Can Cambered Blades Help Cross-Flow Turbine Performance?

Experimental Exploration of Turbine Performance and Blade Forces

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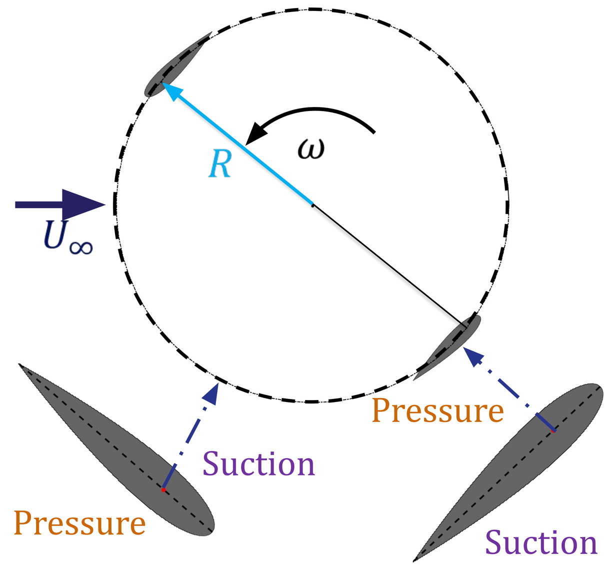
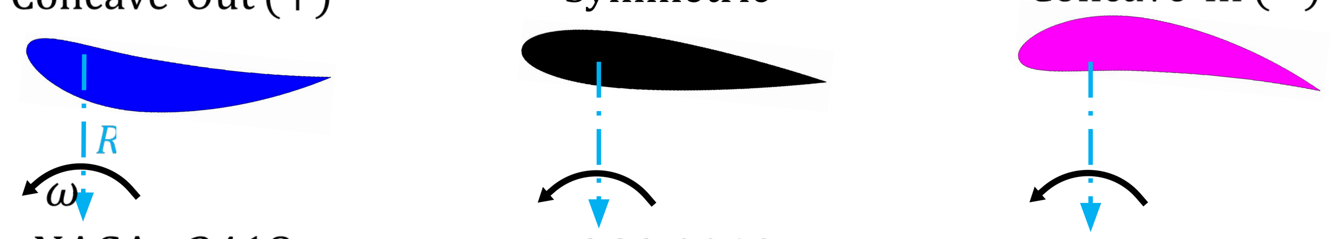
Why Cambered Blades?

As the blades of a cross-flow turbine rotate, the angle of attack changes sign. Symmetrical blades commonly used due to changes in AOA sign, however this is a flawed argument due to curvature effects.

- With the change in angle of attack the suction and pressure sides of the blade switch.
- In rectilinear applications, cambered foils have been used to improve lift and control forces if oriented appropriately to the flow.
- As most of the power in cross-flow turbines is produced upstream, it was hypothesized that total power production would improve by using a cambered blade to augment upstream performance.
- **No extensive experimental work has been conducted on the benefits of cambered blades**

