

Experimental Analysis of Local Aerodynamic Effects for Rotors of Floating Wind Turbines

Using Particle Image Velocimetry

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Experimental Analysis of Local Aerodynamic Effects for Rotors of Floating Wind Turbines

Using Particle Image Velocimetry

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Preface

With this thesis, I am finalising my five years of studies. I started my studies in Delft with three years of my BSc Aerospace Engineering. I got into this study due to my interest in technology and aerodynamics. I took a short sidestep into education with my minor. However, I knew I wanted to continue in aerodynamics for my MSc. Looking for a MSc, I quickly realised the most logical move would be to stay at TU Delft, as it is a high-quality university, but I did want to study abroad for a while as well. So the European Wind Energy Master (EWEM) was a perfect match for me: I could follow a specialisation in aerodynamics, obtain a TU Delft education and diploma, and study abroad at the Technical University of Denmark for two semesters. Although this programme came with a few drawbacks, it was a great fit for me, and I have not had a moment of regret for choosing it.

Over these years, there have been ups and downs. I have grown and learned a lot. Academically, I developed my engineering skills and knowledge. Professionally, I greatly improved my communication skills. Personally, I grew my confidence and views on the world. Looking back, I see that I have matured, and I hope to continue this trend of self-improvement. I met some amazing people over these past years, especially during the MSc. The semesters in Denmark were my favourite, as it is a nice place to live, but even more so due to the people I am lucky enough to call my friends. Although I will not mention them all, I would like to thank Tim by name, as he is not only my friend, but also supported me throughout the thesis. I greatly appreciate our times working side-by-side on our projects, exchanging ideas, holding me accountable, and bringing a great deal of joy during a semester where I otherwise would be working mostly on my own.

I would like to thank my thesis supervisors. I am happy that I was given the opportunity to do a thesis with an experimental campaign. I would like to thank Federico for his guidance, practical views and supervision. I would like to thank Mathis for the frequent and valuable feedback and his supervision. I would like to thank Mac for his valuable scientific views and feedback.

Additionally, I would like to thank Erik for taking the time to meet with me to help me, Guido for his help during the experimental campaign, and Hendrik for his help and knowledge on DaVis and during the setup of the campaign. Finally, I want to thank all professors, support staff, and fellow students that have helped me, educated me, and worked with me over my five years at university.

*Janne Wim Sjaak Jacobs
Delft, August 2026*

Summary

In recent decades, an increasing amount of offshore wind energy has been generated. More recently, a push for floating offshore wind turbines (FOWTs) can be seen. Due to the platform motion, the aerodynamics of FOWTs differs from bottom-fixed wind turbines. Several research studies have investigated the aerodynamic phenomena that occur and the effect of the platform motion on rotor-level parameters: thrust, torque and the wake. These studies found increasing unsteady effects at increasing reduced frequencies. However, only limited research has been done into the local aerodynamics of FOWTs and no study so far has experimentally measured the local aerodynamics.

In this study, the local aerodynamics are investigated in an experimental wind tunnel campaign using a hybrid test setup. The main parameter of interest is the angle of attack (AoA), due to its importance in loads and control. The setup is used to calculate the AoA for four different phases of a surge motion.

A stereoscopic particle image velocimetry (PIV) setup is used to capture the flow field around a blade of a surging turbine. A turbine with a diameter of 1.2 m is placed in the Open Jet Facility at TU Delft. The turbine is placed on a six-degree-of-freedom hexapod to impose sinusoidal surge motion. The PIV setup contains two Imager sCMOS cameras, a Quantel Evergreen 200 laser, and a Safex smoke generator.

Several processing steps are used to remove the background from the raw images, apply cross-correlation, and generate a three-component velocity field in a plane around an airfoil cross-section. From the flow field, the AoA is calculated using the Ferreira-Micallef method. The axial and tangential induction factors are also extracted. The local thrust coefficient is computed using the Kutta-Joukowski theorem.

The flow fields for a turbine surging at a rotor reduced frequency of 0.60 are presented in this study. The flow field is located at 70% of the blade span. A baseline flow field for a bottom-fixed turbine is also presented. A convergence study is performed to confirm the amount of PIV measurements per case are sufficient, and to determine a suitable number of control points and the distance of the control points to the centre of the airfoil when computing the local AoA.

A variation in AoA is shown for the different motion phases of a surge motion. The change in angle of attack from the bottom-fixed case to the surging cases is mostly explained by the hub velocity component. However, the angle of attack is slightly higher than expected by only adding this hub component. For the two surging motion phases where the hub velocity is zero, the angle of attack is also slightly higher. For those motion cases, the axial induction factor and sectional normal force are lower than the base case. A 95 % confidence interval is presented for these results. This confidence interval shows that the deviations in the computed parameters due to the uncertainty in the flow field are smaller than the observed deviations to the baseline case, making the resulting variation significant.

It is concluded that the angle of attack depends on the hub motion, but is overall increased as well due to an aerodynamic effect of the surging motion, with the axial induction factor logically decreasing at the same time. This is found to be consistent with previous studies, which report faster wake recoveries and possibly higher aerodynamic power. The variation in AoA is important when assessing turbine control and fatigue loads in future floating offshore wind farms. Trade-offs between the annual energy production and fatigue loads may be made to increase the expected life-time of the floating offshore wind turbines.

It is recommended to analyse more motion cases, to be able to extract a relation between the surge motion and the change in the angle of attack, including a possible phase lag.

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Acronyms

- mC-nD** m components, n dimensions. 13
- 2C-2D** 2 components, 2 dimensions. 13
- 2D-PIV** Planar PIV. 13, 14
- 3C-2D** 3 components, 2 dimensions. 13, 21
- 3C-3D** 3 components, 3 dimensions. 13
- AEP** annual energy production. ii, 62
- AoA** angle of attack. ii, viii, 3–6, 10–12, 21, 23, 24, 44, 47, 48, 50, 52–54, 60–62
- BEM** blade element momentum. 3, 4, 50, 54
- BFWT** bottom-fixed wind turbine. 2, 3, 5, 10, 12, 60
- BRM** blade root moment. 4, 62, 71
- DAQ** data acquisition. vii, 32, 33
- DoF** degree of freedom. vii, 2, 3, 7, 9, 10, 25, 28, 35, 70
- DTU 10MW** DTU 10 MW Reference Wind Turbine. 10, 12, 27
- EPBT** primary energy payback time. 1
- FM** Ferreira-Micallef method. ii, iii, 21, 23, 24, 39, 60, 62
- FOV** field-of-view. 13, 14, 21, 31, 37, 44
- FOW** floating offshore wind. ii, 1, 2, 5, 10, 62
- FOWT** floating offshore wind turbine. ii, iv, vii, ix, 1–12, 22, 25, 28, 52, 60–62
- FPT** Flow Physics and Technology. ix, 27, 29–31
- GBF** gravity base foundation. 2
- GHG** greenhouse gas. 1
- HWA** hot-wire anemometry. 14
- I/O** input/output. 32
- IEA** International Energy Agency. 2
- IEA 15-MW** IEA Wind 15-MW Reference Wind Turbine. vii, 3, 10
- IP** in-plane. 71
- KJ** Kutta-Joukowski theorem. ii, viii, 25, 50–52, 54, 60
- LCA** life-cycle assessment. 1
- LCOE** levelized cost of energy. 2
- LDA** laser Doppler anemometer. 14
- LiDAR** light detection and ranging. 14

- OEM** original equipment manufacturer. 8
- OJF** Open Jet Facility. ii, 15, 27–29, 32, 43, 58
- OoP** out-of-plane. 71
- PIV** particle image velocimetry. ii, iii, v–vii, 1, 4, 12–18, 20–22, 24, 29, 30, 32, 33, 36, 43, 52, 54, 58, 60, 61
- POV** point-of-view. 16
- PS** pressure side. vii, 17, 19–22, 33, 34, 36–39, 41–44, 54, 60, 69
- PSD** power spectral density. viii, 54–58
- PSP** pressure-sensitive paint. 14
- PTU** programmable timing unit. 15, 32, 33
- PTV** particle tracking velocimetry. 12, 14
- QST** quasi-steady theory. 5, 6
- RNA** rotor-nacelle assembly. 3, 6, 58
- RWT** reference wind turbine. 10
- SPIV** stereoscopic PIV. iii, 12–18, 21, 60
- SS** suction side. vii, 17, 21, 22, 33, 34, 36, 39–44, 60, 69
- TLP** tension leg platform. 2
- Tomo-PIV** tomographic PIV. 13, 14
- TRL** Technology Readiness Level. 2
- TSR** tip-speed ratio. 7, 8, 27
- WTM** wind turbine model. 27

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1

Introduction

Wind energy has been used by humans for thousands of years. From sail boats and wind-powered machines used by the ancient Egyptians, to the early wind turbines in the Middle East during the middle ages, to the pumps used to drain Dutch polders, to the early modern Danish and North-American wind turbines, to the modern multi-MW wind turbines to 83 GW of installed offshore wind power capacity in 2025, wind power has evolved throughout its entire history[1–3]. The next step in wind power that is currently happening is the introduction of floating offshore wind turbines (FOWTs).

This report aims to contribute to the understanding of the aerodynamics of FOWTs and provide a dataset that may be used for validation of numerical models. This is done by an experimental campaign investigating local aerodynamic parameters using a hybrid test setup including a particle image velocimetry system.

Section 1.1 introduces the need for offshore wind energy. Section 1.2 argues the opportunity for floating offshore wind (FOW) specifically. That section also describes the current and prognosed roll-out of FOW-capacity, the different floater types, the kinematics of FOWTs and the aerodynamic challenges connected to FOWTs. The research questions of this study are presented in section 1.3. Finally, an outline of the rest of the report is given in section 1.4.

1.1. The Need for Offshore Wind Energy

Currently, a transition of the electrical mix to use more wind energy is happening. This is driven by multiple factors. One reason is to limit the greenhouse emissions that are associated with electricity generation using fossil fuels to limit global warming. A second reason is to ensure energy independence when the supply chain for other sources of energy is disrupted. A third reasons may be the potential for lower electricity costs, due to the low operational costs for wind energy [4, 5].

As to limit global warming, there are national and international agreements and regulations to reduce carbon emission. The most recent goal is to reach a net greenhouse gas emission reduction of 90% in 2040 compared to 1990 levels [6, 7]. Two useful measures to express the environmental impact of wind turbines are the intensity index in CO₂-equivalent intensity in g CO₂-eq/kWh and the primary energy payback time (EPBT). The EPBT is defined as the time needed to recover the primary energy that was invested during the lifetime of the turbine [8]. Multiple life-cycle assessments (LCAs) have shown a consensus that wind turbine have an EPBT of less than 1 year, or even as low as half a year [8–12]. Instead of the EPBT, the greenhouse gas (GHG) payback time may be used, but this gives similar results of less than a year [12, 13]. The same LCAs report an intensity index of around 7 gCO₂ – eq/kWh to 11 gCO₂ – eq/kWh. This is small compared to the climate change impacts from fossil sources of around 0.5 kgCO₂ – eq/kWh to 1 kgCO₂ – eq/kWh for natural gas and coal[14] and the average 0.2 kgCO₂ – eq/kWh of the current EU energy mix [15]. Thus, increasing the share of wind energy in the energy mix is beneficial to limit the emission of greenhouse gasses.

The global offshore wind energy capacity has increased by 10 % on average each year over the past

decade, reaching a capacity of 83.2 GW in 2024 [3]. This makes offshore wind energy an important share of the overall generated wind energy. The share of offshore wind energy is expected to grow in future years, due to limitation in onshore wind, caused by logistics limiting the rotor size, limited land availability, lower wind resources and visual pollution and noise pollution. Although offshore wind energy can be challenging, it suffers less from the challenges posed for onshore wind energy.

1.2. Introduction to Floating Offshore Wind Turbines

Currently, offshore wind energy is mostly generated by traditional bottom-fixed wind turbines (BFWTs). However, Floating offshore wind turbines (FOWTs) offer a promising alternative to the BFWTs for water depths above ~60 m, where the latter may not be practical or economically feasible [16–18]. This makes FOWTs attractive for countries such as Norway, Spain and Portugal where the potential for BFWTs is limited [17]. Furthermore, FOW can be placed sufficiently far from shore to have a negligible visual impact, compared to the visual pollution from BFWT farms that are typically installed close to shore at the shallower water depths [17, 19].

The International Energy Agency (IEA) recommends to “support the development of floating offshore wind turbines to tap into deeper offshore wind resources”[18]. A majority of offshore wind energy potential is situated in locations with deep water (depth of 60 m to 1000 m) [17], for around 70 % globally, or even 80–90 % in some regions, such as Northern Europe, Southern Europe and Northern America [20]. This makes the development and deployment of FOWTs instrumental in the green energy transition.

In addition to the access to superior wind resources and lower visual impact, the flexibility of the placement due to insensitivity to the depth of water and the composition of the seabed allows FOWTs to more easily avoid protected regions (military, environmental, commercial) in the offshore region and the shipping lanes [19].

