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Effects of inclined flow on cross-flow turbine performance

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Abstract

Cross-flow turbine performance is independent of inflow direction in the plane perpendicular to the axis of rotation — a significant appeal of these devices — but few studies have quantified the effects of inflow off-perpendicular to this axis. In this study, we characterize efficiency of a laboratory-scale turbine across a range of incline angle magnitudes /directions and operating conditions. Similar to prior work, turbine efficiency decreases with inclination angle in the direction of the freestream flow. However, we found efficiency depends on the direction of inclination and exhibits significant nonlinearity for incline angles ≥ 35°, suggesting some three-dimensional fluid-structure interactions. Furthermore, efficiency unexpectedly degrades with inclination in the cross-stream orientation for reasons that are not yet understood.

Keywords: cross-flow turbine; VAWT; inclined flow; skewed flow

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1 Introduction

Cross-flow turbines convert the kinetic energy in wind and water currents into mechanical power. Since, typically, the axis of rotation for a cross-flow turbine is perpendicular to the freestream flow, the ability of this turbine archetype to produce power independent of inflow orientation is an advantage over conventional axial-flow turbines (AFTs). However, their performance is still affected by inflow off-perpendicular, or inclined, to the axis of rotation (often referred to as "skewed" flow). Inclined flow can occur for both wind and water applications of cross-flow turbines,

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Table 1: Averages of the measured and calculated flow parameters for each incline angle, γ.

	Streamwise						Cross-stream					
γ [°]	U_∞ [m/s]	d [cm]	ν [m^2/s]	β [%]	Re_D	Fr_d	U_∞ [m/s]	d [cm]	ν [m^2/s]	β [%]	Re_D	Fr_d
0	0.704	53.99	8.93E-07	15.43	1.36E+05	0.306	0.626	43.63	8.03E-07	15.45	1.34E+05	0.303
5	0.720	56.44	9.12E-07	15.42	1.36E+05	0.306	0.629	44.31	8.08E-07	15.42	1.34E+05	0.302
20	0.744	60.68	9.46E-07	15.43	1.35E+05	0.305	0.644	45.35	8.18E-07	15.42	1.35E+05	0.305
40	0.753	61.91	9.56E-07	15.44	1.35E+05	0.306			–			
45	0.753	61.80	9.54E-07	15.40	1.36E+05	0.306			–			

also referred to as vertical axis wind turbines (VAWTs). In wind, small VAWTs operating in a built environment, such as the roof of a building, experience inclined flow when flow separates over the leading edge of the building. In water, skewed flow could occur for a seabed-mounted turbine on an uneven surface, for a moored turbine deflecting due to thrust, or as a consequence of current direction in a manner analogous to VAWTs on roofs. Therefore, understanding how inclined flow interacts with cross-flow turbines is important for predicting power output.

Misalignment between inflow direction and axis of rotation has been studied extensively for AFTs with empirical corrections developed for power and thrust coefficients [1], as well as modifications to momentum models that describe changes in power output as a function of skew angle, γ [2]. A commonly applied empirical correction to power output is a $\cos^3(\gamma)$ factor [1], but this exponent can vary in practice [2].

For cross-flow turbines, a similar understanding has not yet been developed for how inclined flow affects turbine performance because only a limited number of studies have investigated these conditions either numerically [3–6] or experimentally [4, 6, 7]. Prior work suggests that the relationship between turbine efficiency and the incline angle depends on the rotor aspect ratio (H/D, where H is the blade span and D is the turbine diameter). For low aspect ratio turbines ($D > H$), Mertens *et al.* [4], Bianchini *et al.* [6], and Simão Ferreira *et al.* [7] observed that turbine efficiency increased for small incline angles ($0° < \gamma \leq 30°$) before decreasing significantly with further inclination. Conversely, for higher aspect ratio turbines, turbine efficiency has been observed to monotonically decrease with increasing incline angle [3]. Prior work has explored these effects for a limited range of incline angles and operating conditions (i.e., tip-speed ratios), such that the general evolution of these trends remains ambiguous. Furthermore, variations in rotor geometries across these studies – which can significantly influence turbine performance [8, 9] – complicates cross-comparison. In addition, few studies have considered the implications of incline direction (i.e., incline angles with/against the flow direction or perpendicular to it).