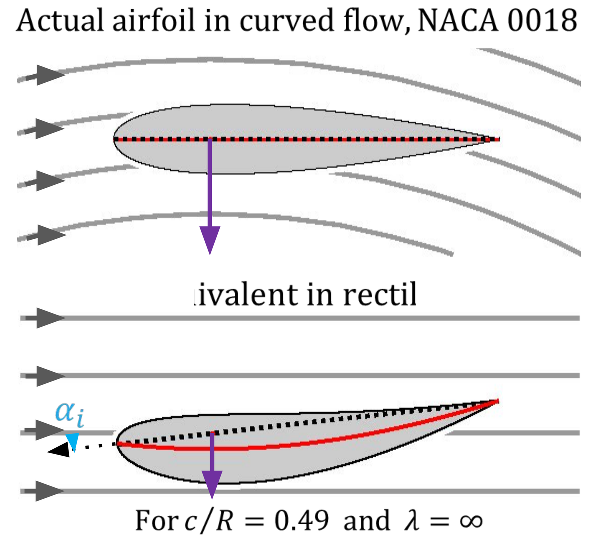


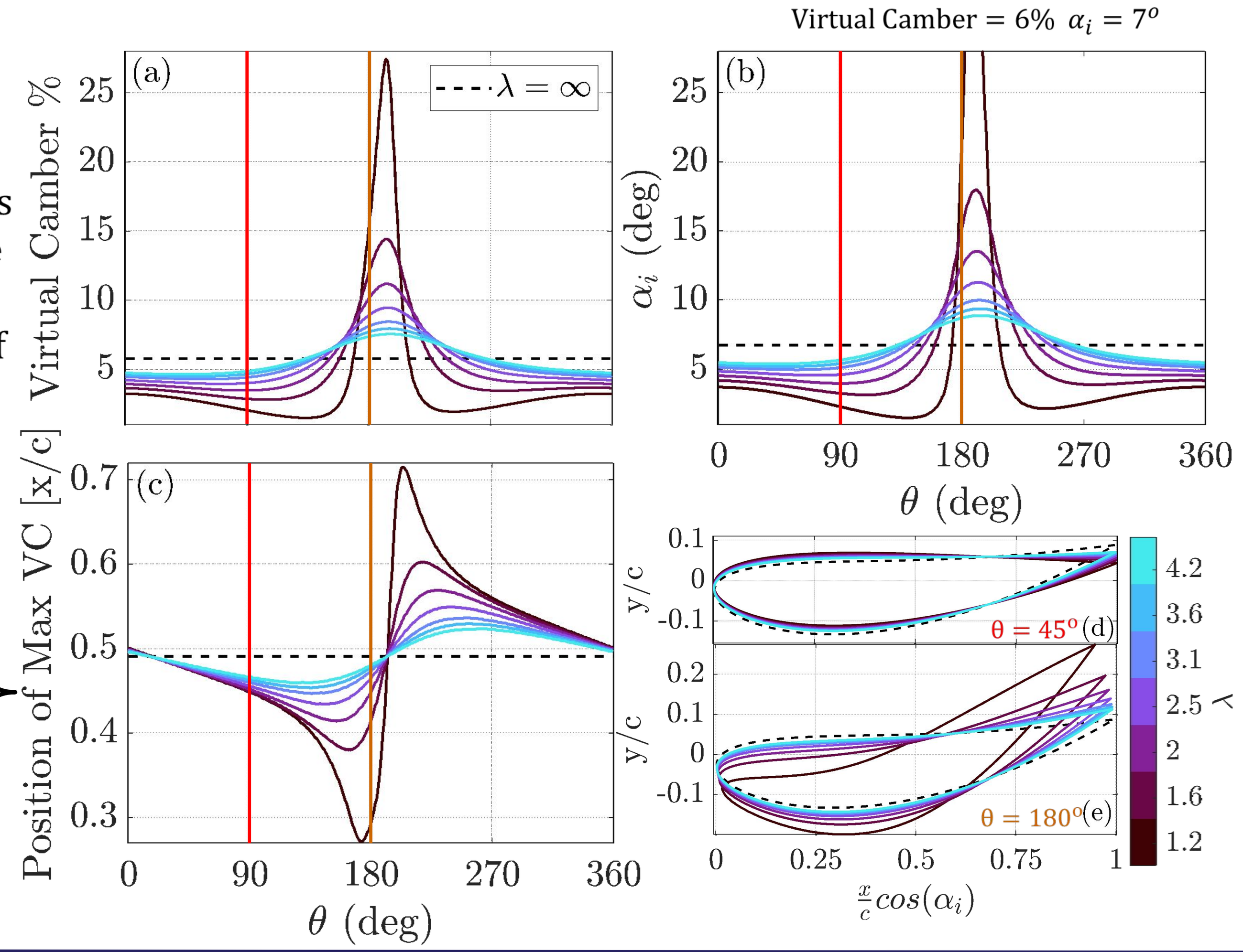
Nomenclature:



