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# Evaluation of Design & Analysis Code, CACTUS, for Predicting Crossflow Hydrokinetic Turbine Performance

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# Evaluation of Design & Analysis Code, CACTUS, for Predicting Crossflow Hydrokinetic Turbine Performance

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## Abstract

CACTUS, developed by Sandia National Laboratories, is an open-source code for the design and analysis of wind and hydrokinetic turbines. While it has undergone extensive validation for both vertical axis and horizontal axis wind turbines, and it has been demonstrated to accurately predict the performance of horizontal (axial-flow) hydrokinetic turbines, its ability to predict the performance of crossflow hydrokinetic turbines has yet to be tested. The present study addresses this problem by comparing the predicted performance curves derived from CACTUS simulations of the U.S. Department of Energy's 1:6 scale reference model crossflow turbine to those derived by experimental measurements in a tow tank using the same model turbine at the University of New Hampshire. It shows that CACTUS cannot accurately predict the performance of this crossflow turbine, raising concerns on its application to crossflow hydrokinetic turbines generally. The lack of quality data on NACA 0021 foil aerodynamic (hydrodynamic) characteristics over the wide range of angles of attack (AoA) and Reynolds numbers is identified as the main cause for poor model prediction. A comparison of several different NACA 0021 foil data sources, derived using both physical and numerical modeling experiments, indicates significant discrepancies at the high AoA experienced by foils on crossflow turbines. Users of CACTUS for crossflow hydrokinetic turbines are, therefore, advised to limit its application to higher tip speed ratios (lower AoA), and to carefully verify the reliability and accuracy of their foil data. Accurate empirical data on the aerodynamic characteristics of the foil is the greatest limitation to predicting performance for crossflow turbines with semi-empirical models like CACTUS. Future improvements of CACTUS for crossflow turbine performance prediction will require the development of accurate foil aerodynamic characteristic data sets within the appropriate ranges of Reynolds numbers and AoA.

# ACKNOWLEDGMENTS

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# EXECUTIVE SUMMARY

For the design of wind or marine hydrokinetic (MHK) turbines, the turbine performance needs to be modeled with reasonable computational effort – on the order of a couple of hours to obtain a full performance curve for a given candidate design. For this reason, the effect of the turbine on the flow is modeled semi-empirically via blade-element based models that require foil section performance data (aerodynamic characteristics), i.e., lift, drag and moment coefficients at relevant Reynolds numbers and angles of attack (AOA), as input. Blade-element-based models vary in complexity and fidelity, from the simplest blade-element-momentum (BEM) models to wake-vortex methods (e.g., CACTUS, Murray and Barone 2012). The latter can be classified as a "mid-fidelity model", since it represents a compromise between computational effort and modeling the essential physical phenomena. As a result of this trade-off, the accuracy of blade-element based models, like CACTUS, rely on the availability of accurate foil section performance data (lift and drag coefficient).

Blade-element based models have been shown to work very well for axial-flow (horizontal axis) turbines, since these are essentially steady-state devices when placed in a uniform approach flow: The blades have a "design angle of attack (AoA)", and that angle is maintained over the span of the blade by giving the blade a twist angle distribution. To use a blade-element based model effectively, input foil coefficient data *only* have to be accurate around the design AoA, which is typically an angle significantly below the stall angle near the maximum lift/drag ratio, where it is easier to obtain reliable foil coefficient data.

Cross-flow turbines, on the other hand, are essentially unsteady devices, and their blades encounter oscillating angles of attack over each rotation. This makes cross-flow turbine simulations with blade-element based models particularly challenging because accurate empirical foil section coefficient data are needed over a large range of AoA. Furthermore, the AoA the blades encounter *increases* with *decreasing tip speed ratio*.

For the cross-flow wind turbines of the 1970s and 80s (Darrieus type), the design tip speed ratios are quite large, and hence the range of angles of attack reasonably small – often below stall angles near the turbine equator where most of the torque/power is produced. Hence poor quality foil data past stall AoA is not as big a concern for predicting performance for these devices.

For MHK cross-flow turbines, which operate at typical tip speed ratios in the range of 2 to 3 at the best performance point, the range of angles of attack encountered is much larger, say 0 to 20 degrees and above. To predict performance accurately, the foil lift and drag coefficient data must be accurate over the entire range of AoA encountered, but particularly in the range of 10 to 20 degrees. –The lower tip speed ratio operation of MHK turbines is caused by higher turbine solidity, which can also add complications of flow curvature or virtual camber effects.

In this report we demonstrate that over the range of angles of attack and the Reynolds numbers encountered by MHK cross flow turbines, the lift and drag coefficients of existing data sets diverge considerably, as do numerical results from XFOIL and the Eppler code. The available data sets which have been used in CACTUS simulations to date, namely the NACA

0021 foil data sets of Sheldahl and Klimas, are suspect. These data sets are, in fact, generated from numerical simulations using the EPPLER code, which was calibrated to full scale Vertical Axis Wind Turbine (VAWT) performance data collected in the field.

We further demonstrate that CACTUS model predictions of the performance of the 1:6 scale Reference Model 2 MHK turbine under-predict performance using the Sheldahl and Klimas data sets and over-predict performance using XFOIL data sets, since XFOIL will produce erroneous values of foil coefficients beyond stall.

An exercise creating a hybrid dataset by combining lift data for a NACA 0021 foil (at one Reynolds number) in wind tunnel experiments with Sheldahl and Klimas data shows promising, improved results when used in CACTUS simulations.

Based on our study findings we recommend the following:

- Limiting the application of the CACTUS model to higher turbine tip speed ratios as follows: The user should verify for what range of angles of attack reliable foil performance data exists for their candidate design, and then limit device simulation using CACTUS to sufficiently high tip speed ratios so that this range of angle of attacks is not exceeded. Unfortunately, at the present time this prohibits accurate predictions of performance using CACTUS for most MHK cross-flow turbine designs.
- For future development of cross-flow turbines we recommend investing in efforts to generate accurate data sets for symmetrical airfoils over a wide range of Reynolds numbers based on chord, from $Re_c \sim 10^4$ to $Re_c \sim 10^7$, and angles of attack up to 30 degrees.

