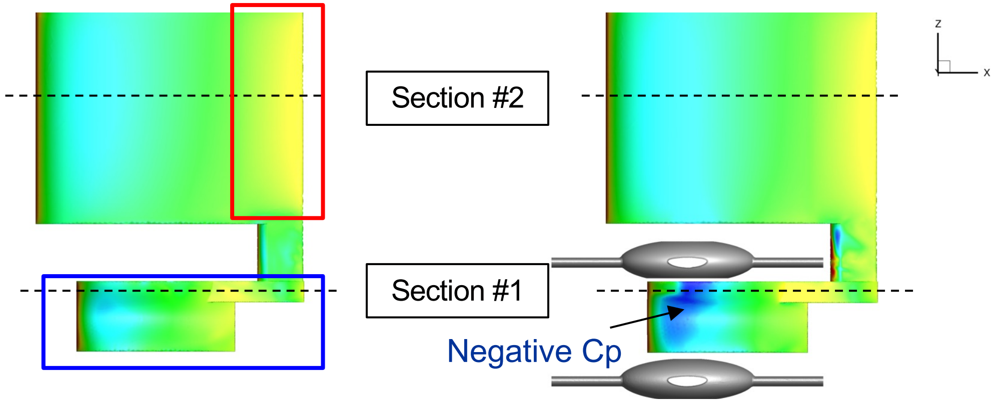
- **Pylon increases the drag by 35.71% from the sail fairing alone**
- **Hub wake case shows 45.11% less drag than the clean air**
  - Aerodynamic interaction with the hub wake reduces the drag of the sail+pylon
- **Hub wake results in high 4/rev, 8/rev, and 12/rev components**



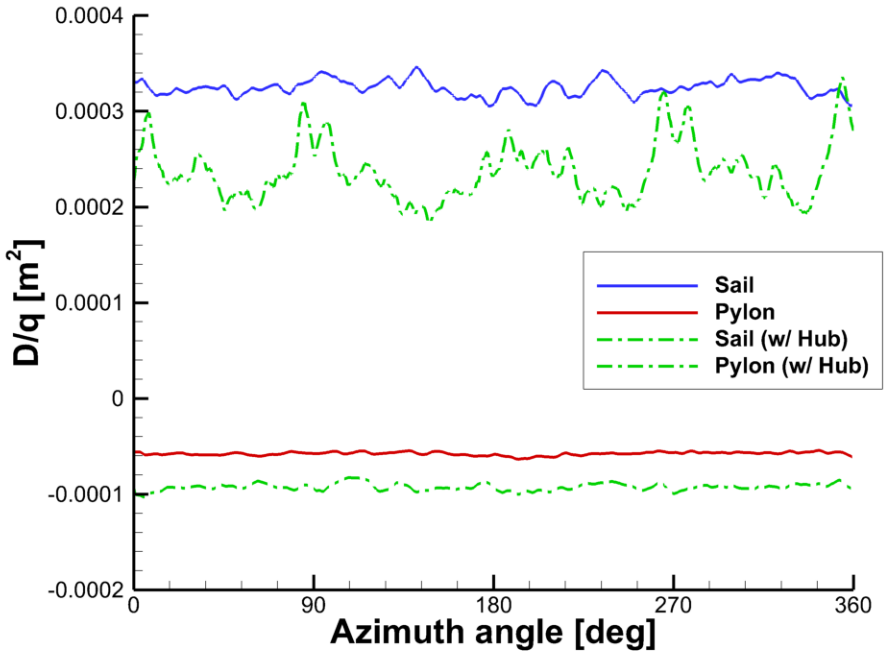


Drag breakdown of Sail fairing and Pylon

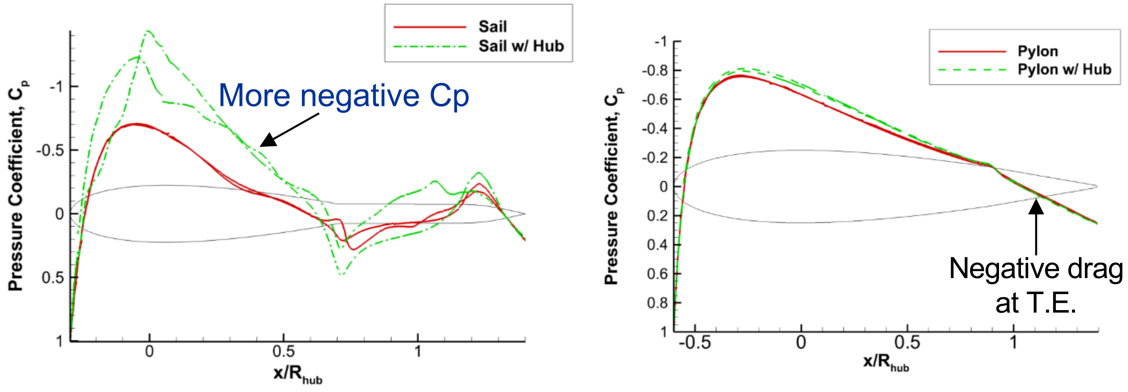
- **Drag reduced at both Sail fairing and Pylon with the hub**
- **Drag reduction at Sail fairing w/ hub is due to more negative pressures near L.E.**
- **Positive Cp near the T.E. of the Pylon results in negative drag**



