# Overview and design of pitchVAWT

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# Overview and Design of PitchVAWT: Vertical Axis Wind Turbine With Active Variable Pitch For Experimental and Numerical Comparison

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**Due to advances in numerical modeling and hardware scaling, aspects of Vertical Axis Wind Turbines (VAWTs) can now be studied in greater detail than ever before. Turbine blade pitch has been proposed as a method to control overall turbine loading. A 1.5 meter diameter, 1.5 meter height 2 bladed H-Darrieus VAWT with individual blade pitch control has been designed, built, and tested at the wind tunnel facilities of Delft University of Technology. A computational model of the turbine has been made using an actuator cylinder formulation for multiple tip speed ratios and pitch offset values. The design of this turbine and initial data is presented. A comparison is made between measured normal force loading on the blades and the models predicted performance for multiple blade pitch scenarios.**

## Nomenclature

| | |
|---|---|
| $\sigma$ | Solidity |
| $\lambda$ | Tip Speed Ratio |
| $\alpha$ | Angle of Attack |
| $\theta$ | Azimuth Position |
| OJF | Open Jet Facility |
| TSR | Tip Speed Ratio |
| F | Force, N |
| VAWT | Vertical Axis Wind Turbine |
| $C_P$ | Power Coefficient |
| $C_T$ | Thrust Coefficient |

## I. Introduction

Research in Vertical Axis Wind Turbines has been increasing in the last decade due to the rapid advance in size scales of wind turbines and a push toward offshore markets. Due to advances in numerical modeling and hardware scaling, aspects of these turbines can now be studied in greater detail than ever before. It is believed that large improvements in cost of energy for floating offshore turbines can be realized with a vertical axis arrangement. In order for this to take place, turbine loading must be limited at high wind speeds. Blade pitch is viewed as a way of accomplishing this. Altering the blade pitch can have multiple uses in the design of a VAWT including improving starting torque, maximizing power capture, maintaining power levels in higher than rated wind speed operation, or minimizing cross-sectional area during survival wind speed events at sea.[1]

Experimental research on VAWTS has largely focused on fixed pitch turbines with the goal of understanding the complex flow nature of the VAWT.[2] Rossander et. al. has completed an experimental campaign

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to measure the rotor loading of a VAWT with incorporated load cells into the strut connection points at the hub.[3] Mauri et. al. have designed an active variable pitch VAWT for use in external conditions and have adapted it for work within the wind tunnel.[4] However, few campaigns have worked to measure the loading with a pitch controlled turbine in controlled conditions. There are two main categories of variable pitch VAWTs, the first is referred to as active pitch or 'forced-pitch', while the second is a passive pitch system. Active pitch VAWTs control the blade angle based upon a defined pitch schedule as a function of azimuth position relative to the wind direction. A passive system allows the airfoil to pivot on a pitch axis due to the natural moments acting on the airfoil due to the wind conditions present. Passive systems have the ability to improve performance of smaller low TSR VAWTs by preventing stall,[5,6]however these systems are not suitable for testing the viability of potential pitch regimes. Active blade pitch systems have largely been limited to sinusoidal excitation with the use of mechanical devices such as cams or gears to prescribe a particular pitch motion.[7] These systems allow the capability to test certain sinusoidal pitch phenomena however are not able to meet the demands of the varying potential pitch schedules required for optimizing power production or limiting thrust loads in higher wind conditions. In order to verify the performance of potential pitch schemes for things such as thrust magnitude and direction control, power control in multiple Tip Speed Ratios (TSRs) and self start ability, an independent pitch control system with the ability to function at a rate greater than once per revolution is required.

In this work, an experimental VAWT with independent active pitch control ability, referred to as PitchVAWT, is designed and tested in the Open Jet Facility (OJF) at the Delft University of Technology. A design overview of the turbine and relevant sensor systems is presented. A 2D numerical formulation of the PitchVAWT turbine, is modeled with an Actuator Cylinder flow model.[8] Initial data is presented and compared with expected results from the numerical model.

