von KARMAN INSTITUTE
FOR FLUID DYNAMICS

# VANE-PROBE INTERACTIONS IN TRANSONIC FLOWS

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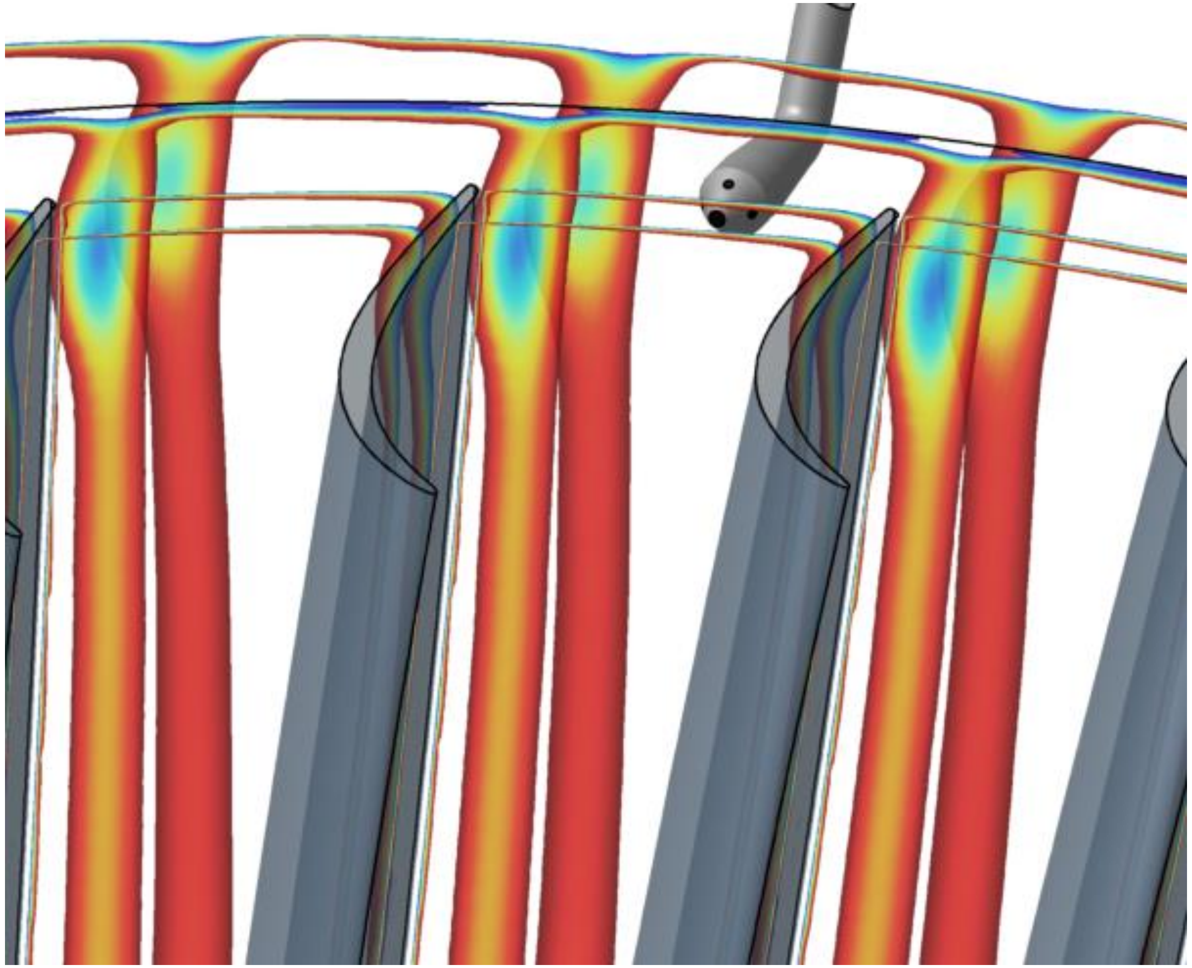
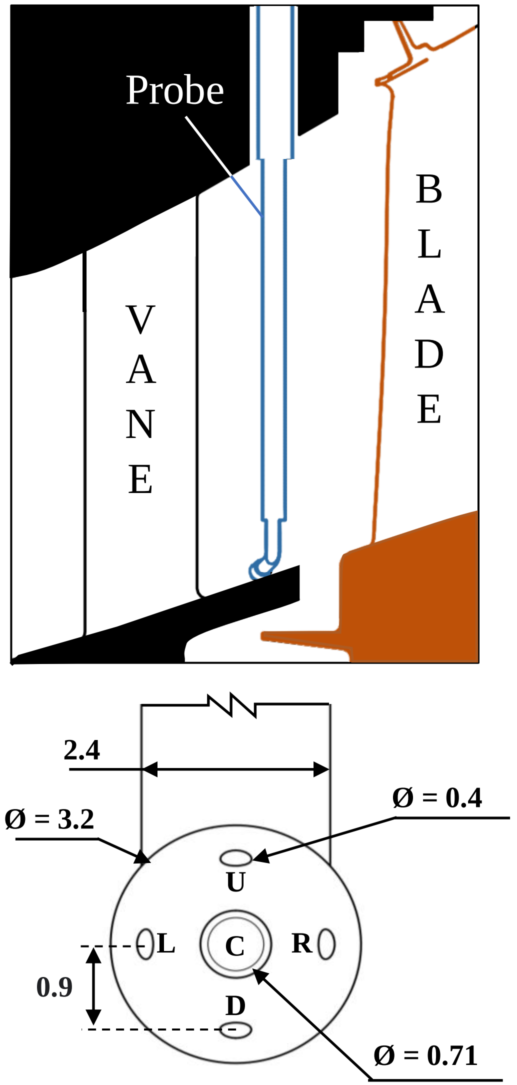
# Motivation



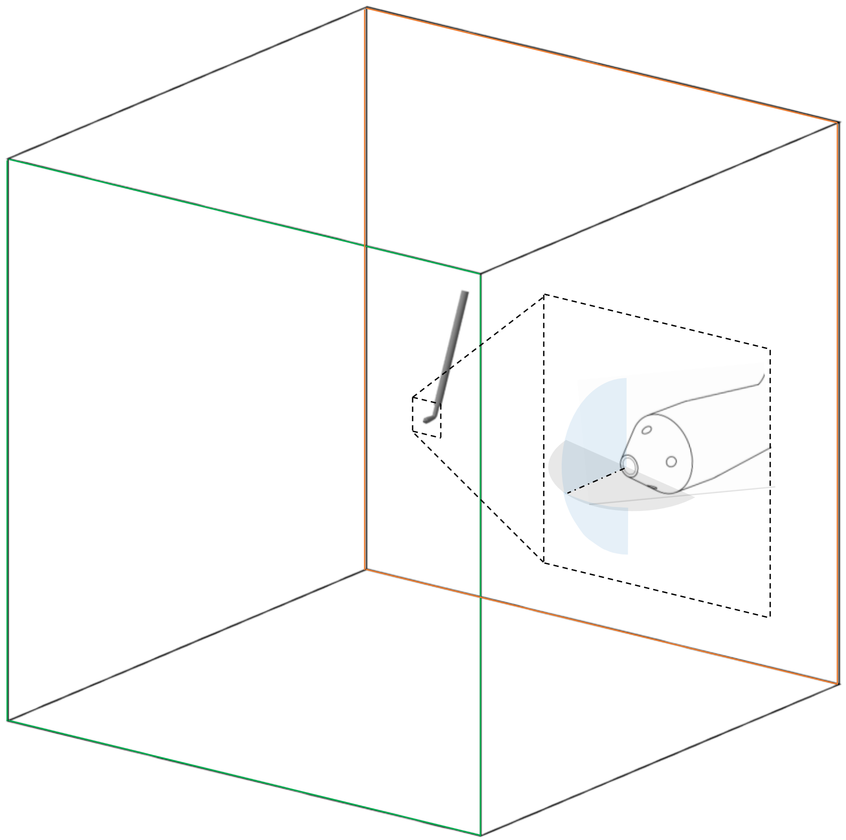
- Higher intrusiveness at transonic Mach numbers
- Probe measurements error due to velocity gradients
- **Objective:** interaction between vane and probe at **transonic Mach** numbers posing the attention on the effect on the measured quantities

# Methodology

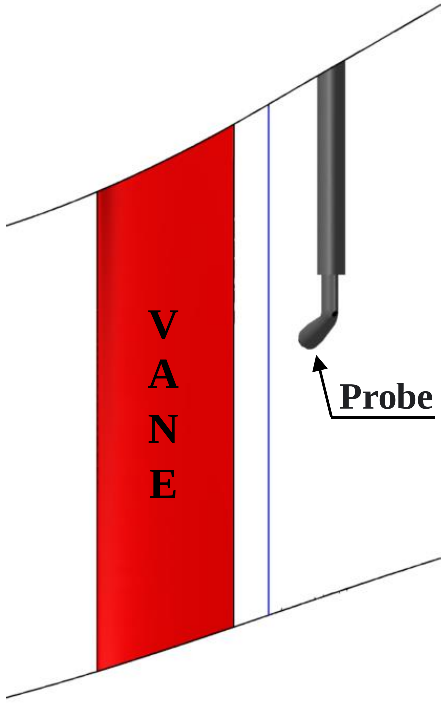
**Generic Problem**




**Numerical Calibration**



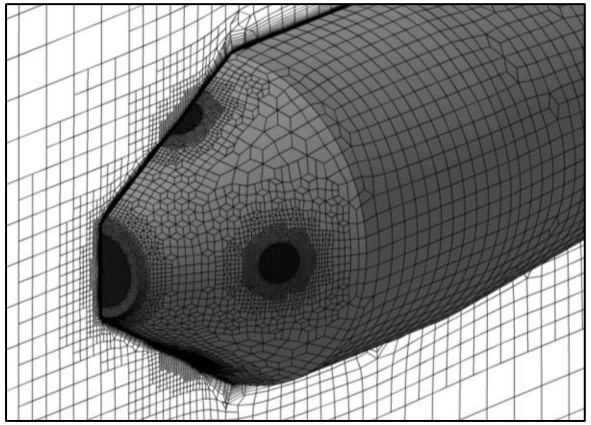
**Vane-Probe Interaction**

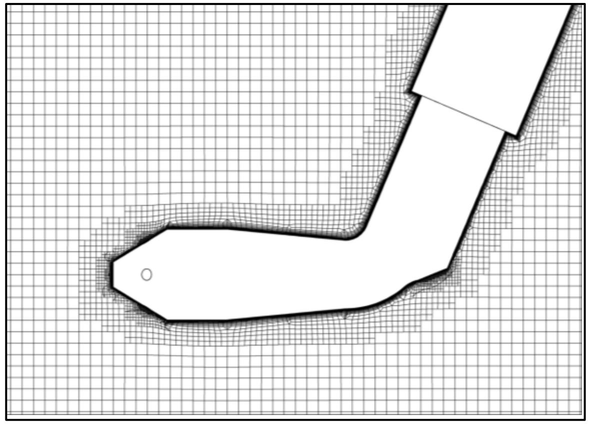


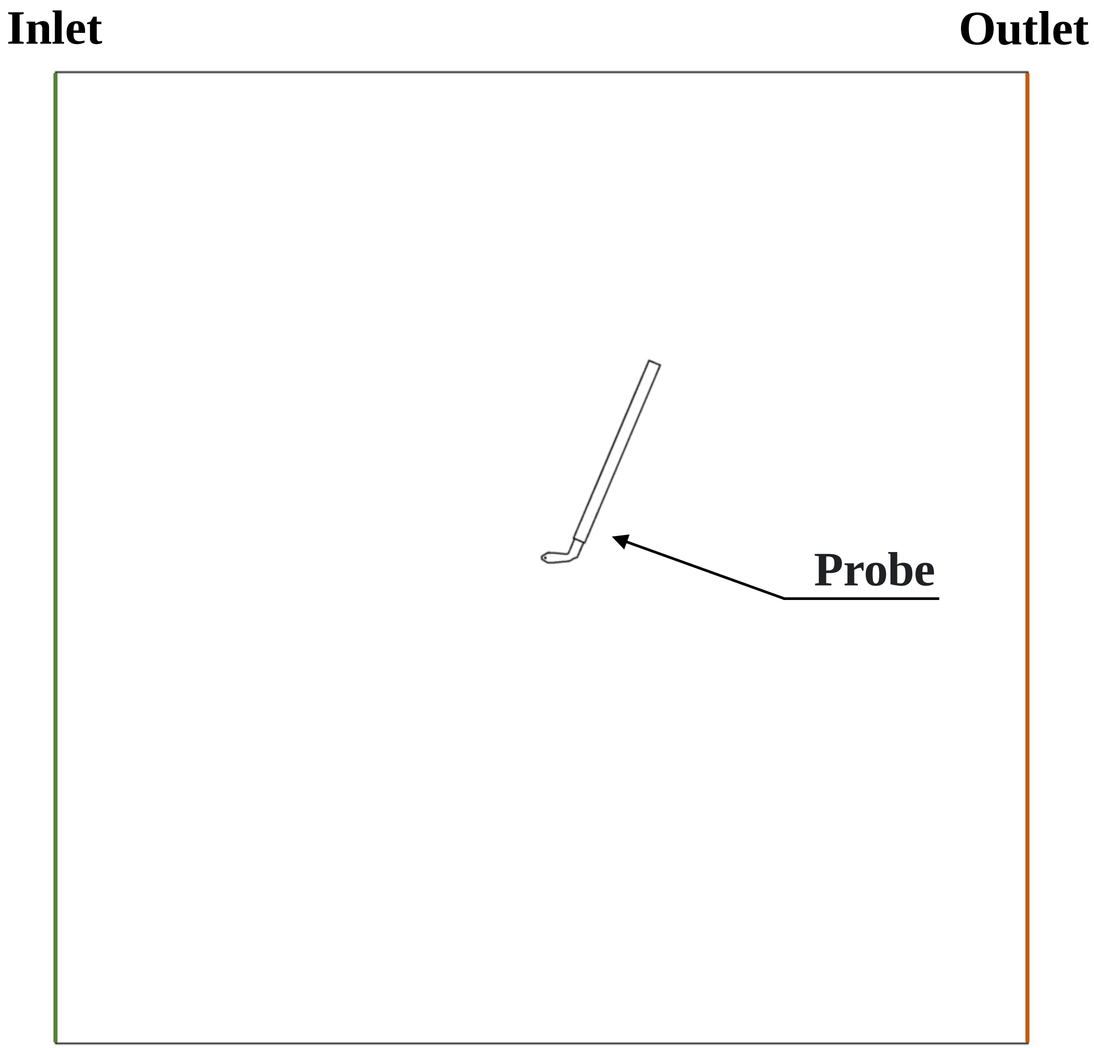
# Numerical Calibration

**Numerical setup**

- ❑ Top, bottom and side surfaces set as periodic
- ❑ Unstructured mesh size is ~3M cells ( y+ < 1 )
- ❑ RANS on Numeca FineOpen 8.2



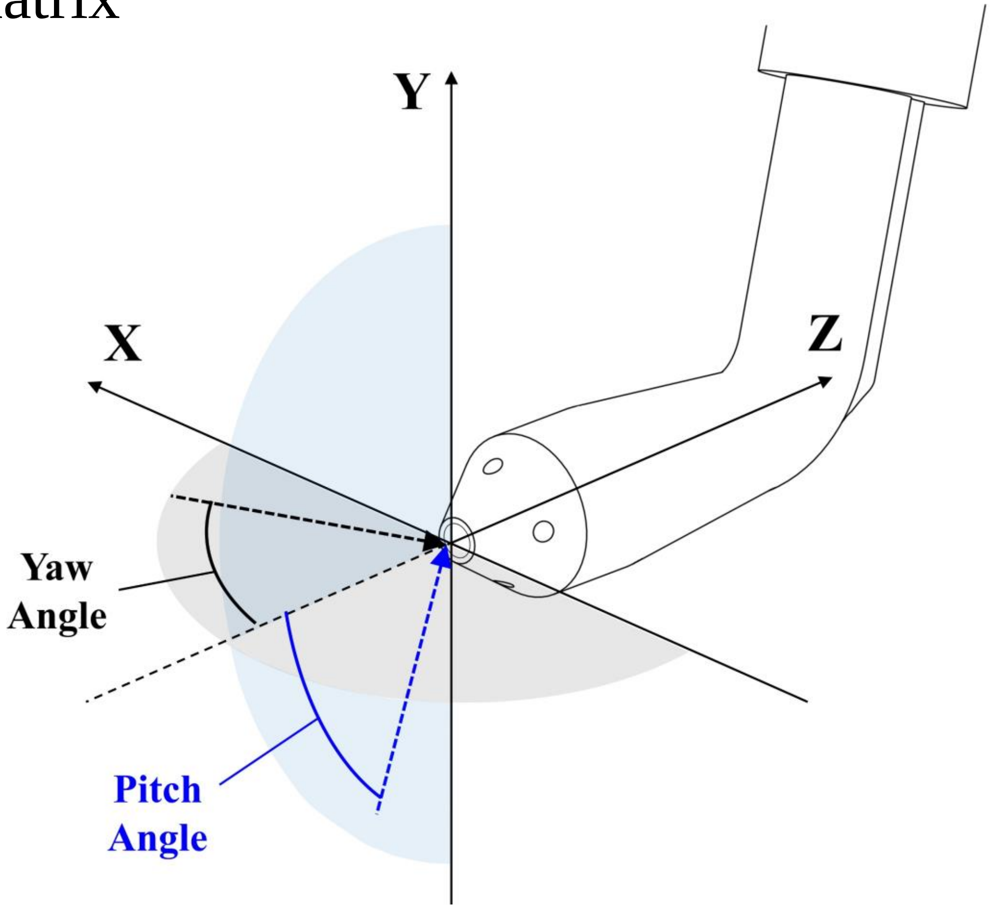




# Numerical Calibration

- ❑ Inlet flow angle varied to match the calibration matrix
- ❑ Fixed inlet total pressure
- ❑ Outlet static pressure to adjust the Mach

| | Min | Max | Step |
|---|---|---|---|
| **Pitch angles** | -15º | 15º | 5º |
| **Yaw angles** | 0º | 15º | 5º |
| **Mach numbers** | 0.55 – 0.70 – 0.8 – 0.9 – 0.95 | | |

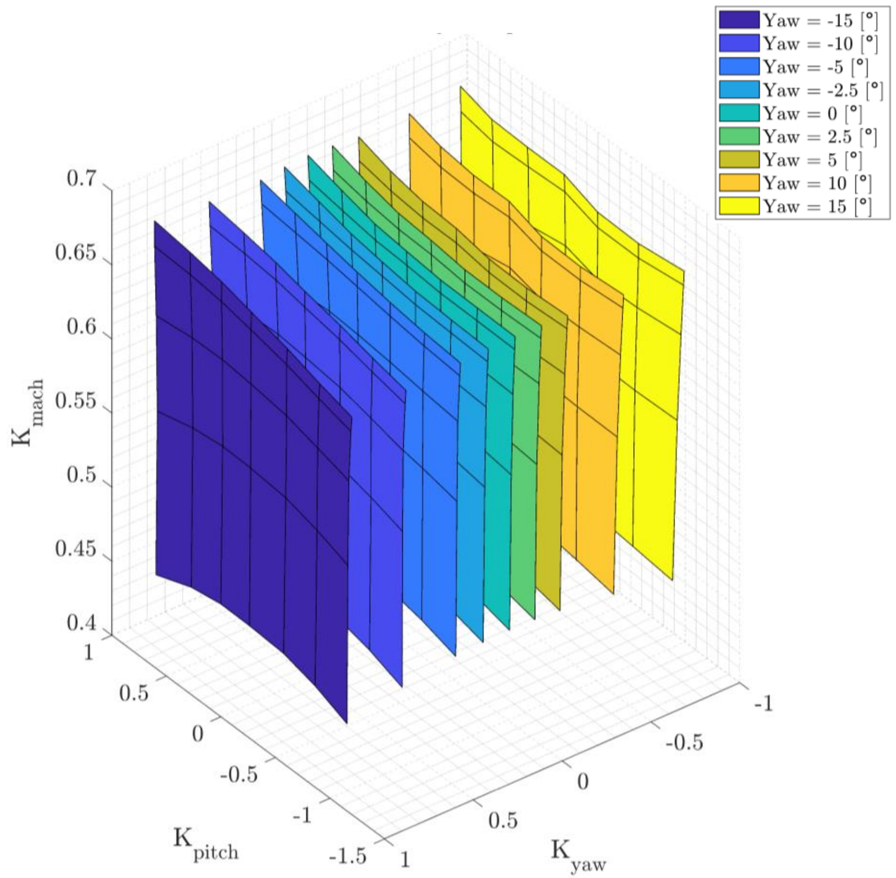


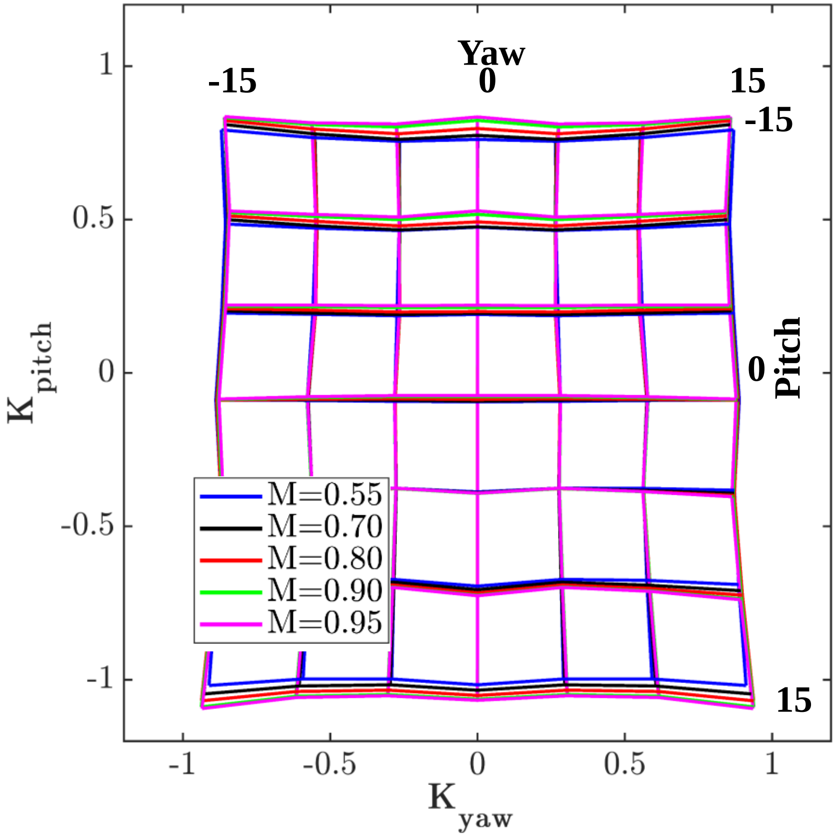

140 calibration points

# Numerical Calibration

## Calibration Results

❑ Calibration coefficients ($K_{yaw}$, $K_{pitch}$ , $K_{Mach}$ and $K_{tot}$ ) used to build calibration maps