Instantaneous surface pressures w/o and w/ hub



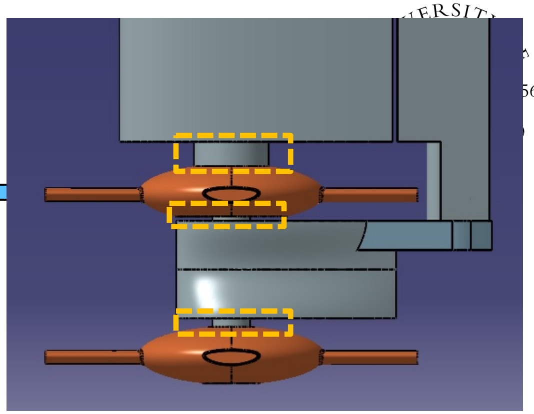
Phase-averaged sail and pylon drag w/ and w/o the hub



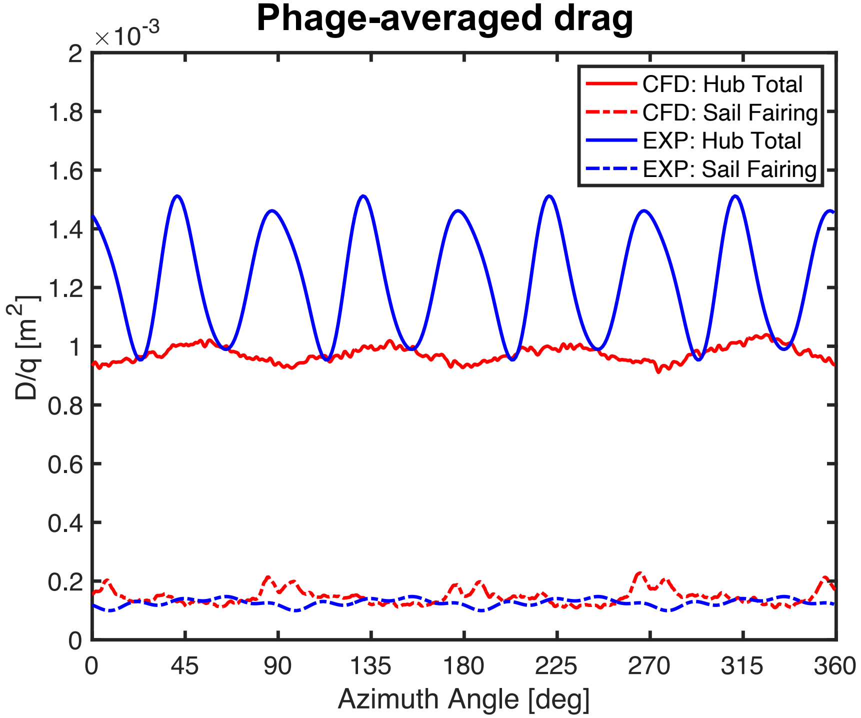
Comparison of surface pressure distributions at Section 1 and 2

