Angle of Attack Estimation for Cross-Flow Turbines

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Introduction

A common parameter used to examine the performance of airfoils is the lift of the blade (see Fig. 1). Lift is defined, traditionally, as the force on the blade normal to the incoming flow, and it experiences variations depending on the relationship between the blade geometry and the flow itself. Too large of an angle of attack (α), and an airfoil will enter stall, where it produces much less lift relative to its drag. In cross flow turbines, or CFTs, the blade rotates around the circumference of the turbine (Fig 2) which drastically changes the angle of attack, creating dynamic stall. Much of our understanding of dynamic stall behavior comes from non-rotating flows, which don't suffer the induction seen in CFTs.

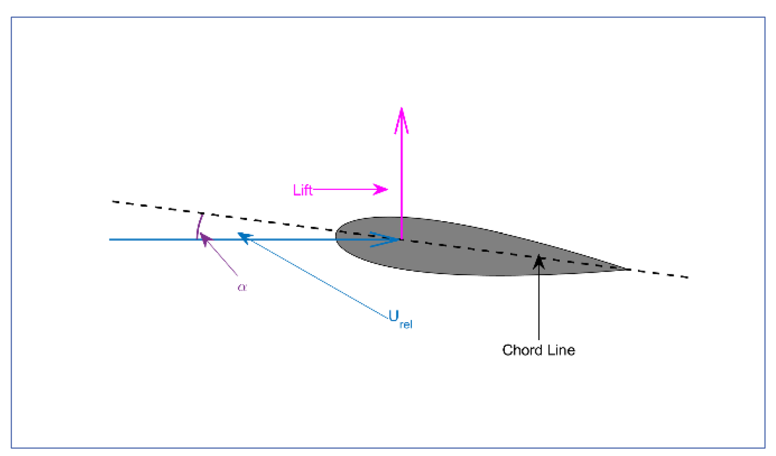

Figure 1: Orientation of significant terms relative to airfoil geometry

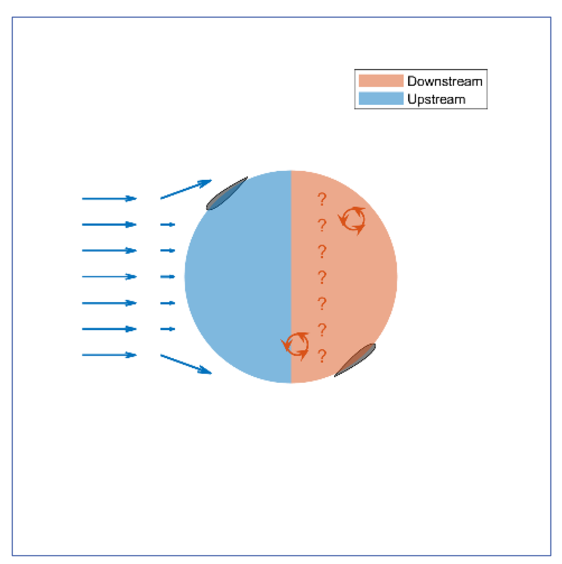

Figure 2: Flow diagram through a standard cross-flow turbine. In the upstream portion of the turbine, flow is simpler, but not truly uniform. In the downstream portion, blade induction significantly complicates the flow.

Motivation

To breach this gap in understanding, we need the angle of attack. If the uniform assumption is used, the nominal values can be calculated as shown below. With this, lift can be extracted from blade level forces, in theory.

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\lambda + \cos\theta}\right) + \alpha_p$$

$$\frac{|U_{rel}|}{U_\infty} = \sqrt{\lambda^2 + 2\lambda\cos\theta + 1}$$

However, when the flow passes through the turbine, it undergoes blade induction, invalidating that assumption. Typically, to get around this, time averaged data is studied. However, this degrades the accuracy of the representation of flow conditions. If we can find some way to select the "important" portions of the flow field and derive the relative velocity and angle of attack for a given phase, we can draw more complete conclusions about the turbine performance.