1.2.1. Roll-out of Floating Offshore Wind Turbines

FOWTs were first proposed by Professor William E. Heronemus at the University of Massachusetts in 1972. However, it took until the 1990’s for the academic community to investigate the idea further, until 2007 for an 80 kW prototype to be built, and until 2017 for the first pilot farm to be deployed[21]. At the end of 2024, a total of 278 MW of floating wind was installed globally [3].

In China, the first 200 MW phase of their first GW-scale floating wind farm has begun construction. Floating offshore wind (FOW) will have an estimated installed capacity of 2.6 GW in 2030, reaching the commercial phase in that year and growing to 19 GW in 2034, for a contribution of 4 % of total offshore installations [3].

With the demand for energy increasing, the Technology Readiness Level reaching maturity [17] and the levelized cost of energy (LCOE) of FOWTs decreasing [22], more FOW projects are expected to be announced. One such example is the recent UK AR7 auction, which allocated 192.5 MW capacity to two FOW projects [23].

1.2.2. Floater Types

The main difference between bottom-fixed wind turbines and floating offshore wind turbine concepts, is the foundation type. BFWTs normally use monopiles, gravity base foundations (GBFs) or jacket foundations [24]. In contrast to those, floating offshore wind turbines use floaters that are moored to the seabed for station-keeping.

The four main types are barge, semi-submersible, spar and tension-leg platform[25]. During operation, FOWTs rely on a combination of three restoring mechanisms for hydrostatic equilibrium. These are ballast-, buoyancy- or mooring-stabilization [24]. Barge and semi-submersible concepts rely mostly on buoyancy-stabilization, spar concepts rely mostly on ballast-stabilization, and tension leg platform (TLP) concepts rely mostly on mooring-stabilization [25].

1.2.3. Kinematics of Floating Offshore Wind Turbines

FOWTs are moored to the sea bed, but due to slack in the cables, the platform can still translate and rotate in all directions. The movement in a certain direction is called a degree of freedom (DoF).

Figure 1.1 shows the DoFs and coordinate system of a floating offshore wind turbine platform. The translational DoFs are surge, sway and heave. The rotational DoFs are pitch, roll and yaw. In terms of observed motion and effect on aerodynamic loading, surge and pitch are the most significant DoFs[19, 26].

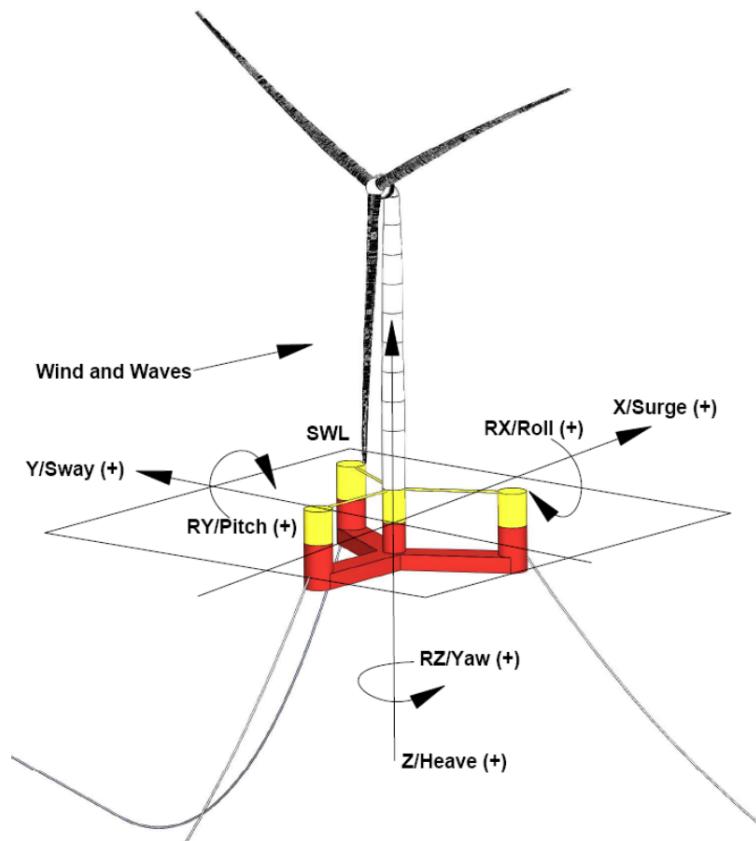


Figure 1.1: A schematic example of a floating offshore wind turbine, the IEA Wind 15-MW Reference Wind Turbine on its semi-submersible floater, showing the coordinate system and associated degree of freedom for each direction [27].

1.2.4. Aerodynamic Challenges of Floating Offshore Wind Turbines

Floating offshore wind turbines are highly dynamic, coupled systems. Interactions that can be neglected for bottom-fixed wind turbine become crucial for FOWTs, such as the gravity load, interactions with met-ocean conditions, and the floating dynamics[28].

Single DoF motion of surge and pitch can increase power production[29, 30], two DoF motion may reduce the power production significantly[31]. Further information on unsteady effects can be found in section 2.1.

The main challenge in the control of a FOWT is the fore-aft motion of the rotor-nacelle assembly (RNA)[32]. In addition to the wind speed, the relative inflow seen by the RNA contains a rigid platform motion component. Control of FOWTs is further outside of the scope of this research.

Also when control is not considered, the fact that the relative inflow varies is still true. This causes variations in the angle of attack (AoA), α . The change in AoA due to the change in relative velocity can be captured by blade element momentum (BEM) theory. Sources of variation of AoA due to unsteady effects are not captured by BEM theory. If the variations in AoA are large, flow separation may occur [28].

Additionally, the AoA is important for the loads on the blade. Extreme increases in AoA may increase the ultimate load. More critical is the variation in AoA. This causes load oscillations, which contribute to an increase in fatigue loads, which may considerably lower the turbine life span.

When designing a FOWT, it is thus important to be able to predict the AoA during platform motion.

Using BEM theory, the AoA and its variation cannot be accurately predicted. CFD simulations, such as Large Eddy Simulations (LES) are computationally expensive, and thus also not ideal. Furthermore, if a numerical model is used, it needs to be validated against an experimental dataset before it can be trusted in building a business model.

1.3. Research Questions

The main aim of this study is to experimentally measure the local angle of attack for a floating offshore wind turbine. The scope is limited to a scaled turbine model, installed in a hybrid test setup. Two main, complementary research questions, RQ1 and RQ2, are posed to achieve this aim of the report. The first research question relates to how the measurement will be carried out and the data processed, the second to the analysis of the processed data to find what the aerodynamic effect of the platform motion is.

- RQ1** How can the local aerodynamics of a scaled FOWT be measured in a wind tunnel?
RQ2 How does imposed sinusoidal platform motion of a FOWT influence the local aerodynamics?

Since floating turbines are a relatively new research area and their aerodynamics can be complex, it cannot be assumed that the numerical simulations will suffice for answering RQ2. Then, the other option is to perform an experimental campaign on a floating offshore wind turbine model. To measure the necessary data, it is necessary to answer RQ1 before being able to answer RQ2.

These main research questions can be split up into multiple sub-questions that are necessary to answer the main question. For RQ1, the following sub-questions are posed:

- RQ1.1** How will the blade reliably be in frame for the PIV measurements taken during imposed platform motion?
RQ1.2 How can the local aerodynamic parameters be reconstructed from the PIV flow fields?

RQ1.1 relates to how the measurement system can be triggered to capture the moment that the blade passes a certain point, while the motion is also at a certain phase. The local aerodynamic parameters referenced in RQ1.2 are the local angle of attack, axial induction factor, tangential induction factor and the local thrust coefficient.

Similarly, RQ2 will be split into sub-questions, see RQ2.1 and RQ2.2.

- RQ2.1** To what extent is quasi-steady theory accurate under the imposed sinusoidal motion, for a rotor reduced frequency of $f_r = 0.60$?
RQ2.2 What is the effect of imposed motion on the angle of attack?

1.4. Report Outline

After the introduction, the state of the art of experimental and numerical aerodynamic research into FOWTs is presented, see chapter 2. Then, the methodology of this study is explained in chapter 3. This includes the general setup and techniques that are used. A more detailed explanation of the setup is found in chapter 4. The results are presented and discussed in chapter 5. The results are used to answer the posed research questions RQ1 and RQ2 in chapter 6. Finally, the appendices contain a declaration on the use of AI, the full test matrix, and an additional method to reconstruct the blade root moment (BRM) from the sectional loads, see Appendix A, B, and C, respectively.

2

State of the Art

In this chapter, the state of the art of research in floating offshore wind is outlined. This shows the current understanding of aerodynamics in the context of floating offshore wind turbine rotors, and the remaining research gap.

Firstly, the unsteady aerodynamic phenomena are presented in section 2.1. Secondly, different methods of testing a floating offshore wind turbine are discussed in section 2.2. The relevant parameters to scale a wind turbine for the experimental tests are listed in section 2.3. To measure the aerodynamic phenomena, a flow measurement technique must be used. Additionally, previous experimental and numerical studies are summarised in section 2.4. Finally, the relevant research gap is presented in section 2.5.

2.1. Unsteady Aerodynamics

When considering the relative inflow of a BFWT, for a constant wind speed, the flow can be steady if no perturbations occur. However, for a FOWT subjected to platform motion, the relative inflow will always vary with the platform motion. Thus, FOWT operate in the realm of unsteady aerodynamics. When the perturbations are small and happen slowly, the flow may be considered quasi-steady, see subsection 2.1.1. The unsteady effects include the unsteady airfoil effect, the dynamic inflow effect, and the returning wake effect, described in subsection 2.1.2, 2.1.3 and 2.1.4, respectively.

Schulz *et al.* states that the returning wake effect and unsteady airfoil effect can be considered as perturbations of the local angle of attack, while the dynamic inflow affects the axial induction[33]. Instead of looking at these parameters directly, they continue to look at rotor torque and thrust, as these are rotor-level parameters affected by the change in AoA and axial induction.

Figure 2.1 shows a sketch of the overall behaviour of the normalized thrust force amplitude and reduced frequency for surge under constant amplitude and varying periods[34]. In the figure, f_a is the airfoil reduced frequency and f_r is the rotor reduced frequency, as explained in subsection 2.1.2 and 2.1.3, respectively. When the rotor reduced frequency is smaller than $f_r = 0.05$, the flow can be considered fully quasi-steady, see subsection 2.1.3 and Equation 2.3 for the definition of f_r . When increasing the reduced frequency (smaller motion period, so towards the left in the plot), the normalized thrust amplitude decreases slowly until $f_r \approx 0.5$ and then plateaus. A decrease in thrust compared to the QST was also seen experimentally in Taruffi *et al.* (2024)[35]. However, in that study the normalized thrust amplitude peaked at $f_r = 1.5$ for the rated condition, whereas Schulz *et al.* predicts a local minimum of the thrust when the blade passing frequency matches the motion frequency (defined by $f_p = 1$ in that paper).

2.1.1. Quasi-Steady Theory

In quasi-steady theory (QST), time derivatives are taken into account, but the flow is not yet fully unsteady. In QST the aerodynamic mass terms can be ignored due to the low associated frequencies. All pressure fluctuations are regarded as occurring instantly, so there is no time lag between changes

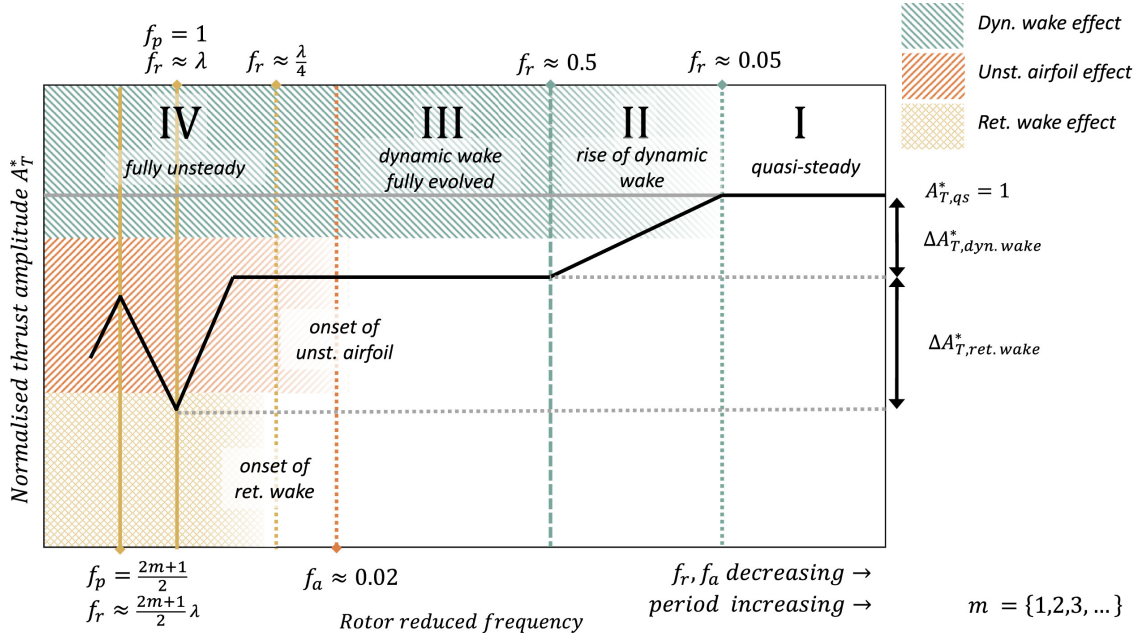


Figure 2.1: Schematic of the overall behaviour between normalized thrust amplitude and reduced frequency [34].

in conditions and the resulting aerodynamic forces. This is in contrast to unsteady flow, where a time lag occurs due to the inertia of the flow.