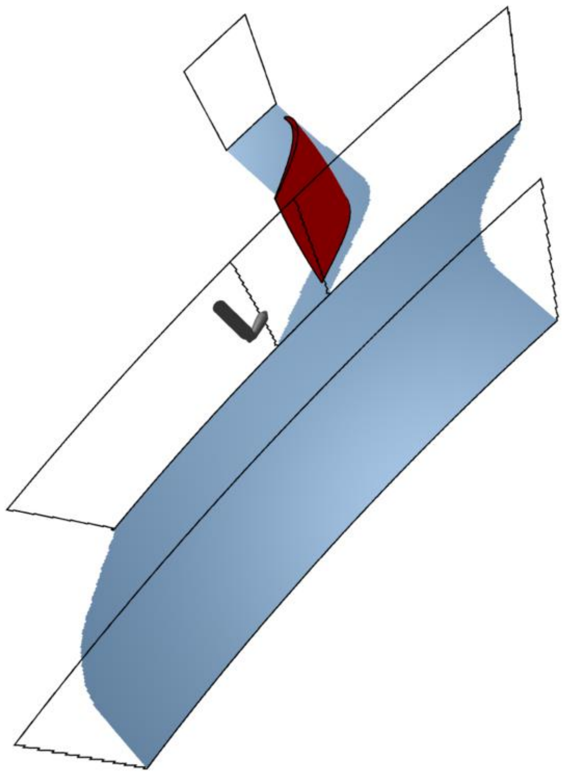


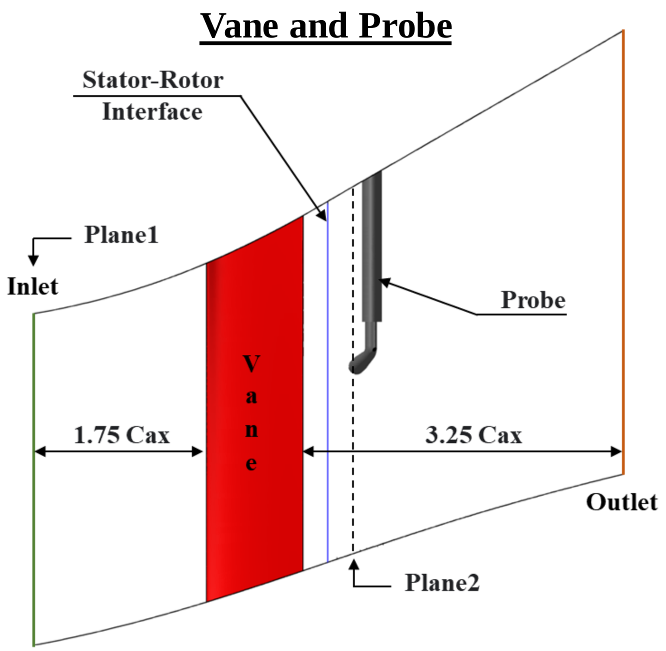



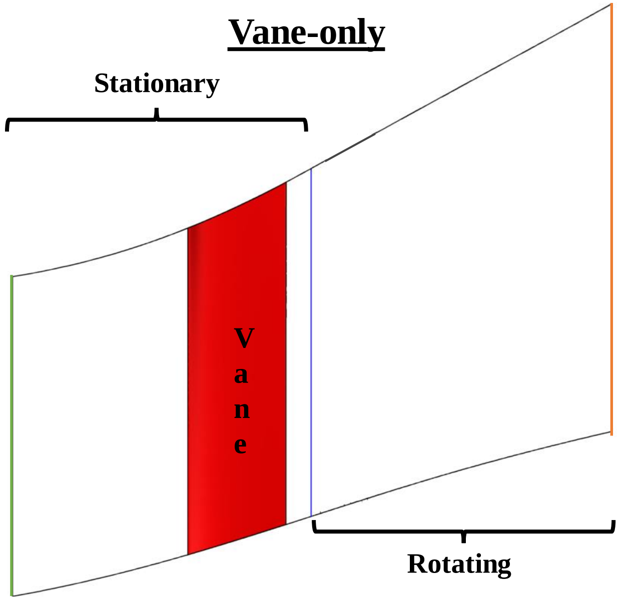
# Effects of the probe-vane interactions

## Numerical Setup

- ❑ Two numerical setups
  - ❑ Vane and probe
  - ❑ Vane-only
- ❑ Rotating probe domain
- ❑ Stator-to-Rotor Periodicity = 8 : 1
- ❑ Probe traverse at 14 spanwise locations





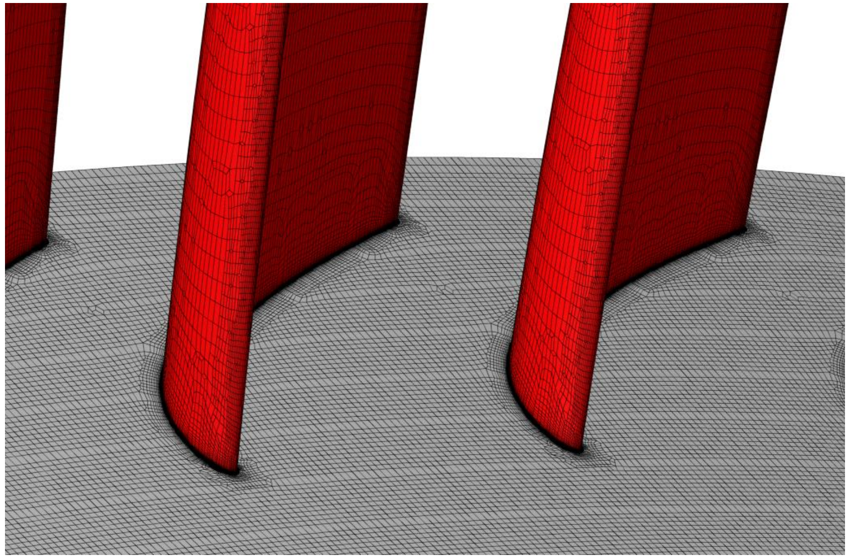



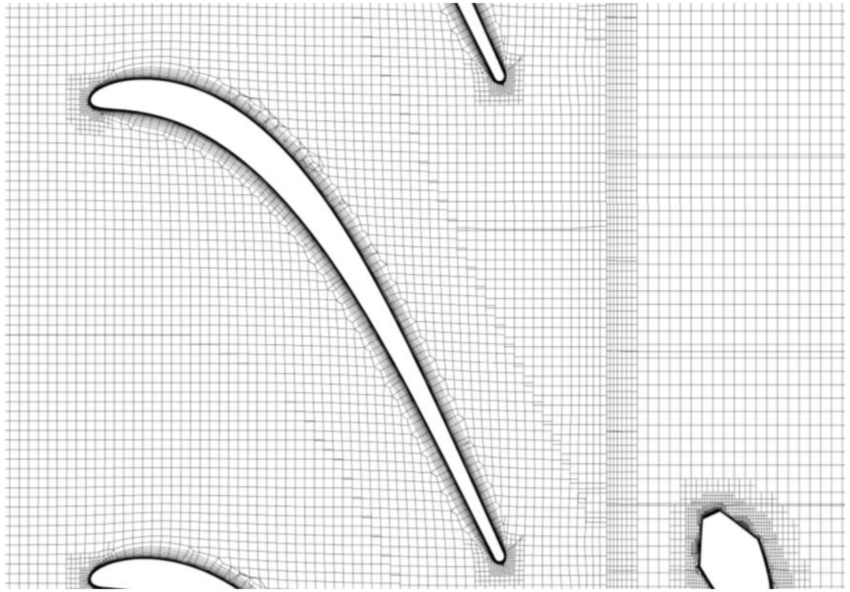
# Effects of the probe-vane interactions

**Mesh and operating conditions**

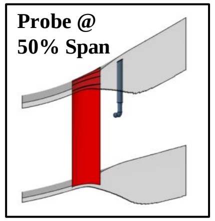
- ❑ Unstructured mesh size is ~11M cells ( y+ < 1 )
- ❑ NLH on Numeca FineOpen 8.2
- ❑ 5 Harmonics

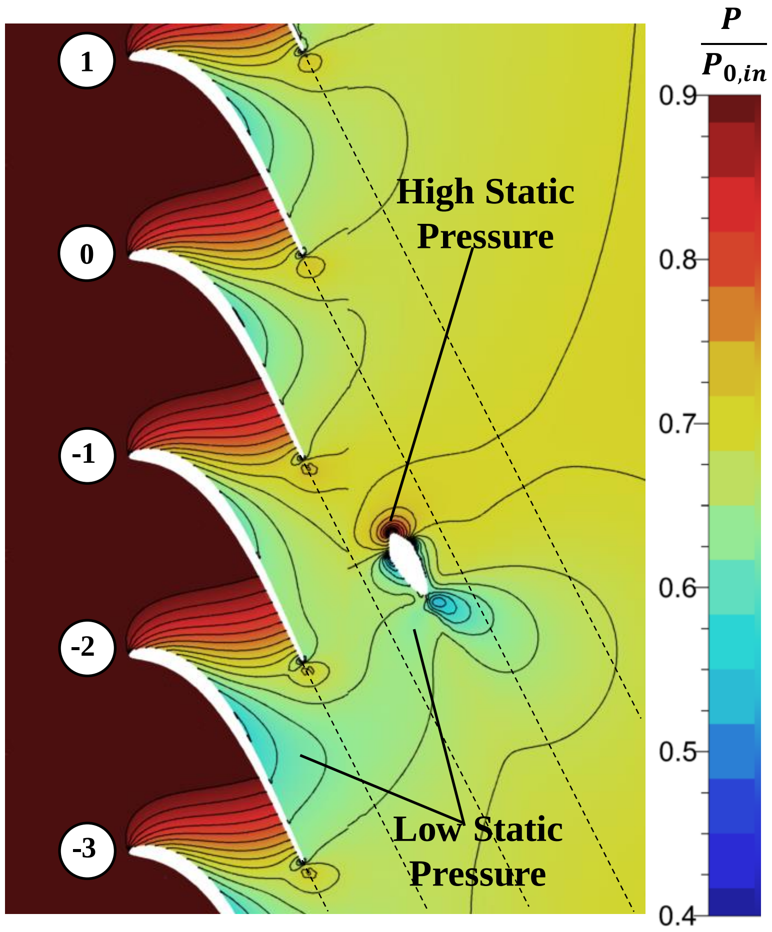
| Parameter | Value |
|---|---|
| Reynolds number (vane outlet and $C_{ax}$), $Re$ | ~1.7 x $10^5$ |
| Vane exit Mach number, $M$ | 0.8 |

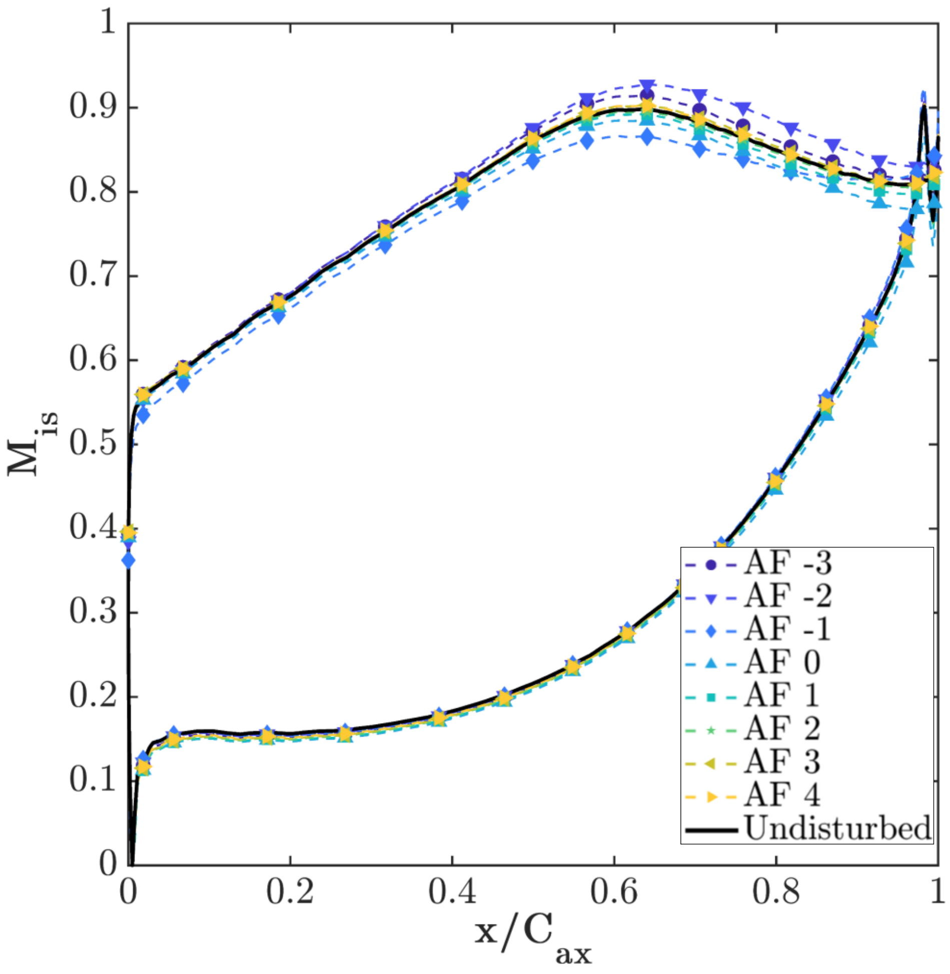




# Effects of the probe-vane interactions



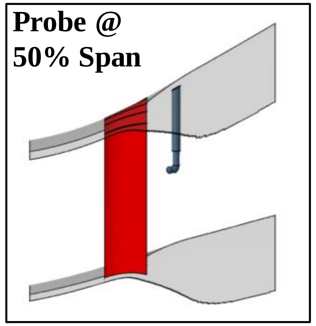



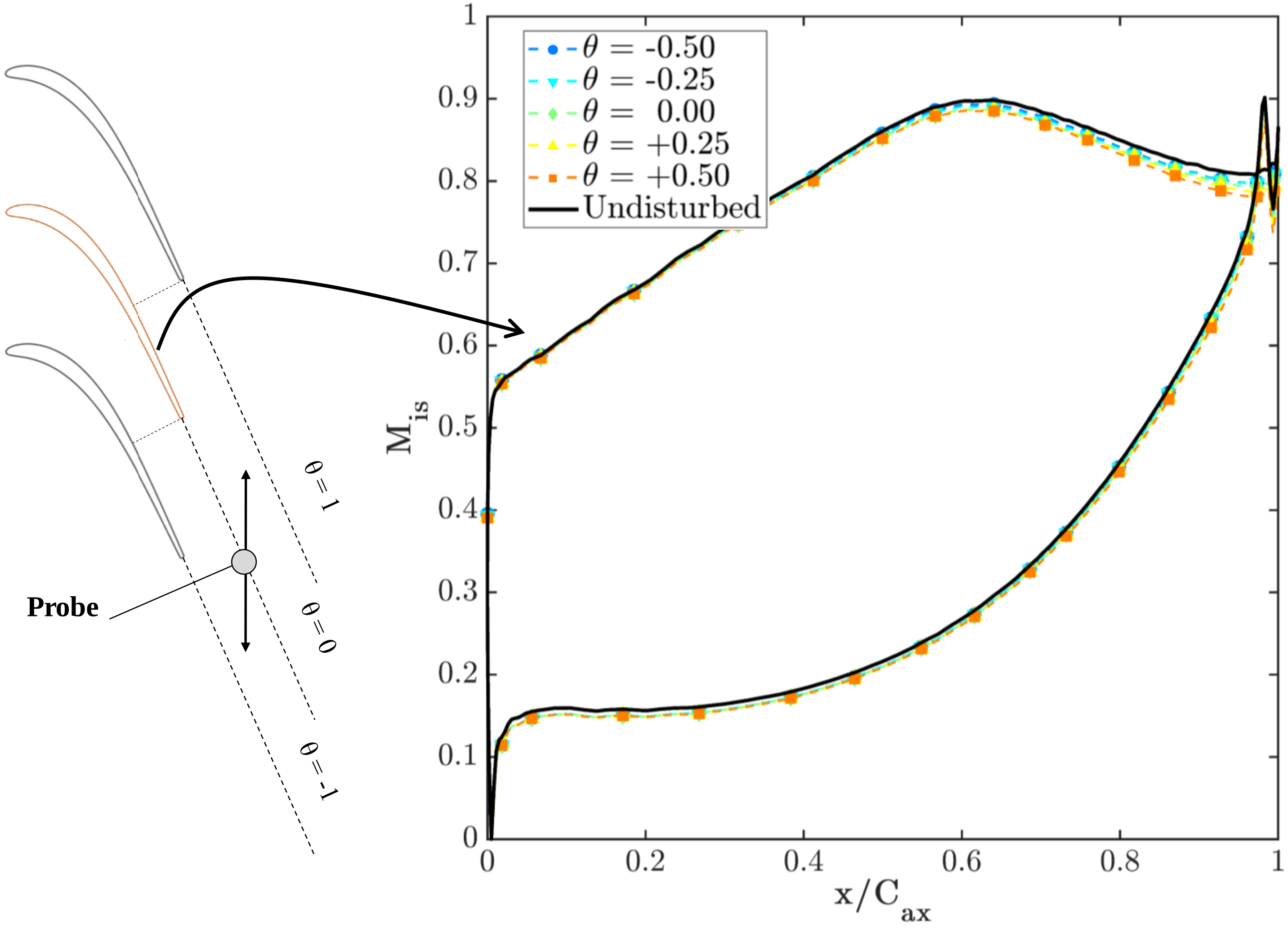




**<u>Effect on the flow-field – Probe at mid-passage</u>**

- High static pressure increase the pressure at exit of nozzle (Vanes -1 to 1)
- Low static pressure interacts with Vane -2 and -3 promoting expansion through the nozzle

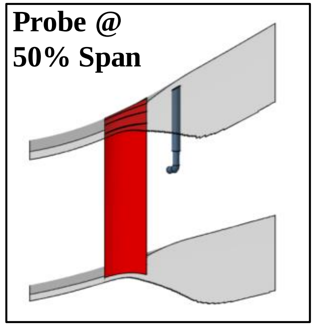
# Effects of the probe-vane interactions