Methods

- Circle Averaged Velocity
  - Captures flow near the blade, but is susceptible vortex formation
- Rectangle Averaged Velocity
  - Not susceptible to vortex formation on the blade, but the phase is shifted significantly, as sampled flow fields do not affect the blade for some unclear time
- Reference Points Velocity
  - Easy, with less phase shift than the rectangles, but sparse and unhelpful if flow reverses

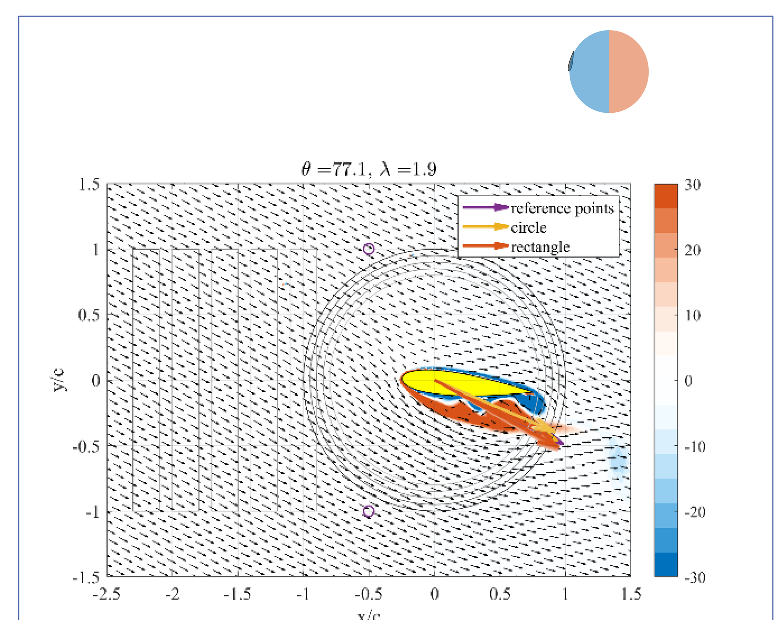

Figure 3: (a) Flow field and vorticity around a blade with a tip speed ratio of 1.9 at 77.1 degrees around the turbine. (b) Position of the blade from (a) in the turbine reference frame

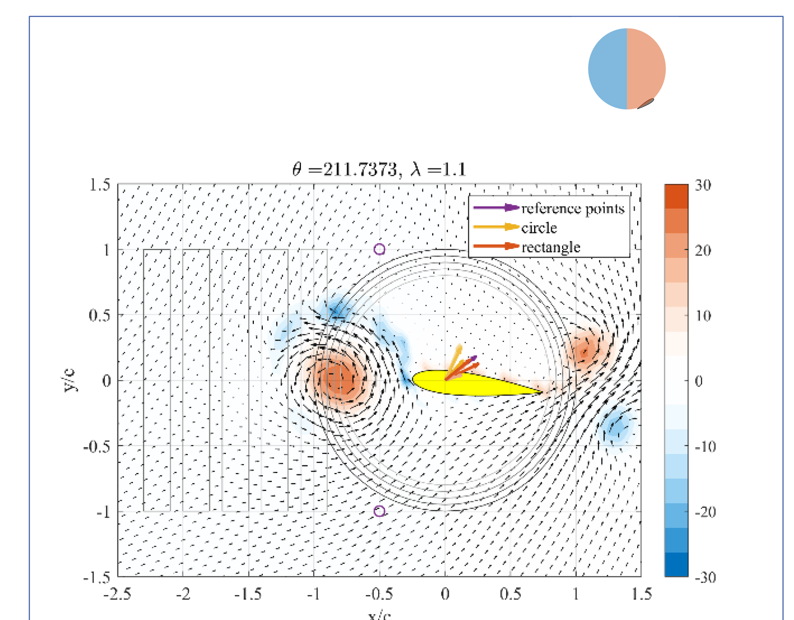

Figure 4: (a) Flow field and vorticity around a blade with a tip speed ratio of 1.1 at 212 degrees around the turbine (b) Position of the blade from (a) in the turbine reference frame

Results

- Velocity fields were averaged to sample an inflow velocity, this was used to determine a relative velocity and then angle of attack for each sample.
- As expected, the rectangle samples show clear phase shift in results as the rectangle moves upstream.