QST can be used when motions are slow and variations over time are small[33]. This is valid for reduced frequencies of $k < 0.05$, where k is defined by Equation 2.1 [19, 36].

$$k = \frac{\omega c}{2V} \quad (2.1)$$

2.1.2. Unsteady Airfoil Effect

For attached flow unsteady airfoil effect describes the circulatory and non-circulatory effects[33]. Separation is also an unsteady effect, but no stall is expected for low angles of attack. The circulatory effect is caused by the vortices that are shed from the trailing edge of an airfoil when its circulation is varied, which influences the angle of attack. The non-circulatory effect refers to the added mass forces that a flow field under accelerations acts upon an airfoil. This may happen when an airfoil is plunging. Under sinusoidal variation of the angle of attack, the circulatory effect is more dominant. When the RNA is surging, the airfoil locally experiences this as a plunging effect.

The extent of unsteady airfoil effect can be characterised by the airfoil based reduced frequency, f_a , see Equation 2.2[19]. This definition is a specific form of the general reduced frequency, k .

$$f_a = \frac{\pi f c(r)}{\sqrt{U_\infty^2 + (r\Omega)^2}} \quad (2.2)$$

Here, U_∞ is the freestream wind speed, Ω is the rotor speed, r and $c(r)$ are the radius and local chord length of a radial section, f is the frequency with which the inflow conditions vary, which will be the motion frequency for a FOWT. The flow can be considered quasi-steady under the condition that $f_a < 0.05$ [36].

2.1.3. Dynamic Inflow Effect

The dynamic inflow effect refers to unsteady effects caused by changes in the wake due to a change in the inflow of the rotor[33]. A change in the inflow leads to a change in the vortex strength of the near wake. This near wake is then transported downstream, and the changed wake structure has a diminishing effect on the axial induction, and thus angle of attack and loads. While the old wake structure is

transported further downstream, the rotor motion continuously resupplies the wake with shed vortices. The rotor reduced frequency, f_r , can characterise this dynamic inflow effect, see Equation 2.3 [19, 33]. The rotor reduced frequency is the inverse of the normalised advection wavelength.

$$f_r = \frac{fD}{U_\infty} \quad (2.3)$$

2.1.4. Returning Wake Effect

The returning wake effect occurs for a rotor when the wake of a blade passes over a following blade. This causes a significant drop in aerodynamic loads. The returning wake effect occurs when the motion frequency is equal to or an integer multiple of the blade-passing frequency, so when $f_p = 1, 2, 3, \dots$, where f_p is the motion to blade-passing frequency ratio as described by Equation 2.4 [33, 36]. In this equation, n_b is the number of blades in the rotor, normally three. So, the returning wake effect occurs when the rotor moves quickly in the downstream direction, such that a blade passes through the wake of the previous blade. In reality, this requires reduced frequency close to the tip-speed ratio (TSR) to trigger the returning wake. The presence of the circulatory unsteady airfoil effect is also a requirement for the returning wake, as these effects are caused by the same shed vortices from the trailing edge.

$$f_p = \frac{2\pi f}{n_b \Omega} \quad (2.4)$$

2.2. Hybrid Testing

In general, in testing one can choose for a ‘full approach’, which entails designing the experiment as close to reality as possible [37]. However, as shown in section 2.3, it is not possible to make a single FOWT-model that is both Froude and Reynolds scaled. This means it is not possible to make a single experimental setup that can be used to accurately analyse both the hydrodynamics and aerodynamics of a FOWT. There is still value in this full approach in observing interaction. For more fundamental research, the other testing strategy, a ‘simplified approach’ can be used. For FOWTs, the simplified approach is a hybrid testing setup. In hybrid testing, one or more actuators replace part of the model [28, 37]. In the context of FOWTs, hybrid testing can be done either in a wind tunnel or in a wave basin.

2.2.1. Hybrid Wind Tunnel Testing

In hybrid wind tunnel testing, the floater has been replaced by an actuator. This actuator can be a hexapod (6-DoF robotic platform) [35, 38, 39], a system of hydraulic actuators [40], or a linear motor [33, 41]. The actuator can either move the turbine in a prescribed motion, or using a numerical model to couple the hydrodynamics. The coupled approach gives more realistic loads and movements. However, for more fundamental research, prescribed motion can be used as well.

2.2.2. Wave Basin Testing

Wave basins can produce met-ocean conditions that are used to test hydrodynamic interactions with the FOWT floaters.

Full Approach Wave Basin Testing

In the full approach, a model turbine on a model floater is placed in a wave basin. This can be used for global assessment of the system [37]. The limitation of this approach is the mismatch of Froude and Reynolds numbers scaling. There are also limited facilities where a wave basin is combined with a high quality wind generator.

Hybrid Wave Basin Testing

In hybrid wave basin testing, the rotor or turbine is replaced with an actuator [28, 37]. This solves the Reynolds scale mismatch and low wind quality. A numerical model calculates the loads that the turbine should exert on the floater, based on the measured motions of the floater. The actuator can be a fan or pulley system.

2.3. Floating Turbine Model Scaling

Full scale testing of turbines is expensive and impractical, especially for full scale floating offshore wind turbine. Testing full scale turbines is done by wind turbine original equipment manufacturers (OEMs) to test and validate their turbines, but this data is rarely shared outside their companies. For academic research, it is difficult to plan and fund such campaigns. Furthermore, the operational conditions in full-scale field testing cannot be controlled. Therefore, in fundamental research and technology development, model-scale testing is necessary. Full-scale wind turbines are scaled down, such that the models fit in existing wind tunnels.

Important non-dimensional numbers are the Reynolds number, Re , the Froude number, Fr , the Mach number, M , and dimensionless frequencies[28]. The frequencies are discussed more in section 2.1; the other parameters and their scaling are discussed in this section.

The tip-speed ratio (TSR) does not scale, this remains the same for full scale and model scale. The TSR, λ is defined by Equation 2.5. Here, R is the rotor radius, Ω the rotor rotational speed and U_∞ the freestream wind speed. For model scales, the rotor radius is decreased, often by a factor of more than 1:100. The rated wind speed for models is also reduced, but often only by a factor of 1:2 or 1:3 with respect to the full-scale turbine. To keep the TSR constant, the rotational speed of models is increased significantly.

$$\lambda = \frac{R\Omega}{U_\infty} \quad (2.5)$$

2.3.1. Reynolds Number Scaling

The Reynolds number, Re , is the ratio of inertia forces to viscous forces in a flow[42, p. 38], see Equation 2.6.

$$Re = \frac{\rho v l}{\mu} \quad (2.6)$$

In this equation, ρ is the air density, v a characteristic speed, l a characteristic length, and μ the fluid dynamic viscosity.

When the geometry of a low-speed ($M < 0.3$, see Equation 2.10) wind tunnel test is fixed, the Reynolds number is the primary similarity parameter. Flows at different Reynolds numbers will exhibit different effects. Therefore, for aerodynamic similarity, the Reynolds number should ideally be the same as for the full-scale turbine [43].

One defines the length scale factor $n = R_M/R_F < 1$, where R is rotor radius, M stands for model scale, and F for the full scale. Similarly, the time scale factor can be defined as $n_t = t_M/t_F = \Omega_F/\Omega_M < 1$, where t is the time scale. Then the Reynolds factor scales with as shown in Equation 2.7[44].

$$\frac{Re_M}{Re_F} = \frac{n^2}{n_t} \quad (2.7)$$

2.3.2. Mismatch of Froude and Reynolds Scaling

For dynamic tests with model motion, such as the moving FOWT-platform, the Froude number is also an important similarity parameter.

The Froude number, Fr , is the square root of the ratio of inertia force to gravity force, see Equation 2.8 [43].

$$Fr = \sqrt{\frac{V^2}{gl}} \quad (2.8)$$

Here, g is the gravitational acceleration ($g = 9.81 \text{ m/s}^2$ in the Netherlands). The characteristic length scale, l , for the Froude number can be taken to be the rotor radius, R .

Using the earlier introduced length and time scale factors, n and n_t , the Froude number scales as shown in Equation 2.9 [44].

$$\frac{Fr_M}{Fr_F} = \frac{n}{n_t^2} \quad (2.9)$$

For a given length scale, the Reynolds number can be matched by setting $n_t = n^2$. However, for a given length scale, the Froude number must be matched by setting $n_t = \sqrt{n}$. For a model, these cannot both be true at once. This is the mismatch between Froude and Reynolds scaling. This means that it is not possible to accurately represent both the gravitational loads and the aerodynamic loads at the same time. This challenge can be overcome using hybrid testing, see section 2.2.

2.3.3. Mach Number

The third main similarity parameter is the Mach number. The Mach number, M is the ratio between the local velocity, V , and the speed of sound, a , see Equation 2.10 [42, p. 39]. The speed of sound in a calorically perfect gas is a function of temperature and the fluid properties, see Equation 2.11.

$$M = \frac{V}{a} \quad (2.10)$$

$$a = \sqrt{\gamma RT} \quad (2.11)$$

Here, γ is the adiabatic index ($\gamma = 1.400$ for dry air at room temperature), R the specific gas constant ($R = 287.05 \text{ J kg}^{-1} \text{ K}^{-1}$ in dry air) and T the absolute temperature.

Just as matching of both the Reynolds number and Froude number is impossible, the Mach number is seldom matched in wind tunnel tests. However, the matching of Mach number is not critical in low-speed regions, where $M < 0.3$ [43, p. 22]. In this low-speed region, the flow is not sensitive to small changes in Mach number, while the airfoil performance is sensitive to changes in the Reynolds number.

2.4. Previous Studies

The floating wind farms that have been deployed, such as Hywind, are projects by commercial companies. To protect their own interests, only limited data have been shared with the academic world. Due to this, research is focused on the more easily realisable model scales.

Over the years, much experimental research has been done on wind turbine models, such as the MEXICO and New Mexico campaigns [45, 46]. In recent years, academic interest in FOWTs has also increased. Several experimental studies have been performed, see subsection 2.4.1. These experimental campaigns are important for understanding and model validation. However, they can be time-consuming, costly at larger scales, and suffer from the scaling limitations discussed in section 2.3. To complement these experimental campaigns, several numerical studies on FOWTs have also been published, see subsection 2.4.2.

Previous studies such as by Schulz *et al.* [34] and Taruffi *et al.* [35] find unsteady effects on the thrust as a function of the rotor reduced frequency, f_r . Both of these studies, the first numerical and the second experimental, show a small reduction in normalised thrust amplitude for low, but non-zero, reduced frequencies.

2.4.1. Previous Work in Experimental Studies

Experimental campaigns into the aerodynamics of FOWTs have been done before in other studies. Table 2.1 shows a subset of these studies. The table summarizes what parameter has been researched, under which motion and for what rotor diameter. The motions are summarised by the degree of freedom (DoF) and rotor-based reduced frequency, f_r , see subsection 2.1.3. The motions in some studies are also given as a normalised velocity variation, ΔV^* , see Equation 2.12[35]. There, ΔV is the platform motion velocity and U_∞ is the freestream wind speed.

$$\Delta V^* = \frac{\Delta V}{U_\infty} \quad (2.12)$$

It must be noted that the table is not a complete list, but is a representative subset of the types of studies that have been done. The previous studies have focused on integral torque and thrust, and

Table 2.1: Summary of experimental studies on wind turbines.

Source	Parameters of Interest	DoF	Rotor diameter [m]	Rotor reduced frequency, f_r
Bayati <i>et al.</i> (2016)[49]	Thrust, torque	Surge, pitch	2.36	0.16–2.15
Fontanella <i>et al.</i> (2021)[40]	Thrust, wake	Surge	2.38	0.07–1.9
Fontanella <i>et al.</i> (2022)[26]	Thrust, torque, wake	Surge, Pitch, Yaw, Sway, Roll	2.4	0.15–2.54
Wei & Dabiri (2022)[41]	Torque	Surge	1.17	0.36–0.83
Taruffi <i>et al.</i> (2024)[35]	Thrust	Surge, pitch, yaw	1.2	0.15–2.4
Schulz <i>et al.</i> (2024)[33]	Torque	Surge	0.93	0.55–1.09
Duan <i>et al.</i> (2025)[50]	Power, wake	Pitch	0.15	0.04–0.15
Fritz <i>et al.</i> (2024)[47]	Local flow field	Fixed	1.8	–
Nietiedt <i>et al.</i> (2022)[48]	Fluid–structure interaction	Fixed	1.8	–

on the wake. However, there is a gap in experimental studies on the local aerodynamics for FOWTs. The study by Fritz *et al.* [47] does look into the local flow field of a turbine, but this is for a BFWT. The study by Nietiedt *et al.* [48] also looks into local aerodynamics, but is focused on aeroelasticity, still for a BFWT.