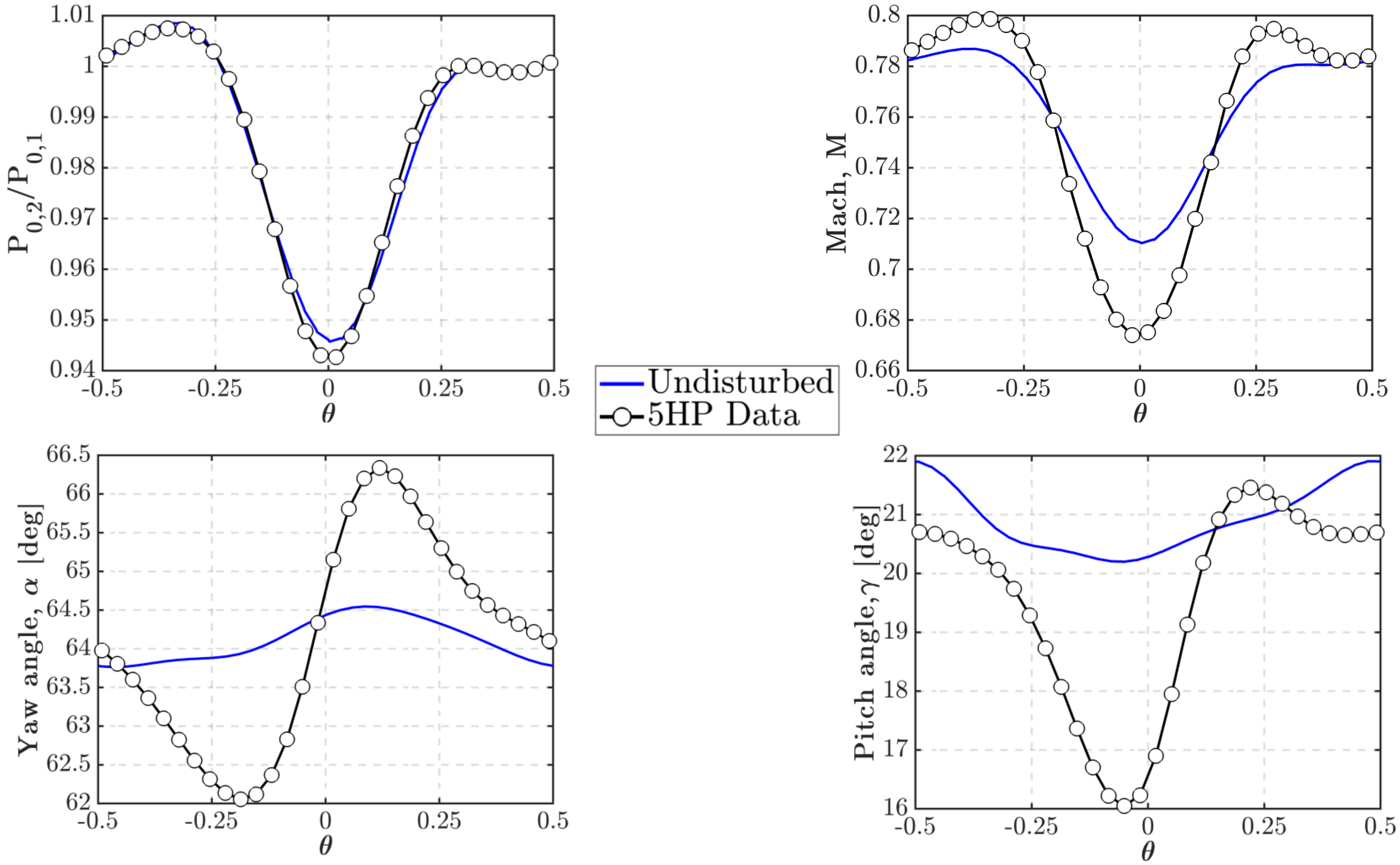



- ❑ Highest reduction ($\Delta M_{max}$ = 0.02) with probe at $\theta$ = + 0.5
- ❑ For $\theta < 0$ there is almost no impact on the isentropic Mach number on the Vane

# Probe traverses at midspan



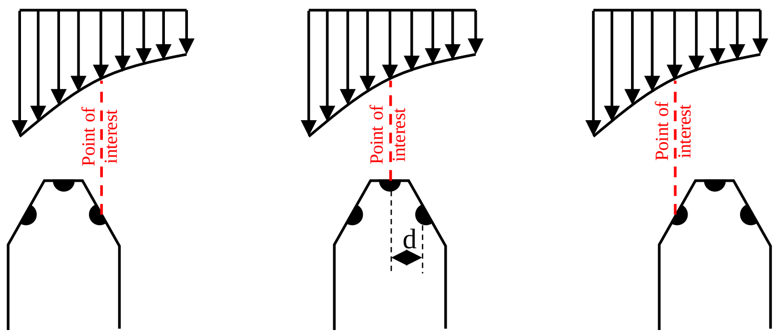




Noticeable short-fallings of the probe on the measured quantities except for the Total pressure measurements

# Correction procedure

**Two step correction (Ligrani et al.)**

1. Compensate the spatial displacement between side holes and central hole



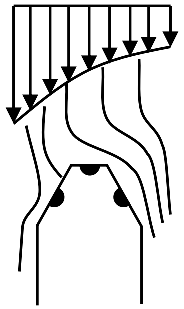

2. Compensate for transversal velocity rising when blunt bodies are immersed in shear flows:

**Tangential direction:**

$$V_t = V_{t,u} + C\ dV_{ax}/dy$$

**Radial direction:**

$$V_r = V_{\mathrm{r},u} + C\ d\ V_{ax}/d\ z$$



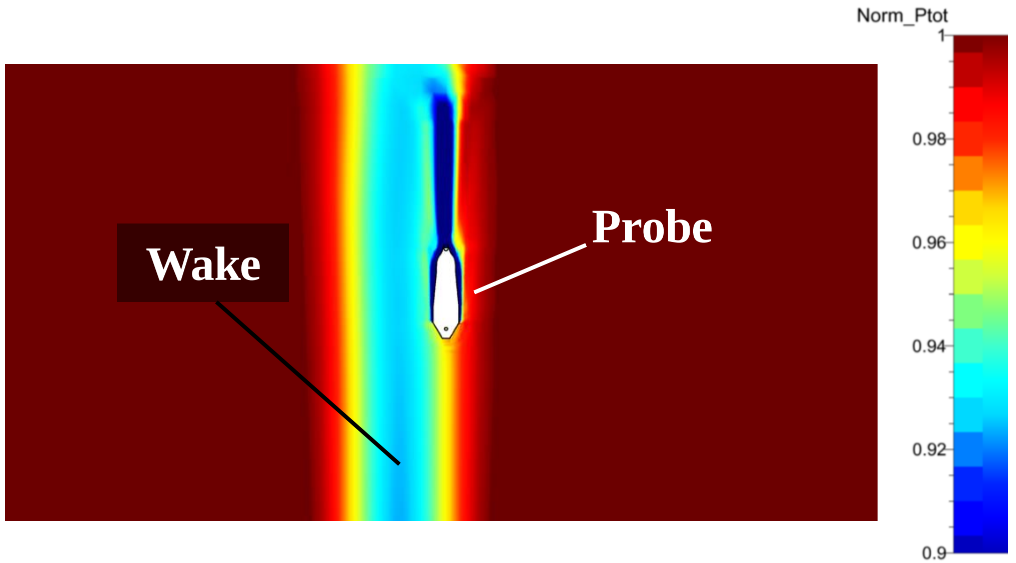
$V_{t,u}$ $V_{r,u}$ = uncorrected velocity components
$V_t$ $V_r$ = corrected velocity components
$V_{ax}$ = axial velocity components

C = 0.2*D according to literature for similar probe shapes

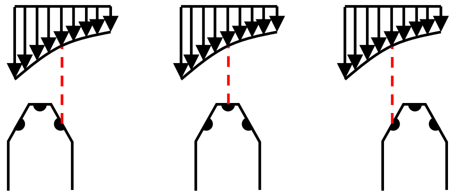
Ligrani, P. M., Baun, L. R., & Singer, B. A. (1989). Spatial resolution and downwash velocity corrections for multiple-hole pressure probes in complex flows. Experiments in Fluids, 7(6), 424-426
Chernoray, V., & Hjärne, J. (2008, January). Improving the accuracy of multihole probe measurements in velocity gradients. In Turbo Expo: Power for Land, Sea, and Air (Vol. 43123, pp. 125-134).

# Correction procedure

- Introduced a wake at the inlet of the domain
- Inlet angle = 0 deg.
- Tests:
  - M=0.7
  - M=0.8 (nominal Mach)
  - M=0.9

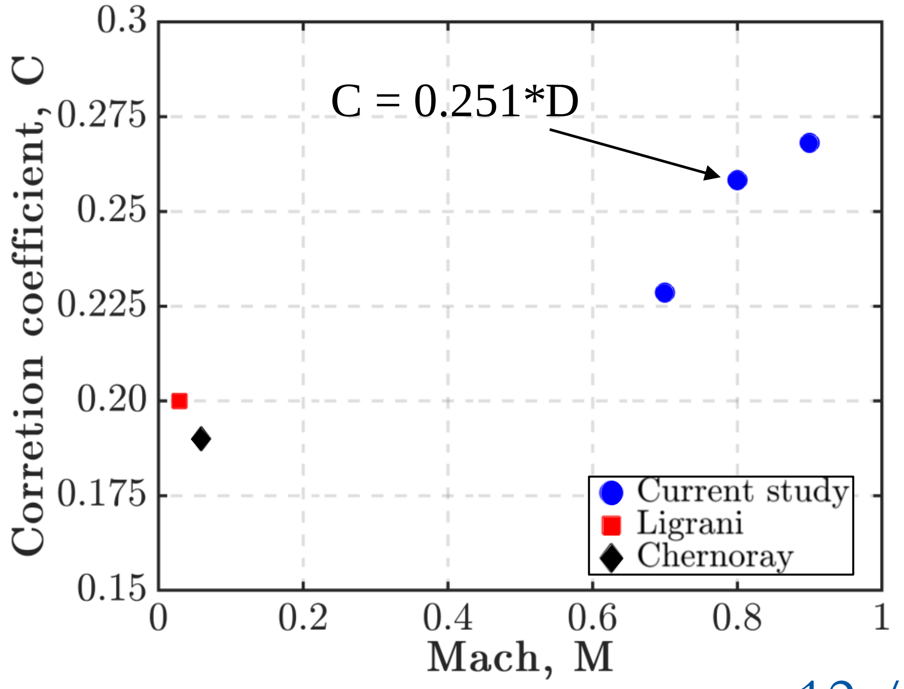



Pressure taps spatial displacement correction

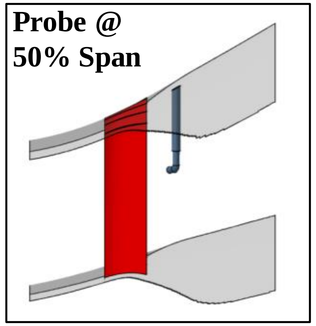


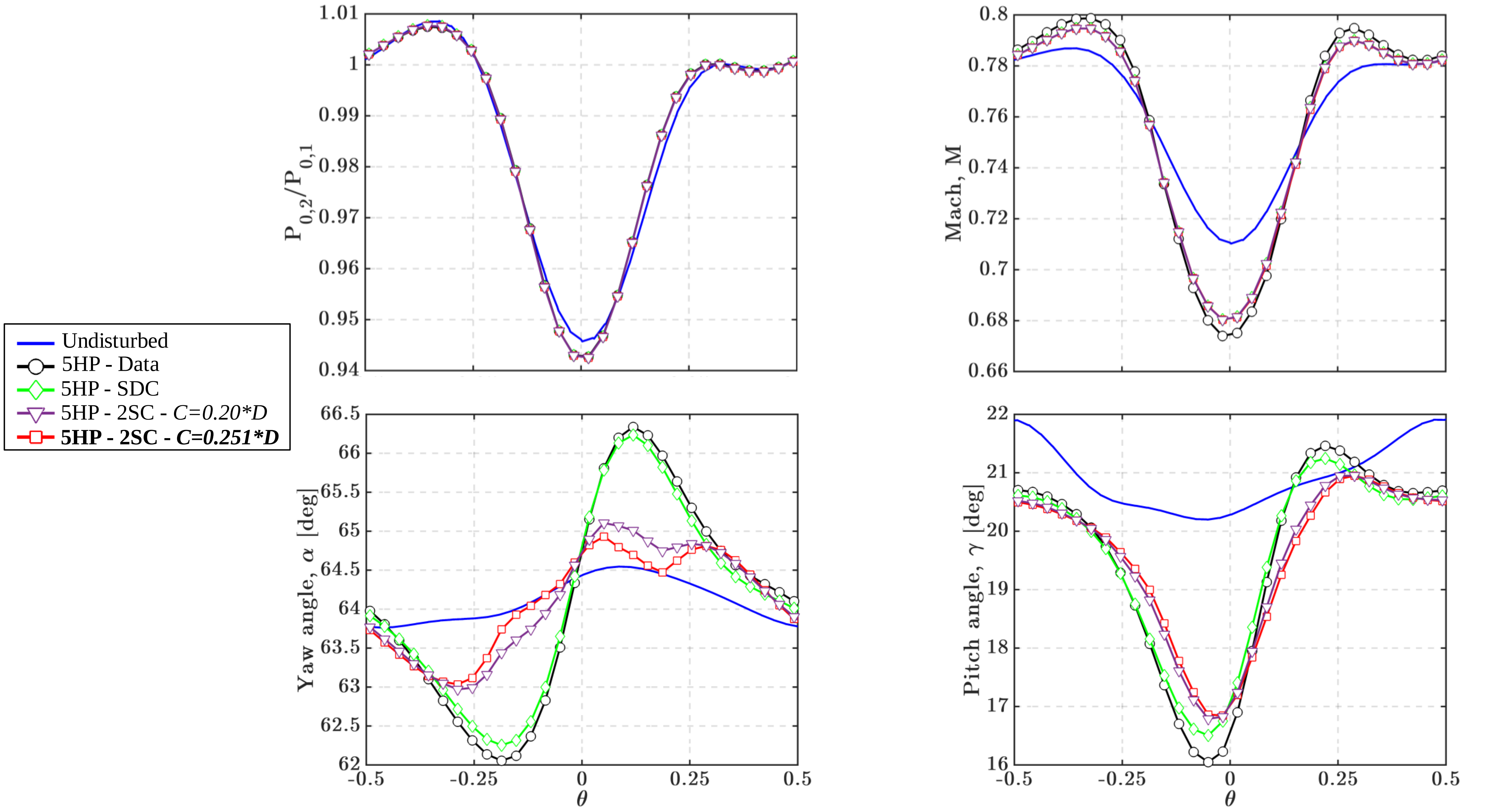
Definition of the correction coefficient

$$C = \frac{-V_{tu}}{\frac{dVax}{dy}D}$$

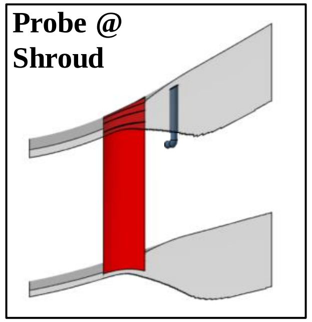


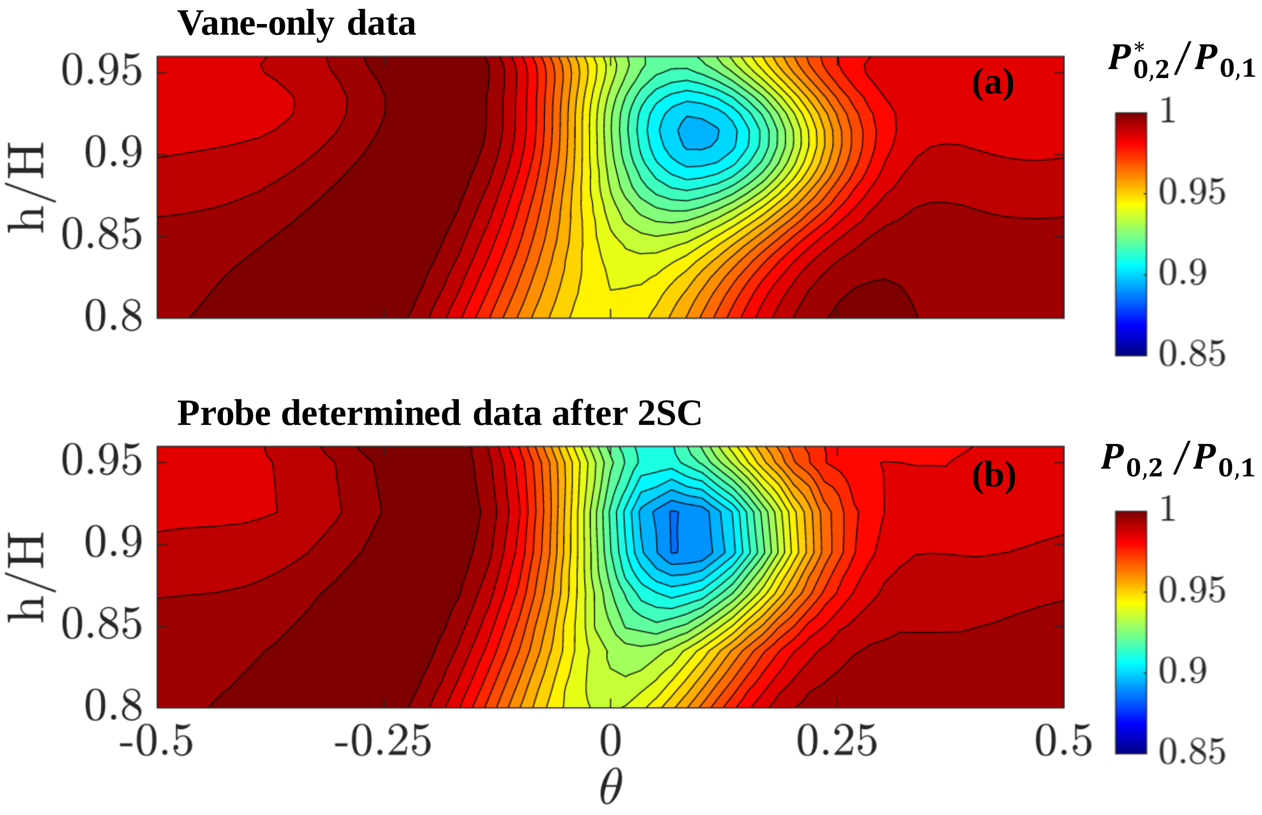
# Probe traverses at midspan

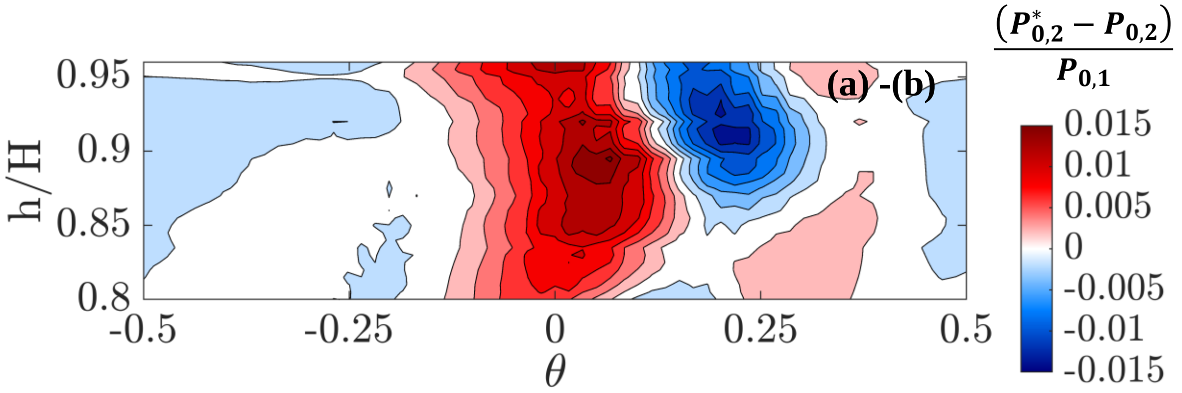


# Probe traverses at shroud



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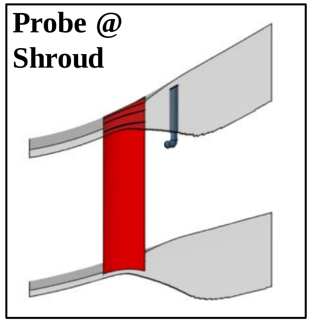