# II. Model Development

## A. Numerical Model

The Actuator Cylinder (AC) is a 2 dimensional flow model developed by Madsen[8] which applies the actuator disk concept to the cylindrical actuation surface that is swept by a vertical axis turbine. The blade forces are calculated and applied to the flow as body forces. The induced velocities on the flow are prescribed by the volume forces and induced forces and consist of both a linear and non-linear solution. A linear approximation published by Madsen[9] allows the order of accuracy of the non-linear solution with the calculation time of the linear solution. This is fundamental for use within aero-elastic codes or optimization functions. The actuator cylinder is divided into a number of azimuthal elements, and the blade loads for each element are determined based upon a lookup table of the given airfoil polars. By using this scheme, models can include aerodynamics such as blade pitch, and dynamic stall.[10]

The implementation of the model for the PitchVAWT turbine has been performed with 144 azimuthal elements to allow for the study of various pitch schedules with a fine azimuth resolution. The 144 elements coincides with a $2.5^o$ azimuth resolution. This is consistent with formulations of other 2D models such as U2Diva[2,11] for comparison purposes. A polar for the NACA0021 airfoil was computed using Xfoil[12] with a free separation and clean surface (Ncrit=9) for a Reynold's number of 120,000. The polar was then extrapolated using the Viterna method,[13] see figure 1. Predicted power and thrust coefficients for three fixed pitch settings are shown in figures 2a and 2b. The model calculations are expected to be an ideal case and the measured values during testing are expected to be much lower due to drag effects and neglecting dynamic stall. However the trends with respect to pitch angle adjustments are expected to be consistent with model predictions.

## B. Experimental Model

The PitchVAWT turbine is a 2 bladed H-shaped vertical axis turbine with two horizontal struts per blade located at approximately 25% and 75% of the blade length to minimize deflection during operation. The general specifications can be seen in Table 1. The sizing of the turbine is controlled by several aspects. First, the pitch system needs to be able to respond at a frequency approximately four times that of the rotational rate of the turbine in order to match potential load distributions for the rotor, and the larger the turbine, the slower the rotational rate required to achieve each TSR value for a given wind speed. The diameter is restricted on the upper end by the dimensions of the wind tunnel. So 1.5m was chosen as the largest

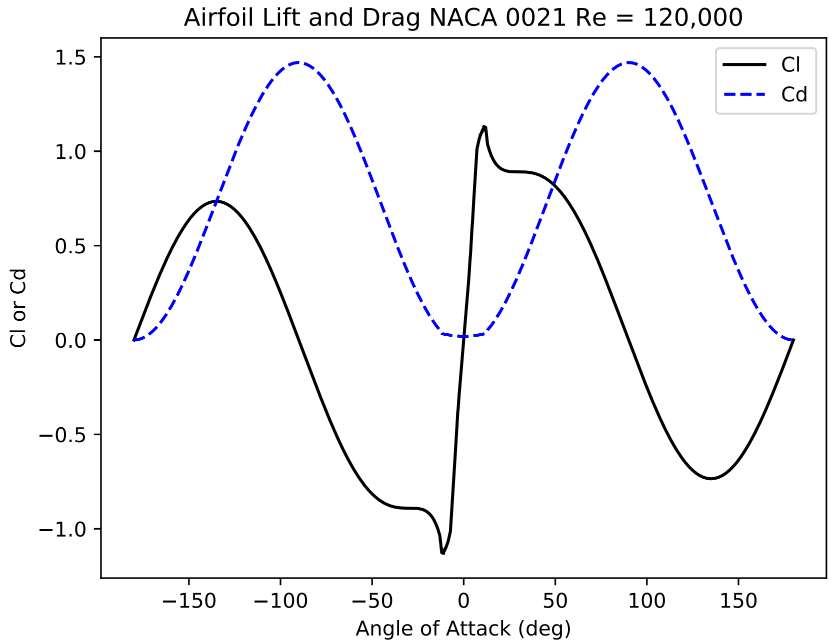
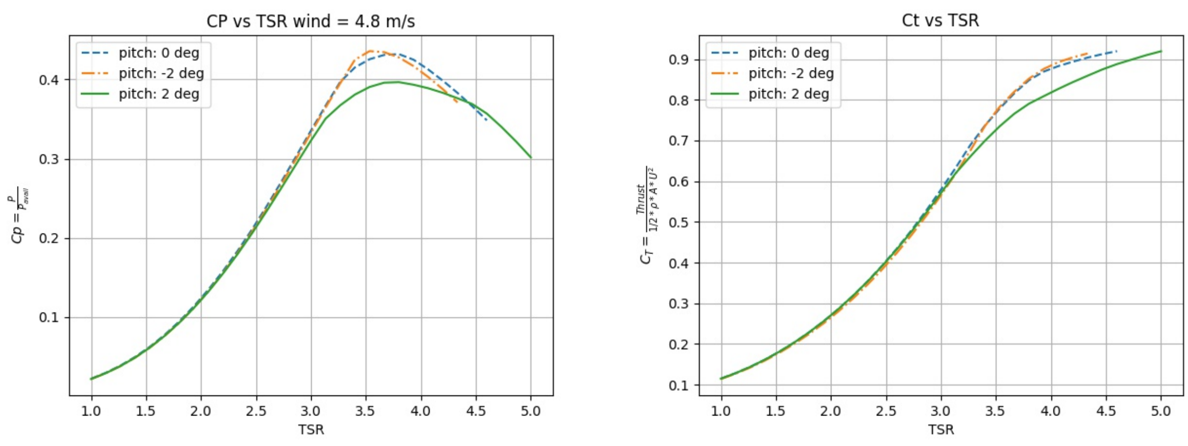