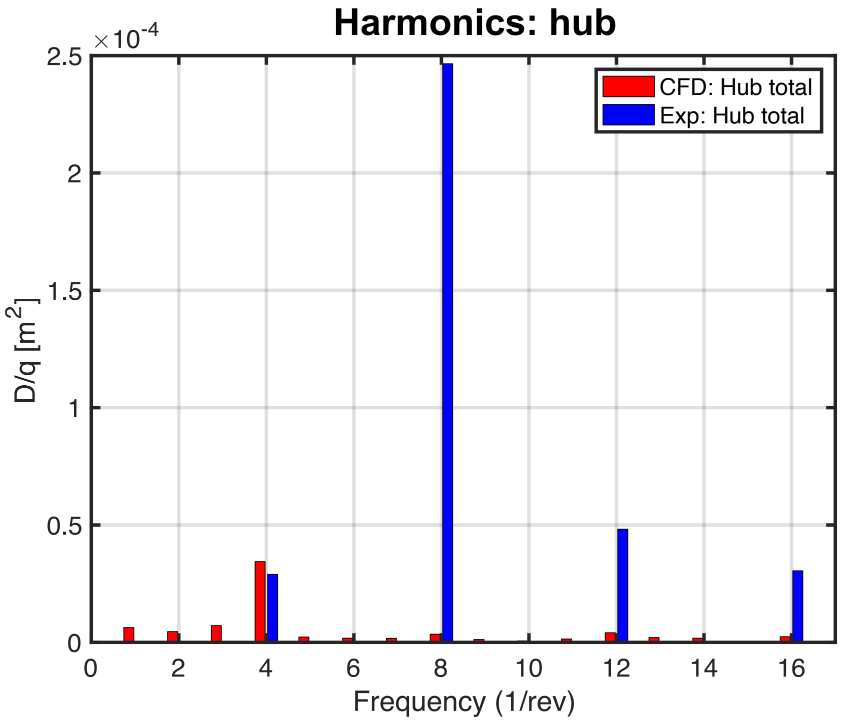
Comparisons with the exp. data: hub

- **CFD predicts 21% less hub drag than the experiment**
  - Hub shafts and water tunnel are not modelled in the CFD simulations
- **Experiment data show much higher 8/rev than the CFD prediction**