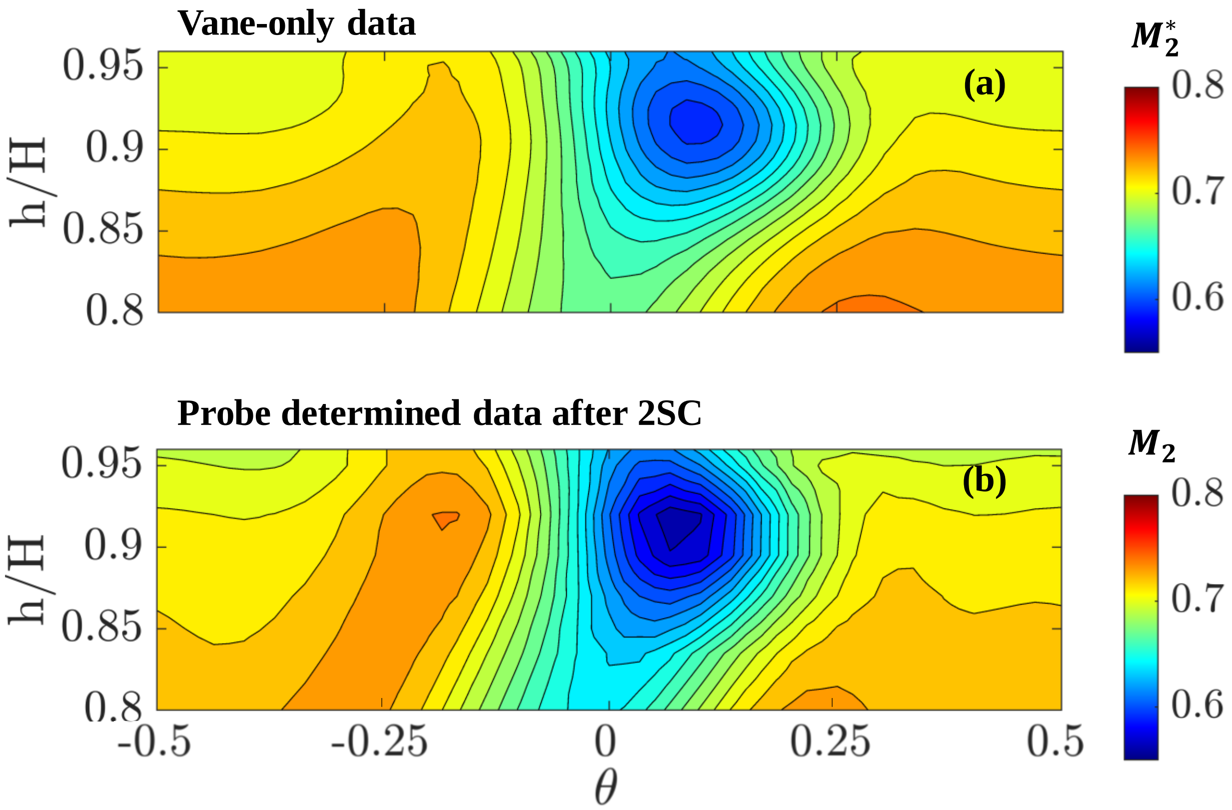


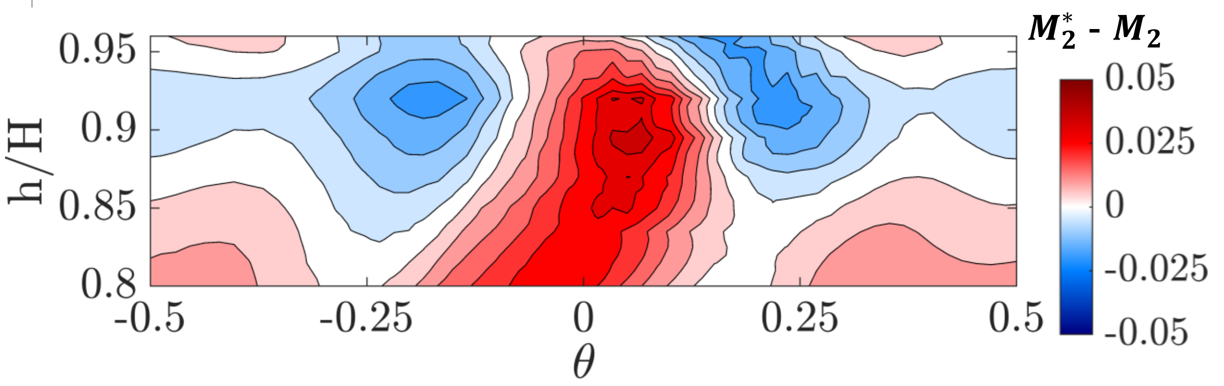

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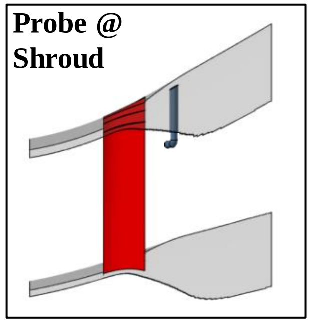
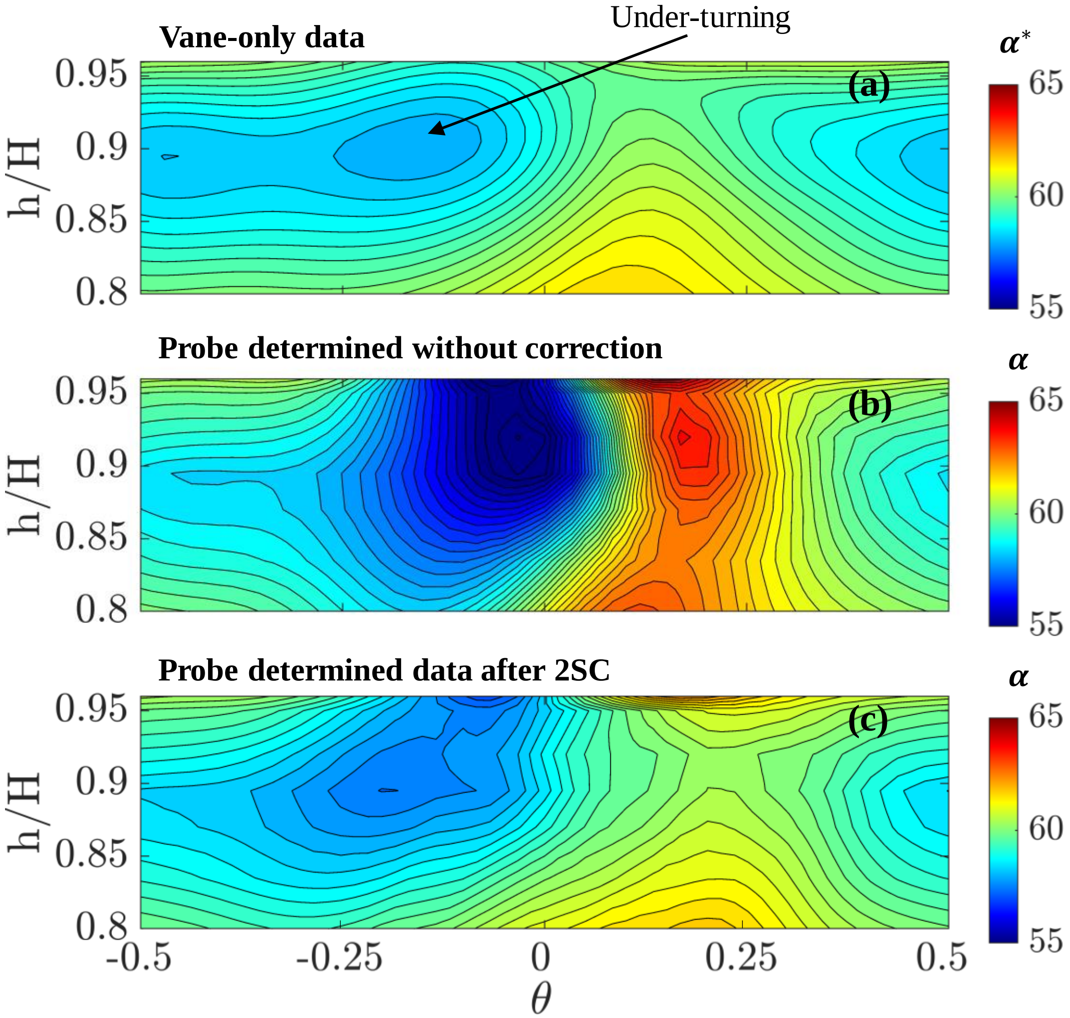
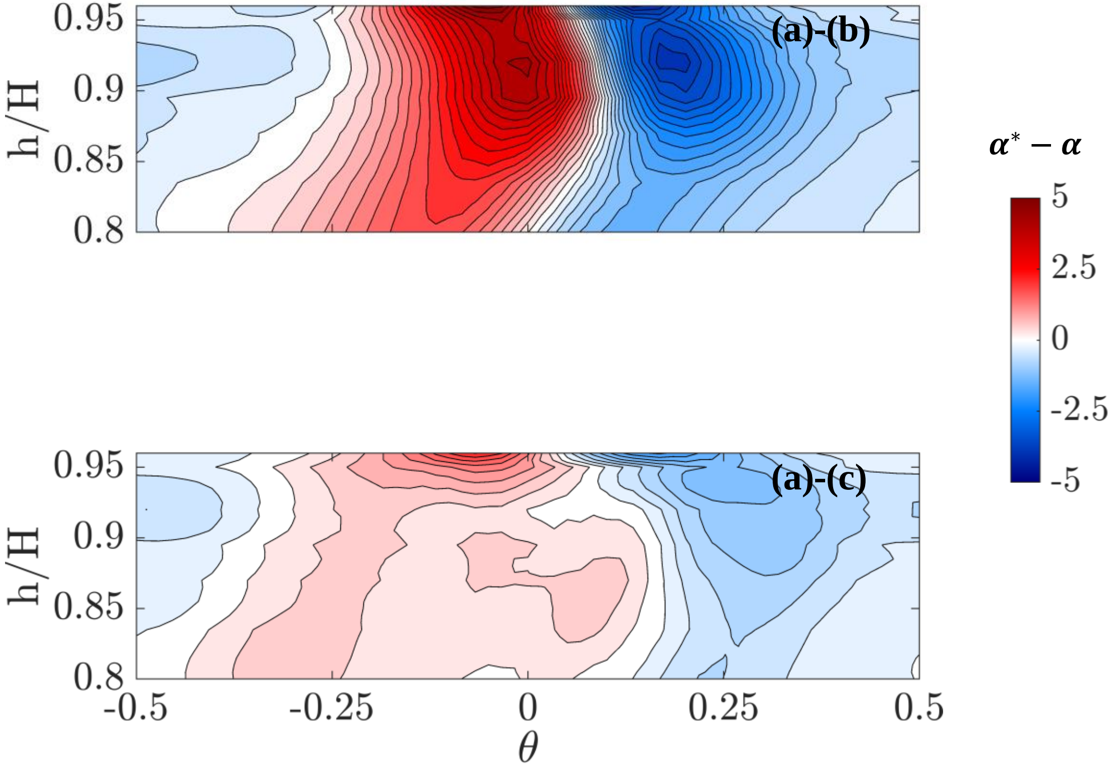
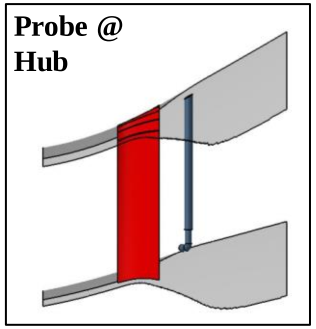
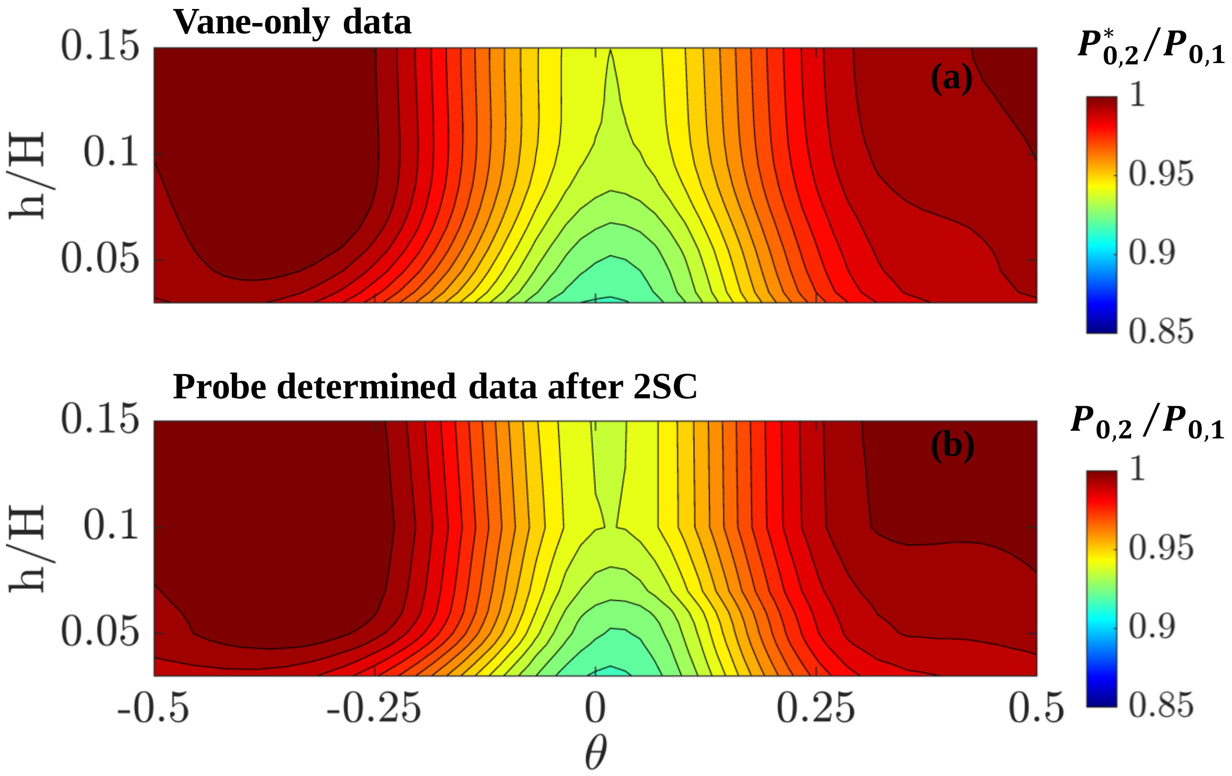