Figure 1: Airfoil polar for NACA0021 computed at $Re = 120,000$with XFoil[12] 360 extrapolation with Viterna Method[13]




(a) (b)

Figure 2: a) $C_P - \lambda$ and b) $C_T - \lambda$ for multiple fixed pitch settings

turbine without significantly restricting the flow of the tunnel causing blockage effects. The aspect ratio of the turbine is important for the characterization of two dimensional flow in the mid-plane of the rotor and should be as large as possible for comparison to two dimensional numerical models and potential future Particle Image Velocimetry (PIV) measurements. The turbine height was constricted to the same size as the diameter due to the symmetrical outlet of the wind tunnel. The airfoil was chosen as NACA0021 due to its relative thickness for better structural performance and its prevalent use in other research turbines of this scale.[4] Rotor solidity, $\sigma$ was chosen due to the performance of the NACA0021 airfoil shown in figure 3, to be 0.1. Two blades were chosen in order to maximize the chord length per blade while maintaining rotor solidity. This allows the blade Reynolds numbers to approach 120,000 allowing better prediction of airfoil performance with available tools such as Xfoil. The consequence of using two blades is a large oscillation in rotor thrust and torque on a twice per revolution, 2P frequency. This becomes apparent in the loading of the turbine, however for the practical measurements to be performed such as blade loading this does not effect the results substantially. Future research of thrust measurement and control will have to take this oscillation into account in the calculation of the method's effectiveness.

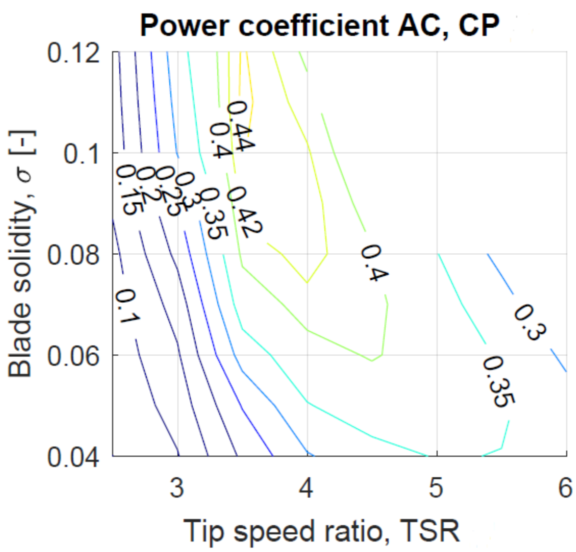



Figure 3: NACA0021 performance for varying $\sigma$ and $\lambda$ at Re=120,000

Table 1: PitchVAWT Design Specifications

| Property | Dimension |
|---|---|
| NBlades | 2 |
| Height | 1.5 m |
| Diameter | 1.5 m |
| Chord | 0.075 m |
| Solidity | 0.1 |
| Airfoil | NACA0021 |

## C. Pitch System

The pitch for each blade is independently controlled with the use of DC micromotors and positioning controllers. These controllers provide signal feedback to the turbine SCADA controller which, depending on the requested pitch scheme being tested, update the pitch position of each blade. This allows for the ability to actively change pitch offset as a constant over the rotation, to tie it to the azimuthal position of the rotor, or to study the effectiveness of advanced turbine controllers. The blades have the ability to rotate

25 degrees to the inside of the rotor (- pitch) or completely perpendicular to the flow (+ pitch) if required. Operating speed of the pitch system is designed to handle 10 degrees of rotation at 10 Hz which corresponds to approximately twice the operational frequency at a turbine rotational speed of 300 RPM. Figure 4 shows the pitch system for a single blade of the turbine.

