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Experimental Determination of Thrust Loading of a 2-Bladed Vertical Axis Wind Turbine

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Abstract. Large floating offshore wind turbines are beginning to show promise as a technology with several pilot projects being completed in recent years with more on the near horizon. Due to the complexities of the floating configuration there are substantial costs associated with the platform and mooring systems for these types of deep water machines. The vertical axis wind turbine has been proposed as a potential solution for lowering the overall costs of turbine installations. This is achieved through a lower center of gravity and a greater tolerance to platform motions than an equivalent horizontal axis machine. The cost of the platform system is related to the overturn moment of the turbine in crucial operational states. The largest contribution to this moment is the rotor thrust. In this work, an experimental wind tunnel model has been made to study the loading of a 2-bladed H-type VAWT. The model is capable of individual active pitch control and is equipped with sensors to measure thrust and side loading with respect to the turbine. This paper introduces the experimental wind tunnel model referred to as PitchVAWT, discusses the method of determining rotor thrust and side loads, and presents measured results for a fixed pitch case with varying tip speed ratio. The data presented will be made available for further evaluation and potential validation of turbine numerical codes.

1. Introduction

Large floating offshore wind turbines are beginning to show promise as a technology with several pilot projects being completed in recent years, and more on the near horizon[1]. Due to the complexities of the floating configuration there are substantial costs associated with the platform and mooring systems for these types of deep water machines. The vertical axis wind turbine has been proposed recently as a potential candidate for lowering the overall costs of turbine installations[2]. This is achieved through a lower center of gravity and a lower sensitivity to platform motions than the horizontal configuration [3, 4]. With the increased control authority provided by active individual blade pitch it becomes possible to influence the thrust load magnitude and direction. The ability to control thrust opens up a large area of possible use cases, such as platform motion alleviation. Due to the lapse in building of Vertical Axis Wind Turbines since the early 1990s, as discussed in [5], there is a considerable gap in test data for VAWT performance. A large amount of the data which does exist is focused on power performance or wake effects, see [6, 7, 8]. Due to this lack of experimental data specifically when it comes to measured rotor thrust, there is an introduced uncertainty in the modeling tools to predict overall rotor loading. As thrust has a potential to be the driving load in floating platform designs, steps must be taken to reduce this knowledge gap.



An experimental model has been developed to study the loading of a 2-bladed H-type VAWT. This model, referred to as PitchVAWT, is capable of active individual pitch control and is equipped with sensors to measure thrust magnitude and direction, as well as turbine torque and blade normal loading. An experimental campaign is undertaken to measure the baseline performance of the PitchVAWT turbine and to generate a thrust curve versus Tip Speed Ratio for a given pitch configuration. This paper gives a quick overview of the turbine design, discusses the method of calculating rotor thrust loading, demonstrates this ability for a single case of fixed pitch and presents the detailed results of the analysis.

2. Turbine Overview

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 chord was chosen based upon a turbine solidity, $\sigma = Nc/2R$ of 0.1. The NACA0021 airfoil was chosen for its common use in VAWT research, and its relative thickness for structural stability. Data is collected from a set of sensors on the turbine allowing to determine quantities of azimuth position, rotor torque, thrust load transferred to the tower base, and normal blade loading. Data is collected, processed, and stored using National InstrumentsTM hardware at a rate of 500 samples per second. The experimental setup is shown in figure 1. Greater detail is given for the design of the PitchVAWT turbine in a previous work, [9].

Table 1. PitchVAWT Design Specifications

Property	Dimension
NBlades	2
Height	1.5 m
Diameter	1.48 m
Load Cells to Rotor Center	1.15 m
Chord	0.075 m
Solidity	0.1
Blade Airfoil	NACA0021
Strut Airfoil	NACA0018

The coordinate system for the turbine is shown in figure 2. This convention will be used for all analysis moving forward. Rotor azimuth position is defined with respect to blade 1, therefore blade 2 lags blade 1 by 180 degrees. The zero azimuth position is defined as the rotor plane perpendicular to the oncoming wind. Positive X is in line with the wind, positive Y is perpendicular to this flow, and positive θ corresponds with the right hand rule. The turbine rotates counter-clockwise, in a positive θ direction.