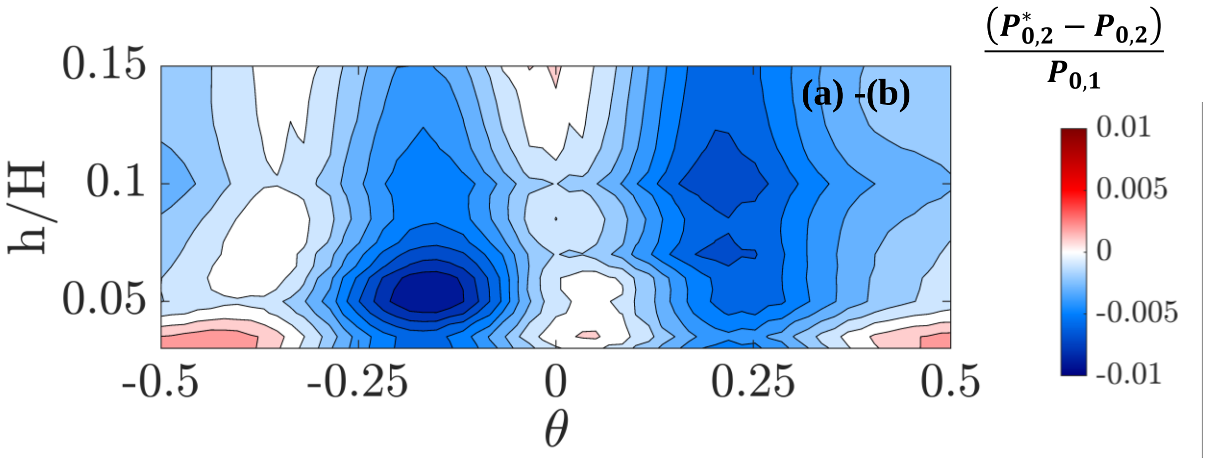



# Probe traverses at hub



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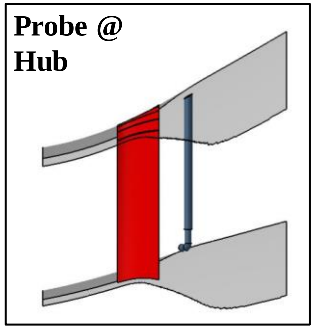
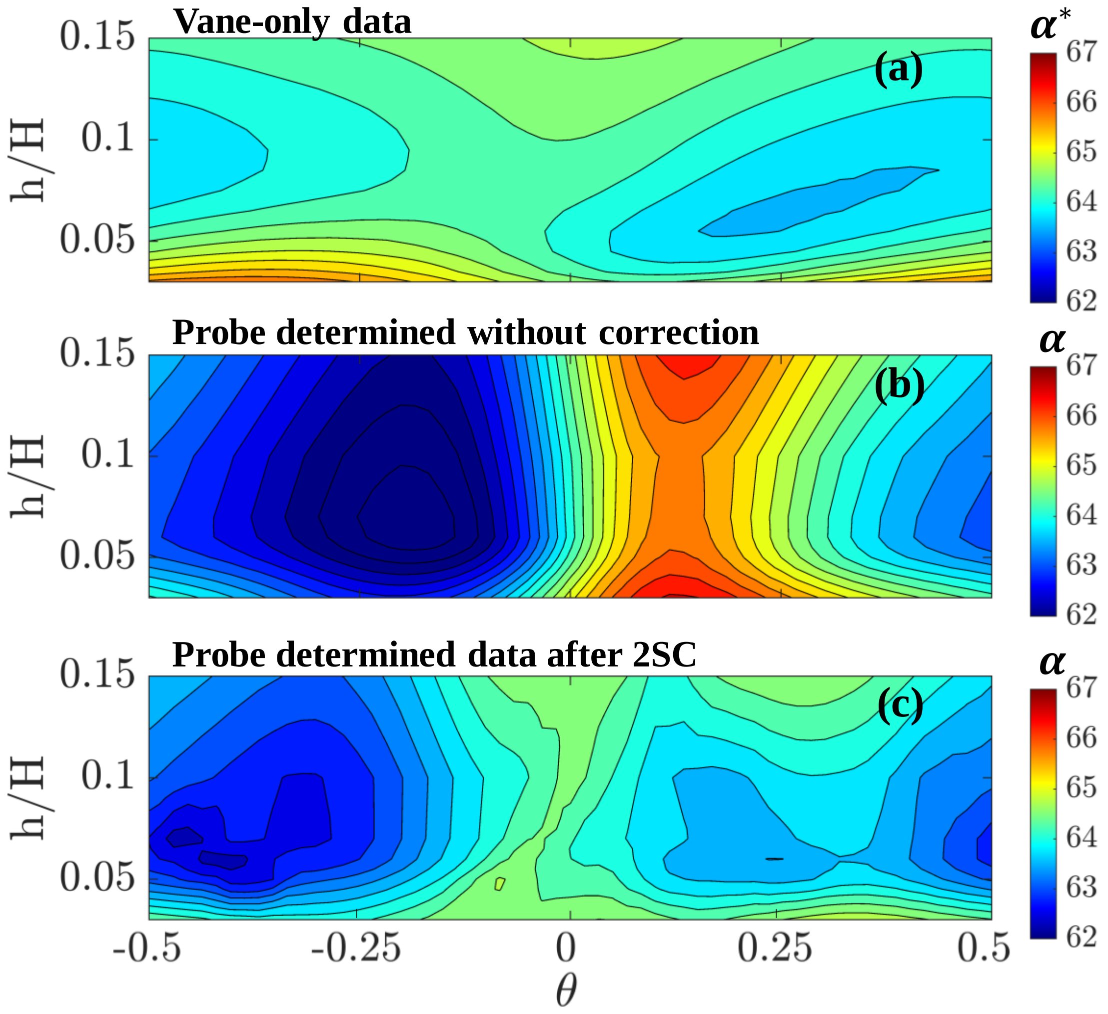
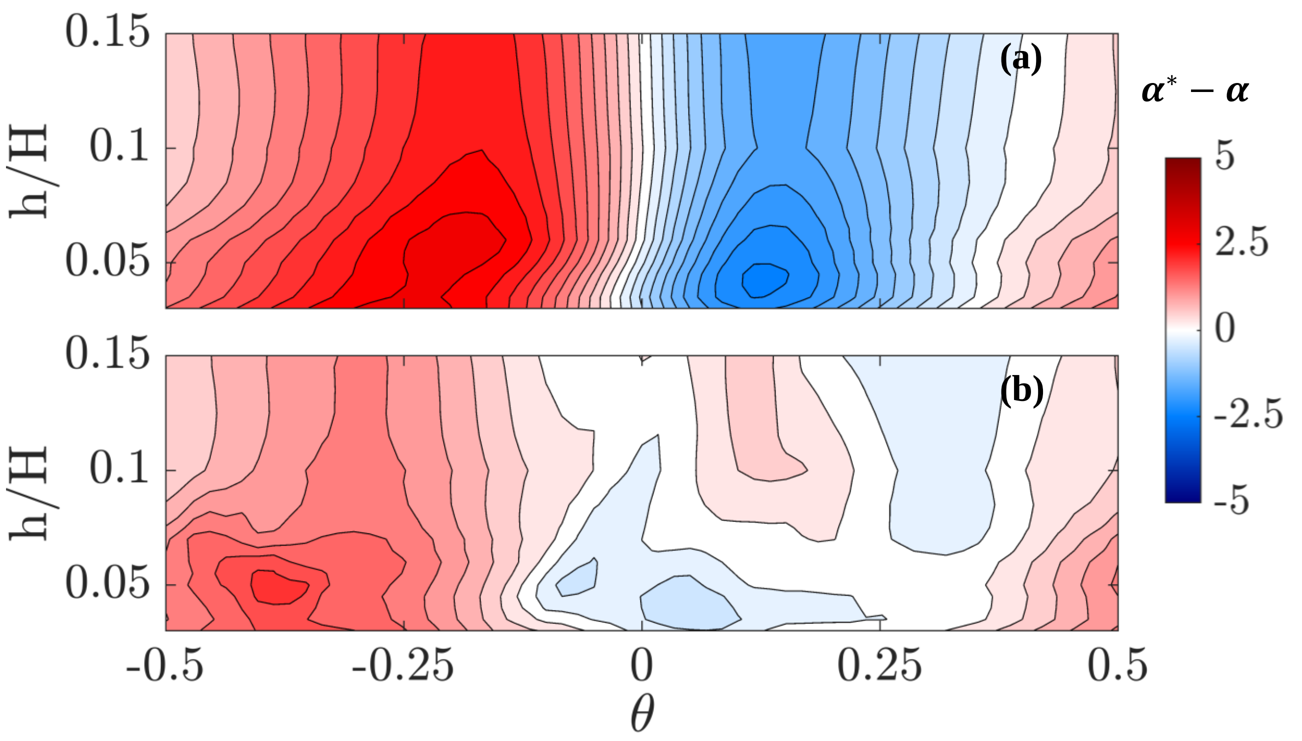
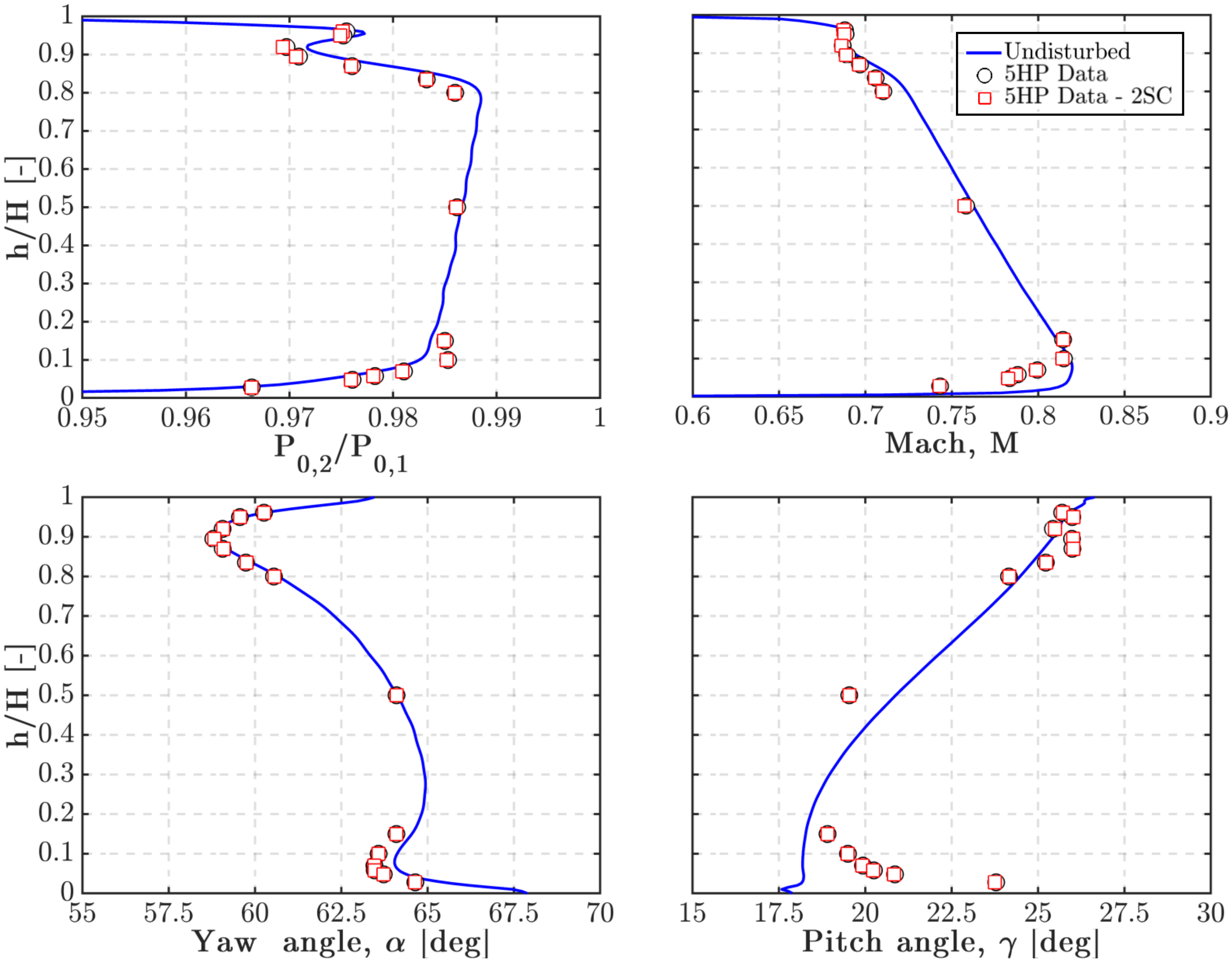
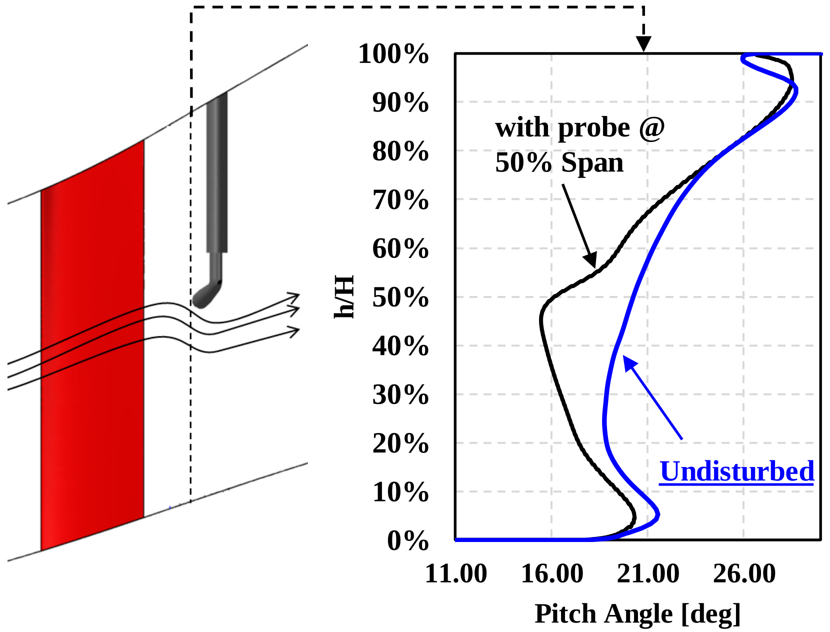


# Pitch-wise averaged quantities



# Conclusions

**<u>Mutual</u>** impact between test article and probe:

1. The impact of the probe is confined between Vane – 3 and +2
   - ❑ Measurement error are higher than variation of $M_{is}$ on the vane due to blockage of the probe

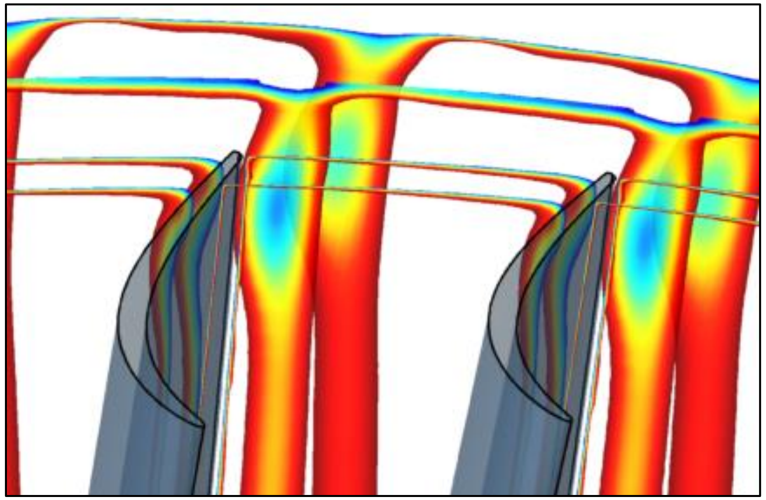
2. A new correction coefficient was computed for transonic Mach numbers
   - ❑ Correction coefficient found in literature does not lose validity at high subsonic regimes

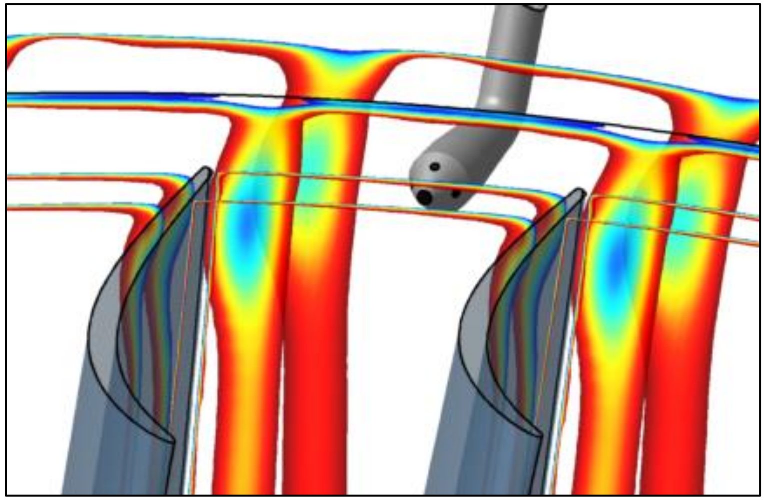
3. The correction does not affect the pitch-wise averaged quantities.

**Use the two-step corrections to reduce the measurement error on the flow angles.**

- ❑ **Miniaturize the probe to be less susceptible to velocity gradients!**

# Thanks for your attention!





**Acknowledgements:**
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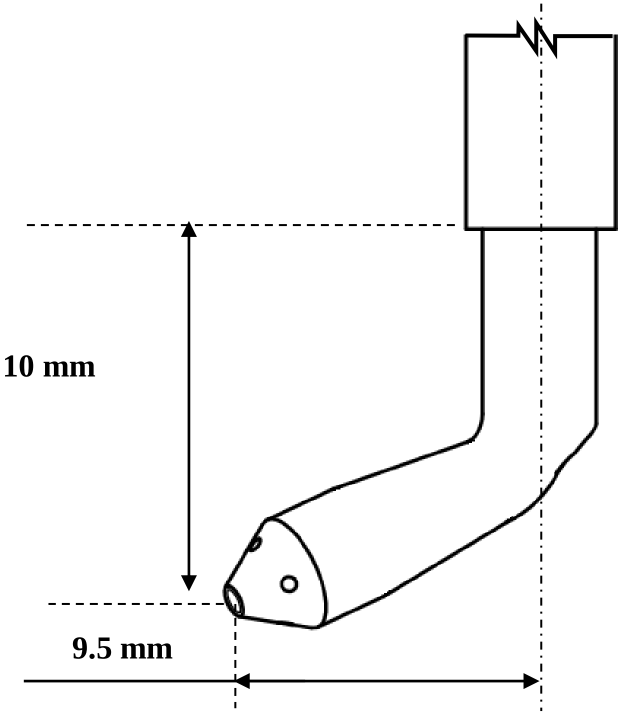
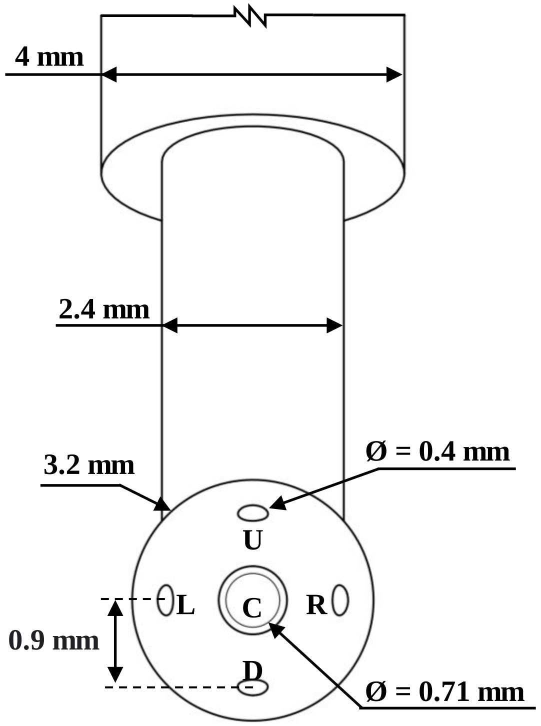
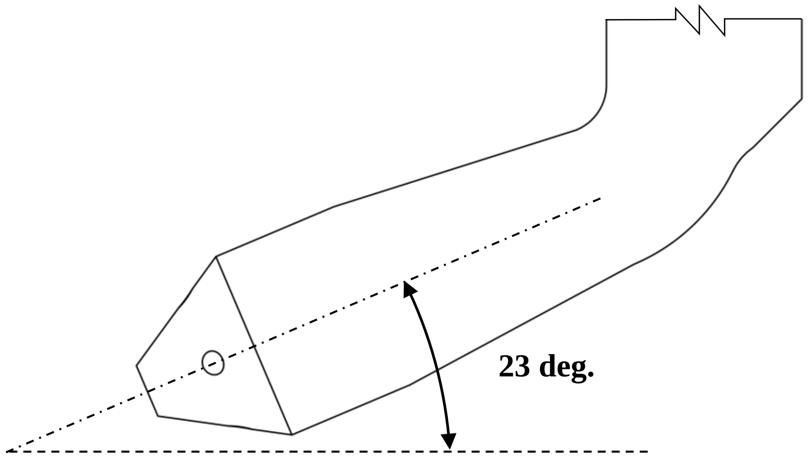
The authors also acknowledge SAFRAN Aircraft Engines for the collaboration.

# Backup Slides

# Probe Geometry




| **Parameter** | **Value** |
|---|---|
| Probe Reynolds Number, *Re* (-) | ~2.7 x $10^4$ |
| Probe area-blockage, $A_P/A_{pass}$ (-) | 8.4% |
| Probe area-blockage, $A_P/A_{dom}$ (-) | 1.04% |

# Calibration

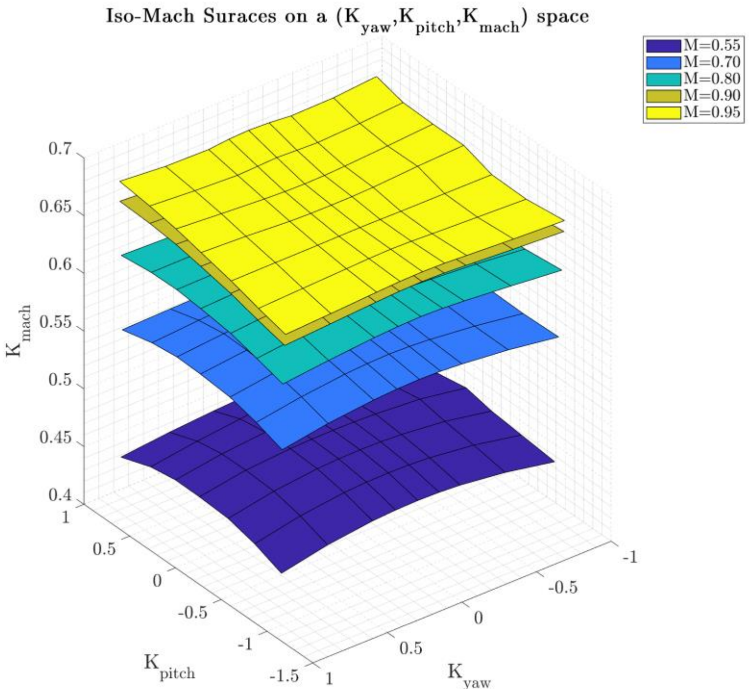
$$K_{yaw} = \frac{P_L - P_R}{P_C - P_{ave}}$$

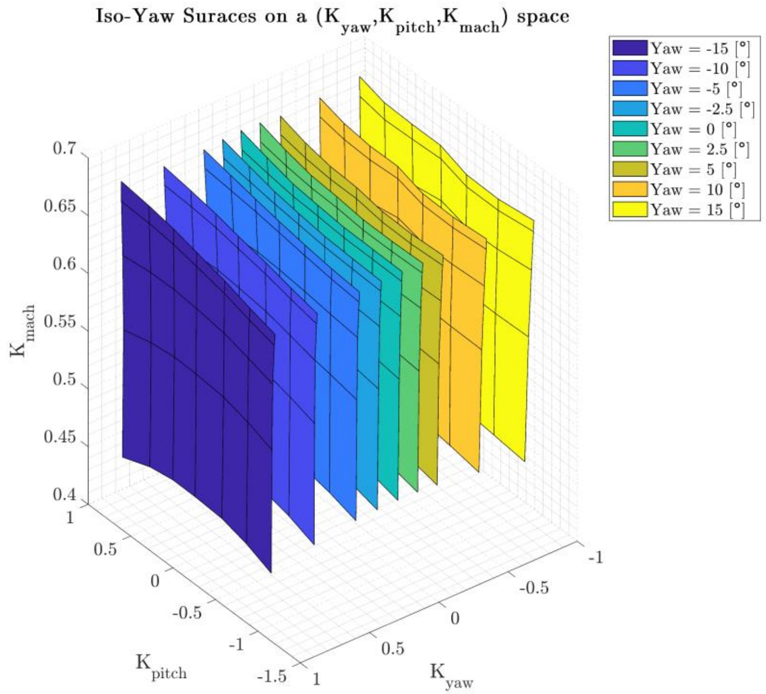
$$K_{pitch} = \frac{P_D - P_U}{P_C - P_{ave}}$$