Geometric vs Virtual Camber

- Rotational motion of blades causes symmetrical foils to behave as a cambered foil at an angle of incidence in a linear flow, this is known as "Virtual Camber"
  - This negates the historical reasoning for the use of symmetric foils
- By considering the virtual camber effect, geometric camber can either accentuate (concave out) or nullify (concave in) the already-present virtual camber the blades perceive due to the rotation
- The virtual airfoil profile fluctuates as a function of λ, chord-to-radius ratio and blade pitch, but independent of geometric camber

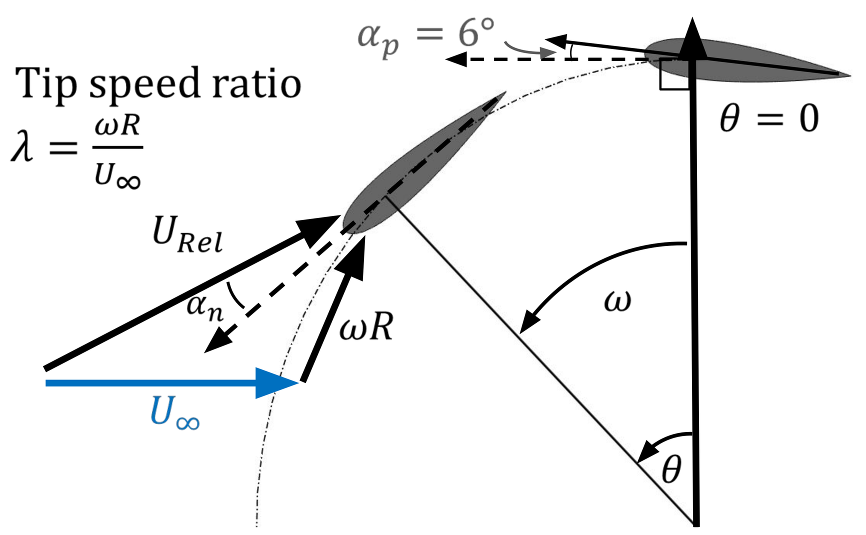


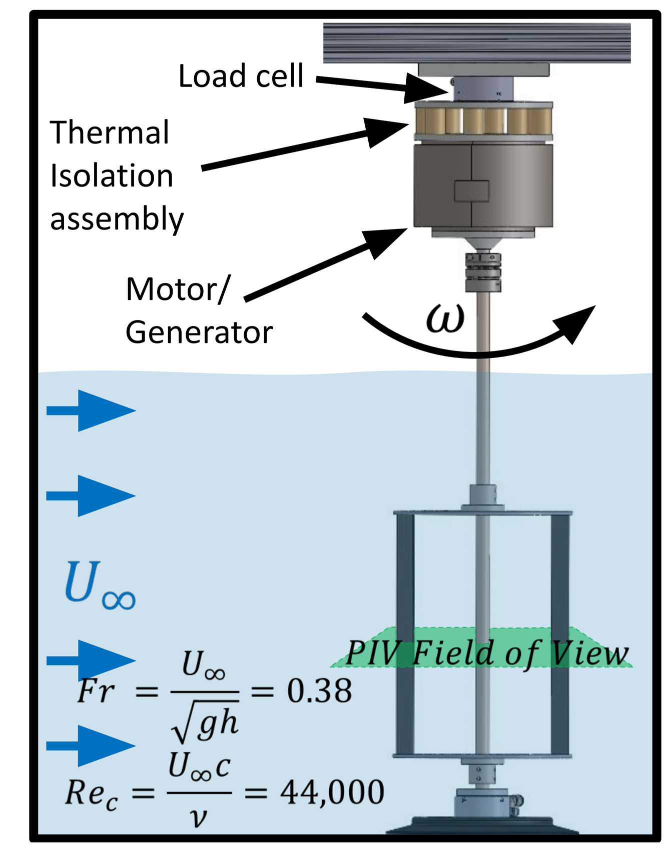


Calculated for our standard turbine geometry (c/R = 0.49 and α_b = 6°) using conformal mapping method developed by Migliore *et al.*, [1]