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# 1. INTRODUCTION

When designing wind or marine hydrokinetic (MHK) turbines, the turbine performance needs to be modeled with reasonable numerical effort – say, on the order of a few hours to obtain a full performance curve for a given candidate design – and with reasonable accuracy with regards to power and thrust coefficients. Typically, blade-element based numerical models are used for this purpose, since blade-resolving simulations have much higher computational cost (on the order of $10^3\ hrs$ of CPU time per second of simulated operating time for a cross-flow turbine of 1m diameter, cf. Bachant and Wosnik, 2016a [1]). Blade-element based models require foil section performance data, i.e., lift and drag coefficients, and possibly moment coefficients, at relevant Reynolds numbers, as input.  Blade-element-based models vary in complexity and fidelity, from the simplest blade-element-momentum (BEM) models to wake-vortex methods (e.g., CACTUS, Murray and Barone, 2012 [2]) or actuator lime models (ALM) within Navier-Stokes simulations (e.g. Bachant et al 2016a [3]). The latter two can be classified as “mid-fidelity models”, since they represent a compromise between reducing computational effort, while still capturing important physical phenomena. Clearly, any blade-element based model relies on the availability of accurate foil section performance data (lift and drag coefficients) over the range of angles of attack and Reynolds numbers of interest to a particular turbine design and scale.

Sandia National Laboratories (SNL) developed the **C**ode for **A**xial and **C**ross-flow **TU**rbine **S**imulation (CACTUS) to accelerate the development of marine hydrokinetic turbine technology (Murray and Barone, 2011 [2]). CACTUS is a mid-fidelity, blade-element vortex-wake code that requires hydrofoil section performance data as input, and is based on Strickland's VDART model (Strickland et al. 1981 [4]). VDART was originally developed for SNL in the 1970s-80s to aid in the design of Darrieus vertical-axis wind turbines (VAWTs). Improvements to CACTUS beyond VDART include ground plane and free surface modeling, a new added mass correction, and the Leishman-Beddoes (LB) dynamic stall (DS) model (Leishman and Beddoes, 1989 [5]), in addition to the Boeing-Vertol (BV) dynamic stall model (Gormont, 1973 [6]). Dynamic stall models are employed to simulate the oscillating angles of attack encountered in the unsteady operation of crossflow turbines. A comprehensive description of CACTUS, including its underlying theory and the validation studies that were performed is given by Murray and Barone (2011) [2].

Note that blade-element based models, including CACTUS, have been shown to work well for axial-flow (horizontal axis) turbines.  Axial-flow wind or MHK turbines are essentially steady-state devices when operating in a uniform approach flow: The blades have a “design angle of attack (AoA)”, and that angle is maintained over the span of the blade by giving the blade a twist angle distribution. To use a blade-element based model effectively, input foil coefficient data *only* has to be accurate around this design AoA, which is typically an angle significantly below the stall angle near the maximum lift/drag ratio, where it is easier to obtain reliable foil coefficient data.

Cross-flow turbines, on the other hand, are essentially unsteady devices, and their blades encounter oscillating angles of attack. This makes cross-flow turbine simulations with blade-element based models particularly challenging because accurate empirical foil section coefficient data are needed over a large range of AoA. The oscillating angle of attack $\alpha$ a cross-flow turbine blade can be described (geometrically) as

$$\alpha = arctan\left[\frac{sin\theta}{cos\theta + \lambda}\right] \tag{1}$$

where $\theta$ is the rotation angle and $\lambda = \omega R/U_\infty$ is the tip speed ratio (This expression is at least approximately valid for the upstream half of rotation of the turbine). This (geometric) angle of attack $\alpha$ is plotted versus turbine rotation (azimuthal) angle $\theta$ at various tip speed ratios $\lambda$ in Figure 1 (from: Bachant, 2016 [7])

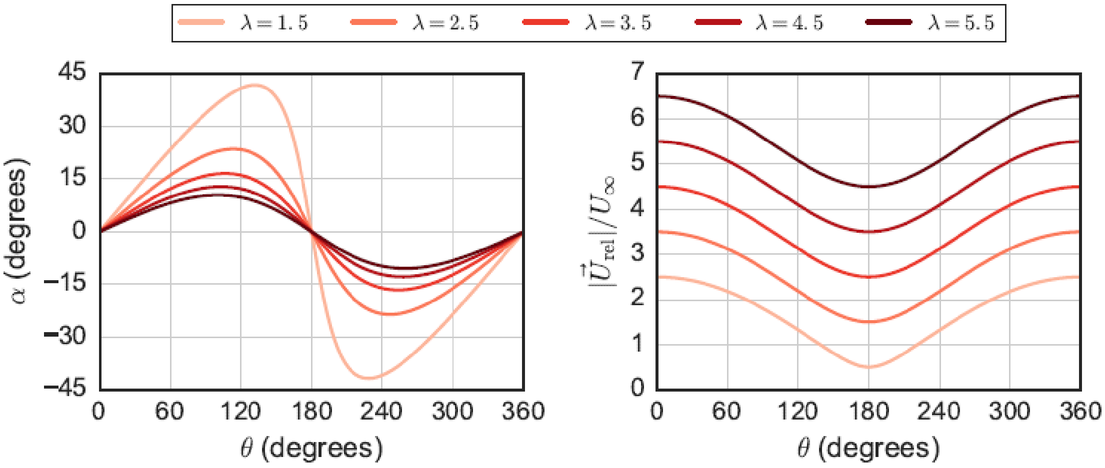

**Figure 1.** Geometric angle of attack (left) and relative velocity (right) versus azimuthal angle at various tip speed ratios $\boldsymbol{\lambda = \omega R/U_\infty}$ (From: Bachant, 2016 [7])

It can be seen that the range of angles of attack a blades encounters throughout one rotation *increases* with *decreasing tip speed ratio*. For MHK CFTs, which operate at typical tip speed ratios in the range of 2 to 3 at the best performance point, the range of angles of attack can be quite large, say from 0 to 20 degrees and above.