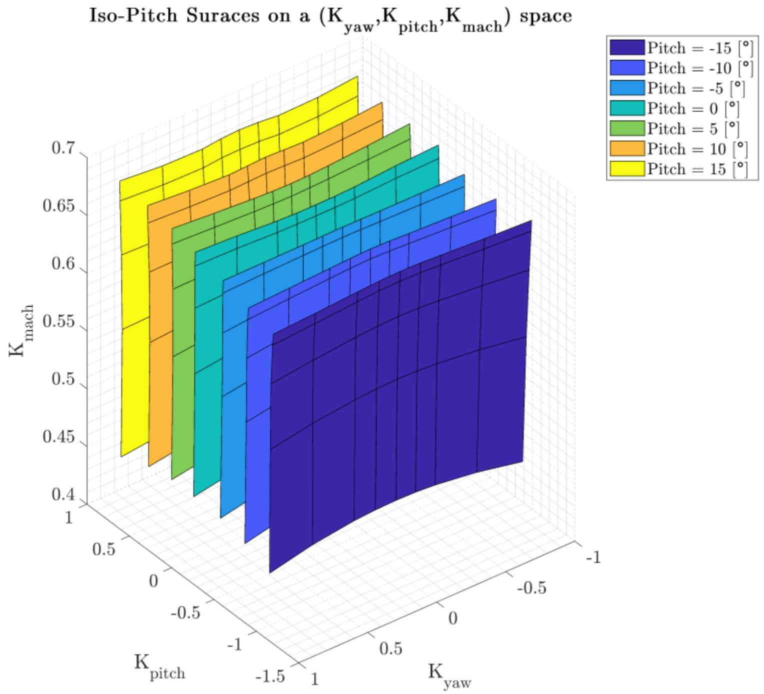
$$K_{mach} = \left(\frac{2}{\gamma - 1}\left[\left(\frac{P_{ave}}{P_C}\right)^{-\frac{\gamma-1}{\gamma}} - 1\right]\right)^{1/2}$$

$$K_{tot} = \frac{P_C - P_{tot}}{P_C - P_{ave}}$$

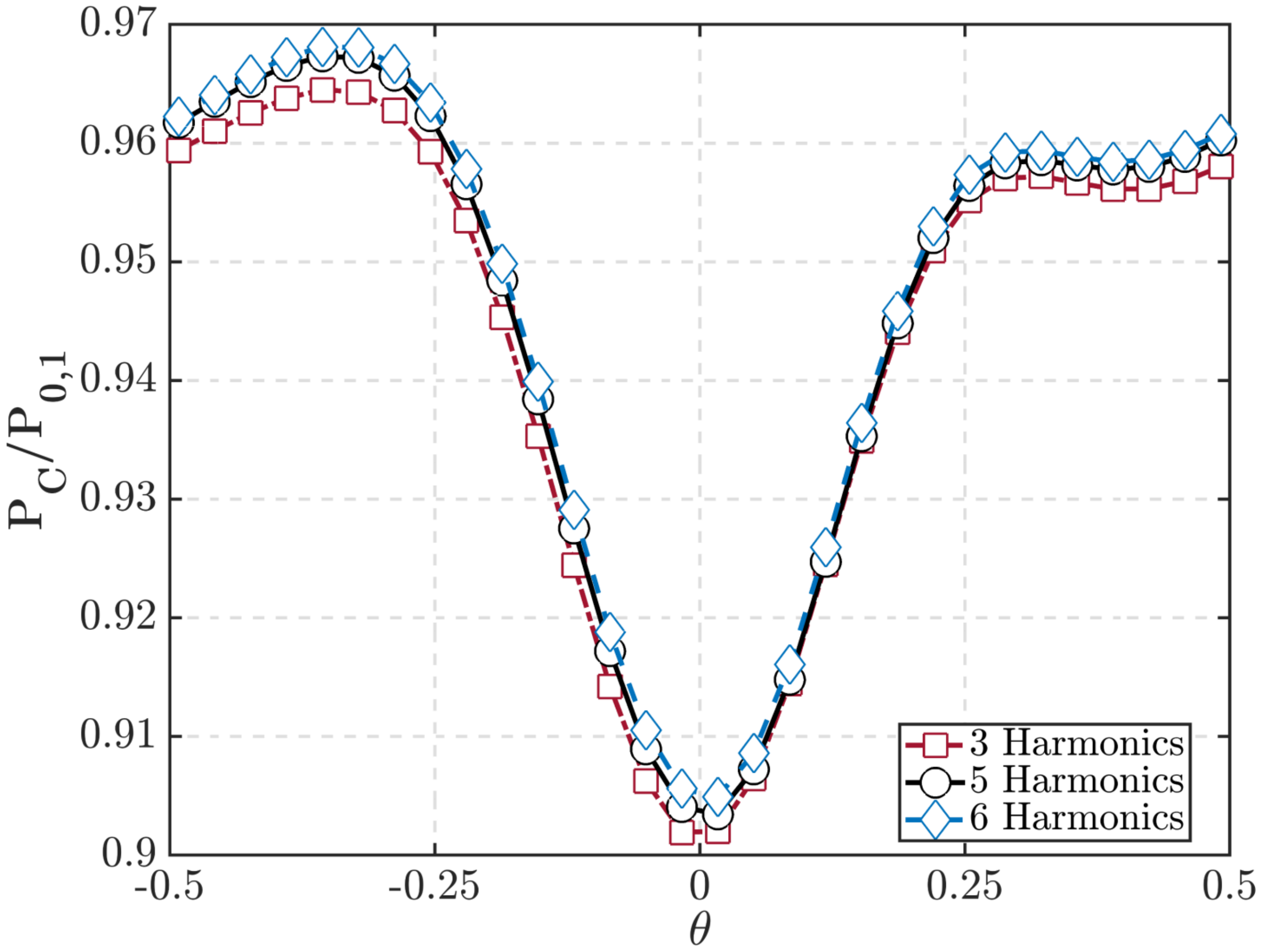
$$P_{ave} = \frac{P_U + P_D + P_L + P_R}{4}$$



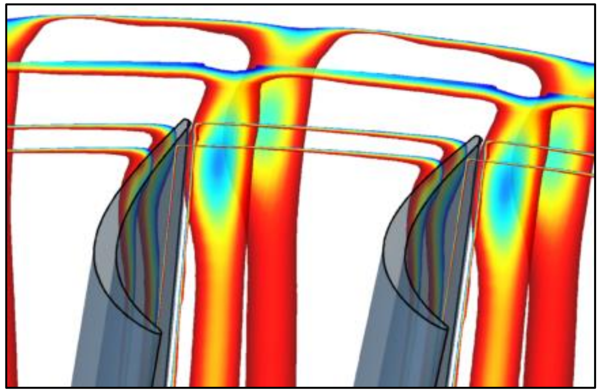



# Number of Harmonics

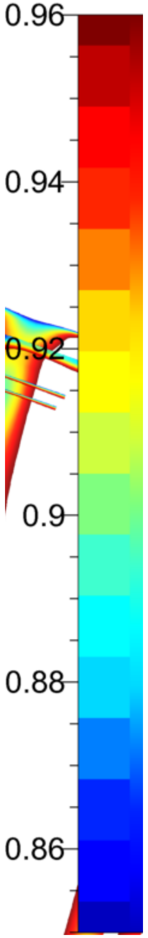


# Aerodynamics

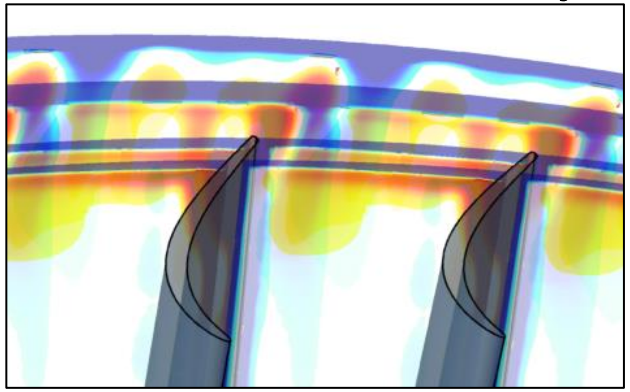
**Vane-only data**

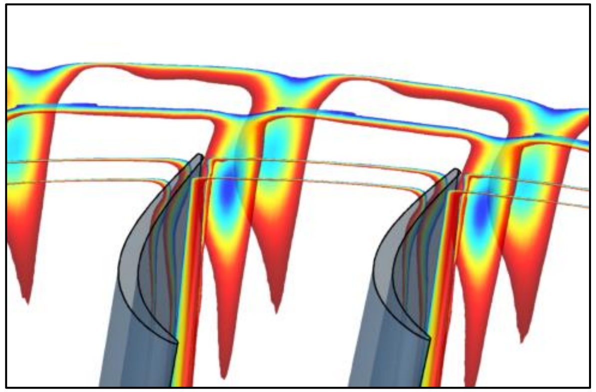


$P^{*}_{0,2}/P_{0,1}$

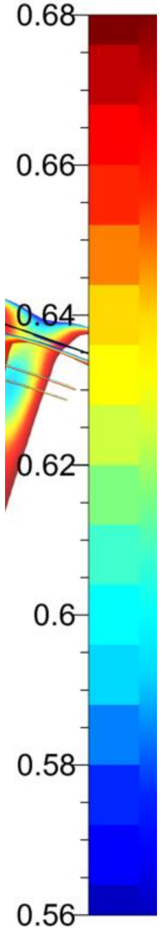



**Axial Vorticity**

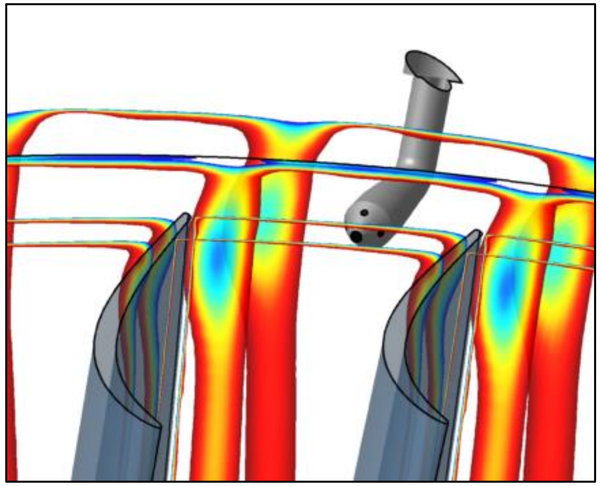


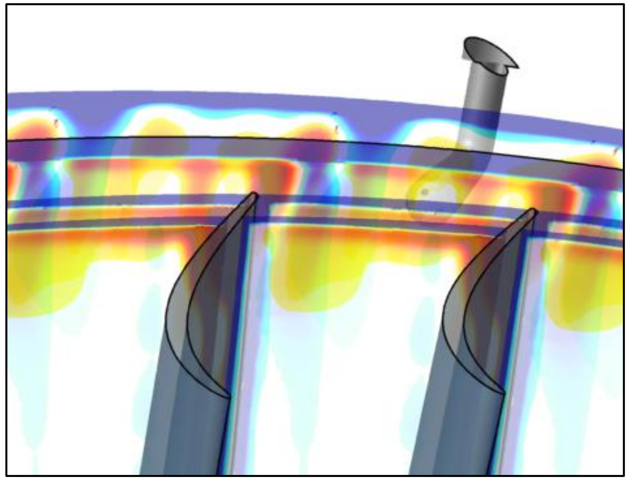


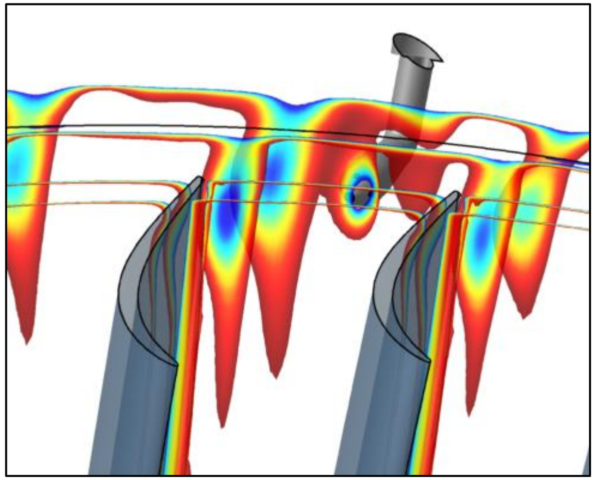
$Mach$




**Probe determined data after 2SC**







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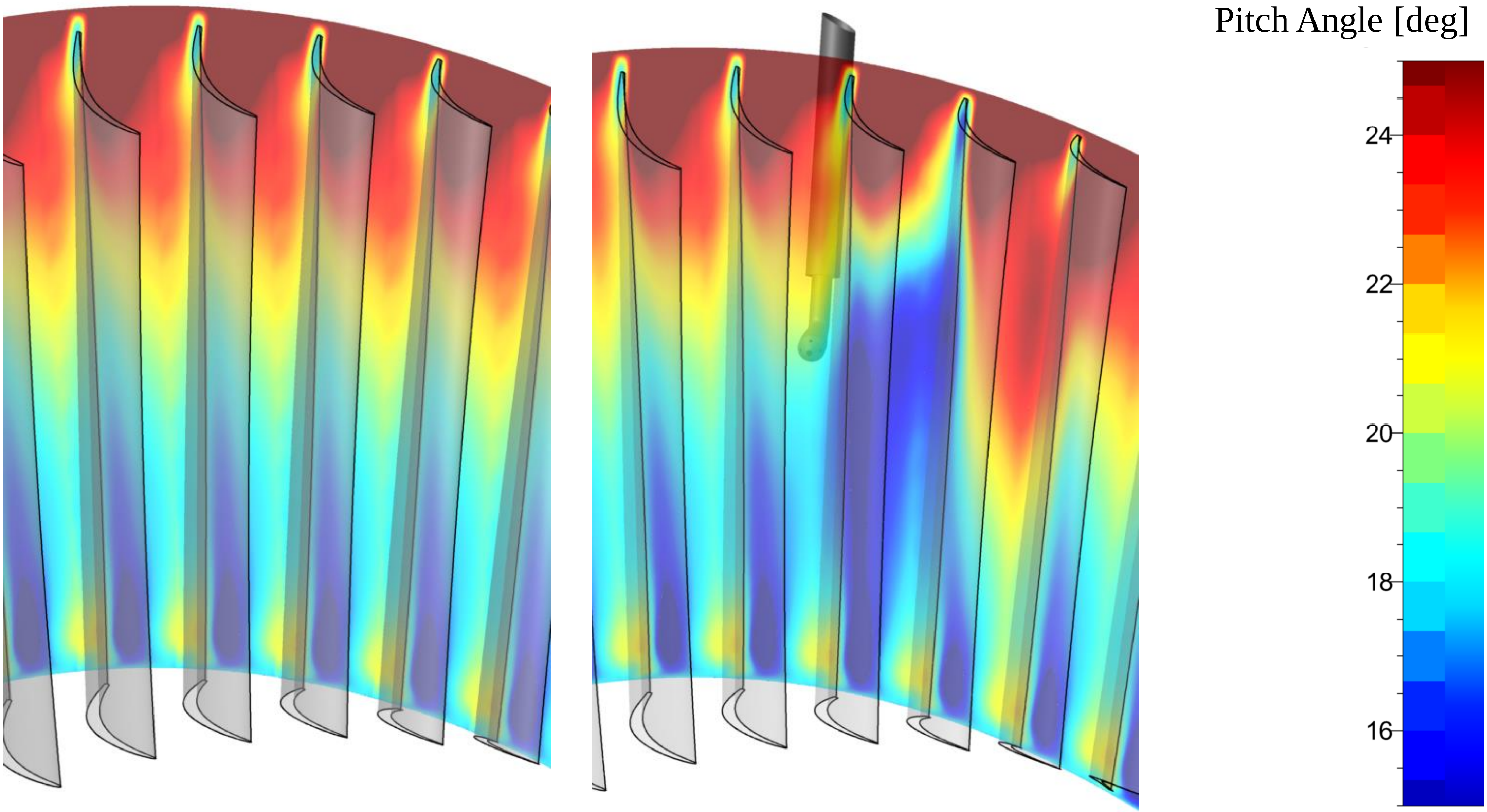

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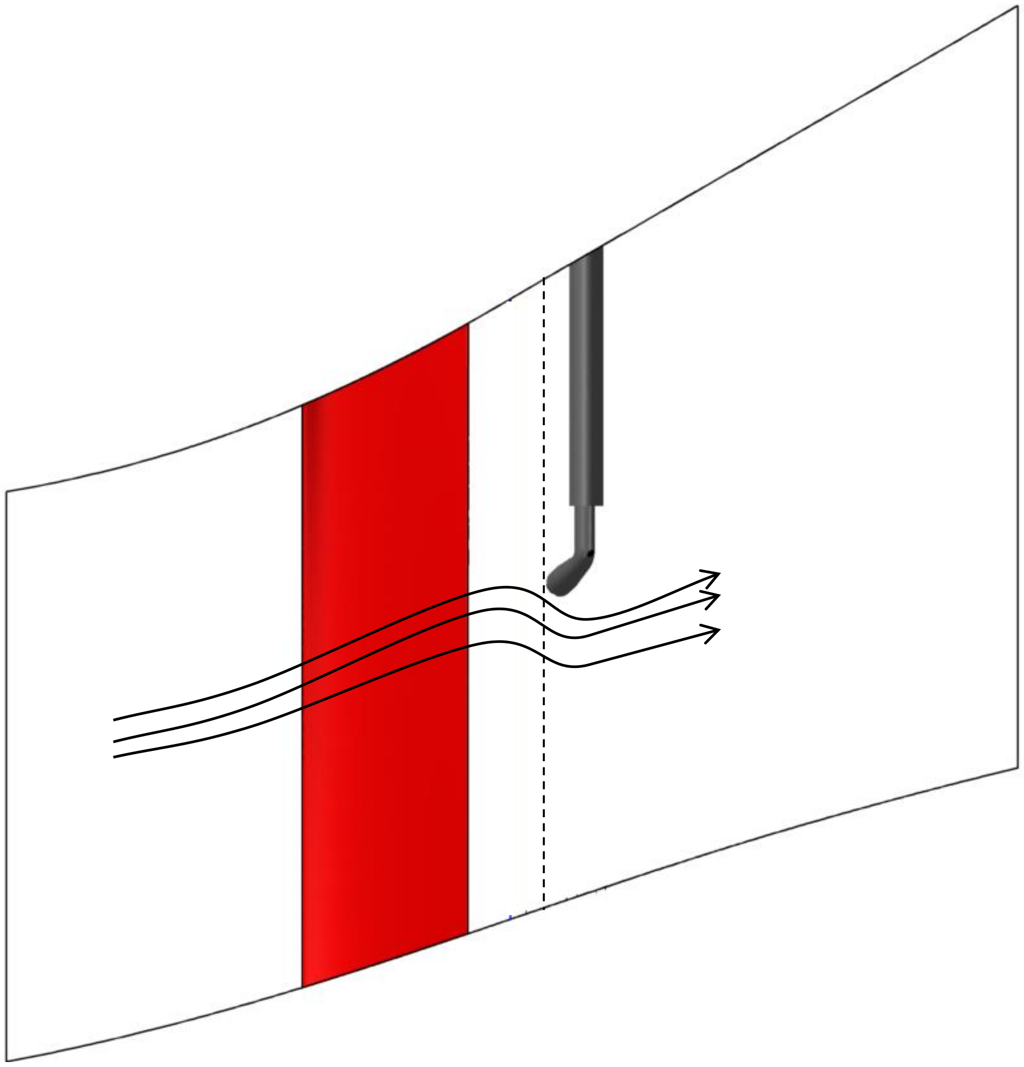