2.4.2. Previous Work in Numerical Studies

Table 2.2 shows a list of numerical studies on FOWTs. Sebastian & Lackner and Cao *et al.* use coupled simulation, the other studies use prescribed motion. Since physical size and setup limitations are not a factor in numerical studies, the rotor diameter used is normally the full-scale rotor, based on reference wind turbine (RWT), such as the IEA Wind 15-MW Reference Wind Turbine and DTU 10 MW Reference Wind Turbine. Also, the rotor reduced frequency f_r is not limited, so larger ranges are tested than in the experimental studies. Some numerical studies use the same conditions as an experimental campaign for comparison, others investigate only the numerical results.

The paper by Sebastian & Lackner [19] is an important paper, as it is one of the first papers in this area of research, and introduces the reduced frequencies in the context of FOWTs. Recently, a paper was published numerically investigating the angle of attack for a FOWT[52].

Table 2.2: Summary of numerical studies on FOWTs.

Source	Parameters of Interest	DoF
Sebastian & Lackner (2013)[19]	Reduced frequency analysis	Coupled platform motion
Tran <i>et al.</i> (2014)[53]	Power, thrust	Pitch
Tran <i>et al.</i> (2015)[54]	Blade–wake interactions	Surge
Micallef & Sant (2015)[55]	Power, thrust	Surge
Leble & Barakos (2017)[56]	Power, thrust	Pitch, yaw
Lienard <i>et al.</i> (2020)[29]	Power, thrust, blade loads	Surge, pitch
Cao <i>et al.</i> (2020)[51]	Power	Coupled platform motion
Feng <i>et al.</i> (2021)[57]	Power	Surge, pitch
Chen <i>et al.</i> (2021)[31]	Power, thrust	Surge, pitch
Taruffi <i>et al.</i> (2024)[58]	Thrust, wake	Surge, pitch
Schulz <i>et al.</i> (2024)[33]	Thrust, torque	Surge
Zhou <i>et al.</i> (2025)[59]	Power, thrust	Six (all platform DoFs)
Schulz <i>et al.</i> (2026)[34]	Thrust, wake, unsteady loads	Surge
Cioni <i>et al.</i> (2026)[52]	Angle of Attack	Pitch

2.5. Research Gap

The AoA, and especially its variation, is important to consider for fatigue loads and turbine control. Both of these may be critical in the continuing rollout of FOWTs. As more FOW farms are being commissioned, the importance of being able to understand and predict the loads on the turbine only continues.

Being able to estimate the fatigue life time before building a wind farm is also crucial for the business case.

Overall, the previous studies on FOWTs have focussed largely on rotor-level parameters: thrust, torque and the wake. Only limited, numerical research is done into the AoA of a FOWT under platform motion. No experimental campaign so far has measured the AoA of a FOWT under platform motion. This study aims to fill this gap using a hybrid test campaign, where a turbine model is placed on a hexapod to impose a sinusoidal platform motion, while measuring the flow field to compute the local AoA. The results can then be used to validate numerical models, or as a starting point for estimating the fatigue loads caused by the AoA variation.

3

Methodology

This chapter describes the methodology used in this research. Firstly, the general methodology of this research is presented in section 3.1. Secondly, the working principles of particle image velocimetry (PIV) and several of its types are explained in section 3.2. Thirdly, a qualitative trade-off has been performed to conclude that stereoscopic PIV (SPIV) is a suitable measurement method; see section 3.3. Then the methodology to capture the data related to RQ1 using SPIV is discussed in section 3.4, followed by the processing steps that are needed to transform the raw PIV data into usable flow fields, see section 3.5. Afterwards, the methods to determine the local aerodynamics are presented for the angle of attack in section 3.6 and the local loads in section 3.7. Then, it is explained that the turbine will be imposed to a sinusoidal platform motion in section 3.8. Finally, the crossflow principle is explained in section 3.9 to validate the use of a 2D flow assumption.

3.1. General Explanation of the Experimental Campaign

This report aims to answer the research questions posed in section 1.3. As mentioned in that section, an experimental campaign will be used to measure local aerodynamics of FOWTs under imposed sinusoidal platform motion. The experimental campaign will be carried out in a wind tunnel with a scaled model of a DTU 10 MW Reference Wind Turbine (DTU 10MW) turbine. The turbine tower will be standing on a hexapod platform. Firstly, the scaled model will be measured without imposed motion, as if it were a BFWT. Then, different relevant motions will be imposed on a hexapod platform to imitate the motions experienced by a FOWT. The measured parameters, mainly angle of attack and local loads, will then be compared for the fixed and the moving cases, to determine and analyse any effect of the motion on these parameters, such that RQ2 can be answered. A detailed explanation of the experimental setup can be found in chapter 4.

3.2. Working Principles and Types of Particle Image Velocimetry

This section aims to explain the working principles of particle image velocimetry (PIV), without delving too much into the practicalities of its setup. In particle tracking velocimetry (PTV), each individual particle is tracked over time. This is a time-resolved Lagrangian approach with sparse tracer seeding. In contrast, PIV, is an Eulerian approach, with denser tracer seeding. In this section, the working principles and different types of PIV are explained. In the next section, 3.3, the method of choice is explained.

Particle image velocimetry (PIV) is one of the optical measurement techniques that can measure the flow velocity based on illuminated tracer particles[60]. Small particles, such as those generated by a smoke machine, are seeded into the flow. In the region of interest, these particles are illuminated. An imaging system captures the position of these particles. By capturing their position twice with a short time interval, a cross-correlation can be performed, from which the mean particle displacement using an interrogation window (subarea of the frame) can be calculated. This window displacement over a short time interval combines to give the flow velocity field. The particles are thus not tracked individually,

but an Eulerian approach of the flow field is used.

In the rest of this subsection, some general advantages and limitations of the different PIV techniques are presented. More details about the theory of its working principles can be found in section 3.2.

PIV as a measurement technique has multiple advantages [60]. Firstly, it is quantitative flow visualisation, whereas other flow visualisations, such as tufts or dye streaklines, are mostly qualitative. Secondly, compared to the other quantitative methods presented earlier in this chapter, PIV can capture an entire flow field instantaneously, showing coherent flow structures. Another big advantage is that PIV can be considered non-intrusive. Both the illumination and capturing system can be placed out of the flow field, and the small particles have a negligible effect on the flow characteristics.

Naturally, there are some limitations to a PIV measurement system. Firstly, both the light sheet and the field-of-view (FOV) of the camera require optical access. Secondly, the tracer particles should be distributed homogeneously in the measurement region. This can pose difficulties in areas with strong separation or gradients in the flow field, or when the tracer particles are injected too close upstream to the test object. Further restrictions arise from technological capabilities of the (available) hardware, such as laser pulse strength, laser pulse repetition rate, camera resolution and frame rate of the cameras.

For convenience in comparing different PIV methods in this section, the mC - nD notation is introduced, which signifies m components, n dimensions. Here, the m components are the number of velocity components that can be measured by a method, and the n dimensions are the spatial dimensions of the resolved flow field.

The main different types of PIV with their main characteristics are listed next[61].

Planar PIV

Planar PIV (2D-PIV) is the simplest form of PIV. It entails one camera, typically positioned perpendicular to the measurement plane for maximum measurement accuracy. The measurement plane is lit by a laser light sheet. It can only resolve the two velocity components in the plane, so it is a 2C-2D PIV technique.

Stereoscopic PIV

A more advanced form of PIV is Stereoscopic PIV (SPIV). In SPIV, a second camera is added to allow the measurement of the out-of-plane component of the tracer particles. This requires a calibration to resolve the relation between the projection on the image planes and the position and velocity in three-dimensional space. The measurement is still limited to the illuminated particles, so this is a 3C-2D technique.

Tomographic PIV

The current typical method to capture a 3C-3D flow field is tomographic PIV (Tomo-PIV). Instead of a measurement plane, a measurement volume is illuminated, which increases the pulse energy compared to planar PIV measurements. To resolve the out-of-plane position of the particles from the projection of the image planes, additional cameras are needed (typically 3 to 6) as well as a calibration procedure. The flow field is then resolved using three-dimensional cross-correlation.

Time-Resolved PIV

The previously listed types of PIV can be applied with different capturing frequencies. At the typical low repetition rates of lasers and capturing frequencies of high resolution cameras, this can be called *low-speed PIV*. However, with advances in high-speed lasers and cameras, PIV measurements can be taken at a much higher frequency. This can be called *high-speed PIV*. If capturing frequency is high enough to resolve the relevant temporal features of the flow field, it can be called *time-resolved PIV*. However, these high speed systems often come with lower pulse energy of the laser and lower resolution of the camera.

3.3. Qualitative Tradeoff for Measurement Technique

In section 3.2, different PIV measurement methods were shortly explained, other flow measurement techniques, such as pressure-based techniques are also possible. The technique to be used in the ex-

perimental campaign must be chosen. To decide on the method, a few conditions for the measurement equipment must be decided on and then a qualitative trade-off can be performed.

Non-intrusive For this research, the local aerodynamics around the blade need to be captured without distorting this flow. To achieve this, a non-intrusive measurement technique is needed.

Quantitative To express the effect of floating platform motion on the aerodynamics and allow fair comparison between different motion cases and the fixed case, it is nice to have a quantitative method instead of a qualitative flow characterization.

Capture flow structures To really analyze the local aerodynamics, it is good to be able to reconstruct the flow field around the turbine blade. However, since the flow is unsteady due to the motion, the measurement technique needs to be able to capture the flow field at multiple points near instantaneous to show any existing flow structures.

Achievable and Available The measurement technique needs to be achievable within the time-frame, within the scope of a MSc thesis project, and within the constraints of the wind tunnel and turbine model, and the equipment needs to be available for use in the relevant wind tunnel.

The possible measurement methods are now tested to these conditions. Firstly, wall tapings will not be used as they are not achievable to be manufactured within the small volume of the model turbine blades. Even if it were possible to place a few small pressure sensors, it would not be possible to place enough pressure taps to obtain the forces through integration of the measured surface pressure [43]. Secondly, Pitot-static tubes are intrusive to the flow, and also measure only at a point location, so are not suitable to capture the flow structures. For the same reason, hot-wire anemometry is discarded. Laser Doppler anemometer and LiDAR can measure only a small measurement volume at a time, so are unsuitable to capture the flow structures. Additionally, LiDAR equipment is not available for small scale measurements in the wind tunnel, as it is normally used for atmospheric measurements, and there is also no available LDA equipment within the used wind tunnel or laboratories. Pressure-sensitive paint is an intrusive technique, as the finite paint thickness will alter the airfoil profile and the surface finish will be different from the blade material[62]. It will also not be achievable to combine a PSP measurement with the more suitable PIV measurement. Particle tracking velocimetry is less suitable for measuring local aerodynamics as only few particles should be introduced to the flow to allow the individual tracking[48]. To access the local flow information, the particle density should be increased, which results in using PIV instead. This method meets all conditions that were presented before.

Within PIV multiple distinctions can still be made as presented in section 3.2. Planar PIV is the most achievable type, but stereoscopic PIV gives more information about the flow structures, as the third velocity component is available, while still being achievable. Tomographic PIV allows even more information on the flow structure, but can be more difficult to realise within the scope of this thesis. The difficulty of optical access and occlusion by the blade or even the tower would further complicate a Tomo-PIV setup. The difficulty of optical occlusion for SPIV is discussed in subsection 3.4.3. In regards to optical occlusion, planar PIV has the same issue and solution as for SPIV.

The inflow velocities will be in the order of 4 m s^{-1} and the motion velocity will be significantly smaller than this. The flow around the turbine might be unsteady. It is assumed that the flow structure for one motion phase is overall similar the flow structure if the same motion phase is repeated several motion periods later. Then, many measurements will be taken to result in mean flow field for a certain motion phase, so no high-speed PIV setup is needed.

3.4. Measurement of Flow Field using Stereoscopic PIV

As concluded in the previous section, stereoscopic PIV will be used to measure the local aerodynamics around the blade. The components needed in this system are shortly introduced in the following subsection, 3.4.1. A more detailed description of the components of the setup and the tradeoff that led to it can be found in chapter 4. Since SPIV only measures the flow in a plane, the orientation and location of these planes needs to be considered. Also, some limitations in the field-of-view (FOV) of the cameras needs to be considered.