In general, the performance and wake characteristics of cross-flow turbines (CFTs) depend on turbine solidity, blade profile (lift/drag, dynamic stall at reduced frequency of turbine rotation, symmetry, thickness, camber), blade pitch, number of blades, strut drag, operational parameters, such as tip speed ratio, and on the Reynolds number (Paraschiviou 1999 [8]). Note that an average blade chord Reynolds number, $Re_{c,avg} \approx \lambda U_\infty c/\nu$, can be expressed in terms of tip speed ratio $\lambda = \omega R/U_\infty$, where $U_\infty$ is the free stream velocity, $c$ is the blade chord length, $\nu$

is the fluid kinematic viscosity, $\omega$ is the rotor's angular velocity, and $R$ is the rotor radius (Bachant and Wosnik, 2016b [9]). The value of $\lambda$ at which a turbine reaches peak performance in general decreases with increasing turbine solidity $\sigma = Nc/2\pi R$ (or simply chord-to-radius ratio $c/R$) (Templin, 1974 [10]), which allows for the use of a simpler Reynolds number based on turbine diameter , $Re_D \approx U_\infty D/\nu$ (Bachant and Wosnik, 2016b). For constant number of blades, solidity directly correlates with the chord-to-radius ratio $c/R$. Rotors with $c/R > 0.1$ are considered to have high solidity (Fiedler et al 2009 [11]), for which so-called flow curvature or virtual camber effects become significant (Migliore et al. 1980 [12]). These effects arise from the blade sections' circular paths and can further complicate the comparison with the behavior of an airfoil in a linear flow, and performance characteristics obtained from such experiments.

For the Darrieus type cross-flow wind turbines of the 1970s and 80s, by contrast, the chord-to-radius ratios were quite low ($c/R$ = 0.05-0.08) and design tip speed ratios were quite large (around $\lambda_{c_{p,max}} \approx 6$), and hence the range of angles of attack remained reasonably small – often remaining below stall angles near the turbine equator where most of the torque (power) was produced. Hence poor quality foil section data past stall AoA was not as big a hurdle for predicting performance for these devices.

Compared to the crossflow wind turbines of the 1970s and 80s, crossflow hydrokinetic turbines have higher solidities, and therefore operate at lower tip speed ratios (2 to 3 at the best efficiency point), as well as lower chord Reynolds numbers (c.f. Figure 1, right). These higher solidities and low tip speed ratios cause the blades of hydrokinetic crossflow turbines to encounter a larger range of AoA than their wind turbine counterparts. Dynamic stall occurs at sufficiently large attack angles or low Reynolds numbers, a complex Reynolds number dependent phenomenon that is difficult to model accurately because empirically derived static foil hydrodynamic characteristics for lift, drag and quarter-chord moment are no longer valid. Hence, to predict performance accurately for hydrokinetic crossflow turbines, the dynamic stall models are critical, and the foil lift and drag coefficient data must be accurate over the entire range of AoA encountered, but particularly in the range of 10 to 20 degrees. Simulating turbine performance in this operating AoA range is problematic because the published hydrodynamic characteristics diverge considerably.

In summary, crossflow turbine geometry (scale, solidity) and the resulting operating parameters dictate the envelope of AoA encountered during turbine operation. The relatively high solidities and low tip speed ratios cause the foils of hydrokinetic crossflow turbines to operate at larger AoA than wind ones (0 to 20 degrees and above) as they rotate around the turbine axis of rotation. Foil section coefficient data sets used in CACTUS simulations have to be of high quality (accuracy) over a large range of AoA, which for low tip speed ratios $\lambda$ exceeds stall angles. **Accurate empirical data on the aerodynamic characteristics of the foil is, therefore, the greatest limitation to predicting power performance for hydrokinetic turbines with mid-fidelity models like CACTUS.**

# 2. STATEMENT OF WORK

In the present study we investigate the accuracy of predictions of the performance of a hydrokinetic crossflow turbine using the mid-fidelity vortex-line model CACTUS.

CACTUS was originally validated using experimental data from relatively low-solidity $\sigma = Nc/2\pi R$ (or simply low chord-to-radius ratio $c/R$) cross-flow turbine rotors: (1) the Sandia 5 m Darrieus turbine ($c/R$ = 0.08), the Sandia 34 m Darrieus test bed ($c/R$ = 0.05), and the VAWT 850 tapered H-rotor ($c/R$ = 0.05), cf. Murray and Barone (2011) [2]. However, when applied to a high solidity H-rotor, the UNH-RVAT ($c/R$ = 0.28, Bachant and Wosnik, 2015 [13]), CACTUS significantly over-predicted blade loading, and, therefore, mean performance coefficients (Michelen et al., 2014 [14]). It was, therefore, of interest to validate CACTUS with a medium solidity vertical-axis (a.k.a. cross-flow) turbine: the US Department of Energy (DOE) "Reference Model 2" (RM2) (tapered blades with $c/R$ = 0.07-0.12. For a description of the RM2 rotor see Barone et al. 2011 [15], Neary et al. 2014 [16]).

The RM2 was the subject of an experimental investigation in the University of New Hampshire (UNH) tow tank, where mechanical power output, overall streamwise drag or thrust, and near-wake velocity were measured with a 1:6 scale single-rotor physical model. A Reynolds number dependence study was performed, which showed strong $Re$-dependence below and weak $Re$-dependence above a chord-based Reynolds number $Re_c \sim 10^5$ (Bachant et al, 2016b [17]). The RM2 cross-flow turbine CAD package is available through Bachant et al. 2016c [18] and the UNH RM2 tow tank experiment reduced dataset and processing code is available through Bachant et al. 2016d [19]. The RM2 CACTUS simulation case files are available at Bachant et al. 2016e [20].