Experimental Methods

- Forces and moments measured with 6-axis load cells mounted at the top and bottom of the turbine for a one- and two-bladed turbine
- Particle Image Velocimetry (PIV) for $\lambda = 2$ to explore near-blade hydrodynamics
- Tip speed ratio $\lambda = \frac{\omega R}{U_\infty}$



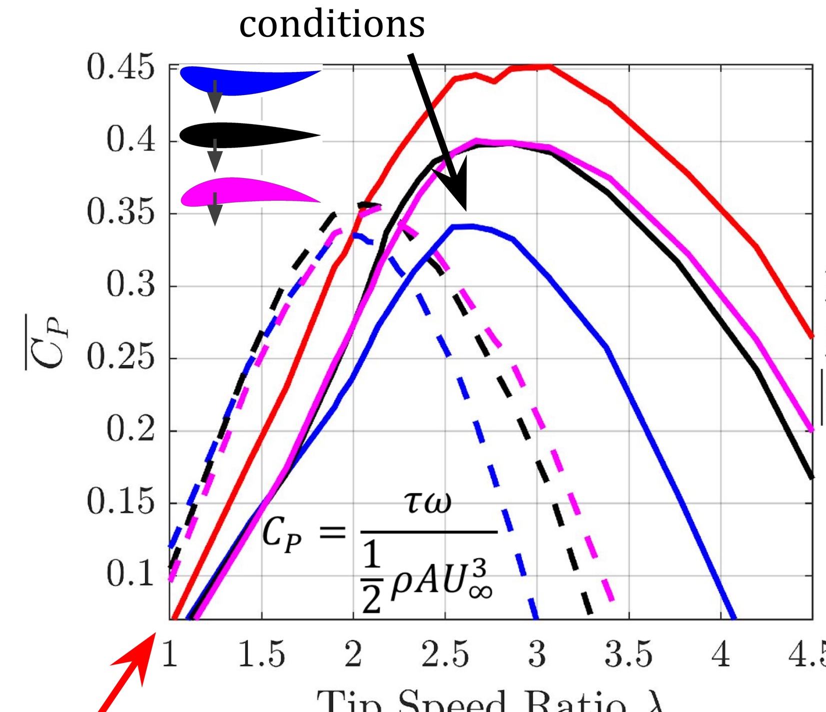


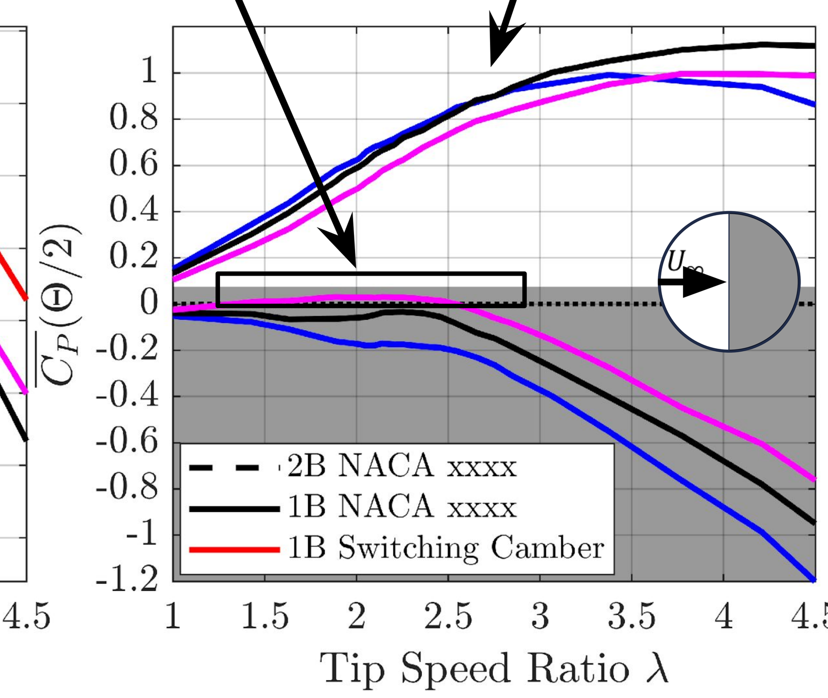
Performance Results

The camber that enhances upstream power generation does not actually increase overall performance under most conditions