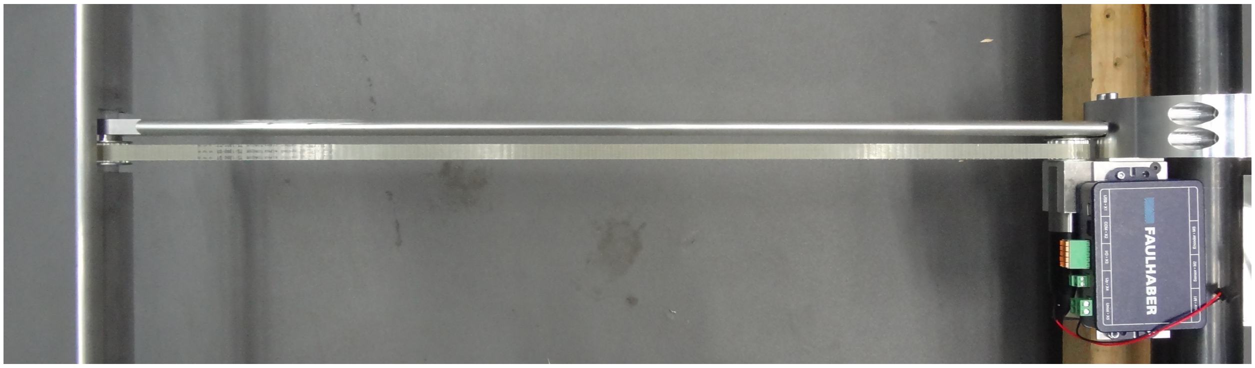



Figure 4: Pitch system for PitchVAWT, pictured is the controller, motor, and actuator mechanism

### D. Instrumentation

The PitchVAWT turbine controller monitors a variety of sensors to maintain speed control of the rotor, pitch position of each blade, and required signals for data processing. These signals are recorded locally on the embedded turbine controller and transferred to a host pc over TCP/IP for storage and processing. National Instruments Compact Rio hardware is used for data acquisition, control decisions, initial processing, and data logging. Figure 5 shows the installed external sensors. A slip ring is used in order to transfer power and data signals to the rotor. Due to limited available channels on this slip ring, only a single blade is monitored with strain gages. There is a strain gage on each support strut of Blade1 measuring the normal force. There is a main bearing housing which supports the full weight of the rotor. This housing is mounted to a thick aluminum base plate by a set of 4 load cells. These load cells measure the forces transferred between the main bearing housing and the base. This can be used to estimate the magnitude and direction of the thrust load. A torque transducer and rotary encoder are inserted into the driveline between the main bearing housing and the generator. The rotary encoder is used to monitor the azimuth position of the rotor which is then used as an input for the blade pitch controller. The complete assembled turbine with highlighted instrumentation is shown in Figure 6.

## III. Experimental Setup

### A. Open Jet Facility

The Open Jet Facility (OJF) at TU Delft, shown in Figure 7 is a closed loop open jet test section facility. It has an outlet cross section which is 2.85 m X 2.85 m opening into a 13 m long, 8 m high test section. The tunnel is capable of up to 35 $\frac{m}{s}$ sustained velocities, however during this testing is limited to approximately 7 $\frac{m}{s}$ due to rotational speed restrictions of the PitchVAWT design. Testing was conducted at 4.8 $\frac{m}{s}$ for all measurements discussed herein.