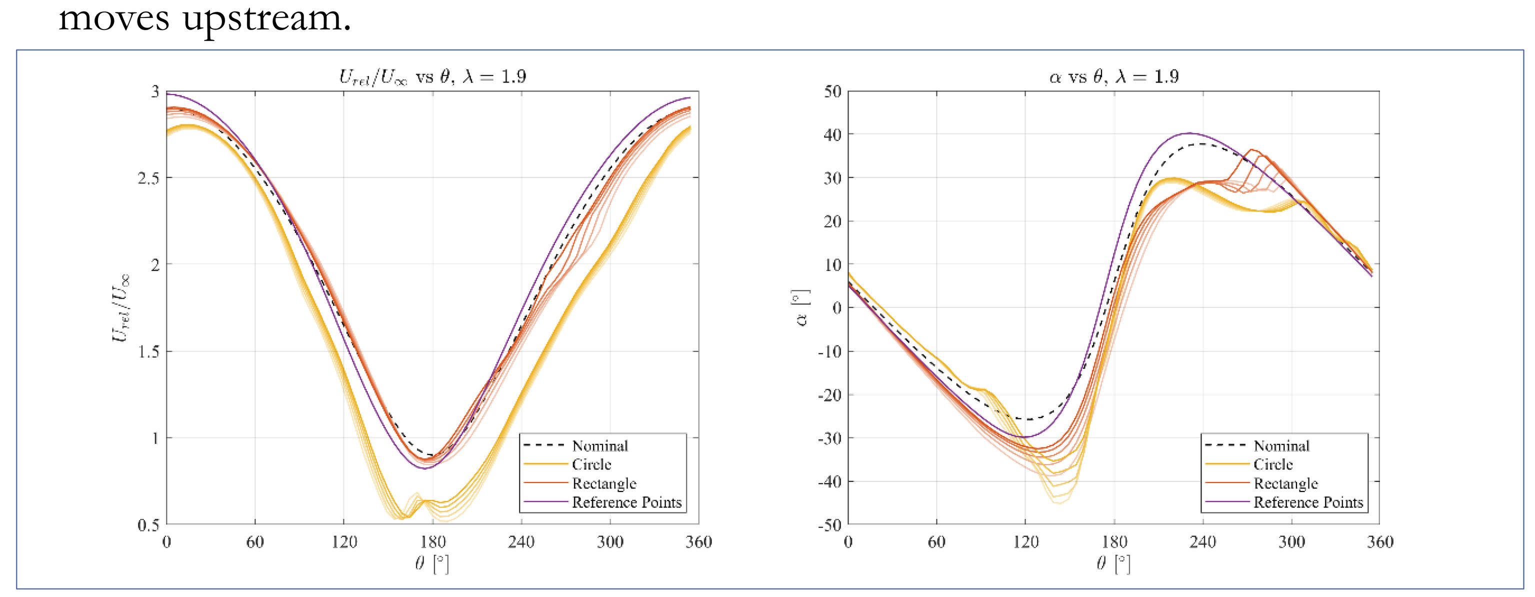

Figure 5: (a) Plot of normalized relative velocity vs phase angle for each sampling method and sample size, at a tip speed ratio of 1.9. and a Reynolds number of 2E3. (b) Plot of angle of attack vs phase angle for the same data.

Results Continued

- Compared with lower Re data, deviations from the nominal values become more prominent in more turbulent flow
- Tip speed ratio also appears to have some affect, as even at relatively low values, irregularities begin to smooth out.