3. Calculation of Thrust Loads

The turbine has four load cell sensors mounted between the tower main bearing assembly and the base support in a square configuration. This is shown in figure 1 and in detail in figure 3. Each load cell has a name corresponding to its location on the turbine as shown in figure 4. The tower base bending moment is calculated by taking the differential loading between the load cells on either side of the corresponding axis multiplied by the physical distance between the load cells, D . This moment is then translated to the equivalent rotor thrust by dividing by the distance to the center of the rotor, H . This calculation is shown for loading in the X-direction, corresponding to rotor thrust, in equation 1 and in the Y-direction, corresponding to side loads, in equation 2.



Figure 1. Experimental setup for PitchVAWT in the Open Jet Facility wind tunnel at TU Delft. Thrust is measured through load cells between the main bearing housing and the base mounting plate (top left image).

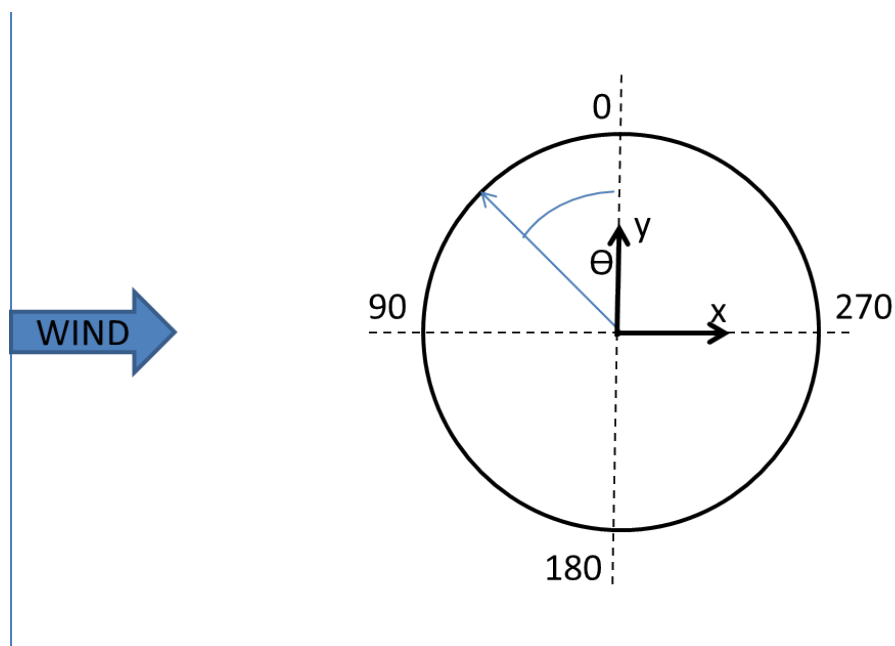


Figure 2. Coordinate system for the PitchVAWT turbine.