In this study

- We evaluate the ability of the CACTUS vortex line model to predict the experimental performance of the 1:6 scale RM2 physical model experiments at UNH.
- We evaluate air/hydro-foil performance data at intermediate Reynolds numbers, including XFOIL data, as applicable to blade-element based numerical models for cross-flow hydrokinetic turbines to help identify the source of discrepancy in performance predictions
- We make recommendations regarding best practice guidelines for the application of CACTUS.

# 3. METHODS

## 3.1 Description of CACTUS

CACTUS assumes an incompressible potential flow field and uses a system of constant-strength vortex filaments to model the unsteady rotor wake. Each blade is modeled as a series of bound vortex filaments which span the blade's quarter-chord line. The strength of each bound vortex is computed based on the local velocity, and on the lift coefficient which is found from the local angle of attack and a specified airfoil table. At each time step, spanwise and trailing vortices are shed from these bound vortices; their strengths are computed in accordance with Helmholtz's circulation theorems (c.f. [21]). Each vortex filament induces a velocity field, and each filament of the wake advects under the total velocity influence of the wake system. Airfoil drag forces contribute to the blade and rotor loads.

The influence of walls on the flow field is modeled using a system of first-order constant strength quadrilateral source panels. The strengths of these source panels are updated at each time step to satisfy the no flow-through condition at each panel's center. As with the vortex filaments representing the wake, each source panel contributes to the velocity field, and thus the velocity influence of the wall system influences both the local velocities along the blade elements and the advection of the wake.

## 3.2 Numerical setup

The 1:6 scale RM2 experiment performed in the UNH tow tank, for which the data is available from Bachant et al. 2016d [19], was replicated for a tow speed of 1.0 m/s, which corresponds to a Reynolds number based on turbine diameter of $Re_D = 1.1 \times 10^6$. To match the experimental blockage ratio (approx. 10%), wall panel source elements were added to the CACTUS model, corresponding to the tank's 3.66 m wide by 2.44 m deep cross-section. Turbine rotor and wall geometry is shown in Figure 2.

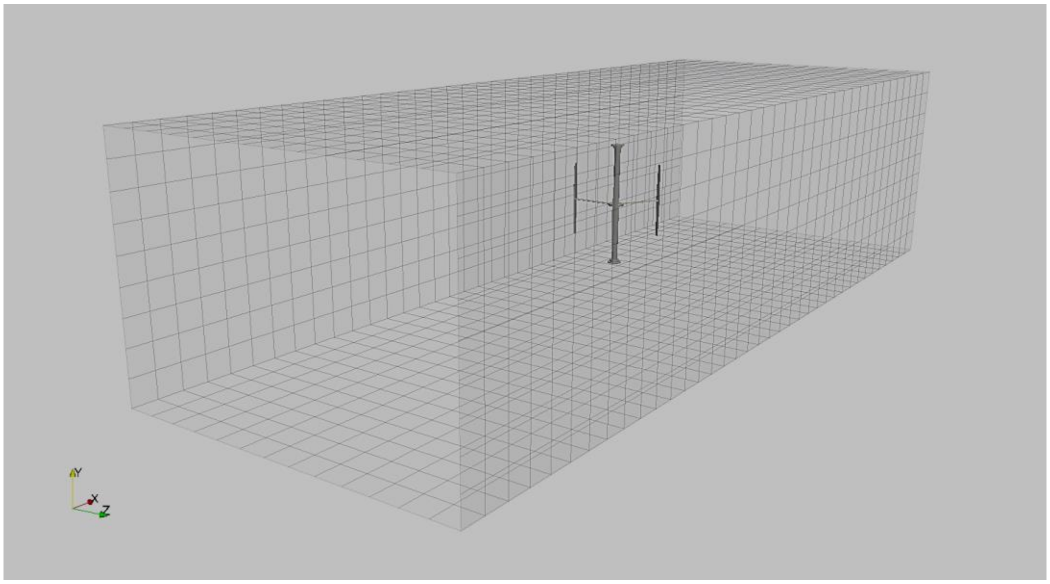

**Figure 2.** Numerical setup for CACTUS simulations: computational domain and wall geometry.

Static foil coefficient data for the NACA 0021 profiles was taken from Sheldahl and Klimas 1981 [22], as it currently is the only dataset available for the range of moderate Reynolds numbers simulated here. However, it is important to note that this “dataset” is not truly measured data, but was extrapolated from other data for less thick symmetrical NACA 00-series foils measured over a limited range of Reynolds numbers. These limitations of the Sheldahl and Klimas dataset are discussed in more detail below. Recently, Bedon et al. (2014) [23] showed with a double multiple streamtube (DMST) momentum model that this dataset may be unreliable at lower Reynolds numbers.

## 3.3 Verification

The CACTUS model was run for eight turbine revolutions, over the latter half of which performance quantities were averaged. Sensitivity of the model results to the time step (or number of time steps per revolution $N_t$) and number of blade elements was assessed, for which the results are shown in Figure 3. Ultimately, the number of time steps per revolution and number of elements per blade were chosen as 24 and 16, respectively. These values may not indicate a typical "converged" configuration, but were chosen for practicality, since the computational expense increases about an order of magnitude when doubling $N_t$. For $N_t = 24$, the expense was approximately 0.1 CPU hours per simulated second.