This paper presents initial results of a study aimed at developing a holistic understanding of how inclined flow affects cross-flow turbine performance. To do this, we experimentally characterize a laboratory-scale turbine across a range of tip-speed ratios at different incline angles and orientations, while controlling for other relevant non-dimensional parameters.

2 Methods

2.1 Turbine and test rig description

We tested a laboratory-scale, single-bladed cross-flow turbine in a recirculating water flume (Fig. 1a) at the University of Washington. The rotor geometry is identical to Snortland *et al.* [10]. The turbine rotation rate is regulated by a servomotor with an integrated encoder. The fluid torque acting on the turbine, Q, is measured by a pair of six-axis load cells: one at the top of the turbine shaft coupled with the servomotor and one at the bottom of the shaft (Fig. 1a). For each γ, the inflow velocity, U_∞, dynamic depth, d, and water temperature (a proxy for kinematic viscosity, ν) are controlled (Table 1) to maintain constant blockage ratio, β, diameter-based Reynolds number, Re_D, and depth-based Froude number, Fr_d, following the method described by Ross and Polagye [11]. These adjustments are required due to changes in the projected area of the turbine and test rig with incline angle that would otherwise alter β. All non-dimensional flow parameters are maintained within 1.5% of their measured target values. Further details on the instrumentation and the data collection procedure used can be found in Hunt *et al.* [12]. The initial results presented here focus primarily on inclination of the turbine in the direction of inflow, designated as the positive streamwise direction ($+\gamma_s$, Fig. 1b). Values of $+\gamma_s$ from 0° to 45° in increments of 5 degrees are considered. A more limited

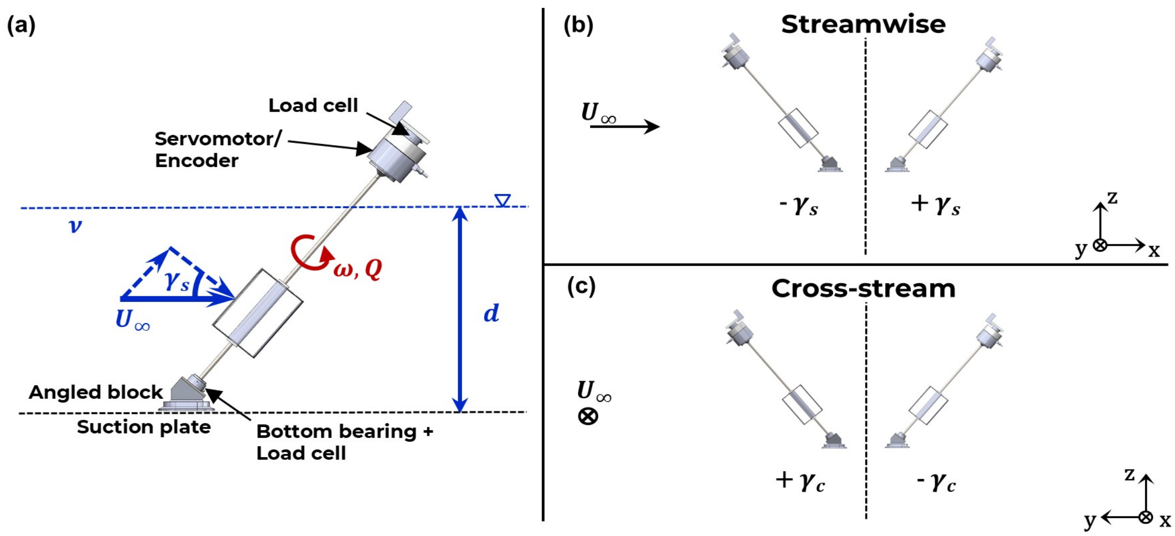

Figure 1: (a) The laboratory-scale turbine and test rig used for experiments and the sign conventions for (b) streamwise and (c) cross-stream orientations. A four-bladed turbine is shown for visual effect, but all experiments involve a single-bladed turbine.