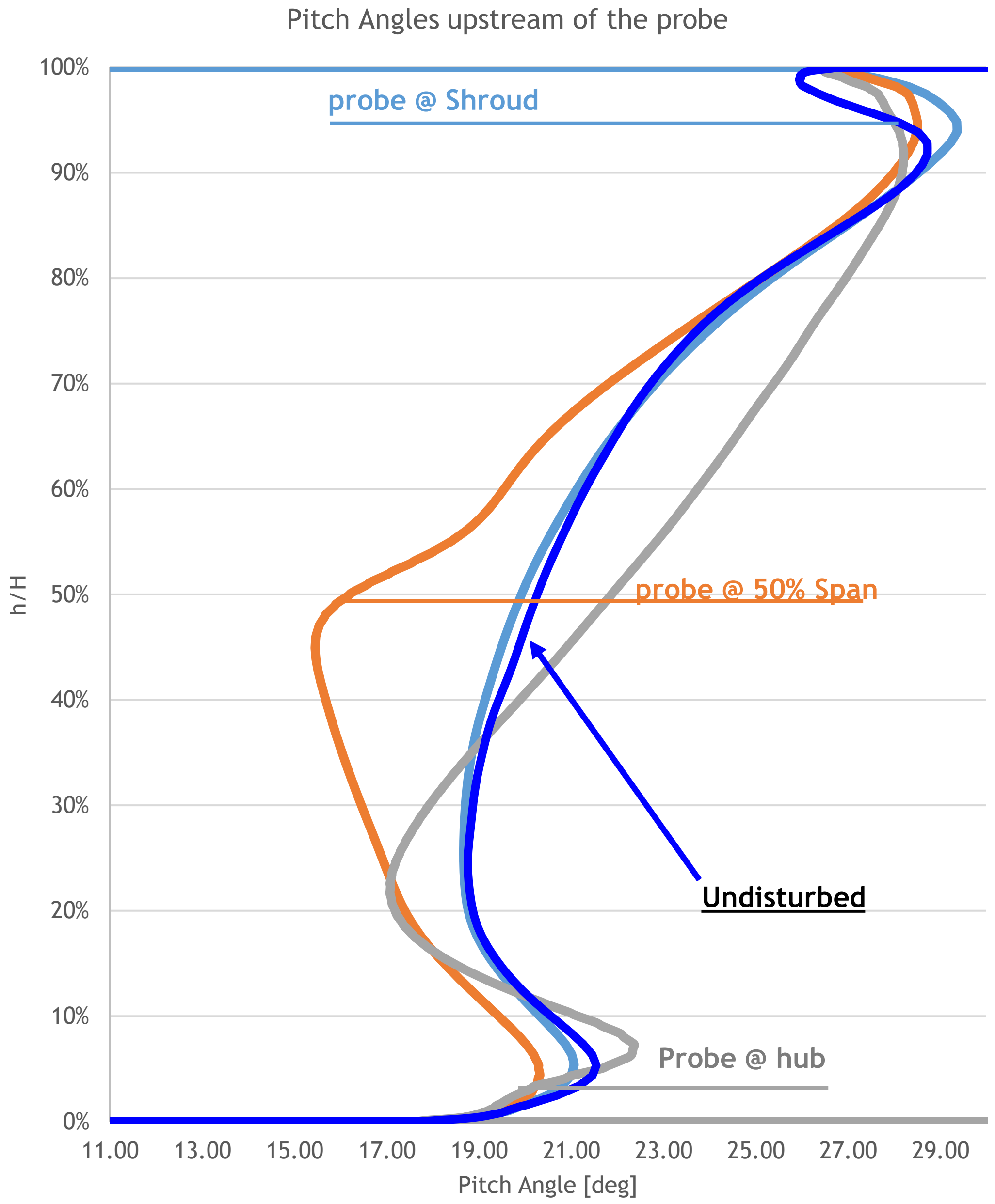

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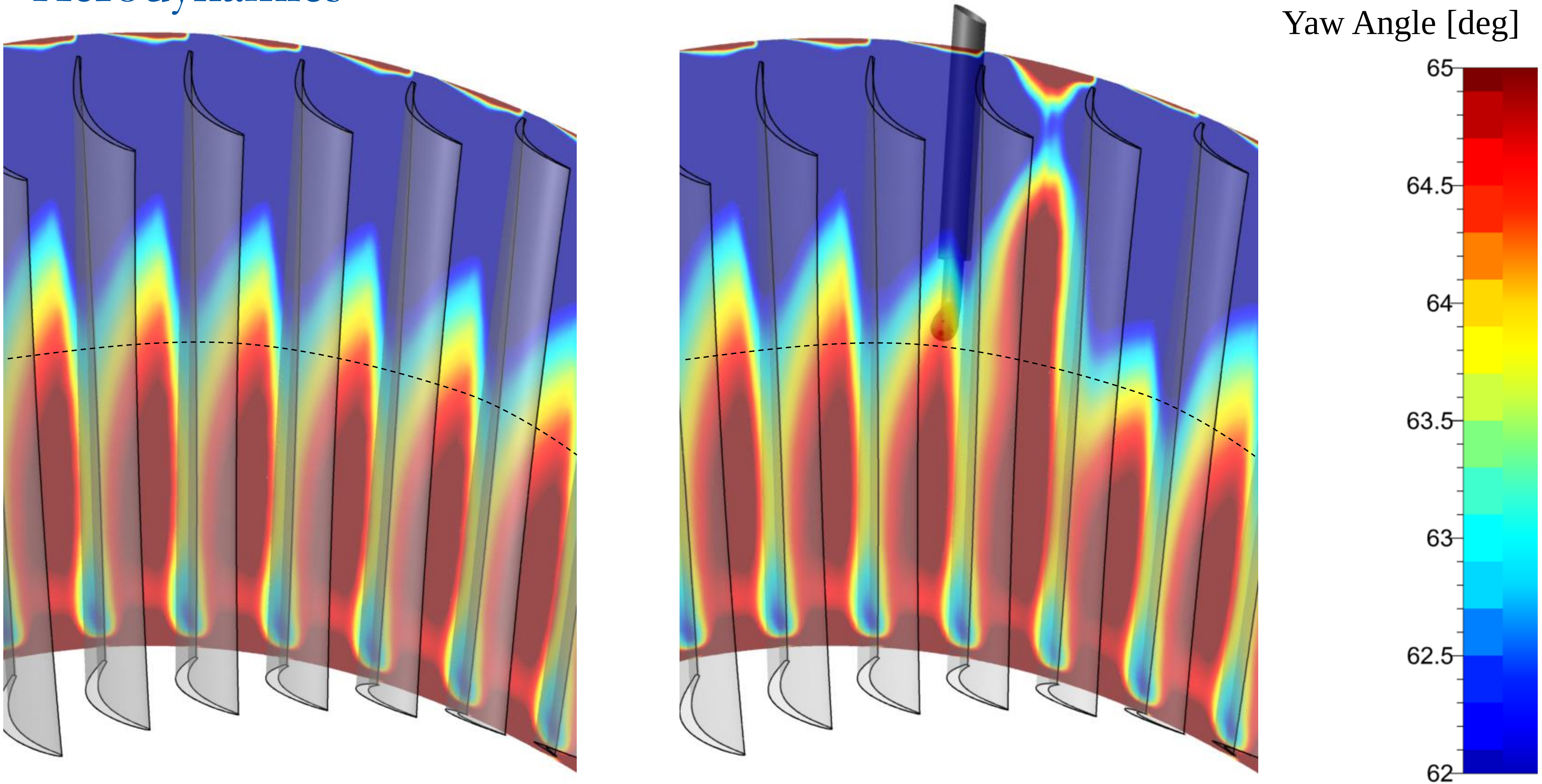

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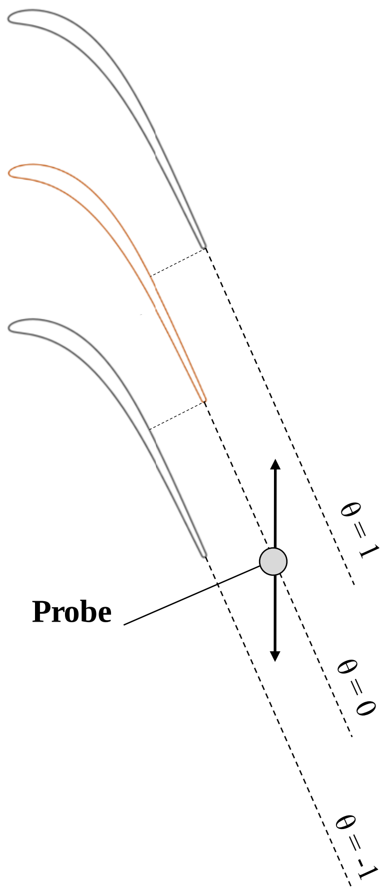


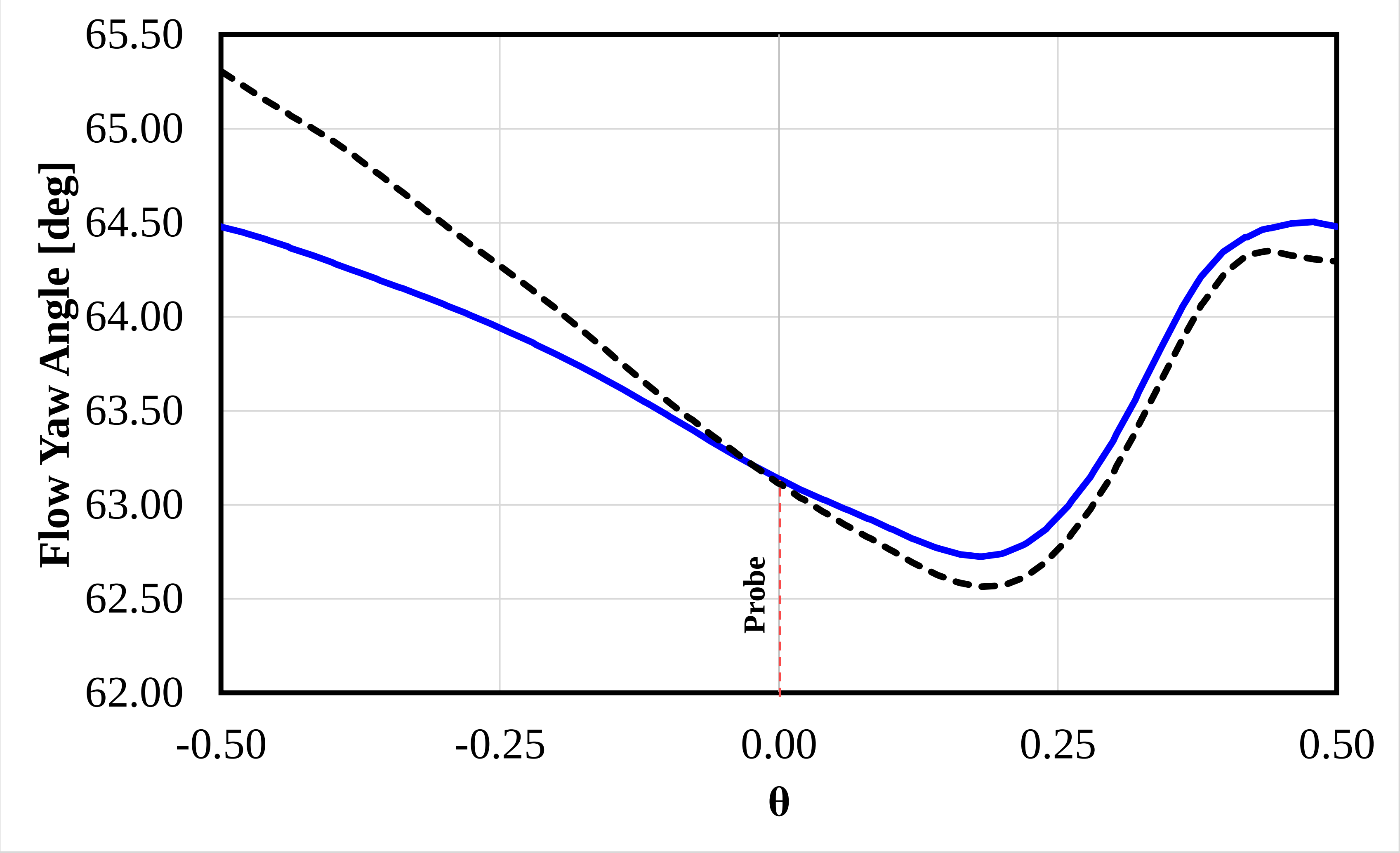

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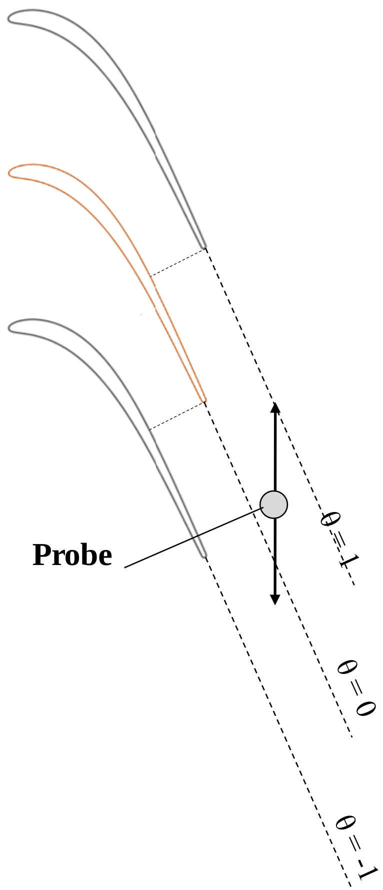


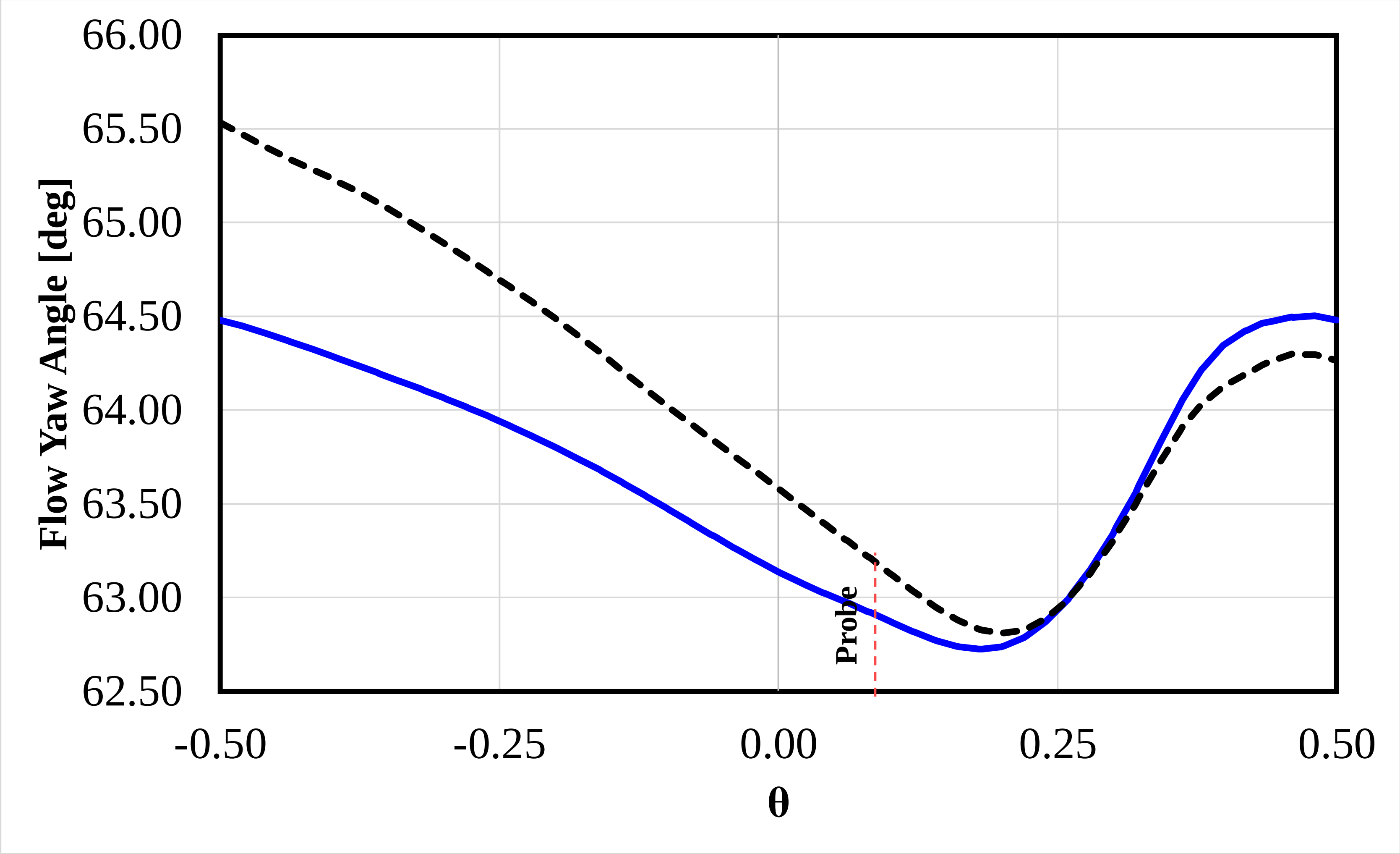

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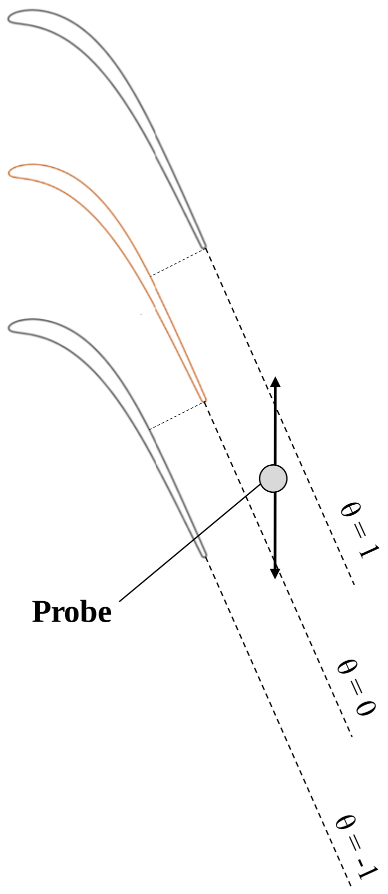


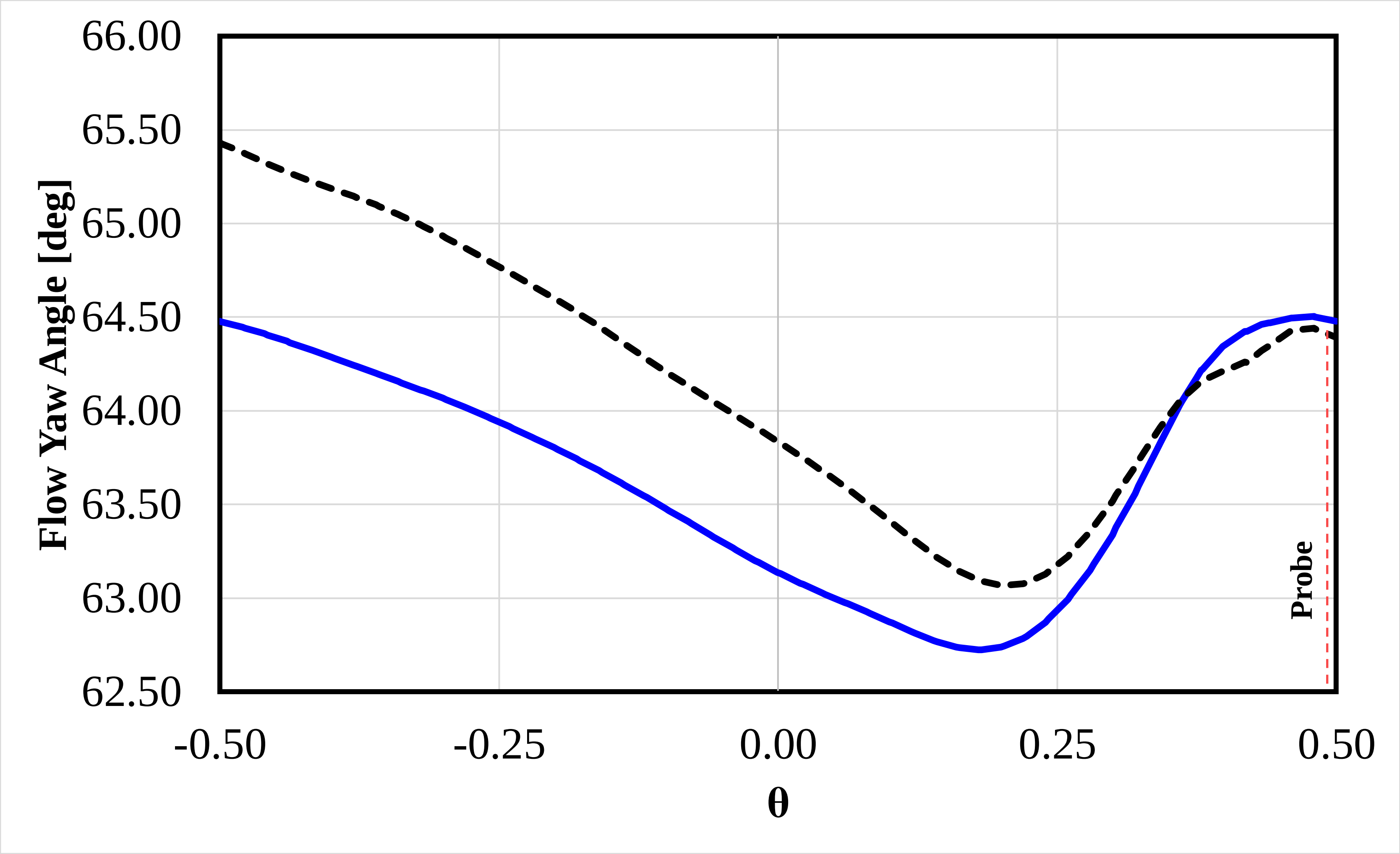

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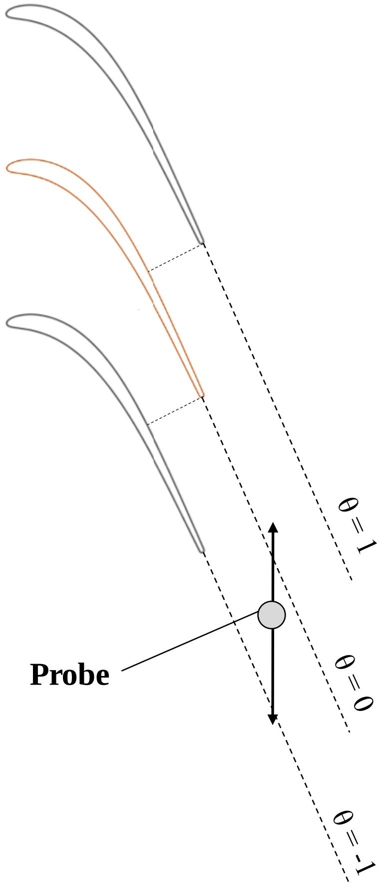