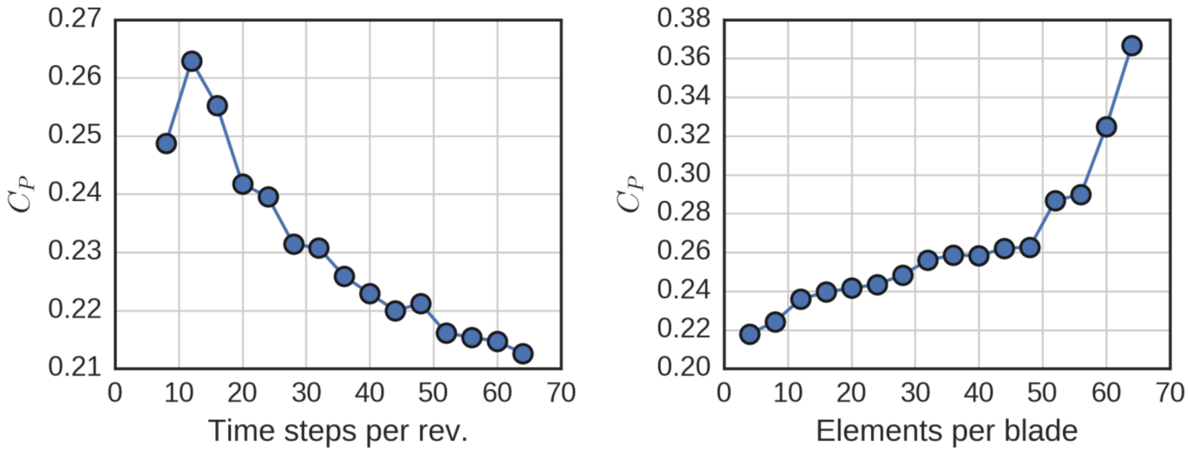

**Figure 3.** Sensitivity of numerical model to time step and number of blade elements.

# 4. RESULTS OF CACTUS SIMULATIONS

## 4.1 Mean turbine performance

The performance of the RM2 was simulated with CACTUS using both the Boeing-Vertol (BV) and Leishman-Beddoes (LB) dynamic stall (DS) models, as well as with dynamic stall modeling deactivated. Results of these simulations are shown in Figure 4. Results from an UNH Actuator Line Model (ALM) for cross-flow turbines, which also uses the Sheldahl and Klimas data set for foil section coefficients, but modeled the flow field with unsteady Reynolds-averaged Navier-Stokes simulations [3] is also plotted.

The Turbine performance parameters used for comparison are the power coefficient

$$C_P \equiv \frac{P}{0.5\rho A\, U_\infty^3} \tag{2}$$

where $P$ is the shaft power of the device, $\rho$ is the fluid density, $A$ is the area perpendicular to the flow swept by the turbine rotor and $U_\infty$ is the undisturbed approach velocity upstream of the turbine, and the rotor drag (or thrust) coefficient

$$C_D \equiv \frac{F_D}{0.5\rho A\, U_\infty^2} \tag{3}$$

where $F_D$ is the overall streamwise drag (thrust) force on the rotor. Tip Speed was defined earlier as $\lambda = \omega R/U_\infty$

These plots show that not simulating dynamic stall has a very significant deleterious effect on predicting $C_P$ at the tip speed ratios of interest, and especially at lower $\lambda$. The LB and BV DS models improve the results somewhat and produce relatively similar results, though the BV performance predictions at lower tip speed ratios do not match the experiments as well as the LB results do. Overall, even with DS models active, the power performance curves are shifted to the right (to higher $\lambda$ values), and do not quite reach the same maximum values as the experimental data. The rotor drag (thrust) coefficients are also systematically under-predicted, although CACTUS with LB DS model and the UNH ALM model do a reasonable job predicting rotor drag (thrust) around the tip speed ratios of interest.

The discrepancy between blade-element model based simulations using the Sheldahl and Klimas static foil data set and experimental results are investigated further below.

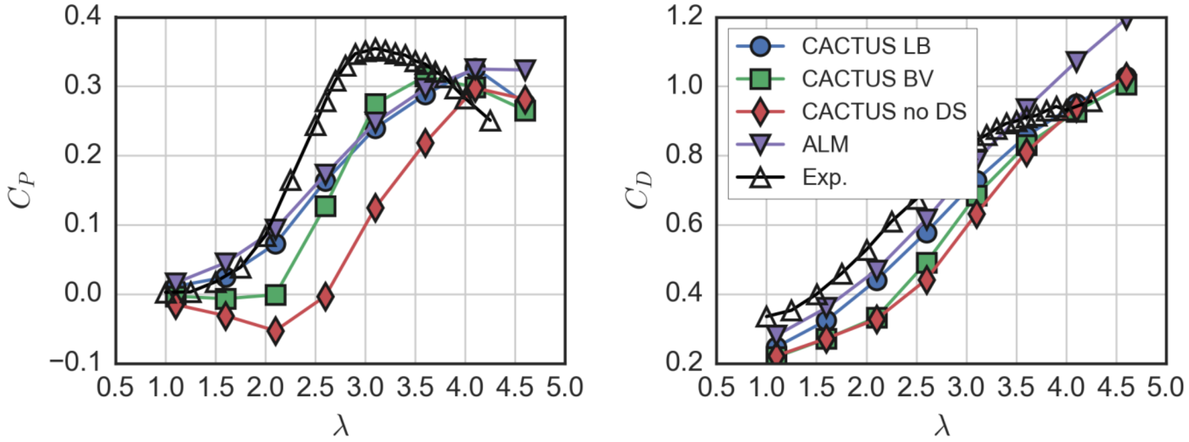

**Figure 4.** Power coefficient $C_P$ and rotor drag (thrust) coefficient $C_D$ comparison: CACTUS with Leishman-Beddoes (LB), Boeing-Vertol (BV) and without Dynamic Stall (DS) models, compared to UNH Actuator Line Model (ALM) and UNH RM2 physical model data.

## 4.2 Reynolds number dependence of performance predictions with CACTUS

The Reynolds number dependence of the CACTUS performance predictions was assessed in a similar fashion as it was in the RM2 tow tank experiment---by holding the tip speed ratio constant at 3.1 and varying the free stream velocity. In this case CACTUS was run using the Sheldahl and Klimas foil data at higher Reynolds numbers than those measured in the experiments, the results from which are shown in Figure 5. In accordance with the Bedon et al. (2014) results (obtained without dynamic stall modeling), the Sheldahl and Klimas data appears to exaggerate the decrease in performance at low $Re$, though the results look like they will converge to the same maximum performance values at higher $Re$ . This hints at the fact that the Sheldahl and Klimas data may not be reliable at low $Re$. Unfortunately, experimental static foil data does not exist or is very hard to find for a NACA 0021 at $Re_c \sim 10^5$, which precludes comparison.