number of contrasting cases are evaluated in the negative streamwise direction ($-\gamma_s$ = 5°, 40°, and 45°, Fig. 1b) and the cross-stream orientation (γ_c = +/-5° and +/-20°, Fig. 1c). For the cross-stream orientation, rather than physically reconfiguring the test rig, negative angles are evaluated by changing the direction of turbine rotation.

2.2 Performance characterization

Turbine performance is quantified by the coefficient of performance, C_P, which is conventionally defined as

$$C_P = \frac{\omega Q}{\frac{1}{2}\rho H D U_\infty^3} \tag{1}$$

where ω is the turbine rotation rate, ρ is the water density, and U_∞ is the free stream velocity. At each incline angle, C_P is evaluated across a range of rotation rates, non-dimensionalized as the tip speed ratio, given as

$$\lambda = \frac{\omega D}{2U_\infty}. \tag{2}$$

Since the spanwise component of inflow is not expected to contribute to power generation, an alternative normalization for the streamwise orientation considers only the blade-normal component of the inflow velocity (i.e., $U_\perp = U_\infty \cos(\gamma)$). The coefficient of performance and tip-speed ratio based on the blade-normal component of inflow velocity are respectively given as

$$C_{P\perp} = \frac{\omega Q}{\frac{1}{2}\rho H D (U_\infty \cos(\gamma_s))^3}, \tag{3}$$ and $$\lambda_\perp = \frac{\omega D}{2U_\infty \cos(\gamma_s)}. \tag{4}$$

Note that, in this formulation, no corresponding change is made to the projected area because the original projected area in Eq. (1) (HD) remains normal to the inflow direction, $U_\perp$. An alternative formulation (not shown here) could instead adjust the projected area to account for inclination of the rotor, rather than the inflow velocity [3, 5, 6]. Neither the blade-normal inflow nor projected area are altered by inclining the turbine in the cross-stream orientation. Hence, this normalization is only applied in the streamwise orientation.