### B. Test Matrix and Procedure

The test matrix for initial testing of turbine behavior is shown in Table 2. Tests were performed for each tip speed ratio and pitch setting for both a constant pitch offset and a sinusoidal offset based upon azimuthal position of the rotor. In total 108 combinations of pitch setting and TSR were collected. This wide range was performed in order to provide a varied baseline of turbine performance for comparative purposes of future tests, and to gain knowledge into the performance envelope of the current rotor. For this analysis focus will be placed on the plus and minus two degrees fixed pitch schemes. This is namely due to outside this fixed pitch range the turbine is operating in substantial stall for even greater times than normal and

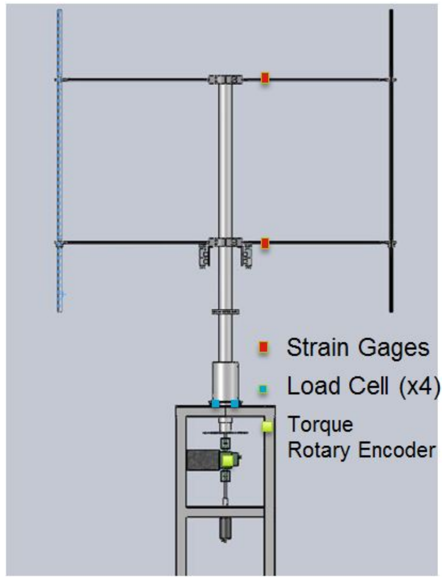



Figure 5: Model of the PitchVAWT turbine with installed sensors.

doesn't produce any meaningful aerodynamic results. These tests were namely for functionality of the pitch system.

Table 2: Test Matrix

| Pitch | Tip Speed Ratio |
|---|---|
| -10 | 2 |
| -7 | 2.5 |
| -5 | 3 |
| -2 | 3.5 |
| 0 | 4 |
| 2 | 4.5 |
| 5 | |
| 7 | |
| 10 | |

Testing was performed by bringing the wind tunnel to a stable wind speed of $4.8\frac{m}{s}$ and stepping the turbine through specified rotational speeds coinciding with tip speed ratios of interest. A typical speed ramp through the TSR values is shown in figure 8. As shown, data was not collected for substantial time periods at a TSR of 3.5. This is due to a vibrational mode of the adjustable platform which the pitchVAWT is mounted to which caused substantial instability in the turbine and had to be passed through quickly. This is unfortunate due to it aligning with the maximum performance of the aifroil models. This will be corrected in future tests by a combination of a new turbine base, and altering wind tunnel speed to allow for measurement of this TSR.

### C. Post Processing

The strain gages for measuring blade normal force are wired through the slip-ring into the National Instruments 9237 C-series strain gage input module. The current configuration consists of one quarter bridge on the top of each strut of blade one. Each gage is then balanced with a dummy $120\Omega$ resistor and wired to the data acquisition card which completes and balances the Wheatstone bridge circuit. The data is then logged as a raw response voltage. The raw voltage is then converted to engineering units of Newtons by applying a