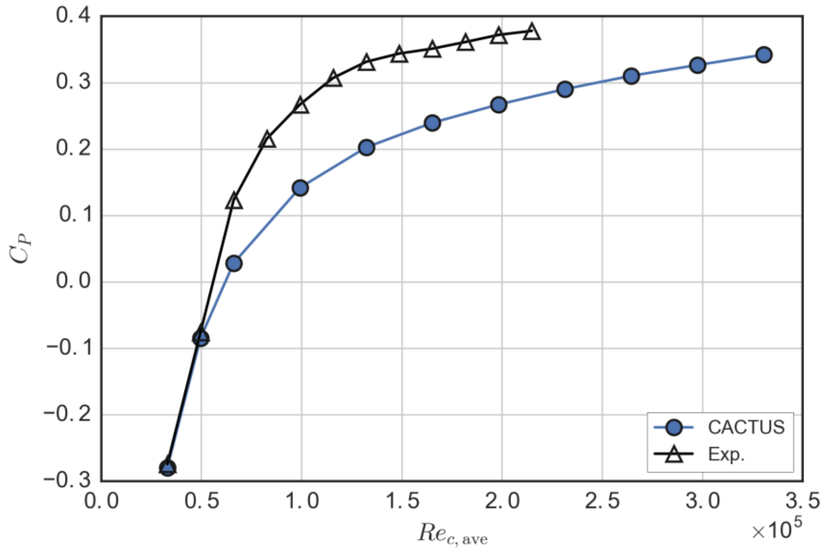

**Figure 5.** Reynolds number dependence of performance predictions with CACTUS.

# 5. AERODYNAMIC CHARACTERISTICS OF (STATIC) FOIL SECTIONS: COMPARISON OF DATA DOCUMENTED IN THE LITERATURE, AND XFOIL GENERATED DATA

## 5.1 Sheldahl and Klimas data sets

in 1980 Sheldahl and Klimas published a report on the "Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections Through 180-Degree Angle of Attack for Use in Aerodynamics Analysis of Vertical Axis Wind Turbines." (report SAND80-2114 [22]).

Actual experiments were conducted with NACA 0009, 0012, 0015 and a modified version of the 12% thick foil designated NACA 0012H, which was designed to reduce the leading edge pressure spike and increase $C_{l,max}$. The foils had a 36 inch span and a 6 inch chord, for an aspect ratio of 6:1. The NACA 0012 foils was also tested with 15 inch chord (36 inch span), for an aspect ratio of 2.4. For the 6 inch chord models, tests were conducted at only three Reynolds numbers: Re_c = 0.35, 0.50 and 0.70 x 10^6.

The Eppler PROFILE code was then used to synthesize data at other Reynolds numbers, and for other, thicker foils (NACA 0018, 0021, 0025). Where the changeover from the measured foil coefficients to synthesized coefficients occurred was determined by the results from the DARTER code, a multiple streamtube model from Sandia. This was done empirically, until the computed performance from DARTER agreed with the measured values from cross-flow wind turbine experiments. Note that this conflates static and dynamic stall performance, which makes the "static" coefficients published by Sheldahl and Klimas highly suspect.

Summary: Sheldahl and Klimas data set

published tabulated data for NACA 0012, 0015, 0018, 0021 and 0025 profiles at Reynolds number based on airfoil chord of

$Re_c = 0.01, 0.02, 0.04, 0.08, 0.16, 0.36, 0.70, 1.0, 2.0, 5.0, 10 \times 10^6$.

Actual measurements: Wichita State Wind Tunnel

Extrapolated datasets: Eppler method (PROFIEL code)

Indirect validation via power performance curves of VAWT.

Info on PROFILE code: http://www.pdas.com/eppler.html

## 5.2 Available NACA 0021 data sets

Published data of static foil section coefficients for the NACA 0021 foil are very sparse, c.f. Table 1. Note that the Reynolds numbers for the 1:6 scale RM2 experiment ranged from very small values to approximately 1,500,000, with the Reynolds numbers at $\lambda(C_{P,max})$ on the order of $Re_{c,avg} \approx 2.5 \times 10^5$, and the highest Reynolds number occurring approximately $Re_c \approx 1.5 \times 10^6$ at $\lambda = 5$, and then only occurring during part of the turbine rotation. Given this range of values, the only other useful data sets are those of Jacobs (1931) [24] and Stack (1931)

[25]. However, these data are limited to angles of attack from about 0 to 26 degrees, and include lift coefficients only. XFOIL or Eppler (Sheldahl and Klimas) model simulations are, therefore, required to populate the static data table with drag and moment coefficients within the 0-26 degrees of AoA, and to extend the data set for AoA from -180 to 180 degrees. Furthermore, these static data sets need to include coefficients over the entire range of Reynolds numbers, say from ~100,000 to ~1,500,000.

**Table 1:** NACA 0021 section coefficients, published data sets.

| | | Coefficients | | | Reynolds Number | | $\alpha$ (AOA) | |
|---|---|---|---|---|---|---|---|---|
| Data source | **Modeled/Measured** | $C_l$ | $C_d$ | $C_m$ | **min** | **max** | **min** | **max** |
| Jacobs (1931) | Measured | y | n | n | 5.15E+04 | 1.50E+06 | 0 | 25 |
| Stack (1931) | Measured | y | n | n | 8.30E+04 | 7.35E+05 | -2 | 26 |
| Gregorek et al. (1989) | Measured | y | y | y | 1.50E+06 | 1.50E+06 | -2 | 45 |
| Swalwell et al. (2001) | Measured | y | y | n | 3.40E+05 | 3.50E+05 | 0 | 90 |
| Sheldahl & Klimas (1981) | Measured & Modeled | y | y | y | 1.00E+04 | 1.00E+07 | 0 | 90 |

## 5.3 Comparison of NACA 0021 data sets at different Reynolds numbers

Since there were significant discrepancies between the CACTUS results and experiments – and also for the ALM using the same static foil data – a comparison of the lift and drag coefficients was made at $Re_c \approx 1.5 \times 10^6$, shown in Figure 4. Four datasets were compared: Sheldahl and Klimas, Gregorek, Jacobs, and one generated with the XFOIL viscous panel code (Drela 1989 [27]) via QBlade (Marten et al. 2013 [28]), for which default settings were used. Note again that this Reynolds number is about an order of magnitude higher than typically encountered for the 1:6 scale RM2 experiment, though foil data at lower $Re$ was not available.