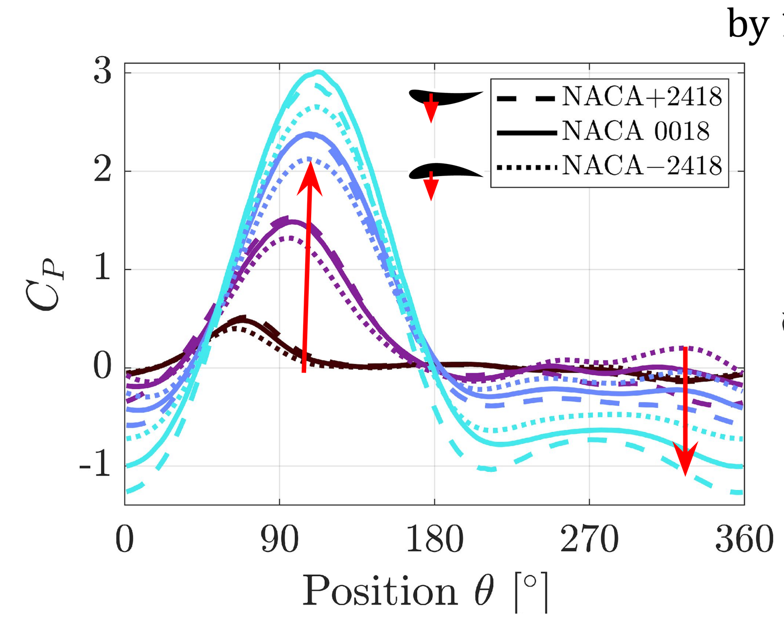
Concave-in can generate power downstream across moderate λ

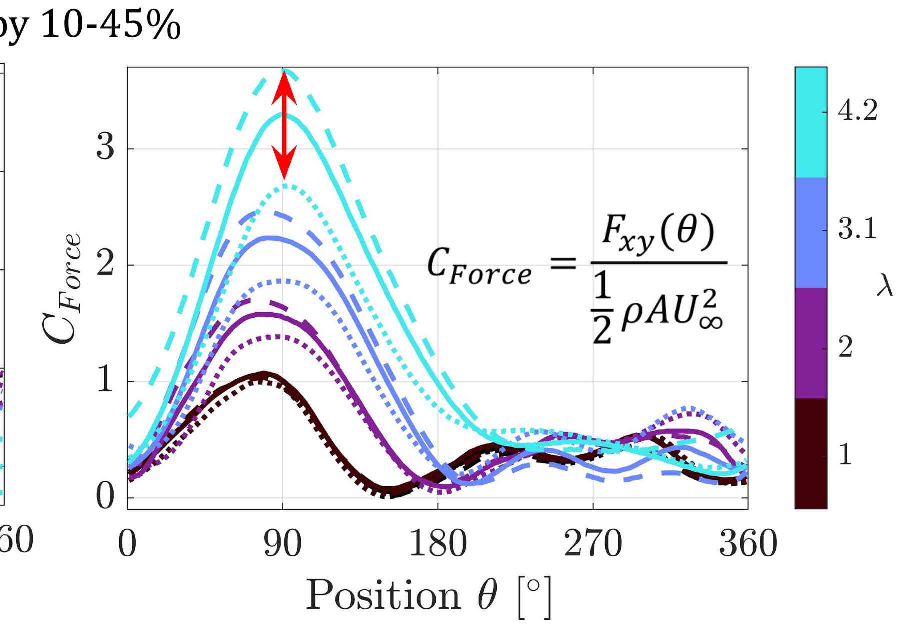
At high λ performance trends switch with the benefits of concave-out dropping off