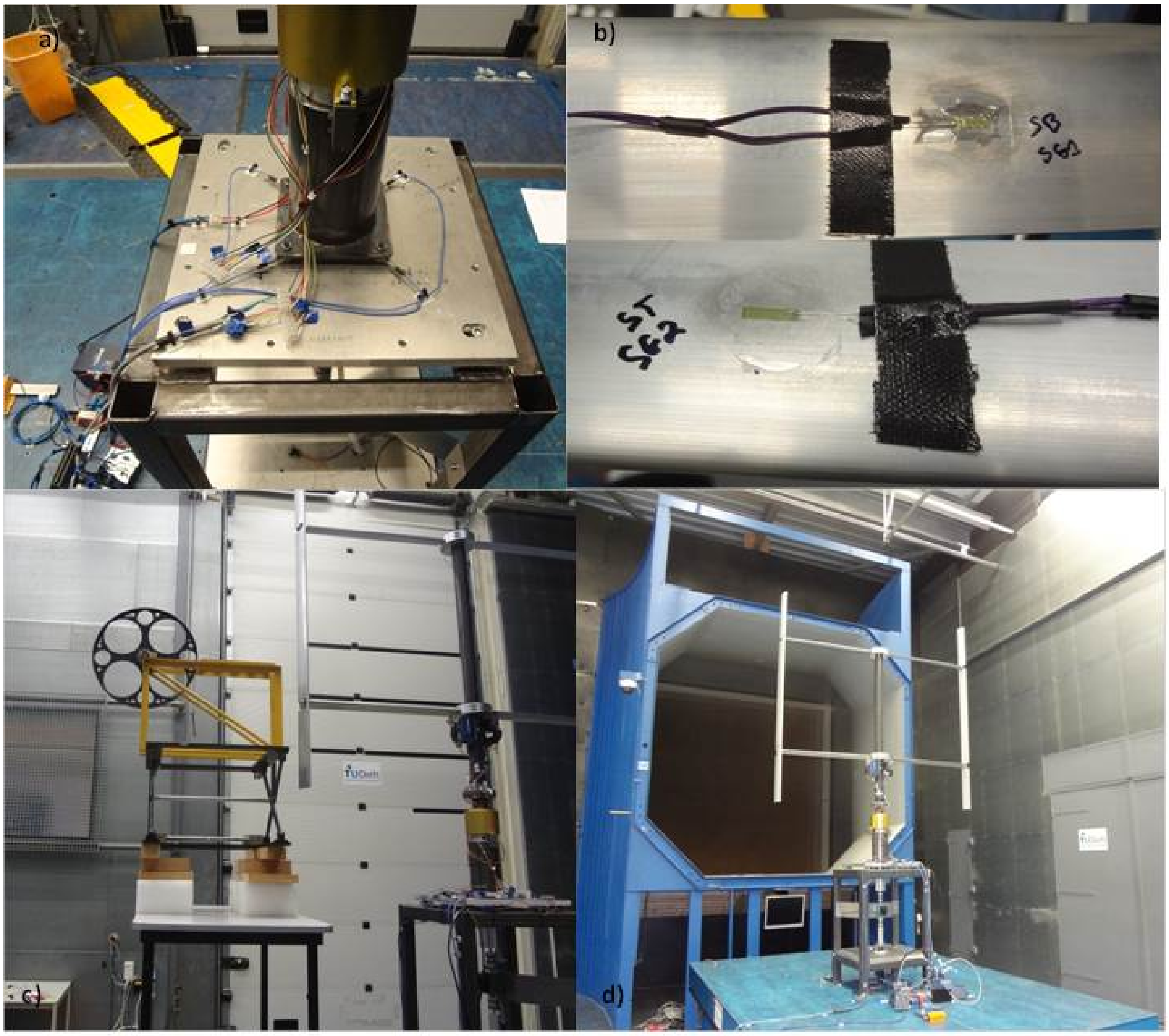



Figure 6: Photos of the installed PitchVAWT Turbine a) Load Cells with wiring b) Installed strut strain gages c) calibration rig for strain gages, d) PitchVAWT in the OJF Facility at TU Delft.

calibration slope and offset. The slope and offset for calibration was determined prior to testing by applying calibration weights to a suspended pulley system which was attached to the mid-plane of the rotor with high strength fishing line. The setup is shown in the bottom left corner of figure 6. Once the data is converted to engineering units, a band pass filter is applied at a pass frequency of 1-10 Hz. This removes the centripetal loading of the turbine under constant RPM and subtle RPM swings during testing at a particular tip speed ratio as well as higher order dynamics that exist due to rotor vibration frequencies. The first flexible bending mode of the turbine is calculated to be 10.4 Hz, results discussed in this paper are taken at tip speed ratios below the above mentioned table vibration frequency as to avoid exciting this mode.

## IV. Discussion of Results

Due to platform vibration Tip Speed Ratio comparisons were limited to below 3.5. Data was collected across each pitch condition at a turbine rotational speed of 180 RPM, or a TSR of 2.9. The actuator cylinder model was run for this TSR at each fixed pitch value. The normal loading was then multiplied by the rotor height to give a value which would compare to the three-dimensional rotor. This analysis ignores

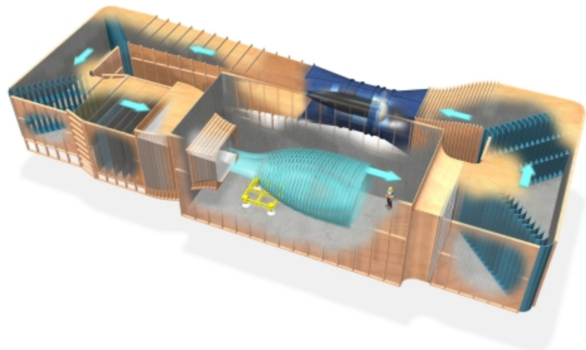


Figure 7: Open Jet Facility at the Delft University of Technology

three dimensional effects, effects of the struts, and effects of the tower. The predicted angle of attack is shown in figure 9a. When compared to the airfoil polar (figure 1) the turbine is expected to be in stall for a large amount of time in both the upwind and downwind pass. with the effect of the added two degrees of pitch causes stall to occur quicker in the rotation. The calculated normal force azimuthal distribution is shown in figure 9b. The stall represents itself in this model as the drop in load for each pitch angle between approximately 45 and 160 degrees of azimuth in the upwind pass, and 190 and 340 degrees in the downwind rotor pass.