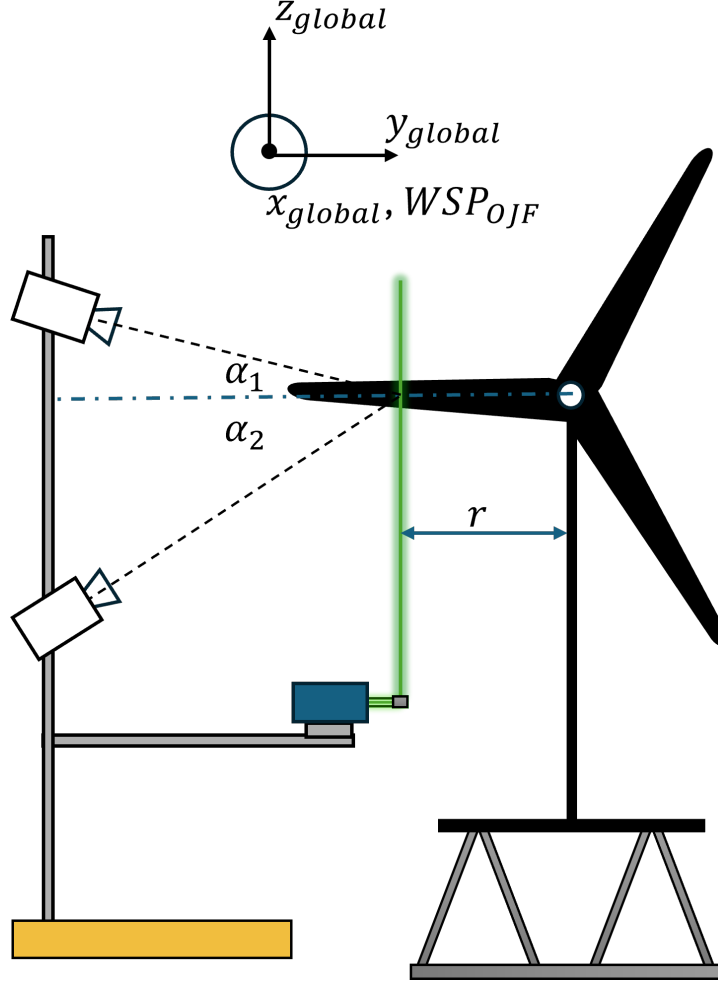


Figure 3.1: Schematic of the PIV setup including global coordinate system.

3.4.1. PIV Setup

In general, the SPIV setup will need two cameras, a laser (sheet), a smoke generator, acquisition PC, programmable timing unit (PTU) and of course the subject of the measurement. The subject in this experiment is a blade section and plane around it. To ensure the desired plane is illuminated by the laser and in focus of the cameras (after calibration), the cameras and laser are mounted on a two axis traversing system. The smoke generator is placed far downstream of the turbine, right behind the heat exchanger mesh. This allows the smoke to travel almost a full lap inside the wind tunnel, to spread the generated smoke cloud more evenly. It is controlled via remote control. The acquisition PC and PTU are placed inside of the control room, connected to the rest of the setup via cables.

Figure 3.1 shows a schematic setup of the placement of the cameras and laser head, together with the hexapod and turbine. The global coordinate system is also defined, where the positive x_{global} is aligned with the direction of the OJF wind speed. Since the location of the smoke machine, acquisition PC and PTU are not very relevant, they are disregarded in the sketch. A condition for the PIV image to be taken, is that the blade subject is in the horizontal azimuthal position. Both the top and bottom camera have a certain angle with respect to this horizontal plane, α_1 and α_2 , respectively. The blade section being imaged is defined by the rotor radius, r .

3.4.2. Measurement Planes

To obtain the spanwise distributions of the local aerodynamic parameters, the measurement plane will be placed and moved between multiple spanwise measurements locations. The number of locations and the positions of these locations will need to be determined a priori. The more locations, the closer

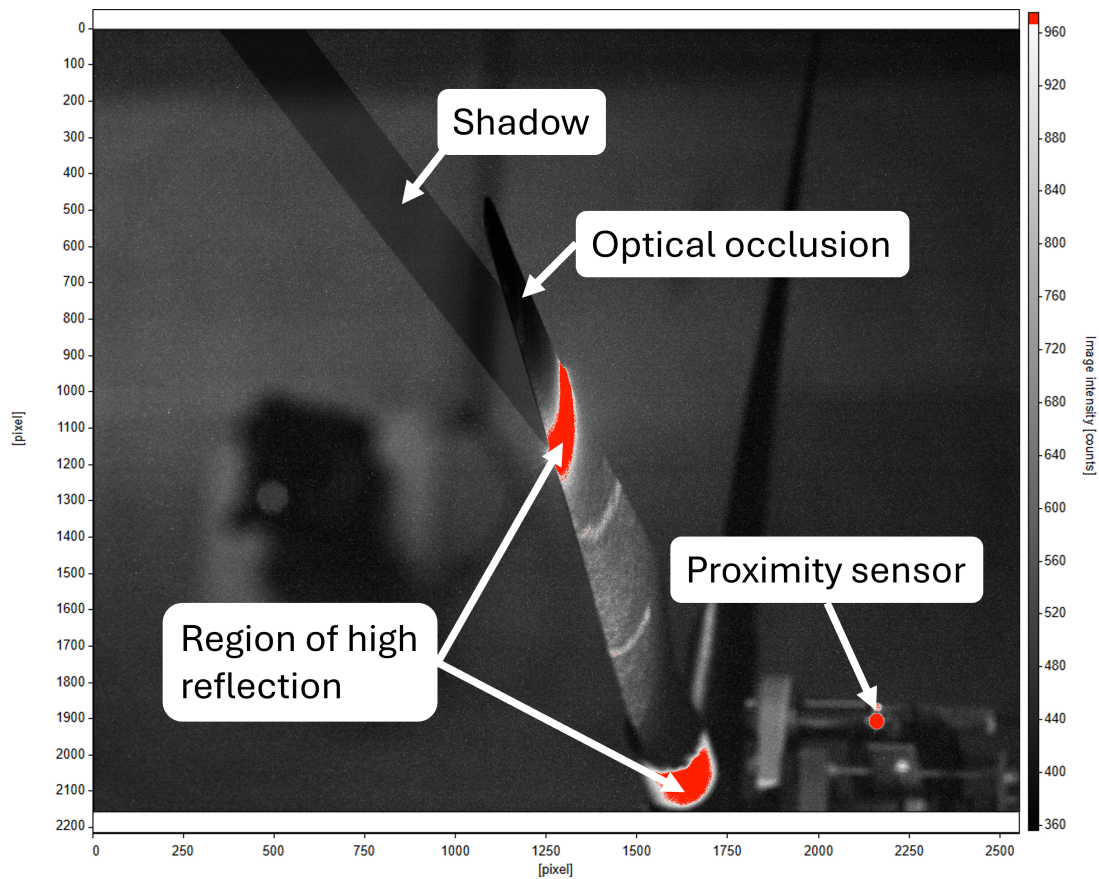


Figure 3.2: Example of the shadow, optical occlusion and high reflection caused by the blade.

the measured data can reconstruct a spanwise distributions. However, this comes at the cost of increasing wind tunnel test time for a certain condition, which will limit the number of cases that can be considered. Therefore, a compromise for the number of measurement locations needs to be found. The measurement locations will be chosen such that the measurements can still approximate a spanwise distribution using the least amount of planes. OpenFAST simulations are run to determine what distribution shape the data should be able to represent. The measurement planes will be placed such that the data can accurately be captured at locations that are aerodynamically relevant. This results in planes within the outboard region ($\sim 70\%$ to 100%). See Appendix B for the final full test matrix.

3.4.3. Blade Shadow and Optical Occlusion

When the laser sheet is pointed towards the blade cross-section, the blade will cast a shadow on the particles. This lack of illumination will prevent any flow field to be extracted in this area. Additionally, the blade itself may optically occlude part of the measurement plane as seen from the point-of-view (POV) of the cameras. This is illustrated in Figure 3.2, which also shows a region of high intensity where the laser sheet hits the blade and the reflections overexpose the camera. It also shows a region of high intensity due to the light from the proximity sensor.

To remove the blade shadow, a beam splitter may be used. A beam splitter allows half of the laser light to pass through and reflects the other half in a different direction. This can be used to aim a laser sheet at the blade section from both sides to fully illuminate the flow field. This will remove the large shadow region, but the illumination intensity will be lower. Another drawback is the complicated setup of the second laser sheet. Setting up the beam splitter will take more time, and it will be difficult to accurately align the two sheets to be in the same plane. Moreover, the addition of a beam splitter does not remove the optical occlusion caused by the blade for the POV of the cameras. This can be solved by adding a third camera to the acquisition system to completely capture the flow field in one instant.

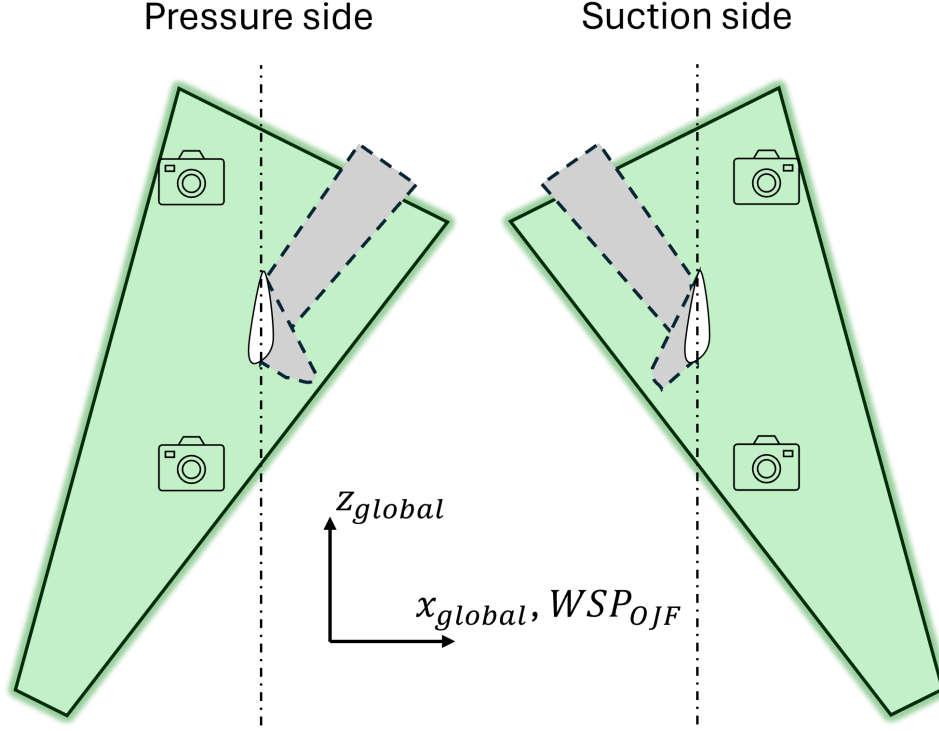


Figure 3.3: Schematic of the difference in shadow and optical occlusion (both in gray) for pressure side and suction side. The green area signifies the laser sheet.

Due to the added complexity of the system, it was chosen not to add a beam splitter and the extra camera that would be needed. The measurement system was deemed to be already more complex by the inclusion of the hexapod, and it was therefore preferred to keep the rest of the system relatively simple, to reduce the number of factors that will need troubleshooting during the campaign or processing of the data.

Instead, to solve the problem of blade shadow and optical occlusion, the PIV measurements will be stitched from two separate measurements. Each case is split into two cases, one where the cameras and laser are located on the pressure side (PS) of the rotor plane, and another where they are located on the suction side (SS) of the rotor plane. Due to the different angles, the shadow and optical occlusion will appear in different areas with respect to the blade section, see Figure 3.3. In this image, the airfoil is seen from the direction of the cameras, looking along the positive y_{global} direction. When combining the flow fields from the PS and SS, the data can be combined in such a way that the only area with missing data is the airfoil itself and the shadow area from one side is filled by the data from the other side. This is referred to as stitching the flow fields.

The stitching is done by averaging the pressure side and suction side based on the number of valid vectors at each point for each field. This means that areas with only valid vectors for one of the sides use only the data for that side, but areas with data for both sides use a weighted average. The number of valid vectors can be lower than the number of images ($n_{images} = 200$ per side), when vector validation removes certain vectors in certain images. To work on the same grid, the PS points are first linearly interpolated to the slightly smaller SS grid.

3.4.4. Blade-Motion Synchronization

Two conditions must be met for the PIV images to be taken. Firstly, the blade must be in the horizontal azimuthal position. Secondly, the motion of the turbine must be in the desired phase.

Locking the blade in the horizontal position is done using a proximity sensor. The proximity sensor outputs a 1P signal when the blade is in the vertical position. The sensor senses the passing of a small metal washer attached to one of the blades. After the 1P signal is received, a time delay is used to

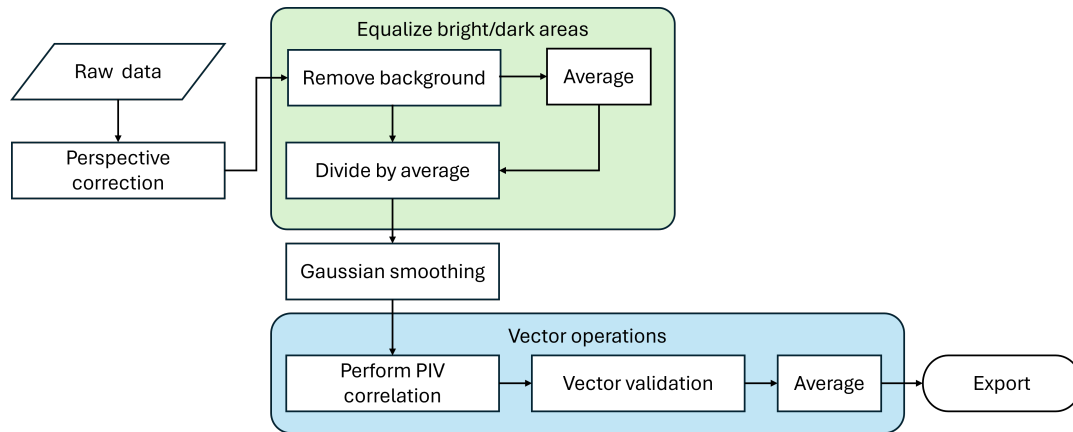


Figure 3.4: Main processing steps implemented in DaVis.

ensure the blade is horizontal at the moment of the PIV trigger.