Red line, actively cambering through the cycle (averaging the best profile upstream and downstream) one blade turbine can improve efficiency relative to the symmetrical blade by 10-45%





Concave-out performs better at the peak for below-optimal λ but has increased losses through the cycle. Concave-in is consistently worse upstream but is compensated by downstream improvement

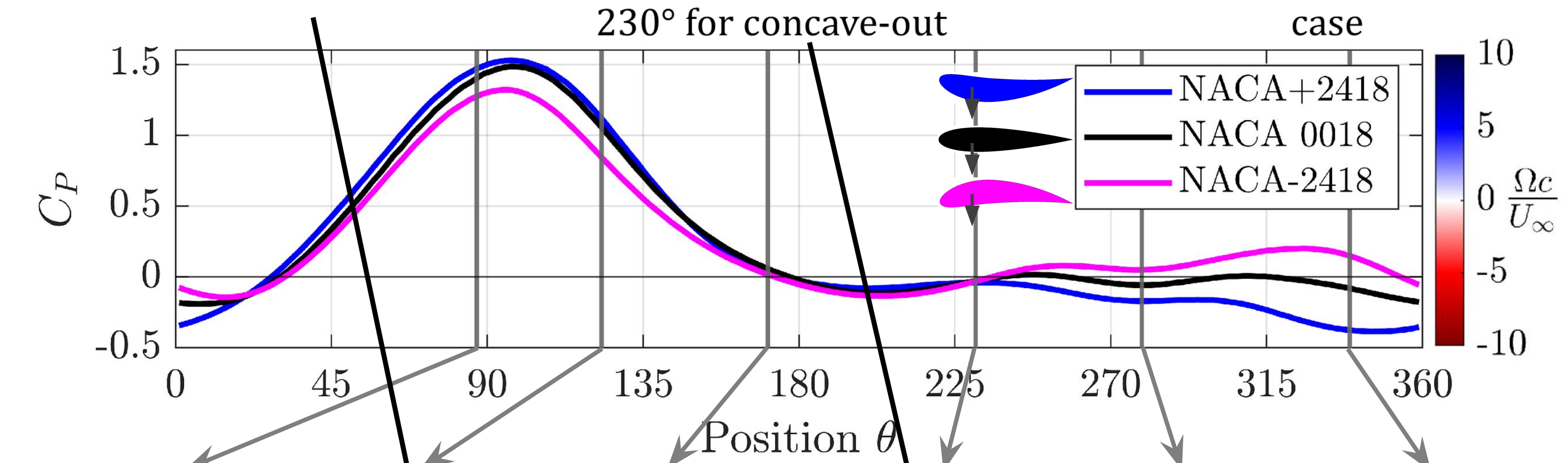
Concave-in consistently reduces peak force while positive camber increases it across all λ while