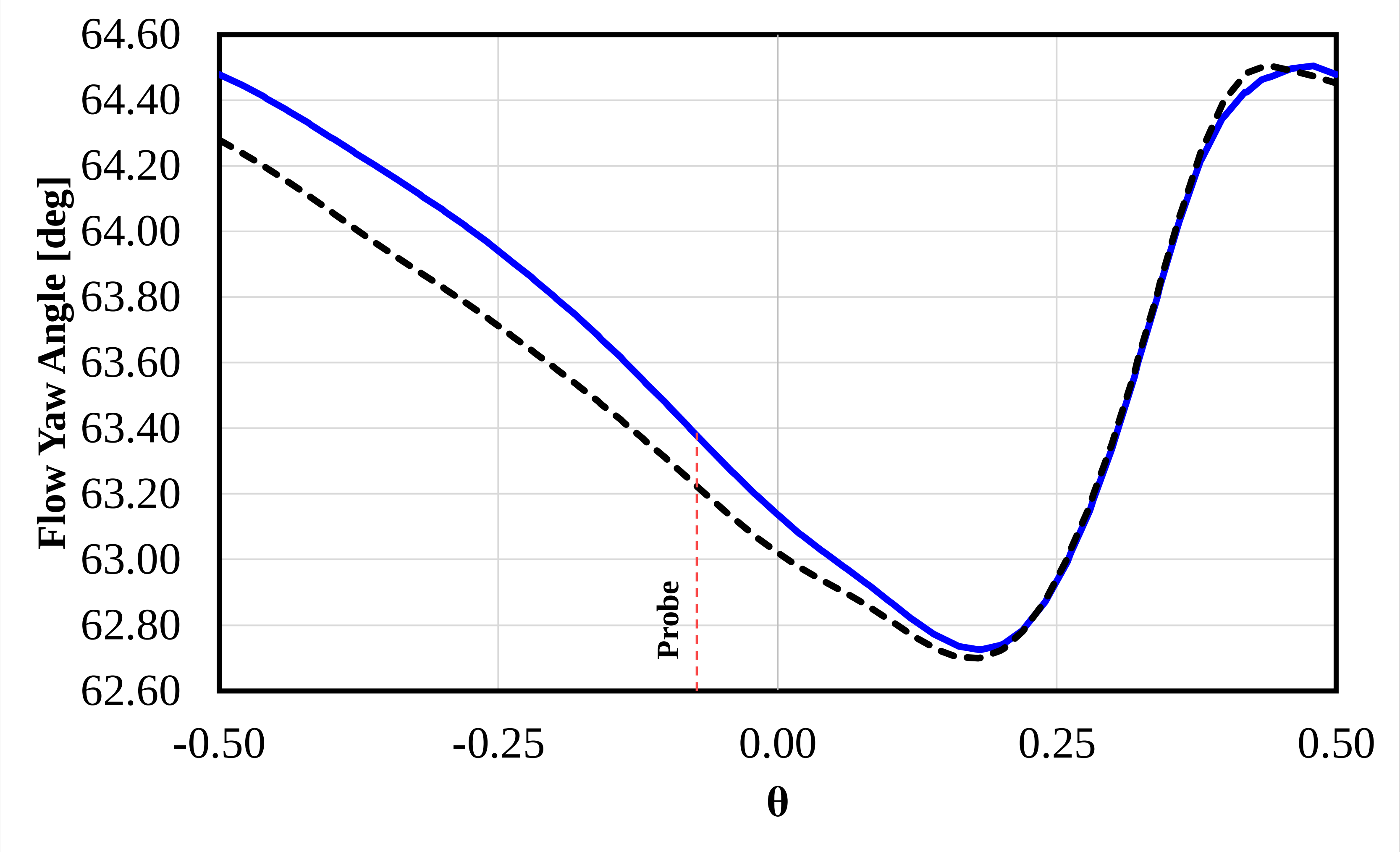

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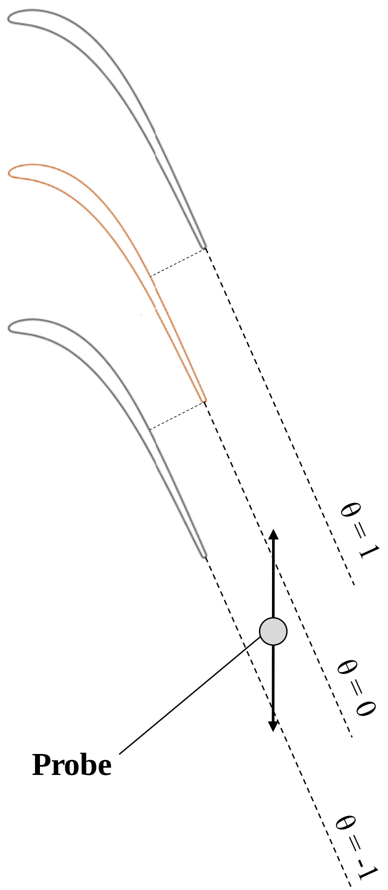


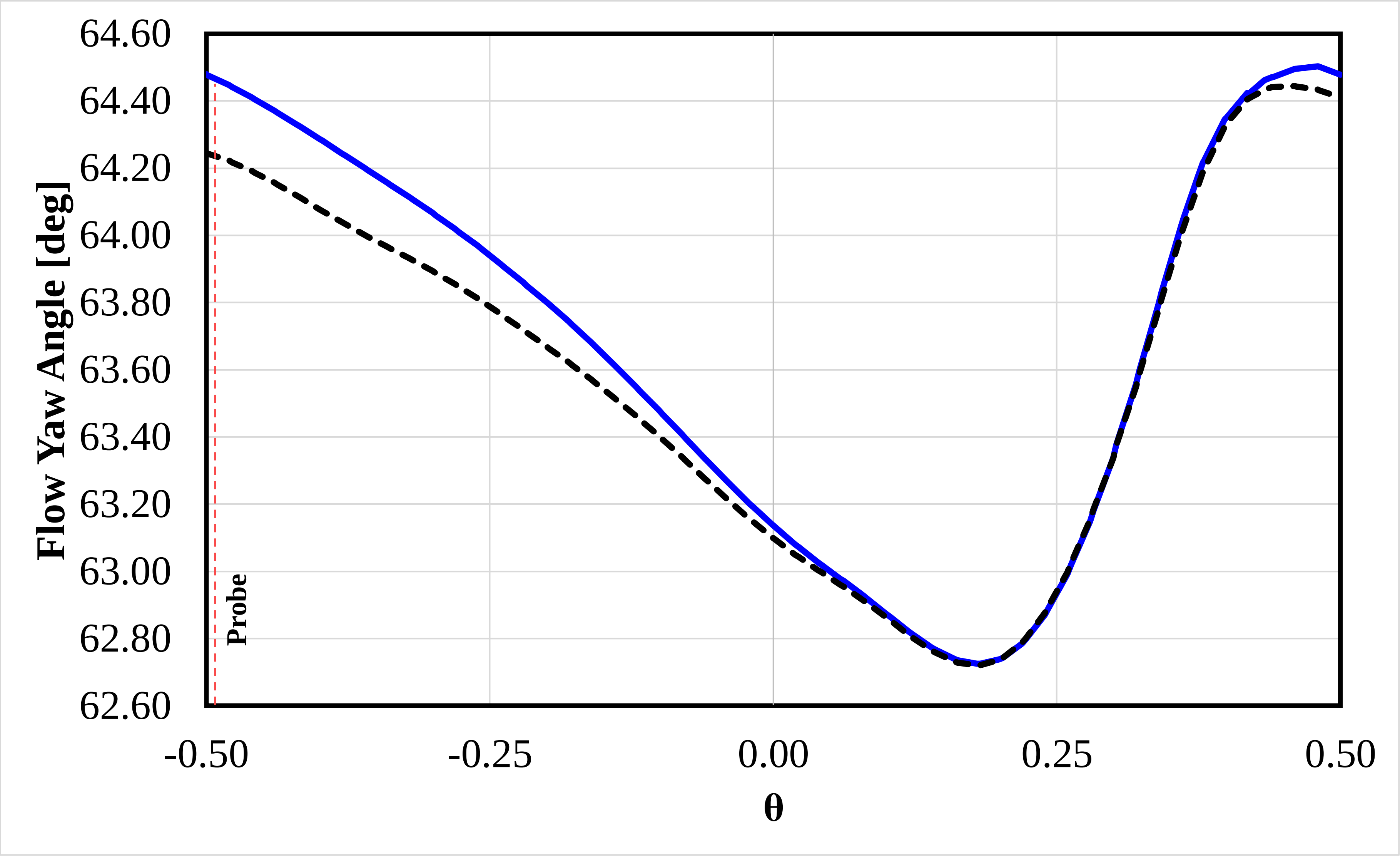

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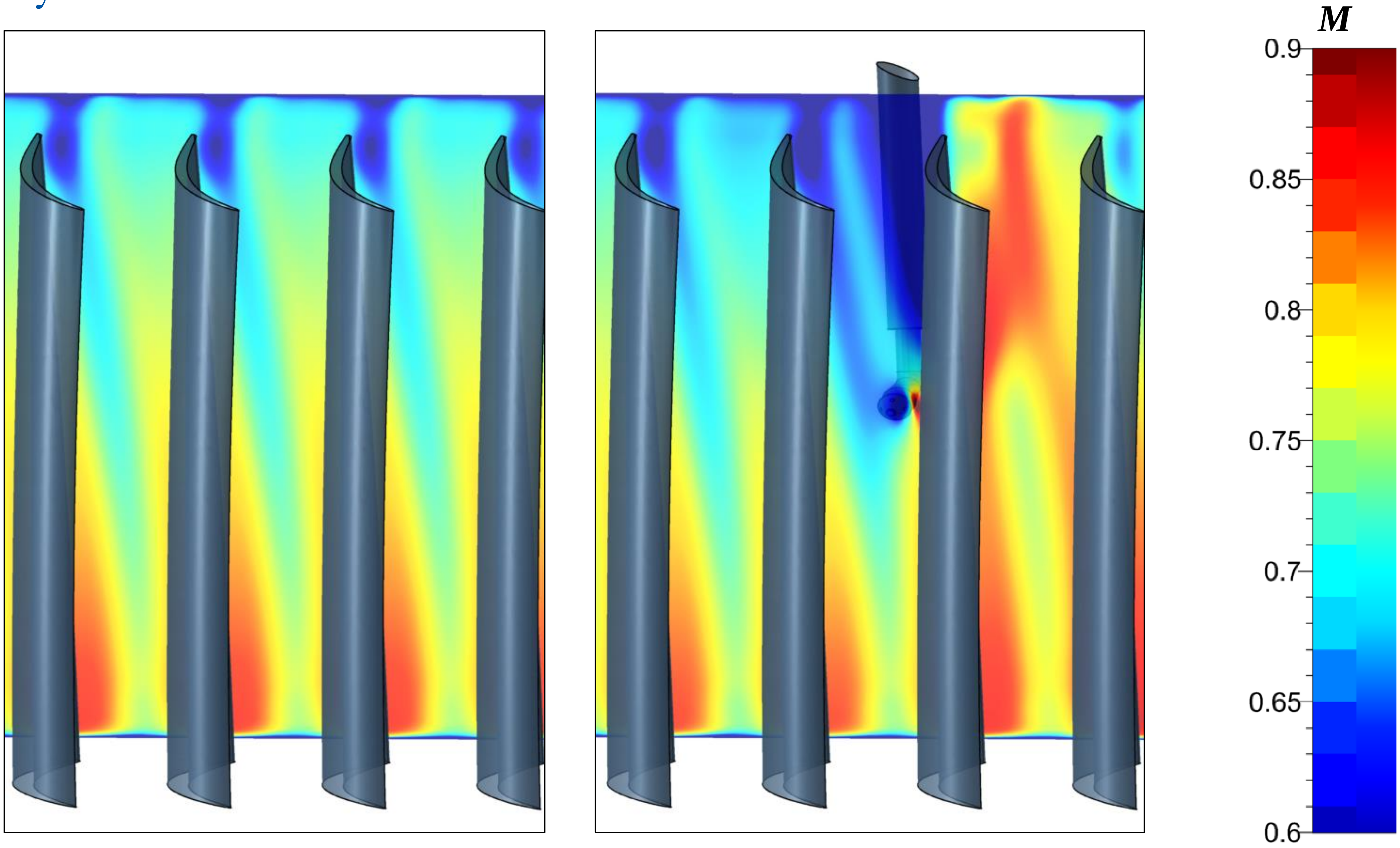

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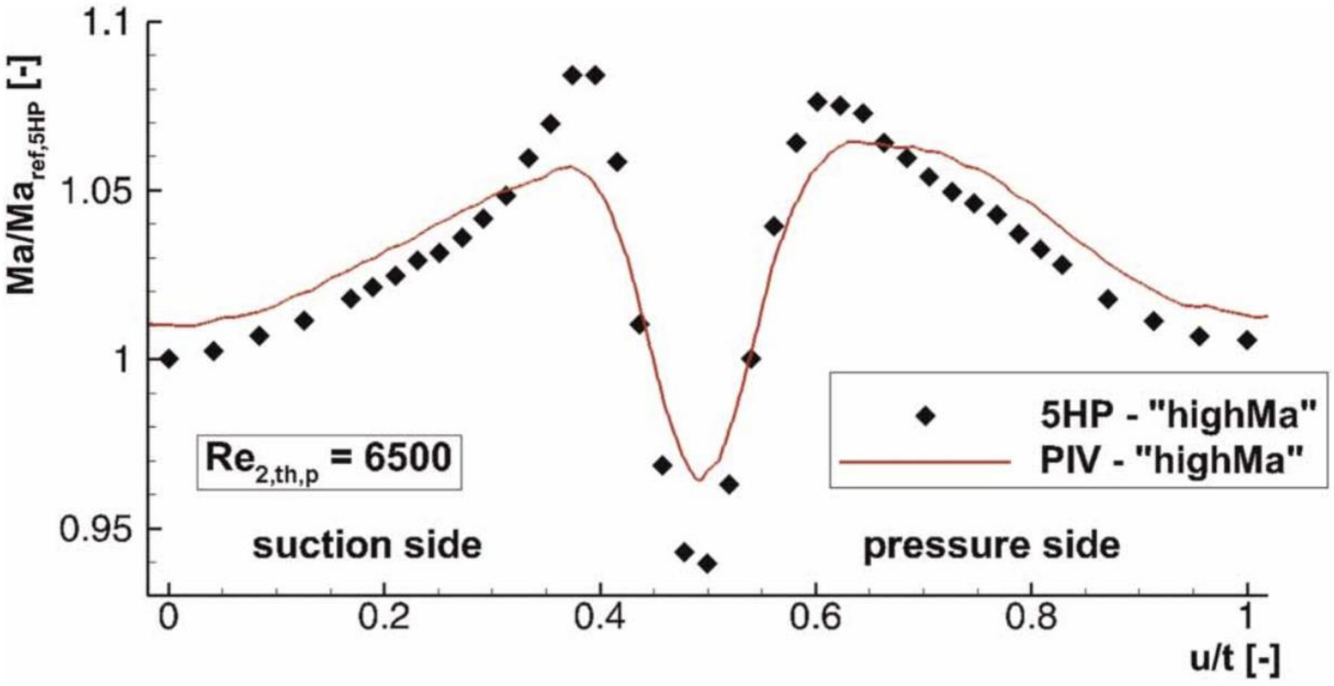


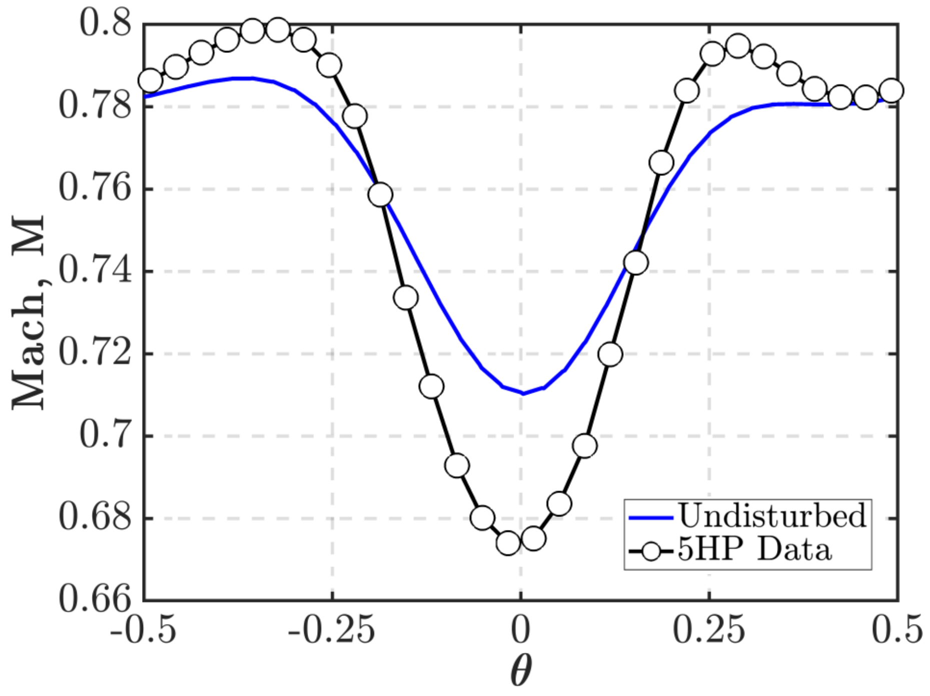

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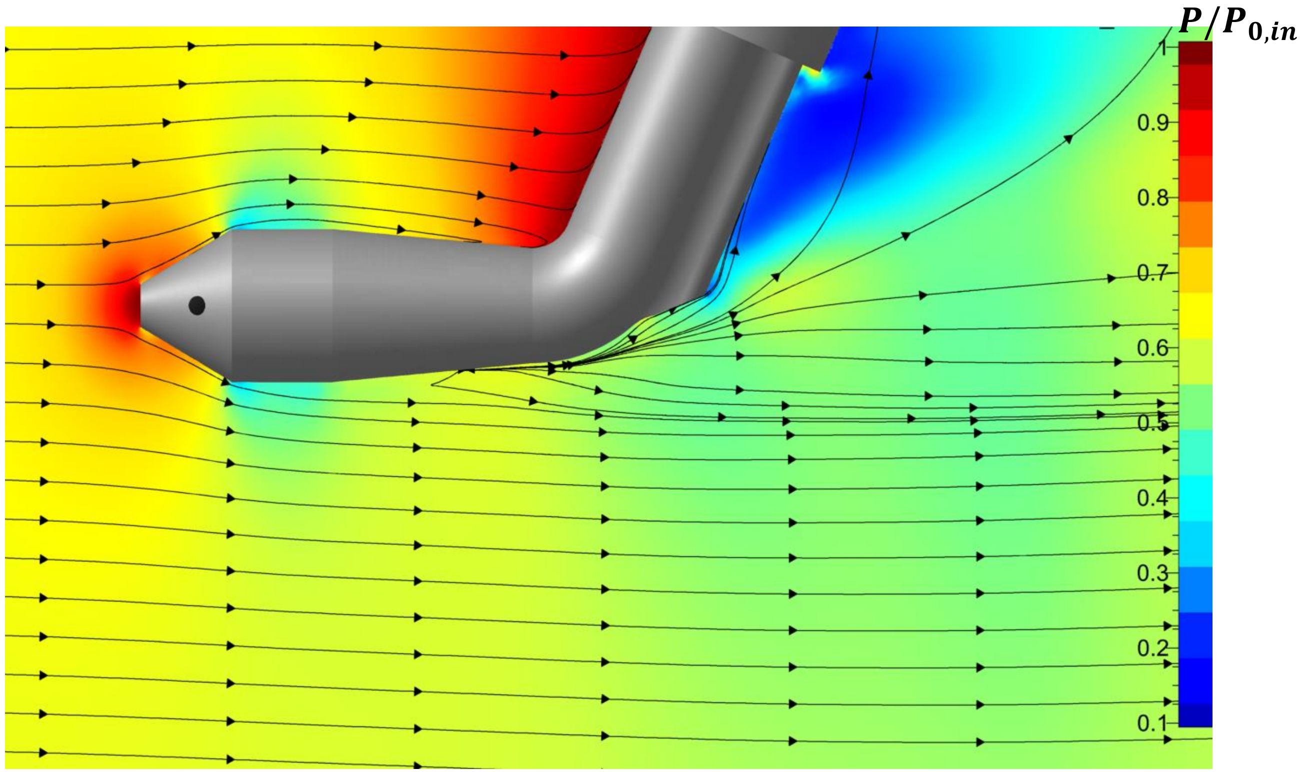

# Probe-determined data: Errors

| | Validation Case #1 | Validation Case #2 | Validation Case #3 |
|---|---|---|---|
| **Inlet Yaw Angle [deg]** | 12.5 | 0 | 15 |
| **Inlet Pitch Angle [deg]** | 0 | 12.5 | -15 |
| **Mach Number** | 0.9 | 0.9 | 0.915 |