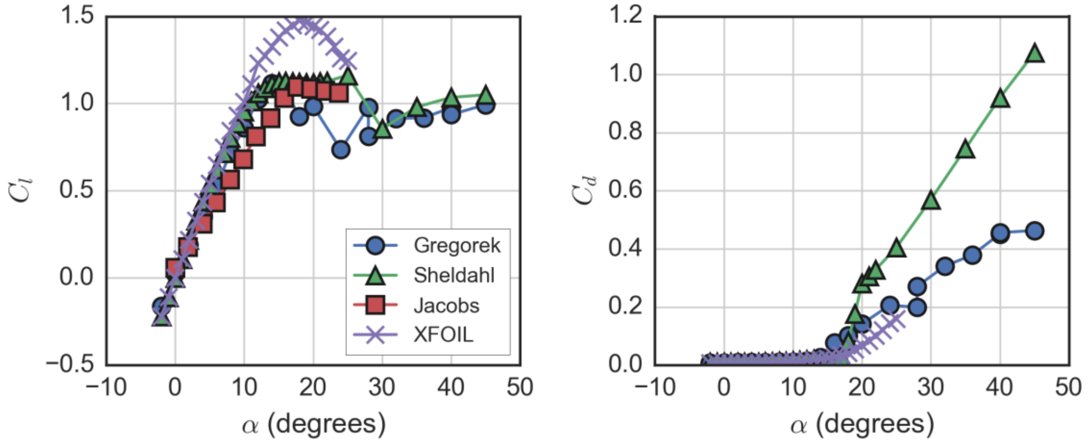

**Figure 6.** Static foil section lift coefficients $C_l$ and drag coefficient $C_d$ from various sources, compared at chord Reynolds number of $Re_c \approx 1.5 \times 10^6$.

This comparison between measured static data (Jacobs 1931 and Gregorek et al. 1989) and simulated data (Sheldhal & Klimas 2001 and XFOIL) indicates important discrepancies between coefficients from these different data sources. In the unstalled regime, all datasets have similar lift slopes ($C_l$ vs $\alpha$) except for the measurements of Jacobs, which may be due to three dimensional effects. The XFOIL data shows overprediction of lift at stall compared with the two experimental (Gregorek, Jacobs) and the Sheldahl and Klimas data set. This over-prediction would ultimately result in higher mean performance for the RM2 when used in CACTUS, though this may not be physically accurate, as the XFOIL panel method may not be considered reliable in the post-stall regime.

The post-stall drag coefficients in the Sheldahl and Klimas dataset are significantly higher than those measured by Gregorek and simulated with XFOIL. However, this may not affect the results when using the LB DS model, since the force coefficients are parameterized based on the trailing edge separation point [5]. For $C_d$ this parameterized force coefficient is then added to the zero-lift drag coefficient, which is similar for all datasets considered.

The largest discrepancies are observed between XFOIL simulated lift coefficients and measured values from Jacobs (1931) and Gregorek et al. (1989) [26] for AoA between 10 and 25 degrees. XFOIL lift coefficients in this AoA range are significantly higher than those measured. XFOIL drag coefficients, on the other hand, are significantly lower than those predicted using the Eppler model (Sheldahl). There is better agreement with Jacobs measured values.

The validity of the Sheldahl and Klimas dataset was also assessed for a NACA 0021 airfoil at low Reynolds number--- $Re_c \approx 1.6 \times 10^5$, by comparing with the wind tunnel data from Jacobs and Sherman (1937) [29]. The results plotted in Figure 7 show how in the attached regime both datasets agree reasonably well, but the stall characteristic in the Sheldahl data appears to overestimate the detrimental effects of separation on the lift coefficient. This comparison implies that the use of the Sheldahl and Klimas static 0021 foil data are the likely cause of the discrepancies in predicted turbine performance, which is reinforced by the aforementioned potential extrapolation of the Reynolds number dependence plotted in Figure 5. Note that the Jacobs 0021 database does not include drag coefficient data at the Reynolds numbers of interest.

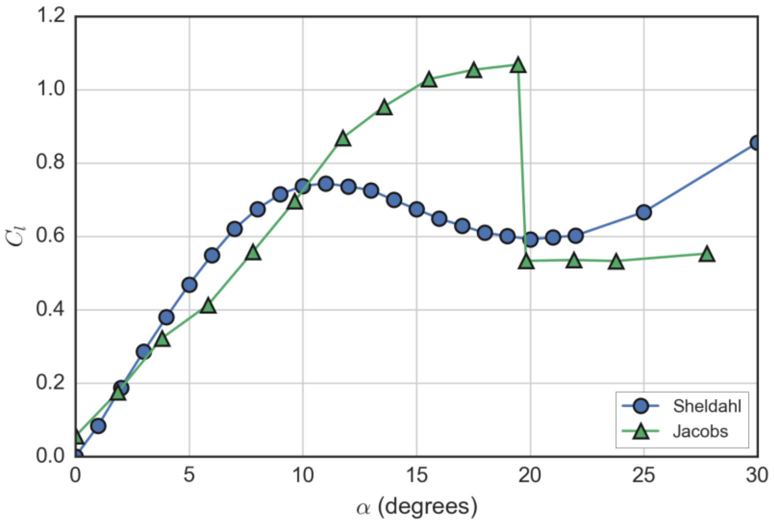

**Figure 7.** Static foil section lift coefficients $C_l$ form Sheldahl and Klimas and Jacobs and Sherman compared at chord Reynolds number of $Re_c \approx 1.6 \times 10^7$.