The numerical model controlling the hexapod motion also receives this 1P trigger. When enabling the synchronisation, the sinusoidal motion is phase-shifted, such that the desired phase motion is achieved at the same moment as a 1P trigger is received. Every two seconds, after sixteen multiples of 1P triggers, the motion is corrected to ensure the same motion phase is locked to a multiple of the 1P trigger. Every other second, a PIV image can be taken, when the motion is not being corrected. After starting up, the corrections are small, as only a small drift in rotor speed needs to be corrected.

3.5. Flow Field Processing Steps

The PIV data is captured, collected and analysed in the DaVis software. DaVis is developed by LaVision for analysing laser imaging techniques, among which PIV. The data is captured on DaVis version 10.2.1, while analysis is performed on the newer DaVis 11.2.5. No major changes between these versions were made that would significantly impact the results of the analysis of SPIV.

Within DaVis, the PIV analysis is performed, but multiple processing steps need to be taken before the actual cross-correlation step can be performed. The list of operations is presented schematically in Figure 3.4. In the rest of this subsection, they are explained. More details or information may be found in the DaVis and FlowMaster product manuals [63, 64].

Perspective correction (raw → world). The calibration obtained using the calibration plate is applied to each image, mapping pixel coordinates to physical world coordinates. See Figure 3.5 for the image after perspective correction.

Changing the interpolation mode produced slight image warping, but no setting consistently improved the results. Likewise, the calibration mapping step size had a negligible influence on the particle statistics. Image stitching was disabled because it would superimpose the two camera images, causing the blade to appear twice.

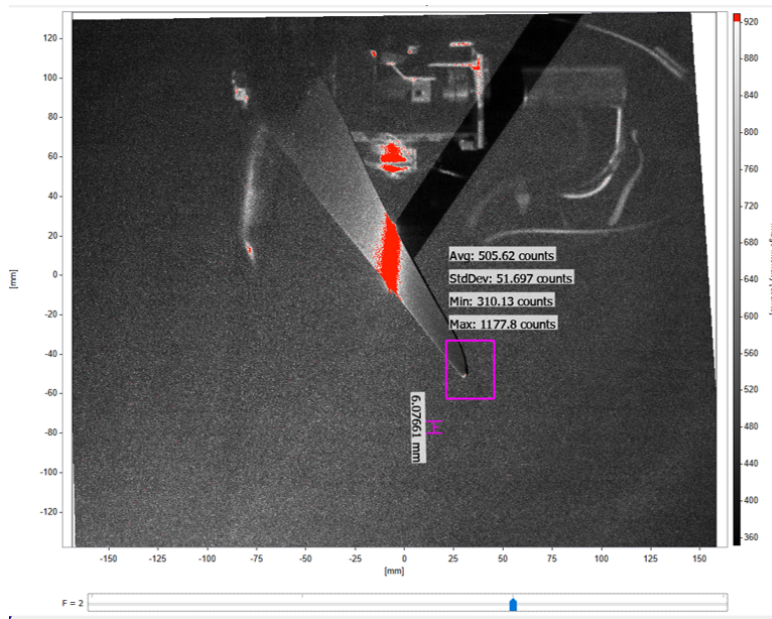


Figure 3.5: First frame of double image pair for the top camera for the pressure side after perspective correction.

Remove background. Remove the background using directional minimum, with $n = 7$, computes the background for every pixel by taking the minimum along multiple lines evenly spaced over different spatial directions, then taking the maximum of these minima. The filter size represents the radius around each pixel in which the calculation is performed. See Figure 3.6 for the image after background removal.

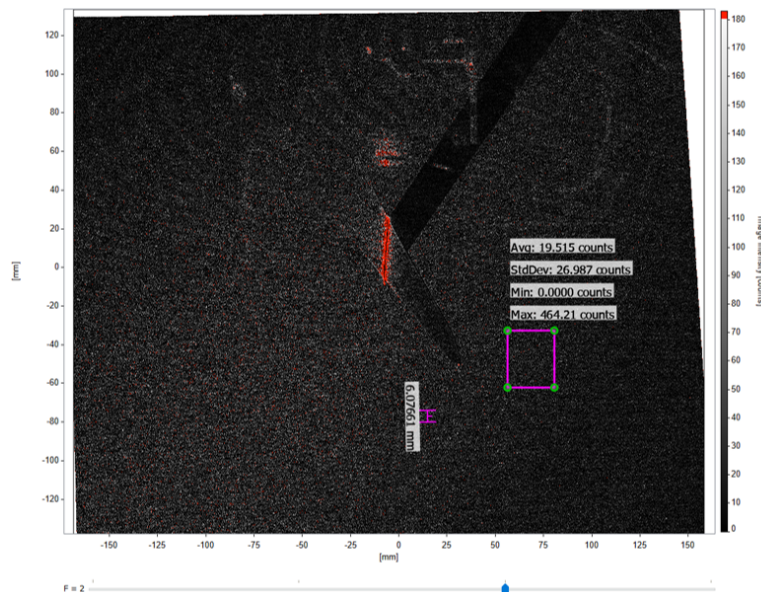


Figure 3.6: First frame of double image pair for the top camera for the pressure side after directional minimum background removal.

Average. For each frame, all 200 images in the recording are averaged together. This gives the average intensity of each pixel. See Figure 3.7 for one of the averaged frames.

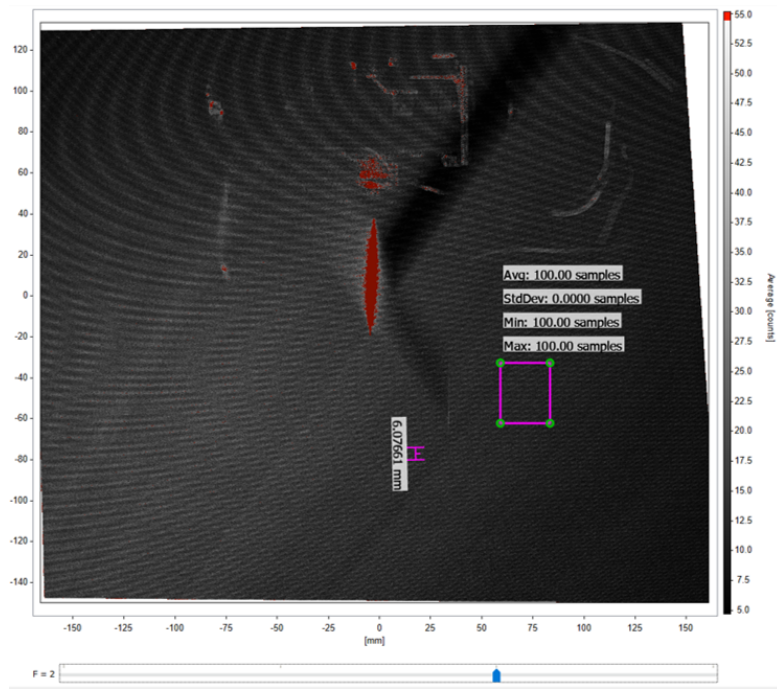


Figure 3.7: First frame of double image pair for the top camera for the pressure side after averaging.

Divide by average. All images generated by removing the background are divided pixel-wise by the averaged frames. This normalises any bright and dark spots, such that the PIV can be performed on a homogeneous particle field.

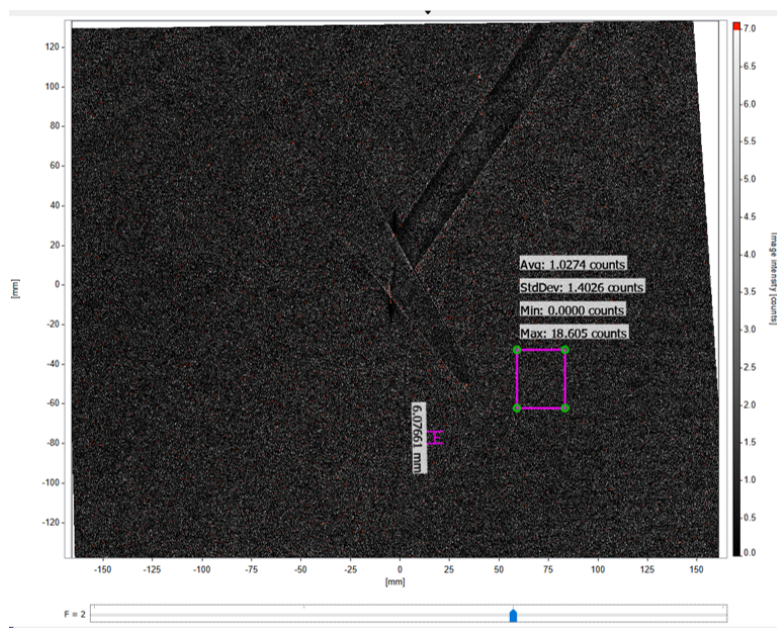


Figure 3.8: First frame of double image pair for the top camera for the pressure side after dividing by its average.

Gaussian smoothing. Gaussian smoothing using a $[3 \times 3]$ kernel to smooth the particles' edges to reduce peak-locking. See Figure 3.9 to compare the particles before and after the Gaussian smoothing.

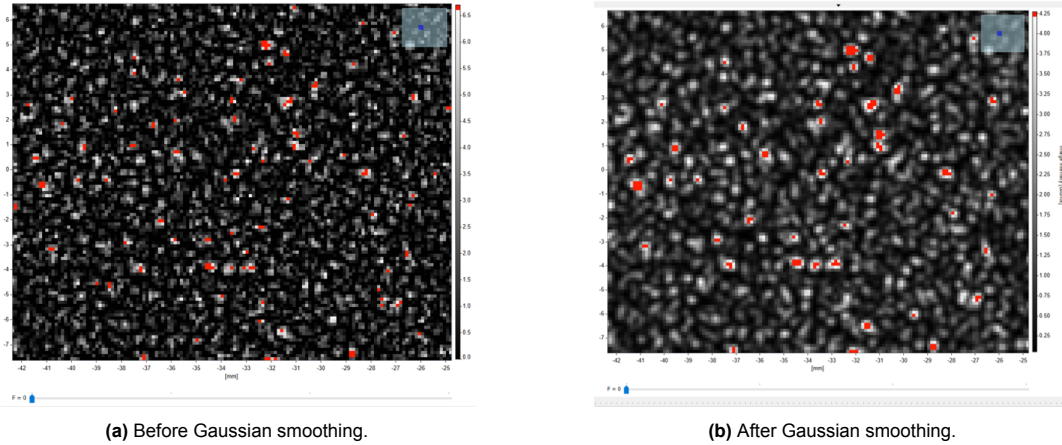


Figure 3.9: Zoomed-in part of the flow field, showing the particles before and after Gaussian smoothing with a $[3 \times 3]$ kernel.

PIV cross-correlation. Determines the average displacement of tracer particles in an interrogation window between image pairs. 3C-2D Stereoscopic PIV cross-correlation is performed using an interrogation window of $48 \text{ px} \times 48 \text{ px}$, with four passes with 75 % overlap. For the results of the cross-correlation and later steps, see the flow fields in section 5.1.

Since pre-processing is done in earlier steps, and post-processing is done in later steps, these settings are turned off. This is done on purpose to more clearly show the effects of the pre- and post-processing, and allow variations of this processing without rerunning the costly PIV cross-correlation.

Vector validation. Several vector post-processing steps are applied to remove nonphysical vectors.

- Allowed vector range. Vectors outside of $u = 4.0 \pm 9.0, v = 0.0 \pm 9.0, w = 0.0 \pm 4.0 \text{ m s}^{-1}$ are discarded.
- Vector length filter. Delete any vector outside the range $0 \leq |V| \leq 11.0 \text{ m s}^{-1}$.
- Delete vector if correlation value < 0.2 . This discards vectors where the cross-correlation is not confident in the vector, e.g. when the particles within the window have moved. For good correlation, the values are close to 0.70 to 0.8.
- Fill small gaps in the vector field using interpolation, using one fill-up pass.

Average. Average the 200 flow fields into one flow field, with information on the average velocity, its standard deviation and its uncertainty. Any point with less than 10 valid vectors is discarded.

Export. For each grid point, the three velocity components, their standard deviation, the number of valid vectors, and the uncertainty of the absolute velocity are exported in .csv-files.

Uncertainty threshold. This step is performed in Python rather than DaVis to allow rapid testing. After averaging, vectors with an uncertainty exceeding 0.19 m s^{-1} (approximately 5 % of U_∞) are discarded. Only a small fraction of the field exceeds this threshold, primarily near the trailing edge, at the FOV boundary, and near shadow edges.

Adding velocity components. This step is also performed in Python. The structural and rotational velocity components are added uniformly to the measured flow field, as described in section 3.6.