Normal loading measured on the PitchVAWT turbine is presented in figure 10a for a TSR of 2.4 and in figure 10b for a TSR of 2.9. The measurements were taken by averaging the data over the time period at the respective azimuth position for each TSR. Averages are shown as the data point and the standard deviation for each measurement is plotted as vertical error bars. The positive two degree pitch curve in the case of TSR 2.4 seems to be functioning in a stalled state a majority of the rotor pass, most likely due to a combination of the high angles of attack, and the unsteadyness of the flow in rapid angle of attack changes. The minus two degree pitch case shows a better turbine performance and flow more akin to what is expected and predicted by the model. However, a phase shift appears between the model and the observed results for each case. Stall is also noted in this measurement by the drop in load at the 130 deg azimuth position. At a TSR of 2.9 loading for both pitch values begin to show more consistent tendencies. The 2 degree pitch has a higher load set prior to stall than the -2 degree pitch value for the upwind pass. The stall is also largely averted for the upwind pass of this value as well. The downwind pass for each pitch position is chaotic due to flow disturbances of the struts, tower, and upwind blade pass. A trend can be seen for both pitch scenarios with an increasing load between 180 and 225 degrees prior to dipping back negative at the 270 deg (directly behind the tower) azimuth position.

Overall the loading values are much higher than those predicted from the model. This is most likely due to the large amount of drag on the struts, connection points, and pitch actuator mechanisms that are not accounted for in the model. This likely affects the loading on the downwind pass of the blades as well. Steps will be taken to adjust the model for future tests in order to eliminate any unnecessary drag and loading effects on the rotor. Modeling of three dimensional effects and dynamic stall will also be included to help improve the capability of the model to predict the loading.

## V. Conclusions

A turbine has been designed to operate in the Open Jet Facility at Delft University of Technology which has the capability of individual active pitch control. The turbine is modeled with a two dimensional actuator cylinder model in order to predict turbine performance and blade loading. A test campaign was completed providing a baseline of as built turbine loads. The turbine generates a large amount of drag which has not been modeled such as struts, strut connections, three dimensional effects, and most likely effects such as dynamic stall. These issues cause the values of the measured blades loads to be much higher than the model

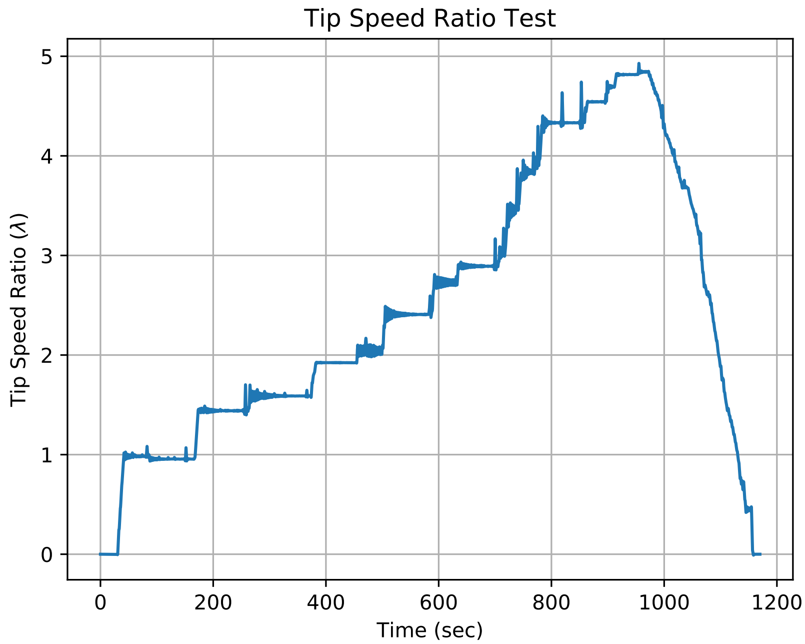



Figure 8: Example of tip speed ratio ramp during testing (-2 degree pitch test shown)

predicts. Although load in the upwind versus downwind passes, and how this varies with fixed pitch angle are demonstrated to follow the modeling trends. Steps are being taken in further testing to reduce the drag of these areas on the experimental model and efforts will also be made to include more of the flow effects which are present and currently neglected such as struts and dynamic stall in the numerical model.