# 6. CACTUS SIMULATIONS WITH A “HYBRID” DATASET

For this set of simulation runs the Jacobs data is used over its available range of angle of attack, and is extended beyond with Sheldahl data. The reasoning for this procedure in creating a “hybrid” data set is that the Jacobs data is actually measured lift data and considered somewhat trustworthy, whereas the Sheldahl and Klimas data is “synthetic” data. Since the Jacobs data set only includes lift data, the drag coefficient data for the “hybrid” data set comes from Sheldahl and Klimas as well. Performance curves from CACTUS runs using XFOIL coefficient data are included as well. Figure 8 shows the results for the Boeing-Vertol (BV) Dynamic Stall (DS) model, and Figure 9 shows the results for the Leishman-Beddoes (LB) DS model. This exercise looks quite promising for the BV DS model, however, for higher tip speed ratios convergence could not be achieved.

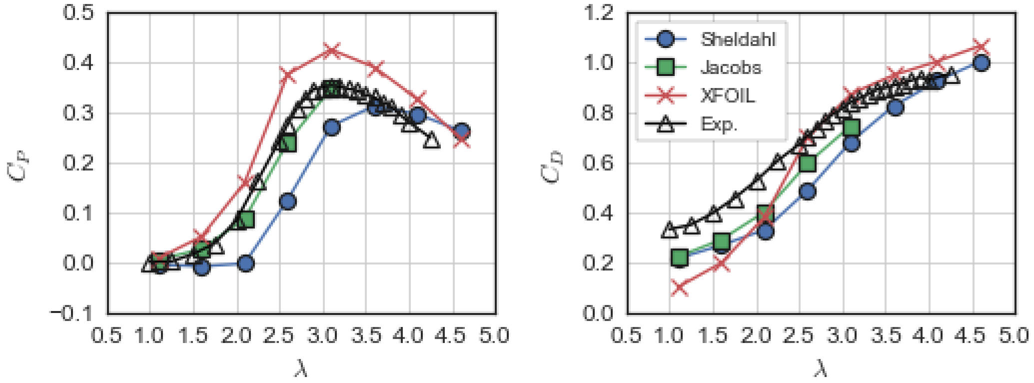

**Figure 8.** Power coefficient $C_P$ and rotor drag (thrust) coefficient $C_D$ comparison for CACTUS with Boeing-Vertol (BV) Dynamic Stall (DS) model, compared to UNH RM2 physical model data.

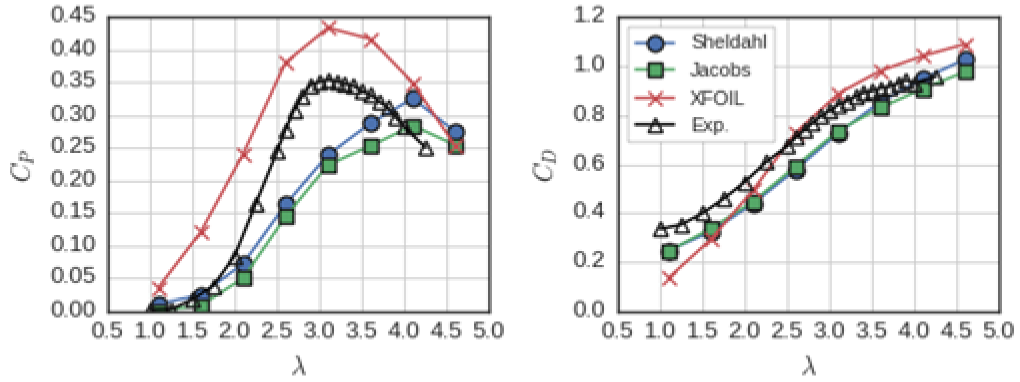

**Figure 9.** Power coefficient $C_P$ and rotor drag (thrust) coefficient $C_D$ comparison for CACTUS with Leishman-Beddoes (LB) Dynamic Stall (DS) model, compared to UNH RM2 physical model data.

# 7. SUMMARY AND RECOMMENDATIONS

The present study demonstrates that over the range of angles of attack and the Reynolds numbers encountered by MHK cross flow turbines, the existing data sets for the NACA 0021 foil diverge considerably, as do numerical results from XFOIL and the Eppler foil data synthesis model. The available data sets used in CACTUS simulations to date –namely the data sets of Sheldahl and Klimas for the NACA 0021 foils derived from Eppler code with matching to Vertical Axis Wind Turbine (VAWT) performance data – are suspect.

It is further demonstrated that CACTUS model predictions of the performance of the 1:6 scale Reference Model 2 MHK turbine under-predict performance using the Sheldahl and Klimas data sets and over-predict performance using XFOIL data sets, since XFOIL will produce erroneous values of foil coefficient beyond stall.

An exercise creating a hybrid dataset combining older, real experimental lift data for a NACA 0021 (at one Reynolds number) and Sheldahl and Klimas data shows promising, improved results when used in CACTUS simulations.

We recommend:

- Limiting the use of CACTUS to higher turbine tip speed ratios: The user should verify for what range of angles of attack reliable foil performance data exists for their candidate design, and then limit device simulation using CACTUS to sufficiently high tip speed ratios so that this range of angle of attacks is not exceeded. Unfortunately, at the present time this will exclude most MHK cross-flow turbine design from being able to use CACTUS to predict performance.
- For future development of cross-flow turbines we recommend investing in creating accurate data sets for symmetrical airfoils over a wide range of Reynolds number based on chord, from $Re_c \sim 10^4$ to $Re_c \sim 10^7$, and AoA up to 25-30 degrees, as needed by the turbine design under consideration.

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