Original CAD file

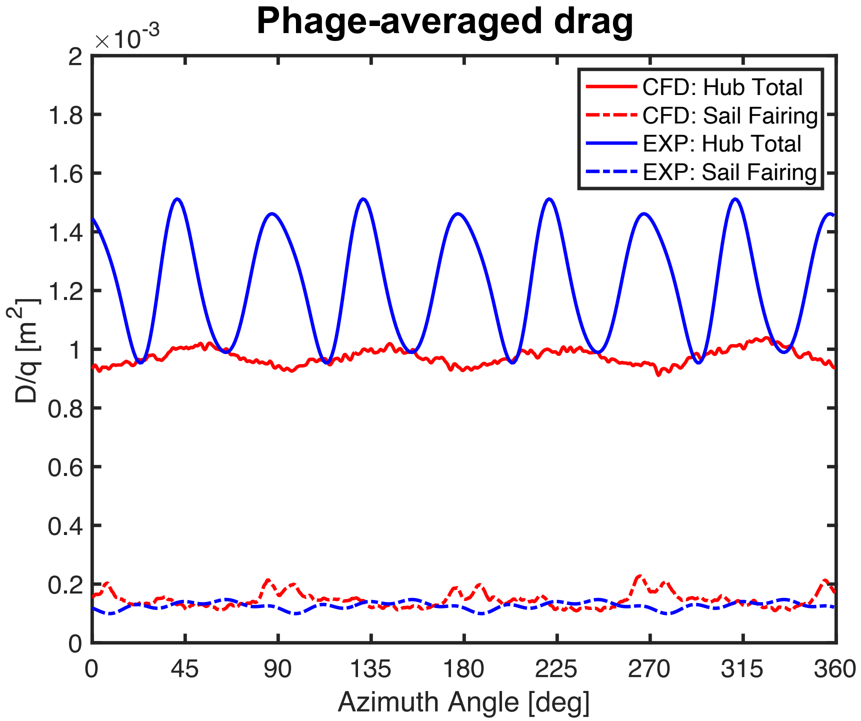


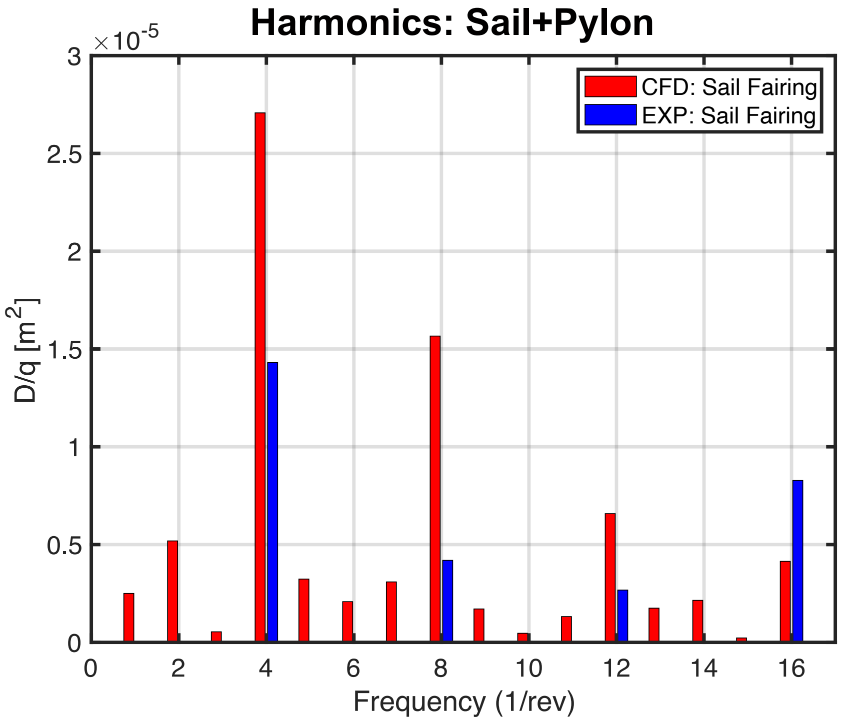


	CFD	Exp	Error [%]
Hub Total	0.000974	0.001228	-20.68
Sail Fairing	0.000146	0.000127	14.96

Comparisons with the exp. data: sail fairing and pylon

- **CFD over-predicts sail and pylon drag by 15%**
  - Hub shafts and water tunnel are not modelled in the CFD simulations
- **CFD result shows more harmonics than the experiment: higher 4/rev and 8/rev**



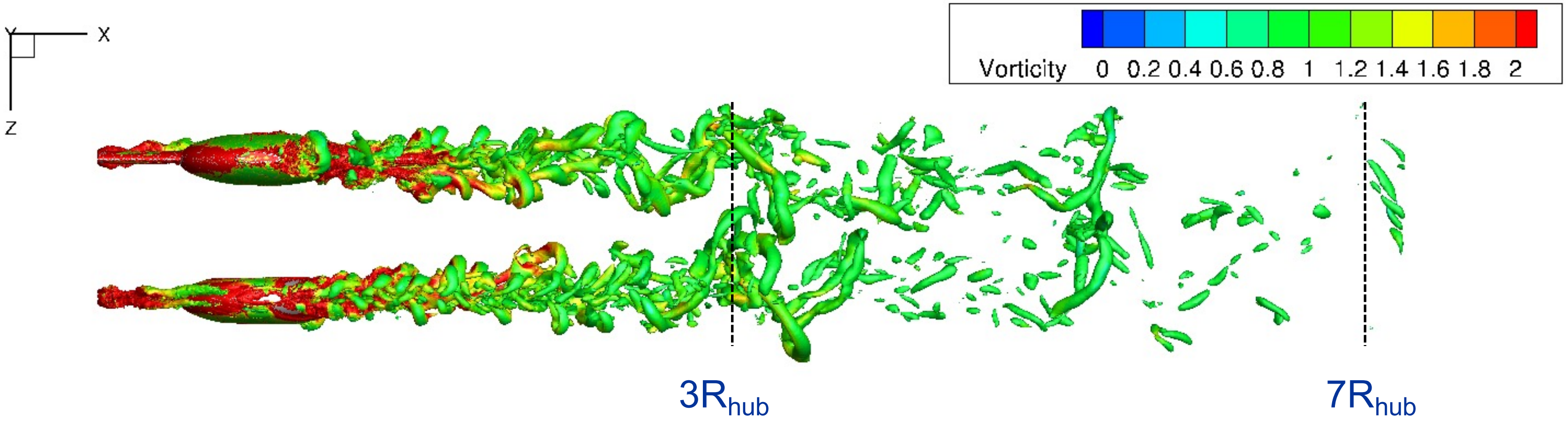


	CFD	Exp	Error [%]
Hub Total	0.000974	0.001228	-20.68
Sail Fairing	0.000146	0.000127	14.96