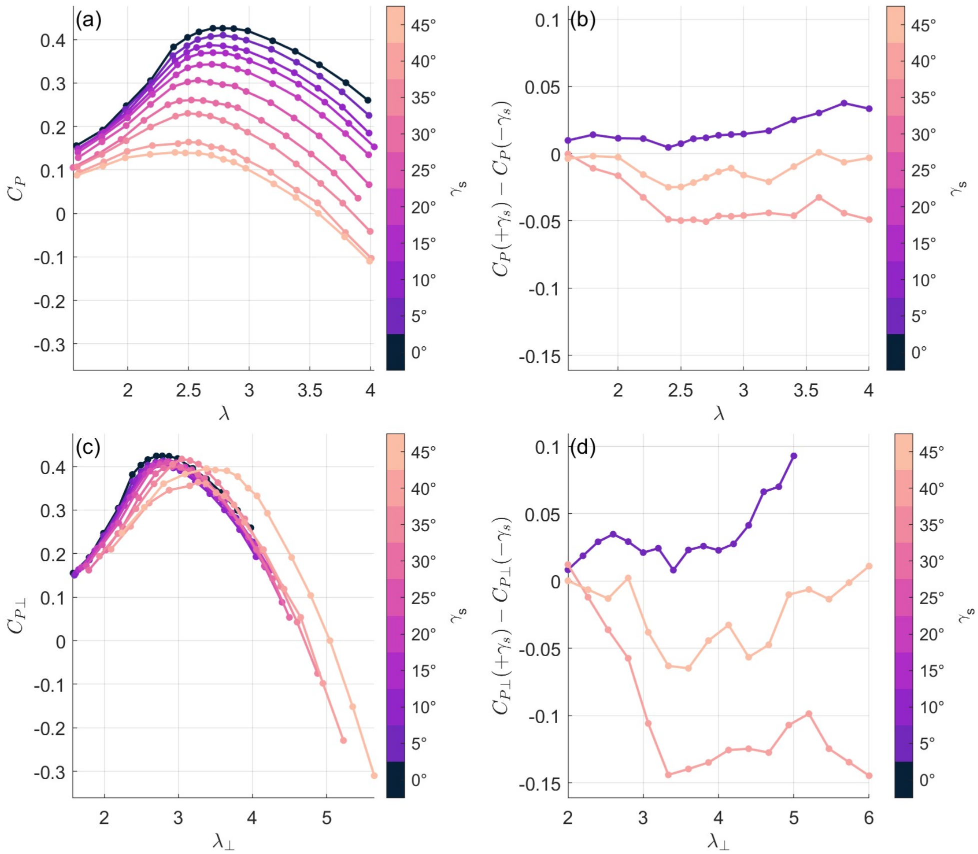

Figure 2: (a) The power coefficient normalized using the nominal inflow velocity as a function of tip-speed ratio for each incline angle tested in the positive streamwise direction ($+\gamma_s$). (b) The difference between the power coefficient for $+\gamma_s$ and comparable negative streamwise direction ($-\gamma_s$). (c) The power coefficient and tip-speed ratio normalized using the blade-normal component of the inflow velocity, $C_{P\perp}$, for each $+\gamma_s$. (d) The difference between $C_{P\perp}$ for $+\gamma_s$ and $-\gamma_s$.

3 Results

When C_P and λ are calculated using the nominal inflow speed (Eqs. (1) and (2)), turbine efficiency is observed to monotonically decrease with increasing $+\gamma_s$ (Fig. 2a). These trends are consistent with prior momentum modeling by Mertens *et al.* [3] for turbines with $H/D > 1$. However, efficiency depends on both the magnitude and direction of the streamwise inclination. While C_P also decreases monotonically with $-\gamma_s$, for a given magnitude of γ_s the values of C_P obtained can differ significantly between directions (Fig. 2b). For the $\gamma_s = \pm 5°$ cases, performance is comparable between the positive and negative directions at lower λ, with $+\gamma_s$ yielding higher C_P at higher λ. However, for the 40° and 45° cases, $-\gamma_s$ outperforms $+\gamma_s$ across a wider range of λ. Although decreasing performance with incline angle is expected based on prior work, the nonlinearity in performance degradation with incline angle and directional dependence was not anticipated from prior literature. This may be a consequence of three-dimensional fluid-structure interactions along the blade or an experimental artifact associated with the wake from the angled block (Fig. 1a).

Unlike for the streamwise orientation, changes in turbine performance with cross-stream inclination is independent of direction. Both $\gamma_c = +20°$ and $\gamma_c = -20°$ resulted in similar $C_P - \lambda$ curves within experimental error. Therefore, only results from one inclination direction are presented for simplicity. For a given γ_c, turbine efficiency decreases less than $+\gamma_s$ of the same magnitude (Fig. 3) and, for the $\gamma_c = 5°$ case, performance is comparable to the non-inclined case. However, for $\gamma_c = 20°$, performance is significantly reduced across all λ. While C_P decreasing with γ_s was expected, we did not expect performance to change from the zero incline case for γ_c since the turbine remains normal to the direction of inflow. Prior studies have not investigated cross-stream inclination, presenting results primarily for

$+\gamma_s$ inclination with limited results for $-\gamma_s$.