Stitching. The pressure side and suction side fields are combined in Python using weighted averaging, as described in subsection 3.4.3.

3.6. Angle of Attack Determination

In this section, the method to determine the angle of attack (AoA) is explained. Firstly, the SS velocity is normalised to the PS, as explained in subsection 3.6.1. Afterwards, the airfoil velocity triangle is shown in subsection 3.6.2. Then, the Ferreira-Micallef method (FM) is presented in subsection 3.6.3. Finally, the method of calculating the confidence level is explained in subsection 3.6.4.

3.6.1. Velocity Normalization

One velocity field is obtained using two separate measurements. While these measurements are supposed to be taken under the same conditions, those operating conditions may vary during the experimental campaign. Additionally, the change in laser sheet focus or camera calibration may introduce a small bias. Taking a measurement of the pressure side and suction side will give two different realisations of the flow, but should give the same flow field in converged areas under equal operating conditions. For the area upstream of the rotor plane, the uncertainty is low. Since the flow should be equal on average, the flows are normalised based on the average magnitude of the in-plane flow, (u, v) , on an upstream square. Since the uncertainty for the PS is lower than for the SS, the PS is taken as the baseline, as the SS field is changed to match the average magnitude of (u, v) of the PS in that square.

Normalisation using the mean wind speed obtained by the pitot tube was also tested. In this method, the u - and v -components are scaled by the factor obtained by dividing the target wind speed (4 m s^{-1}) by the measured mean wind speed. This method actually increased the difference in (u, v) -magnitude of the PS and SS fields for most vectors. Therefore, this was not implemented in the final results.

3.6.2. Velocity Triangle

The flow field that will be captured by the PIV data will be in a global stationary reference system. Alternatively, a rotating reference system that is moving with the blade section can be chosen. In this rotating reference system, the time derivative of the blade position becomes zero, instead being replaced by adding the apparent rotational velocity $v_{rot} = -\Omega r$ [47]. However, in the case of a FOWT under motion, a velocity component due to hub motion, V_{hub} must also be added.

In the considered cases, V_{hub} does not contain a v -component. In the case of surge, the motion is purely in the x_a -direction, so only a u component exists.

In the case of pitch, the vertical velocity is zero at $\phi = 0^\circ$ or $\phi = 180^\circ$, as the hub moves horizontally in those phases, and the vertical velocity is zero at $\phi = 90^\circ$ or $\phi = 270^\circ$ at whole velocity is zero. Since V_{hub} can only have a u -component, it will from now be referred to as U_{hub} .

Together, this rotational component $-\Omega r$ and the velocity component due to the hub motion, U_{hub} form the structural velocity, $V_{structural}$. This is the physical velocity of the blade. The original captured flow field includes both the wind speed V_{wind} and the induced velocity component $V_{induced}$. Together, these three components form the relative velocity experienced by the blade, V_{rel} , see Equation 3.1.

$$V_{rel} = V_{wind} - V_{structural} + V_{induced} \quad (3.1)$$

These components are visualised in Figure 3.10 as a velocity triangle. Note that while positive $x_a > 0$ is to the right of the blade, a positive $U_{hub} > 0$ has a contribution to the left.

In normal considerations, $V_{structural} = 0$, and with U_∞ being the u - and only component of V_{wind} , the axial induction factor, a , becomes

$$u_{rel} = U_\infty(1 - a) \rightarrow a = 1 - \frac{u_{rel}}{U_\infty}$$

. When the structural velocity, U_{hub} , is added, this becomes Equation 3.2.

$$u_{rel} = U_\infty(1 - a) - U_{hub} \rightarrow a = 1 - \left(\frac{u_{rel} + U_{hub}}{U_\infty} \right) \quad (3.2)$$

The definition of the tangential induction factor stays unchanged with respect to the standard bottom-fixed case, see Equation 3.3.

$$a' = \frac{v_{rel}}{\Omega r} - 1 \quad (3.3)$$

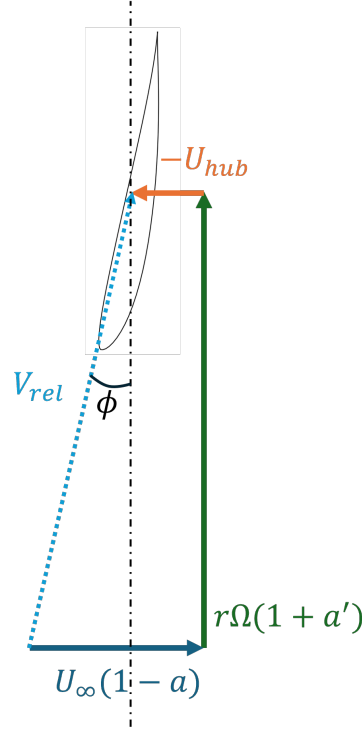


Figure 3.10: The velocity triangle of the blade section under motion.

3.6.3. Ferreira-Micallef method

Determining the angle of attack (AoA) in a 3D-flow is not trivial, since the AoA is a two-dimensional concept. Using the crossflow principle as presented in section 3.9, the local sections can be approximated as 2D flows, which allows the definition and use of the angle of attack. To then determine the value of the AoA, the Ferreira-Micallef method (FM) will be used. In this method, the measured velocity at a point p in the flow field is the sum of the induced velocity caused by the free and bound vortices, $\sum \mathbf{u}_{ind}$, and the freestream wind velocity, $\mathbf{V}_{rel}$, see Equation 3.4 [47, 65, 66].

$$\mathbf{u}_p = \sum \mathbf{u}_{ind} + \mathbf{V}_{rel} \quad (3.4)$$

The induced velocities can be found using the Biot-Savart law, see Equation 3.5, where $\mathbf{x}_p$ is the position vector of a control point, and $\mathbf{x}$ is the position vector of a vortex inducing element. In a flow field ordered in a grid, each cell contains a vortex element with associated position and circulation, Γ .

$$\mathbf{u}_{ind} = \frac{\Gamma}{2\pi} \frac{\mathbf{x}_p - \mathbf{x}}{|\mathbf{x}_p - \mathbf{x}|^2} \quad (3.5)$$

When all induced velocities in the control points are known, and the measured velocities are known, the relative inflow vector $\mathbf{V}_{rel}$ can be determined using a least-squares approach.

The flow angle is then determined as Equation 3.6.

$$\phi = \arctan \left(\frac{V_{rel,y}}{V_{rel,x}} \right) \quad (3.6)$$

Then finally, AoA is given by $\alpha = \phi - (\theta + \beta)$, where θ and β are the twist and pitch respectively. The test will be performed on a fixed pitch rotor, so $\beta = 0$.

When the relative velocity is known, the axial and tangential induction factors can also be calculated as given in Equation 3.2 and 3.3.

The FM method assumes that the flow is 2D, incompressible and irrotational. The 2D assumption means that for this method to be applied accurately, only the 2D sections can be analysed, and the crossflow principle needs to hold for these sections. As a result, the determined AoA near the tip region where large 3D flow effects are present may not be reliable. It has also been shown that the FM method differs in result from several other angle of attack-determination methods for $\frac{r}{R} > 80\%$ [65]. The assumption of incompressible flow is well met, as explained in section 4.2.

A circle of control points around the airfoil is placed to calculate the induced velocity part caused by the entire flow field. The number of control points, n_{cp} and the radius of the circle can be varied, which is done in the convergence study. The radius of the circle is defined as $r_{cp} = r_{scale}c$, where c is the airfoil chord, and r_{scale} can be freely varied, as long as all control points lie within valid data points.

3.6.4. Confidence Level for Angle of Attack

To get any reliability when comparing measurements, a confidence level must be used to indicate whether differences could be caused by a physical effect or are more likely to be statistical anomalies caused by the uncertainty. For the velocity flow field, the standard deviation of each component is obtained for each vector by DaVis. Assuming a normal distribution of the vectors around the calculated mean vector for a point, it is possible to estimate the new velocity vectors that could occur with a certain probability, as shown for the u -component in Equation 3.7.

$$X_u = \bar{u} + \frac{Z}{\sqrt{n_{vectors}}} \sigma_u \quad (3.7)$$

, where X_u is the expected u -component at a point for a given confidence level, Z is the Z-score of that confidence level for the assumed normal distribution, $\bar{u}$ is the mean u -component for that point, $n_{vectors}$ is number of available vectors at that point and σ_u is the standard deviation of the u -component at that point.

However, going from the standard deviation of a set of vectors to the standard deviation of the angle of attack is not trivial, since the correlation between the standard deviations of the vectors is not determined. In other words, when subtracting a u -component in one vector, it is not evident if the u -component in another vector should also be fully subtracted, or if a flow structure can signify that the standard deviation in a vector should be added to the mean value. It is also not evident to solve how the u - and v -component and their standard deviation are correlated.

To solve this issue in a conservative manner, the standard deviation of the u - and v -components is added in such a way as to maximise the change in angle of attack. This means that, for the high 97.5 % probability level calculation for all points, the positive standard deviation is added to the u -components, and negative to the v -component. This maximises the calculated AoA. The vice versa is done when the 2.5 % probability level, meaning a lower AoA is expected in only 2.5% of new realisations. Together, this 97.5% and 2.5% level AoAs give the 95 % confidence level of the angle of attack.

These two constructed flow fields, with the added and subtracted standard deviations, are used to calculate the other aerodynamic parameters: the axial induction factor; tangential induction factor; and sectional normal force. For the cases where the angle of attack decreases, the induction factor and normal load actually increase, as the larger AoA produces a larger force against the direction of the wind.

3.7. Local Load Determination using the Kutta-Joukowski Theorem

The aerodynamic loads over a body are caused by the pressure and shear stress distribution over the body surface [42, p. 19]. However, the pressure distribution over a blade section is difficult to determine. The techniques that can measure pressure directly, such as wall tappings, would be physically challenging to install in the blade model, as the blade will be significantly smaller than the blades that have previously been tested with pressure instrumentation [67]. Reconstructing the pressure distribution with the velocity field as obtained by PIV is possible, but will result in a too-low resolution for reliable integration

Since load determination via pressure measurements is thus not possible, another method needs to be

found to reconstruct the loads. In this section, the Kutta-Joukowski KJ theorem method is presented. The KJ theorem is based on circulation. Circulation, Γ , is a powerful aerodynamic tool, defined as the negative of the line integral around a closed curve in a flow field, see Equation 3.8 [42, p. 174].

$$\Gamma \equiv - \oint_C \mathbf{V} \cdot d\mathbf{s} \quad (3.8)$$

The importance of circulation is its connection to generated lift. The Kutta-Joukowski theorem (KJ) states that sectional lift is proportionally related to the fluid density, ρ , the relative velocity, V_{rel} , and the circulation, see Equation 3.9[42, pp. 280–282]. The KJ theorem assumes incompressible, potential flow theory. This means that any viscous drag contribution is neglected.

$$L' = \rho V_{\text{rel}} \Gamma \quad (3.9)$$

Equation 3.9 can be decomposed into the normal and tangential force components, see Equation 3.10 and 3.11, respectively[47].

$$F_N = \rho \omega r (1 + a') \Gamma \quad (3.10)$$

$$F_T = \rho U_{\infty} (1 - a) \Gamma \quad (3.11)$$

From the sectional loads, the local thrust and power coefficients, C_t and C_p can be calculated. The local thrust coefficient is calculated by non-dimensionalising the sectional normal load over an annular element, $dA = 2\pi r dr$, see Equation 3.12. The local tangential load coefficient C_{tan} is defined similarly, but using the tangential load, F_T , see Equation 3.13. This coefficient can be used to calculate the local power coefficient, C_p , see Equation 3.14. In these equations, N_B is the number of blades, which is 3, to account for the fact that the sectional loads, F_N and F_T are computed for a single blade.

$$C_t = \frac{F_N N_B}{\pi \rho U_{\infty}^2 r} \quad (3.12)$$

$$C_{tan} = \frac{F_T N_B}{\pi \rho U_{\infty}^2 r} \quad (3.13)$$

$$C_p = C_{tan} \frac{\omega r}{U_{\infty}} \quad (3.14)$$

3.8. Imposed Platform Motion

The hexapod platform, on which the turbine is mounted, is instructed to follow imposed motion to mimic the floating motion of FOWTs. Full coupling of aerodynamic and floater dynamics is outside the scope of this research, so the imposed motion will be determined a priori of the wind tunnel measurements. This then means that the relevant motions need to be determined without knowledge of measured aerodynamic forces.

To study the aerodynamic effects of the different degrees of freedom independently, only one DoF is active for each test case. The imposed motion is chosen to be of sinusoidal nature. This motion is both easy to analyse and also possible to implement in a physical test setup, in contrast to something like a step- or sawtooth-function.

There are an infinite number of possible combinations of frequency and amplitude that can define the sinusoidal single-DoF motion. Several combinations that can be seen as representative for full-scale coupled motion with all six DoFs are chosen. See section 4.5 for the chosen test cases.