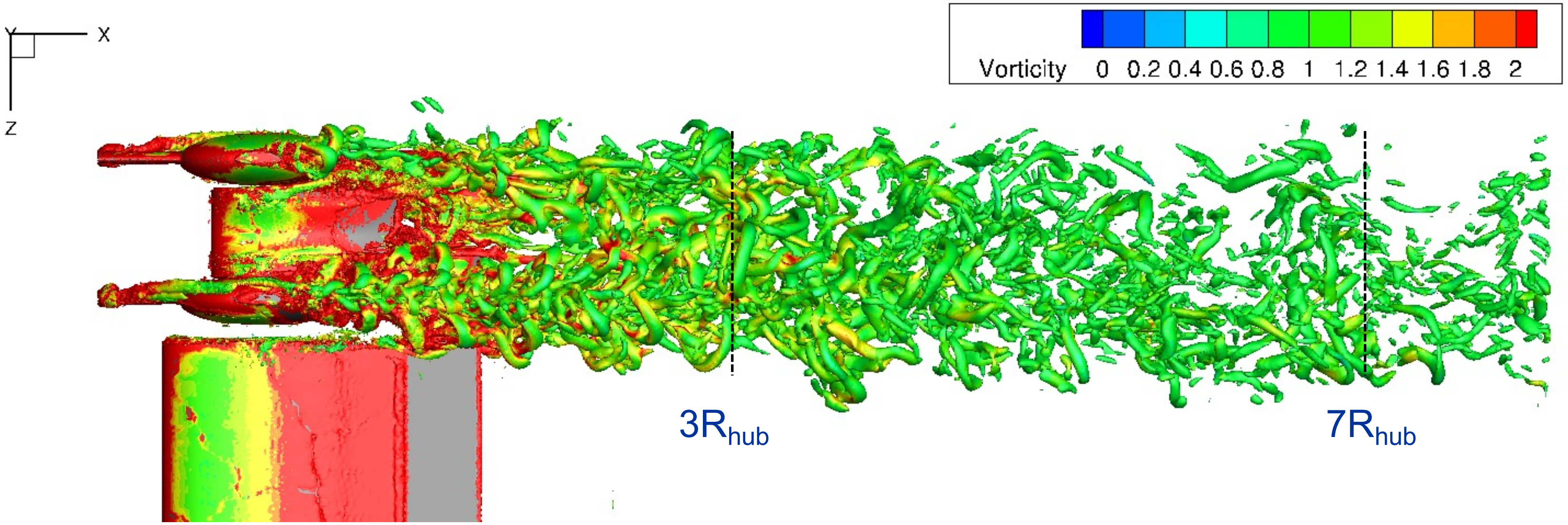
Comparison of wake structures

- **Iso-surface of Q-criterion colored by vorticity magnitude**

Hub alone

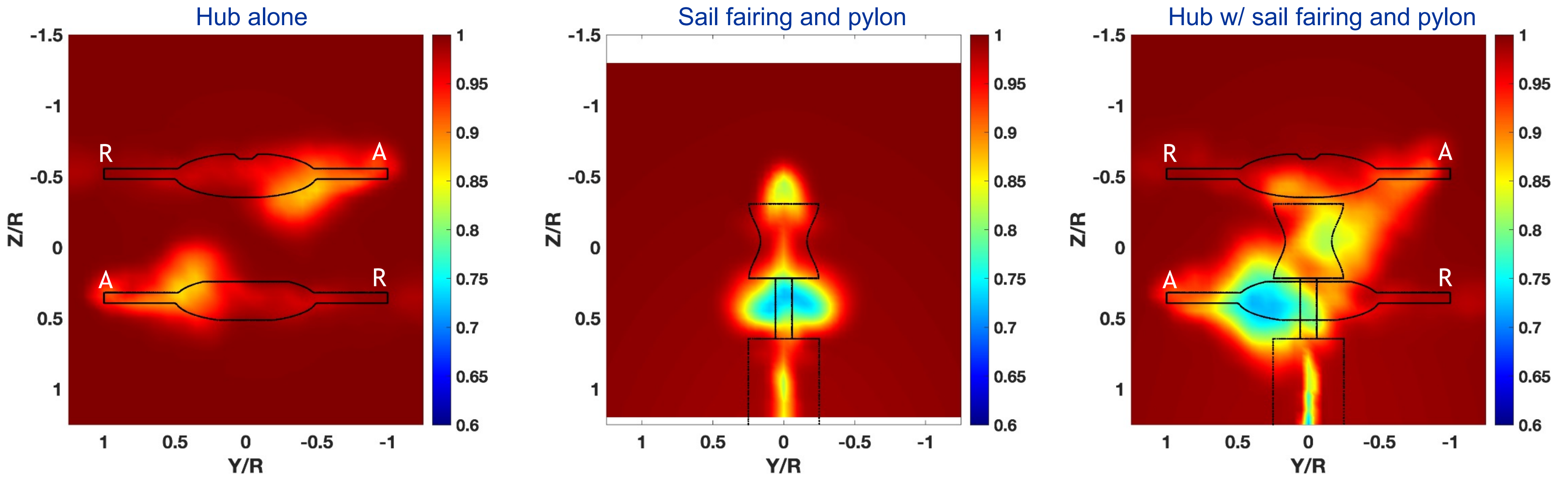


Hub w/ sail fairing and pylon



Mean wake profiles at $x/R_{hub} = 3$

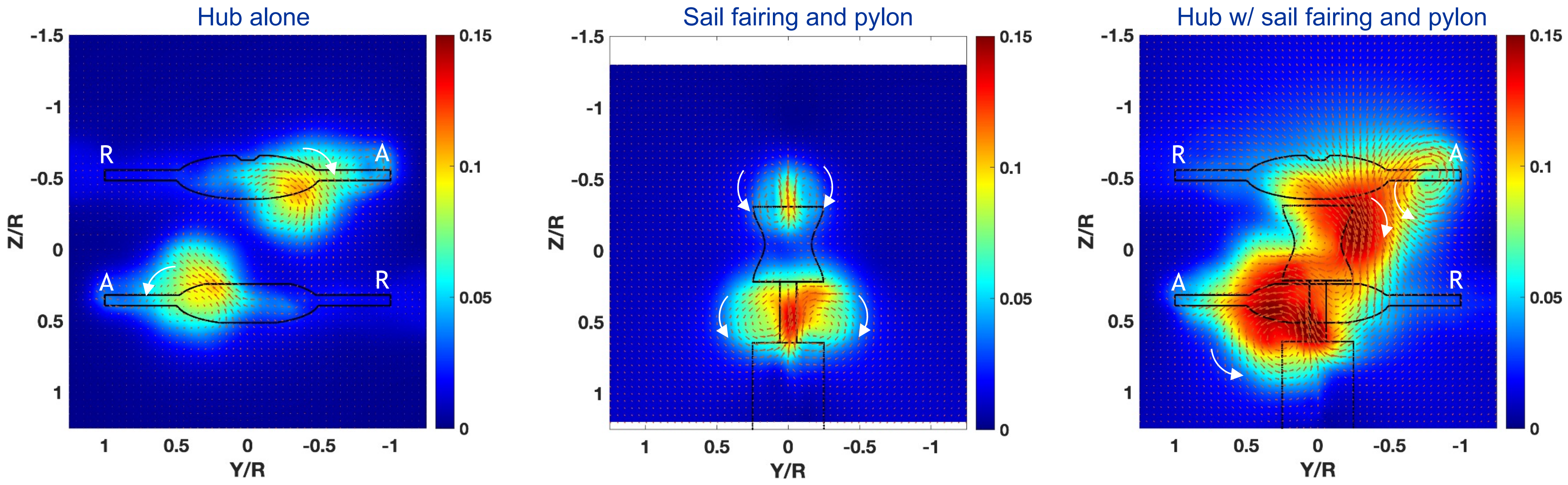
- **Streamwise velocity, u/U_∞**