When turbine efficiency and tip-speed ratio for the streamwise orientation are normalized using the blade-normal component of the inflow velocity (Eqs. (3) and (4)), the resulting power curves collapse for $+\gamma_s < 25°$ (Fig. 2c). At larger incline angles, a broadening of the performance curves is observed with a notable difference at the largest angles tested ($+\gamma_s = 40°$ and 45°). The collapse in $C_{P\perp}$ observed at lower incline angles suggests that changes in C_P with $+\gamma_s$ in this regime are well described by a simple projection of the nominal inflow velocity into the blade-normal reference frame. In contrast, the different behavior of $C_{P\perp}$ at higher $+\gamma_s$ suggests that at higher incline angles, more complicated fluid-structure interactions contribute to changes in performance. Similar to trends observed in Fig. 2b, performance between $-\gamma_s$ and $+\gamma_s$ at 5° diverges at larger λ (Fig. 2d), resulting in only a partial collapse for $\lambda \leq 4$. For the other two $-\gamma_s$ cases tested, performance compared to the $+\gamma_s$ cases of the same magnitude diverge more rapidly than for a normalization with the nominal inflow (Fig. 2d). Furthermore, $-\gamma_s = 40°$ and $-\gamma_s = 45°$ surpass the maximum $C_{P\perp}$ for the non-inclined case unlike any of the $+\gamma_s$ cases.

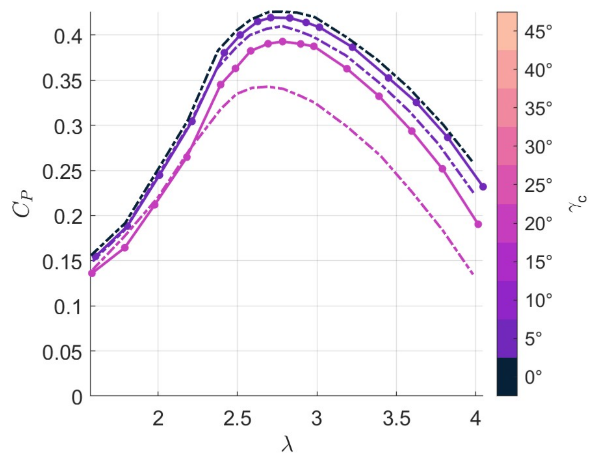

Figure 3: The power coefficient as a function of cross-stream incline angle (γ_c, solid lines). C_P for the non-inclined case (black) and corresponding angles in the positive streamwise direction ($+\gamma_s$) are shown as dash-dotted lines.

4 Discussion and conclusions

While our initial results presented in Figs. 2 and 3 suggest some interesting trends, further work is needed to evaluate the full set of inclination angles and understand how the results change for turbines with a more practical number of blades. The nonlinearity and directional dependence in the observed trends suggest there may exist some three-dimensional fluid-structure interactions that are causing the observed performance changes. While some wake visualization for inclined cross-flow turbines has been presented in previous literature [7], there have been neither near-blade nor in-rotor flow field measurements. Such measurements could help to quantify spanwise flow (i.e., the component of flow parallel to the blade span), which has been hypothesized to contribute to changes in C_P with incline angle [4, 7]. For streamwise inclination, 40° or 45° angles in both directions would be good, contrasting candidates to explore near-blade flow phenomena as well as a small and large incline angle (e.g., 5° and 45°). Similarly, streamwise and cross-stream inclinations with differing performance at the same angle magnitude (e.g., $\gamma = 20°$) could be compared. Future flow field measurements will utilize laser Doppler velocimetry (LDV), a pointwise measurement, to explore these flow phenomena. While particle image velocimetry (PIV) is often used to visualize flow fields, shadowing near the blade would be exacerbated by inclining the turbine, making near-blade measurements particularly difficult. Therefore, a pointwise measurement technique is likely to provide greater insight. In addition, future work will include characterization of the structural forces acting on the rotor, which are an important consideration for system design. Nonetheless, our preliminary results suggest dynamically-rich relationships between turbine performance and incline angle, as well as highlighting the limits of inflow normalization corrections to describe these effects.

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