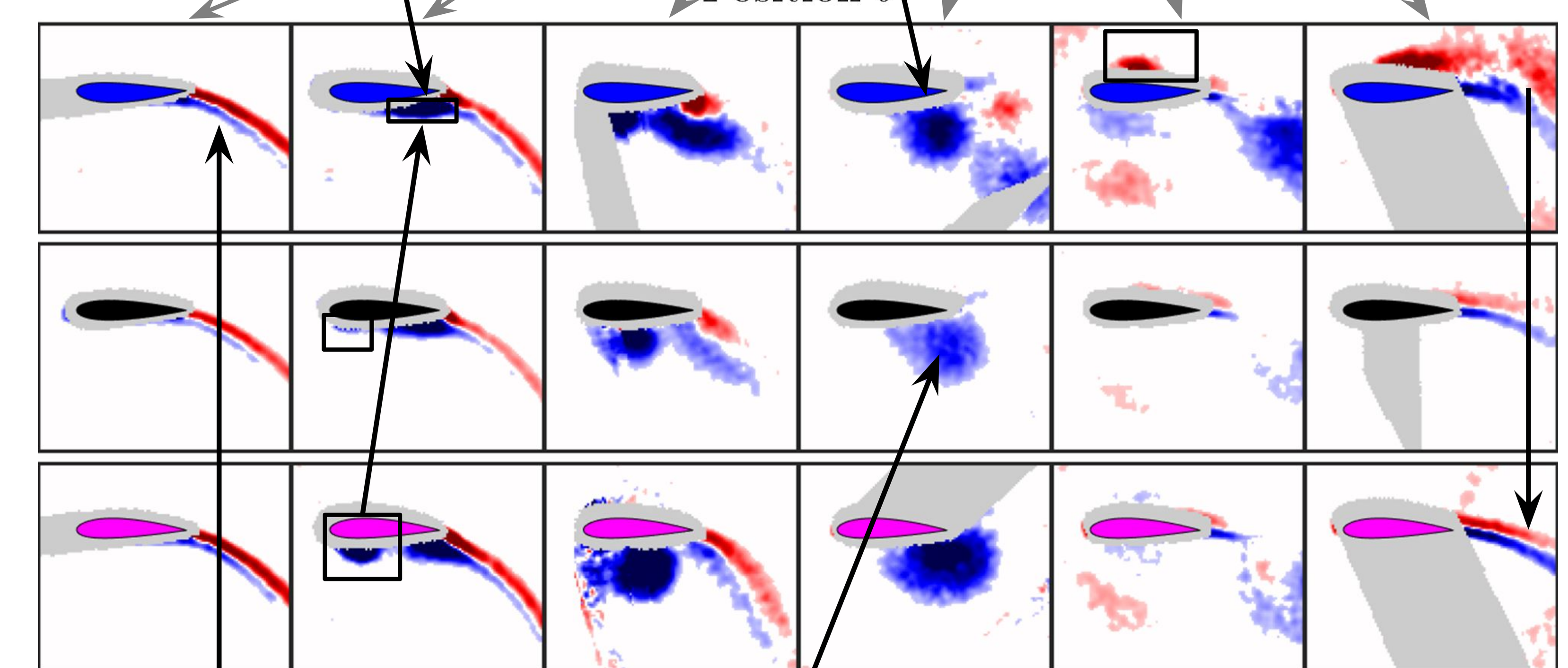
Near Blade Flow Fields $\lambda = 2$

Delayed flow separation upstream in the concave-out case

Unlike other cases **two** counterclockwise (blue) vortices seen at 230° for concave-out

Additional flow separation occurring downstream at 280° in the concave-out case





All cases see similar dynamics near peak power production (90°)

Symmetric case sees the weakest dynamic stall vortex in the flow near 230°

Improved reattachment with concave-in case around 340°

Key Take Aways

- **Concave-in camber can match or improve efficiency at or above peak λ while diminishing maximum loading compared to a symmetrical bladed turbine**
- Concave-out camber performs best upstream until high λ and concave-in is best downstream, but the <u>**peak time average is nearly equivalent for 2% concave-in and symmetrical blades**</u>
- The different cambered blades were shown to perform better relative to a symmetric blade at over-speed or under-speed control but not across a full range of λ
  - Supporting recent work by Abigale Snortland indicating the importance of downstream improvement at high λ values [2]
- **Active cambering** shows potential to significantly improve efficiency!
- See talk by Caelan Consing (Session 10, 3:30-5*pm* the 8th) to learn more about the flow-field phenomena and a wider range of camber geometries explored through CFD

Acknowledgments: Thank you too Abigale Snortland, Mukul Dave, and Aidan Hunt for helpful discussions on the effects of camber

References: [1] Migliore et al., West Virginia University. 1980. [2] Snortland, et al., *EWTEC.* Vol 15. 2023.

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