- **Hub alone: streamwise wake deficit near the root of the advancing side arm**
- **Sail fairing and Pylon: wake deficit behind of the support of the sail fairing**
- **Hub with the sail fairing and pylon: more wake deficits near the advancing side of the lower hub**

Mean wake profiles at x/R_{hub} = 3

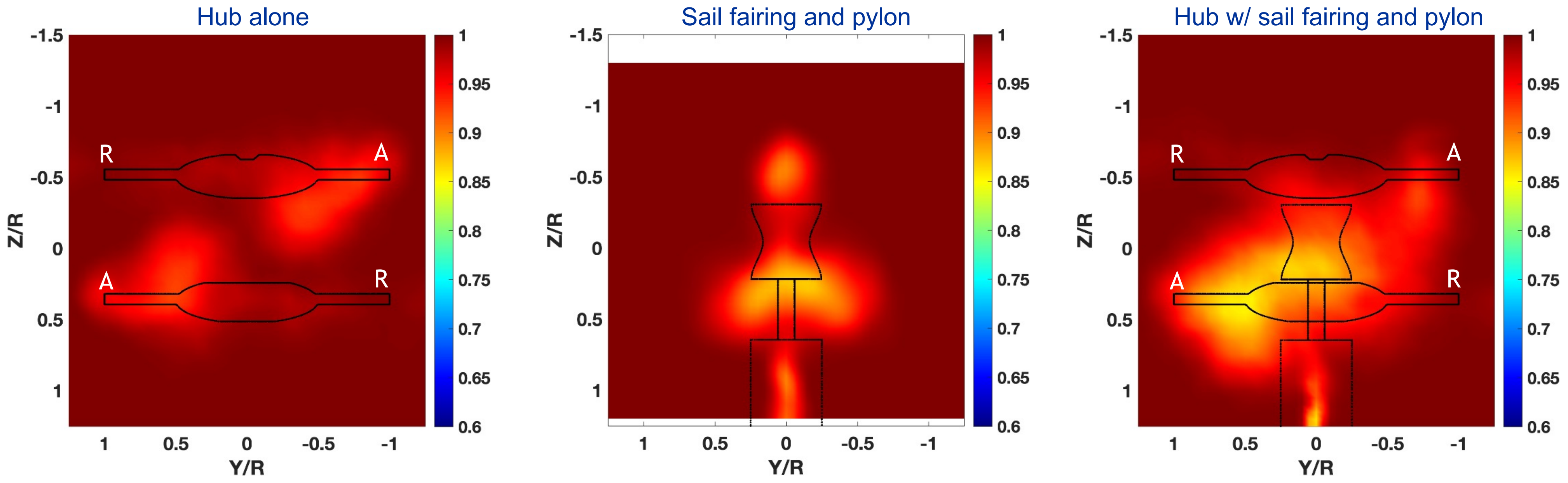
- **In-plane velocity, $\sqrt{v^2 + w^2}/U_\infty$**