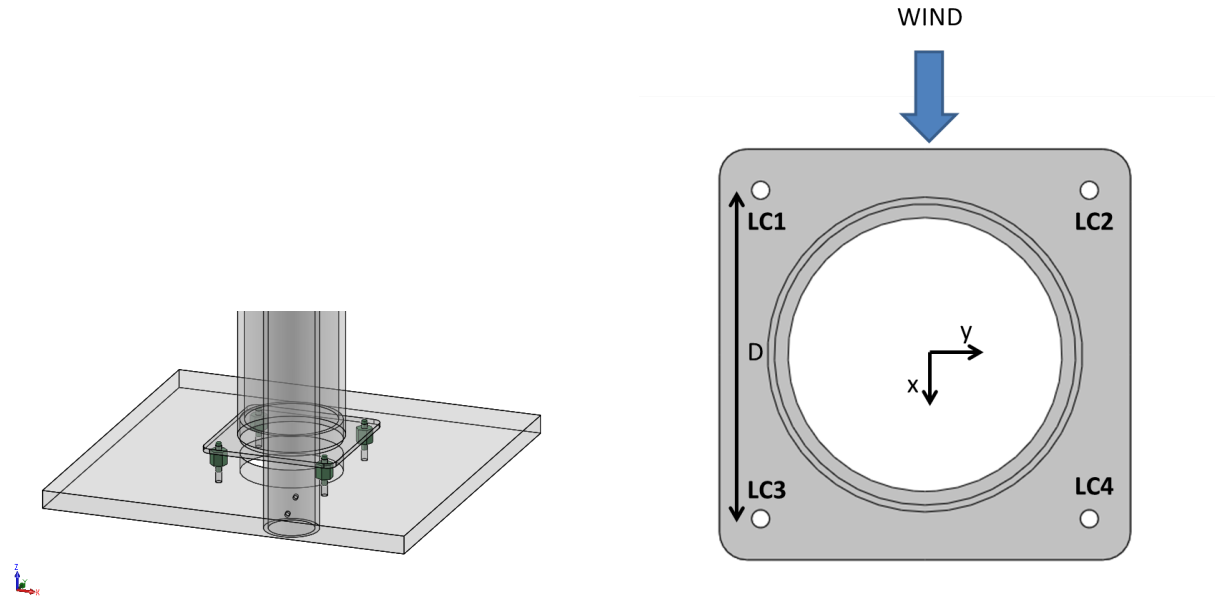


Figure 3. Dimetric view of load cell arrangement on PitchVAWT

Figure 4. Load cell naming scheme for tower bending moment

$$F_x = \frac{M_{yy}}{H} = \frac{((LC3 + LC4) - (LC1 + LC2)) * D}{H} \quad (1)$$

$$F_y = \frac{M_{xx}}{H} = \frac{((LC2 + LC4) - (LC1 + LC3)) * D}{H} \quad (2)$$

where:

- F_x = Force at rotor center in X-direction
- F_y = Force at rotor center in Y-direction
- M_{xx} = Moment about x-axis
- M_{yy} = Moment about y-axis
- H = Distance between load cells and rotor center
- D = Distance between load cells
- $LC1 - LC4$ = Individual load cells as depicted in figure 4

3.1. Data Processing

The load cell data is acquired using the NI-9234 sound and vibration measurement module configured to run in IEPE, Integrated Electronic Piezoelectric, signal conditioning mode to interface with the Piezoelectric load cells (PCB 208C02) at a rate of 500 samples per second. Due to this signal conditioning the load cell signals are AC-coupled during A/D conversion. This AC - coupling effects the DC offset expected in the X-direction thrust measurement (0 to max load rather than oscillating about zero). This is compensated for in the thrust measurements by adding the offset back to the measured x values. Due to the loading phenomena itself occurring at a frequency higher than 0, minimal loading information is lost during this conversion. The raw voltage load cell signals are converted to engineering units of Newtons by applying the individually calibrated sensitivity (about $10 \frac{mV}{N}$) for these load cells. The unfiltered time response

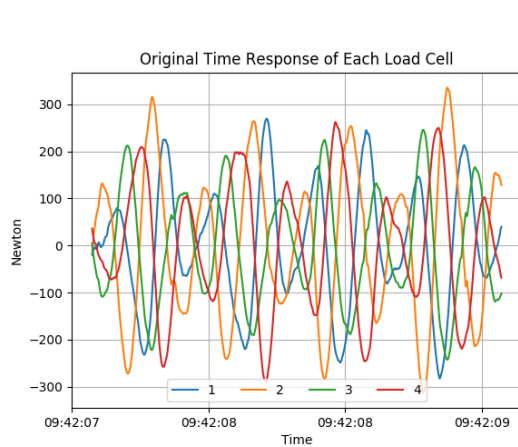


Figure 5. Unfiltered time response of each load cell at TSR 3.25

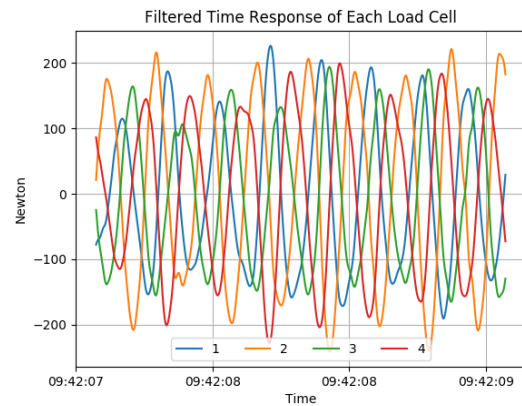


Figure 6. Time response with BandPass filter removing signals outside the frequency range of interest (4 - 45 Hz)