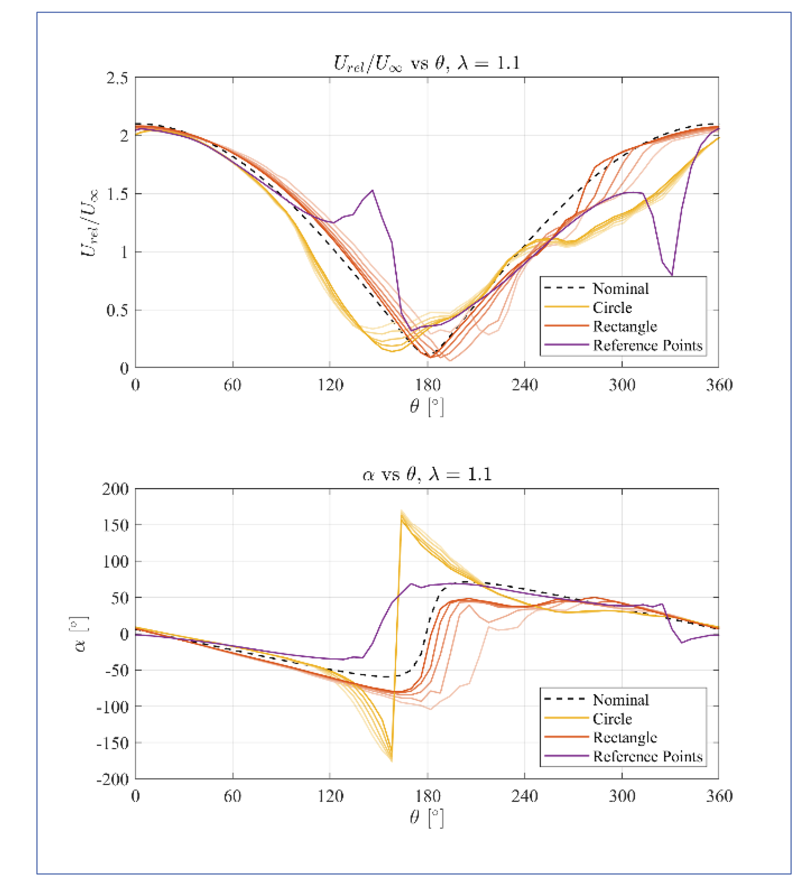

Figure 6: (a) Plot of normalized relative velocity vs phase angle for each sampling method and sample size, at a tip speed ratio of 1.1 and Reynolds number of 4.5E4. (b) Plot of angle of attack vs phase angle for each sampling method and sample size, at a tip speed ratio of 1.1

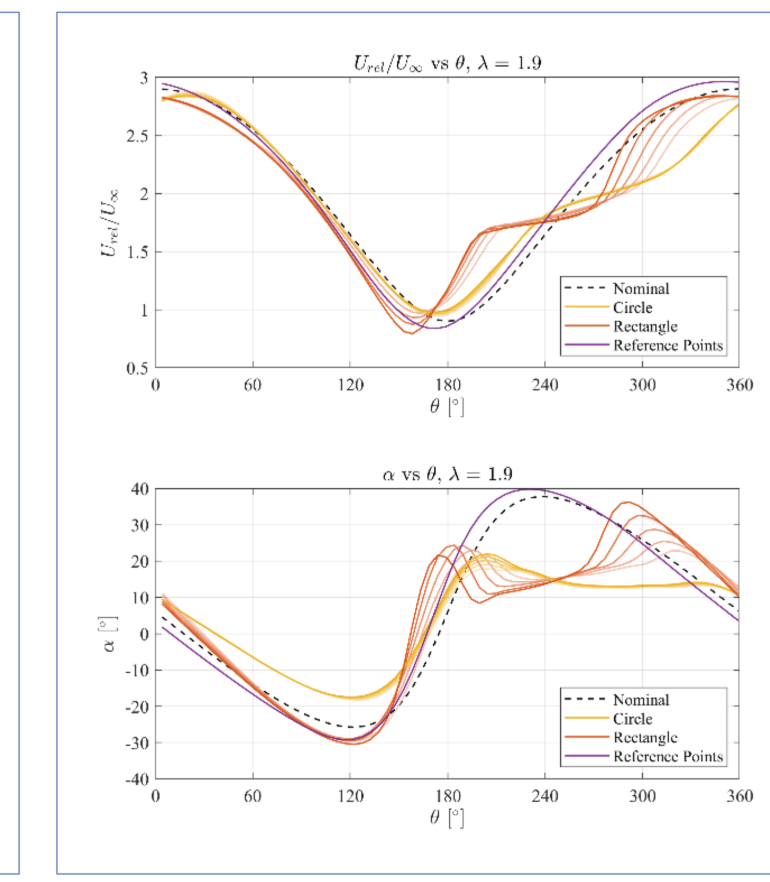

Figure 7: (a) Plot of normalized relative velocity vs phase angle for each sampling method and sample size, at a tip speed ratio of 1.9 and Reynolds number of 4.5E4. (b) Plot of angle of attack vs phase angle for each sampling method and sample size, at a tip speed ratio of 1.9.

Conclusions and Future Work

With just this data, we cannot say if one method of flow sampling is better than the others, but we can build a reasonable bound for the actual angle of attack and relative velocity from these values. Moving forward with this line of research, we intend to apply these methods to different computational models approximating rotational flow at increasing levels of complexity. Breaking models down into pitching motion, pitching and surging motion, and then pitching, surging and rotational motion should provide an interesting test of the accuracy of these models.

References

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