## Acknowledgments

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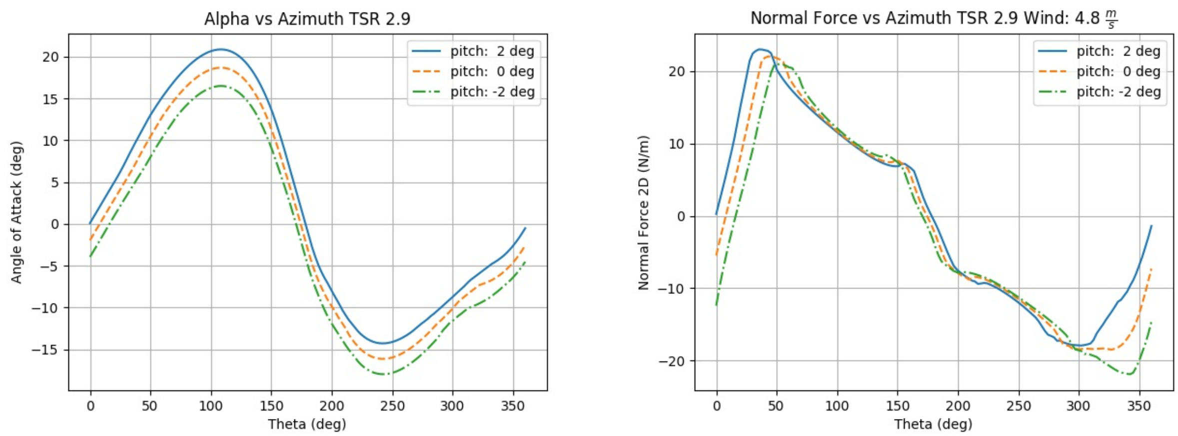
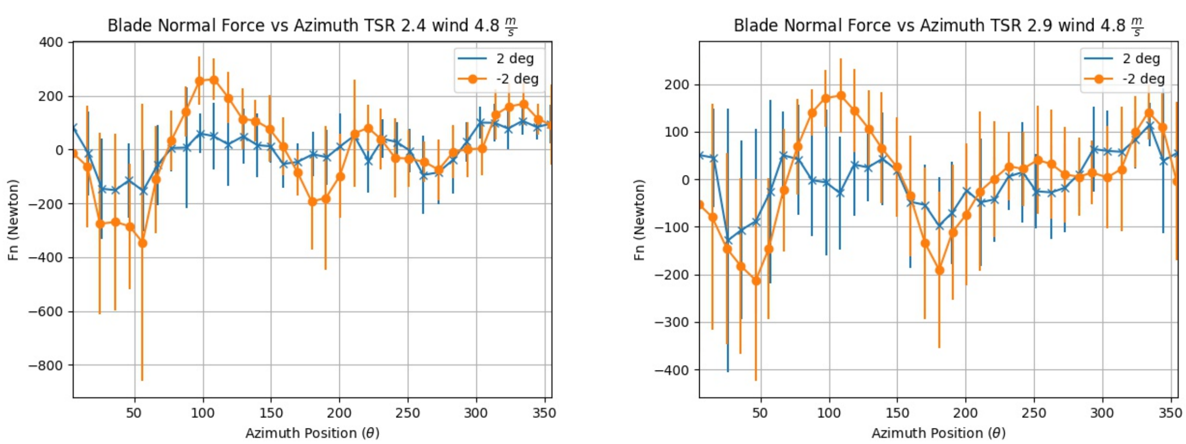



(a) Angle of attack with fixed pitch variation (b)

Figure 9: Turbine blade loading at TSR 2.9 as calculated with the two-dimensional actuator cylinder model and translated to full turbine response through multiplying by blade height.




(a) (b)

Figure 10: Measured normal force from strain gage response vs rotor azimuth for a)TSR 2.4 and b) TSR 2.9.

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