- **Trend of the in-plane velocity is similar to that of the streamwise velocity**
- **Overall, aerodynamic interaction with the sail fairing and pylon makes wake structures biased**

Mean wake profiles at $x/R_{hub} = 7$

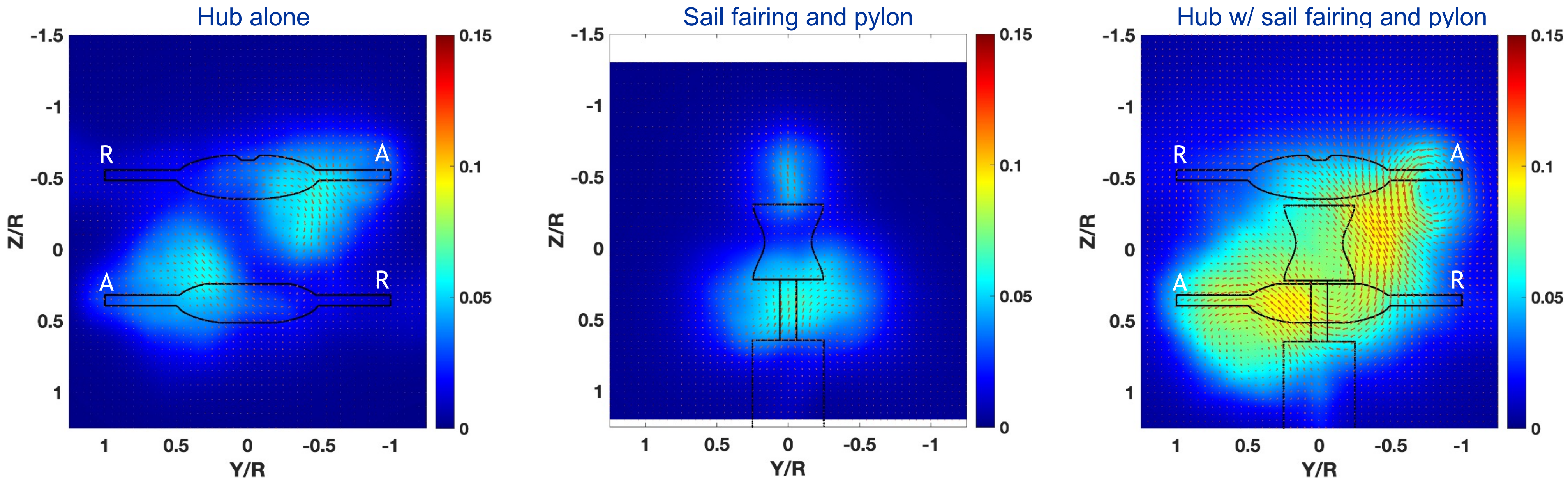
- **Streamwise velocity, u/U_∞**



- **Similar trends with the results at x/R_{hub}=3 but more dissipated**
- **Further analysis will be performed along with comparisons against the experimental data**

Mean wake profiles at x/R_{hub} = 7

- **In-plane velocity, $\sqrt{v^2 + w^2}/U_\infty$**



- **Similar trends with the results at x/R_{hub}=3 but more dissipated**
- **Further analysis will be performed along with comparisons against the experimental data**

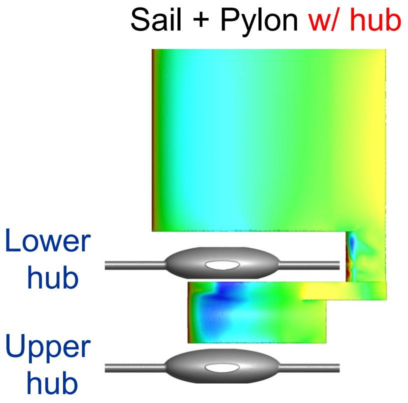
Outline

- Introduction
- Computational Methodology
  - Mercury framework
  - Mesh generation
  - Simulation setup
- Results and Discussion
  - Hub drag and harmonics
  - Mean wake profiles at SPIV plane, x/R_{hub} = 2 and 6
- **Concluding Remarks**