for a TSR of 3.25 is shown in figure 5. There are several effects which are noticed in this signal which are not of significance to the analysis. The first is any rotor imbalance due to differing weights of each blade, this phenomena occurs at a rate of once per revolution, or 1P. Due to the PitchVAWT turbine having two blades, the excitation frequency for the thrust begins at a rotational rate of 2P, so the once per revolution loading can be safely filtered out. The next effect is a sort of beating phenomena, this is a function of the turbine speed controller during a transient start-up and can also be safely filtered out as a signal which is far below our frequency range of interest. During previous testing discussed in [9], a vibration mode of the turbine system was discovered at 3.47 Hz. In order to avoid this resonance, steps were taken to increase the stiffness of the platform which the turbine is mounted on, and the wind speed was reduced to allow higher TSR ratio measurements at a lower operational RPM. The first flexible vibration mode of the blades is modeled in this configuration to be approximately 13 Hz. This frequency is outside the range of the operational rotational speed and should not have a large impact on the 2P force excitation which is at 6.8 Hz for a TSR of 4 for this testing. The last quantity discussed here is electronic noise which can be present above 50 Hz. These frequencies are filtered out with a 6 order butterworth bandpass filter with a pass range between 4 and 45 Hz. A notch filter is then applied to remove the higher order harmonics of the 1P excitation. The resultant time response is shown in figure 6.

Once the load cell responses have been properly filtered, the reaction forces on the rotor are calculated using equations 1 and 2. The time response for the reaction forces are shown in figure 7. This data is very useful with regards to understanding how fatigue loads accumulate over time or for understanding the current state of the turbine for things like controller input, however it is less useful from an aerodynamic comparative analysis standpoint. For that, the data is resampled in the azimuthal domain, shown in figure 8.

4. Experiment

Data was collected for the PitchVAWT turbine at the Open Jet Facility, or OJF, wind tunnel at the Delft University of Technology, see figure 9. The OJF is a closed loop open jet test section facility. It has a $2.85m \times 2.85m$ outlet cross section with a $8m$ high, $13m$ long test section. The goal of this experiment was to measure the thrust of the turbine at a variety of tip speed ratios. This was accomplished by setting the wind to a constant speed and controlling the rotational rate of the turbine. The wind was measured to remain constant at $4.01m/s$ throughout the

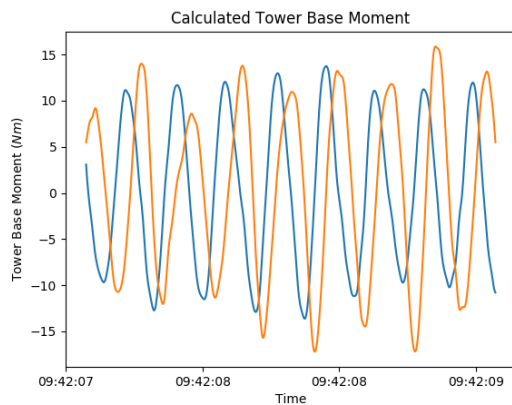


Figure 7. Example of turbine base moment over time

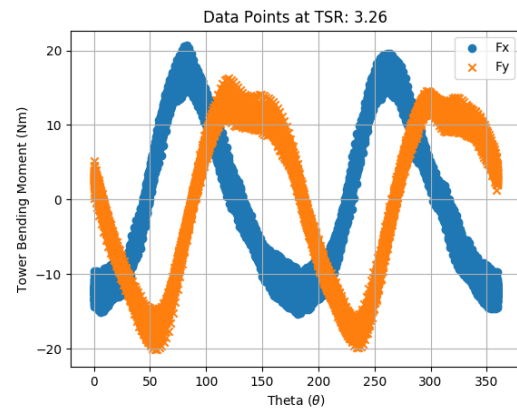


Figure 8. Example of turbine base moment data resampled over rotor azimuth position

Table 2. Experimental Conditions

Property	Dimension
U	4.01 m/s
Temperature	19.7 C
ρ	1.207 kg/m ³

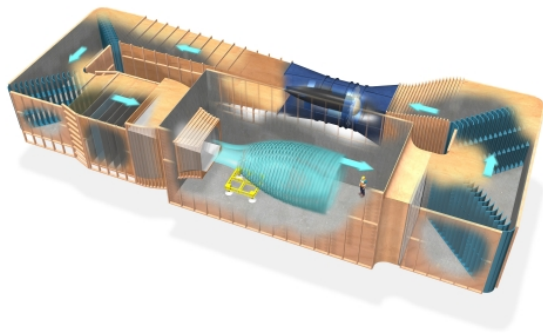


Figure 9. Open Jet Facility at TU Delft

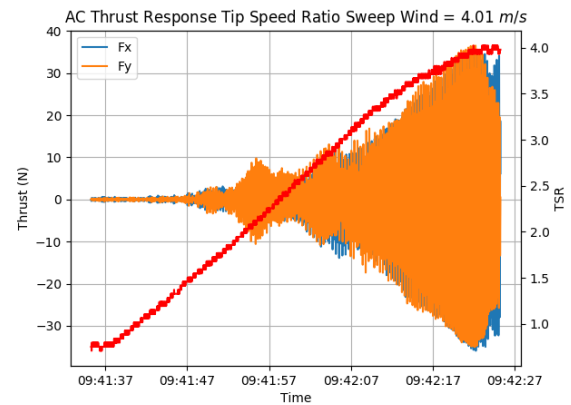


Figure 10. Time trace of Tip Speed Ratio sweep showing rotor response in X and Y. $U = 4.01 \text{ m/s}$, $\rho = 1.207 \frac{\text{kg}}{\text{m}^3}$