Concluding Remarks

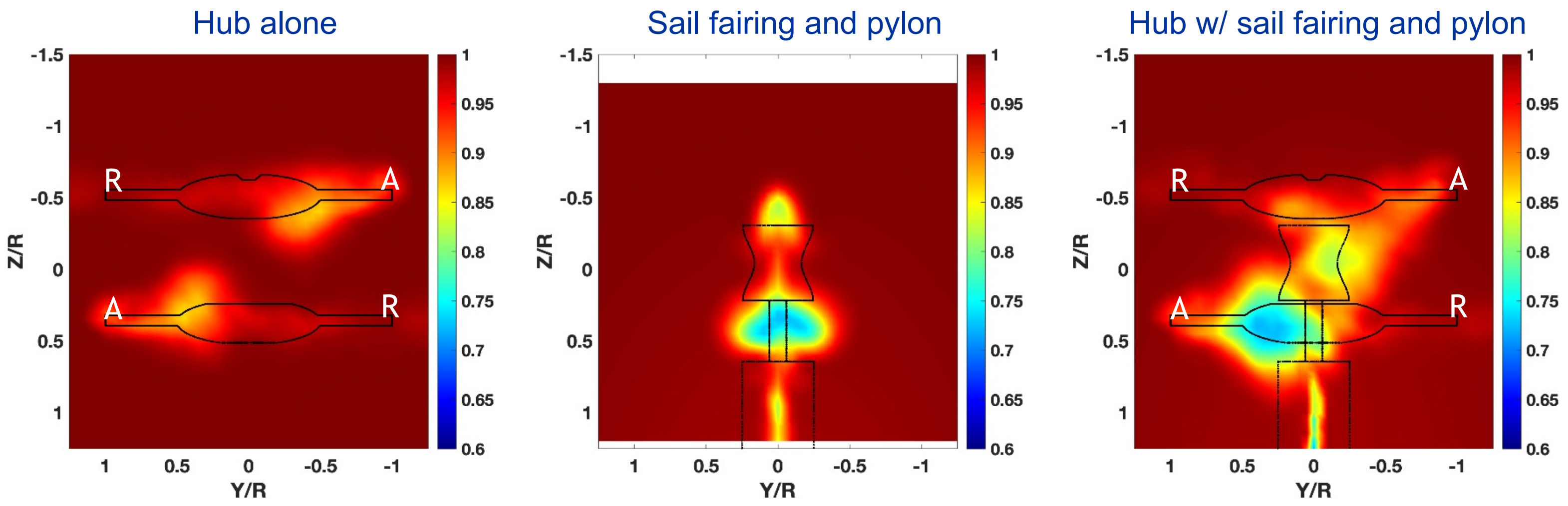
- **Coaxial rotor hub simulations are performed using an overset CFD framework, Mercury**
  - The effects of hub elements on the drag and wake structures are investigated
    - Isolated hub, isolated sail fairing, hub with the sail fairing and pylon

- **Hub drag and harmonics**
  - For the hub alone case, drag difference between the upper and lower hub is negligible
  - Aerodynamic interaction with the sail fairing and pylon increases the total hub drag
    - Lower hub by 76.2%, upper hub 56.4%
    - The interaction also increases 4/rev in the hub drag
  - For the sail fairing and pylon, the hub wake simulation gives 45.11% less drag than the clean air simulation
    - Hub wake also results in strong 4/rev and 8/rev components in the drag
  - CFD simulations predict 21% lower hub drag and 15% higher sail fairing and pylon drag
    - Hub shafts and water tunnel are not modelled in the CFD simulations



Concluding Remarks

- **Wake profiles at two downstream locations: x/R_{hub} = 3 and 7**
  - Aerodynamic interaction with the sail fairing and pylon makes mean hub wake structures biased



Comparison of streamwise velocity at x/R_{hub}=3

  - More wake deficits at x/R_{hub} = 3 / dissipated wake structures at the far wake x/R_{hub} = 7
- **Future Work**
  - Include the hub shafts and water tunnel in CFD simulations
  - Additional revolutions for the hub drag, mean wake, and wake harmonics
  - Comparison of the wake profiles with the experiment
  - Perform simulations for the advance ratio of 0.6

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Question

Thank you for your attention to the presentation!

Any Questions?

Prediction of Coaxial Rotor Hub Flow Using Mercury Framework

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