testing period. The speed of the turbine was increased from rest to 200 *rot/min*. The TSR and measured turbine load are shown in figure 10 for the test period. The atmospheric conditions in the wind tunnel during testing are given in table 2.

5. Results

The shown azimuthal data in figure 8 is taken from a large set of time response data (150 rotations) so as to show the repeatability of the load response. Due to the nature of vertical axis

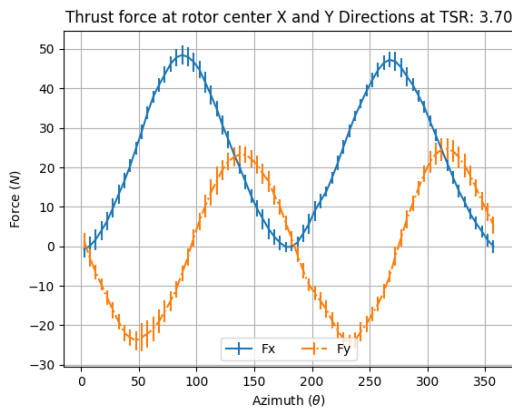


Figure 11. Thrust force at a wind speed of $4.01 \frac{m}{s}$ and a TSR of 3.7 over 22 rotations with standard deviation. $\overline{\sigma_{F_x}} = 1.9N$; $\overline{\sigma_{F_y}} = 2.3N$

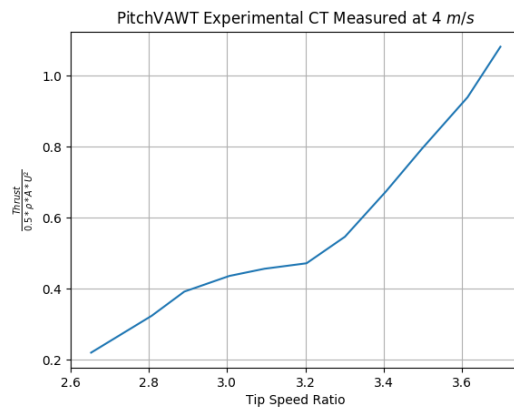


Figure 12. Measured CT vs Tip Speed Ratio for PitchVAWT with Zero degree fixed pitch

wind turbines, which vary loading considerably over every rotation, it is necessary to view the data in this domain in order to draw conclusions about aerodynamic performance. For instance, there is a maximum thrust in the X direction expected at 90 and 270 degrees of rotor azimuth, blade 1 furthest upwind and blade 2 furthest upwind, respectively. The off axis loading, in the Y-direction, reliably has peaks 90 degrees lagging in phase.

For proper comparison between the tip speed ratios, the azimuthal data was binned into 72 5 degree segments, and averaged. A minimum of 5 rotor rotations at each tip speed ratio were measured. The measured thrust and side loads for a tip speed ratio of 3.7 are shown in figure 11. This measurement is averaged over 22 turbine rotations. The standard deviation of the measurement is displayed on each data point with a vertical bar. The average standard deviation for force in the X-direction is $1.9N$ and $2.3N$ for load in the Y-direction. The behavior is consistent with expectations for a VAWT of this configuration showing the distinct 2P behavior in both thrust and side loading with the loading peaks corresponding with expected maximum blade loading at an azimuth of 90 and 270 degrees.

This analysis was performed for each TSR in the testing range from 0-4. Data below a TSR of 2.5 is excluded from the analysis due to poor aerodynamic performance in this region as to be expected due to the high angles of attack experienced during operation. The turbine loads were non-dimensionalized to provide coefficients of thrust in both x and y directions for each TSR. These were then averaged over the rotation of the turbine and plotted. Figure 12 shows the Thrust coefficient CT in the X direction versus TSR, λ . The corresponding forces in the x and y direction for a selection of the TSR values is shown versus azimuth position in figure 13. The measured thrust load clearly increases as expected with the increasing tip speed ratio. This is to be expected for several reasons, namely the rotational speed of the turbine increases linearly with TSR, therefore the local velocity at the blade is higher and the blade loads increase with the local velocity squared. Due to the ratio of rotor speed to incoming wind speed increasing, the angle of attack variations per rotation also become smaller, therefore the airfoil spends less of the rotation in a stalled condition. Thirdly, the local velocity at the airfoil increasing also has the effect of increasing the Reynold's number that the flow is experiencing, resulting in greater airfoil performance at the higher angles attack experienced.

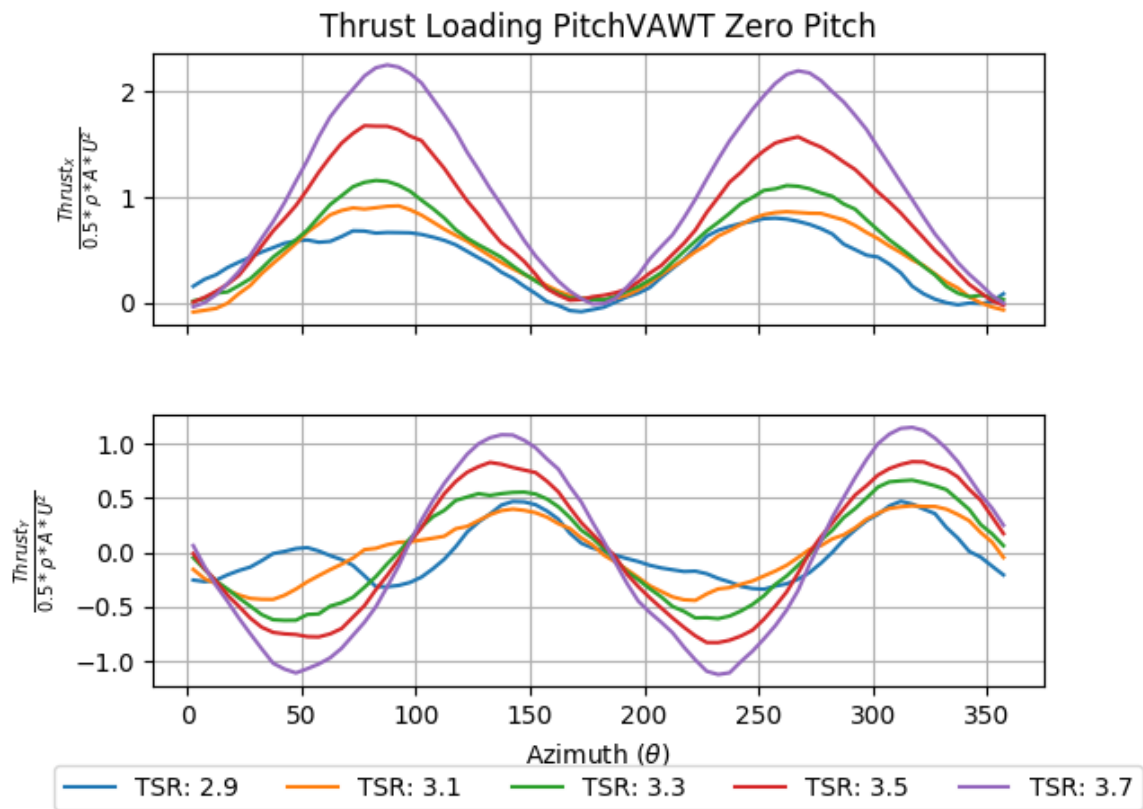


Figure 13. Measured CT in X and Y directions vs azimuth position for varying tip speed ratio

6. Conclusion

A 1.5 meter square Vertical Axis Wind Turbine with active pitch control ability has been designed and tested in the Open Jet Facility at the Delft University of Technology in The Netherlands. A method to measure turbine thrust and side to side loads on the PitchVAWT turbine has been presented. The PitchVAWT turbine was controlled through a Tip Speed Ratio sweep from 0 to 4 by maintaining a constant wind speed of 4 m/s and varying turbine speed. From this test, an experimental $C_T - \lambda$ curve was presented for the turbine. Rotor thrust and side to side loads are presented versus azimuth position for varying tip speed ratios. This analysis enables the study of VAWT thrust and side to side loading in a large variety of fixed and active pitch operating regimes and provides a platform for code validation. All data will be made available along with turbine specifics and models for further analysis and potential model comparisons through the 4TU.Centre for Research Data, www.4tu.nl.

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