3.9. Crossflow Principle

The crossflow principle states that the flow over a swept wing can be projected into a component along and a component perpendicular to a blade section[68]. If viscous drag is not of importance, the component perpendicular to the blade section does not impact the pressure forces produced by the component along the blade section. This means that the spanwise flow over a turbine blade can be

ignored when considering the lift [69]. The crossflow principle might not be fully accurate near the root of the blade due to strong 3D effects [68]. However, the crossflow principle is still satisfactory for most of the blade, due to the high aspect ratio of the blades. Additionally, the root region is insignificant for aerodynamic forces due to its low relative velocity and swept area compared to the outer blade regions.

4

Experimental Setup

Whereas chapter 3 describes the methods that are used in this study, this chapter explains the experimental setup in more detail. The experimental campaign is performed in the Open Jet Facility (OJF), which is part of Flow Physics and Technology (FPT) at TU Delft. This chapter starts by presenting this wind tunnel in section 4.1 and the wind turbine model that is used in section 4.2. Then, the hexapod that is used to impose the surge motion, and its motion limitations, is described in section 4.3. The flow measurement system is described in section 4.4. Finally, the analysed test cases are shown in section 4.5.

4.1. Wind Tunnel

The wind tunnel used in this campaign is the Open Jet Facility (OJF), part of the Flow Physics and Technology (FPT) department at TU Delft. This is a closed-loop wind tunnel capable of generating low-turbulence wind speeds using a 500 kW fan. The nozzle is an octagon with a diameter of 2.85 m, resulting in a nozzle area of 6.7 m². However, the test section of the tunnel is a large room, with a cross section of 13 m × 8 m, giving an area of more than 100 m². Downstream of the test section, the air is cooled by a 350 kW heat exchanger. Further characterisation of the OJF can be found in [70].

4.2. Wind Turbine Model

The wind turbine model (WTM) is a scale model of the DTU 10 MW Reference Wind Turbine (DTU 10MW)[71]. The main parameters of this turbine are presented in Table 4.1. The rotor has a fixed pitch and no sweep or tilt angle. The WTM is equipped with two 4030-002 MEMS accelerometers. One of these is located at the nacelle and will be referred to as the ‘top’ accelerometer, and the other is on the base plate of the turbine, referred to as the ‘bottom’ accelerometer. The nacelle is connected to the tower via a 9105-TW-MINI45-E transducer, which will be referred to as the ‘load cell’. This load cell measures the loads and moments in all six axes. At the start of a measurement series, the load cell is zeroed with an offset, which is the measured mean over a previous period.

Blockage refers to when the flow in a wind tunnel test section loses momentum due to the presence of

Table 4.1: The main properties of the Wind turbine model and rotor.

Parameter	Value	Unit
Rotor diameter	1.20	m
Rotor mass	0.578	kg
Nacelle mass (excl. rotor)	1.1	kg
Max chord (at $\frac{r}{R} = 31\%$)	6.3	mm
Design tip-speed ratio	7.5	-
Rated wind speed	4	m s ⁻¹

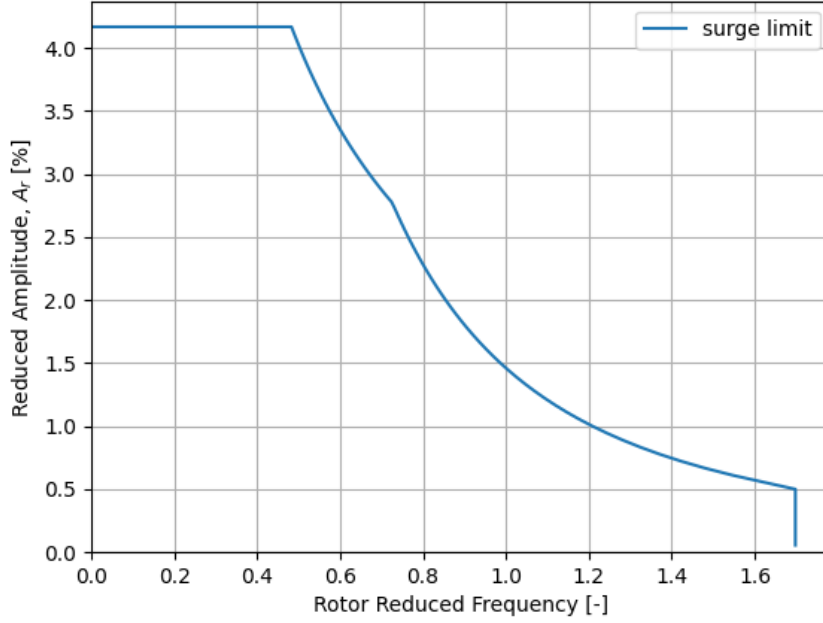


Figure 4.1: Hexapod limitations in surge, expressed in reduced motion amplitude and rotor reduced frequency. All motions on the lower-left side of the limit are technically viable.

the test subject. This effect becomes significant and needs a correction when the test subject exerts a significant force on the flow, and its size is significant relative to the area of the tunnel cross section. Blockage corrections are presented in [43, 72, 73]. The rotor area is 1.13 m^2 . The turbine is placed 3 m downstream of the nozzle, inside the large test section of the OJF. This means that the area ratio of the turbine rotor to the test section is approximately 1 %. While most of the test section will experience negligible flow, there is enough room for expansion that the blockage effect can be considered negligible and will not be accounted for.

4.3. Hexapod

The turbine will be mounted on a 6-DoF parallel robot hexapod to mimic the motions of the floating platform of FOWTs. The hexapod is produced by Quanser, and the limitations on its movement are reported in Table 4.2.

This movement envelope limits the possible test cases, as certain combinations of frequencies and amplitudes will not be possible. The position, x , of the platform under sinusoidal motion is given by Equation 4.1. The derivative and second derivative can be used to find the relation between maximum velocity, $v_{\max}$, or maximum acceleration, $a_{\max}$, where A_m is the motion amplitude and f is the motion frequency, see Equation 4.2 and Equation 4.3, respectively.

Due to the hexapod limits, the test cases are also limited in the rotor reduced frequency f_r or normalised velocity variation ΔV^* that can be tested. This is shown in terms of reduced amplitude $A_r = A/D$ and rotor reduced frequency in Figure 4.1. The normalised velocity variation for the rated condition is limited to at most $\Delta V^* = 17\%$.

$$x = A_m \cos(2\pi ft + \phi) \quad (4.1)$$

$$v_{\max} = A_m 2\pi f \quad (4.2)$$

$$a_{\max} = A_m 4\pi^2 f^2 \quad (4.3)$$

Table 4.2: Hexapod motion limitations.

Parameter	Max. value	Unit
Translational amplitude (surge + sway)	75	mm
Translational velocity	0.67	m s^{-1}
Translational acceleration	9	m s^{-2}
Rotational amplitude	15	$^{\circ}$
Rotational velocity	80	$^{\circ}/\text{s}$
Rotational acceleration	800	$^{\circ}/\text{s}^2$
Frequency	5	Hz

4.4. Flow Measurement System

The flow measurement system encompasses all components that are used to be able to measure and save the flow data. The flow is mainly measured using the PIV setup. A short, general overview of the particle image velocimetry system is given in subsection 4.4.1. Firstly, the PIV system contains a smoke generator. Secondly, it contains two cameras, see subsection 4.4.2 for how the type was selected. Thirdly, a laser with optics to form a thin laser sheet, see subsection 4.4.3 for the selection of the laser. Furthermore, a calibration plate is mounted for calibrating the camera view, see subsection 4.4.4. Additionally, a proximity sensor is used for timing the PIV trigger, see subsection 4.4.5. Finally, all data needs to be acquired and stored, see subsection 4.4.6.

4.4.1. Particle Image Velocimetry System Overview

The PIV system is mounted on a beam structure to measure a plane around a blade section. The setup is placed in the test section of the OJF and connected to a commanding PC in the control room. The hardware of the PIV system consists of the two Imager sCMOS CLHS cameras with Scheimpflug adapters and $f = 105\text{ mm}$ lenses; the Safex smoke generator; the Quantal Evergreen 200 laser, and the PTU X, together with the acquisition PC.

The physical setup of the setup with the X-beams that the camera and laser are mounted, which is located on the traversing system, is shown in Figure 4.2. The picture is annotated to more easily identify the key components. Firstly, the cameras and laser head can be seen in the same position as in the previous sketch. The beam structure is reinforced with a diagonal and an extra vertical beam to minimise vibrations and relative position shifts. The laser head is also placed on a cross-beam to place the laser head further downstream, in the positive x_{global} direction. This is explained in subsection 3.4.3. The beam structure is mounted on the yellow two-axis traversing system. One axis is aligned with y_{global} , to vary the imaged rotor radius, r . The other axis is aligned with x_{global} . The traversing system allows the setup to move to the desired spanwise blade section. This figure includes the calibration plate, which is removed before the rotor measurements need to be taken. The laser head is connected to the laser power and cooling supply, which is located stationary on the traversing system. On the right of the image, the hexapod and turbine can be seen. Between the PIV system and the turbine is a calibration plate. This plate is used to allow the pixel coordinates to be transformed into physical space by the PIV software, see subsection 4.4.4.

4.4.2. Camera Selection

Five types of cameras are available within the FPT laboratories. These five and some of their main properties are shown in Table 4.3. A trade-off on these parameters was performed for the cameras. In the trade-off, the main considerations were the resolution, meaning the number of pixels, and the frame rate, meaning the maximum acquisition frequency at full resolution. The two Photron cameras are meant for high-speed PIV. Therefore, they have a very high frame rate, far exceeding the passing blade frequency as described in section 4.2, at the cost of a lower resolution. The Mpix16 has by far the best resolution, but at the cost of a frame rate significantly lower than the blade passing frequency. From the remaining Bobcat and Imager sCMOS CLHS, the latter has a better resolution and was thus chosen to be used.

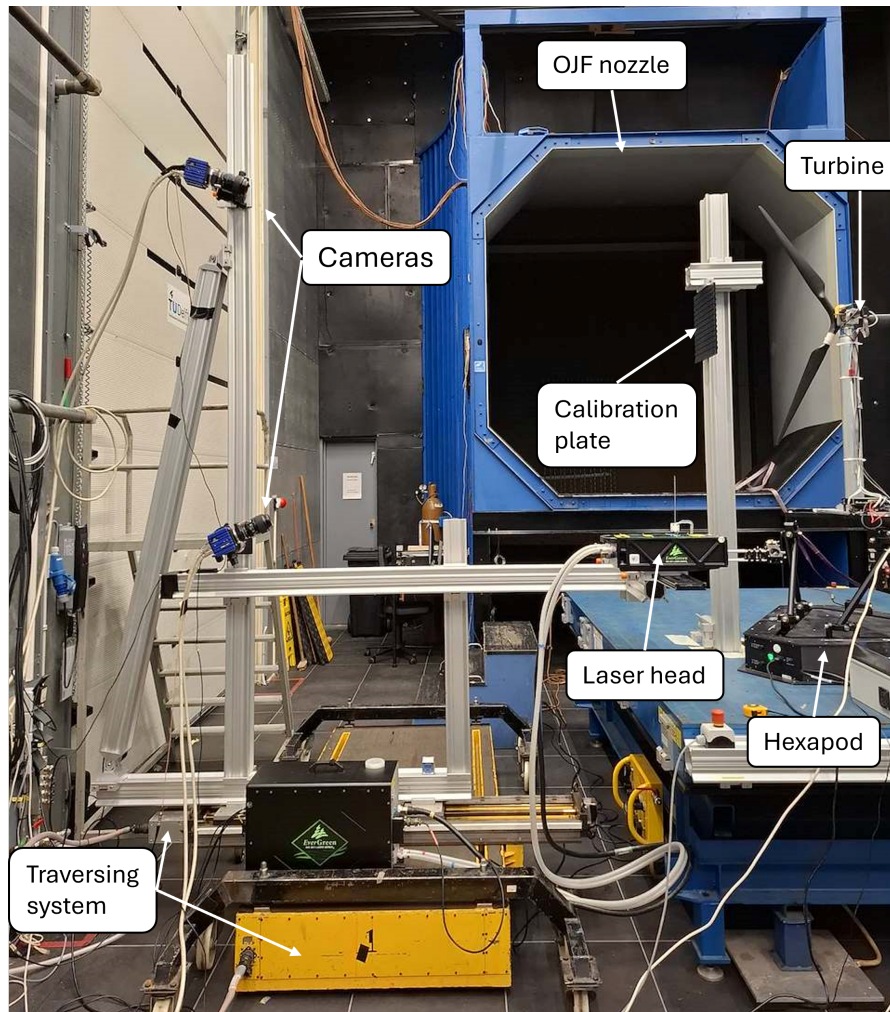


Figure 4.2: Annotated picture of the PIV setup.

Table 4.3: Available cameras at the FPT laboratories and their main parameters.

Parameter	Bobcat	Imager sCMOS CLHS	Mpix16 (Imager Pro LX)	Photron AX100	Photron Fastcam SA1.1
Resolution [px ²]	1628 × 1236	2560 × 2160	4870 × 3246	1024 × 1024	1024 × 1024
Frame rate [Hz]	25	50	1	4000	5400
Pixel pitch [μm]	4.4	6.5	7.4	20.48	20

Table 4.4: Available lasers at the FPT laboratories and their main parameters.

Parameter	Continuum MESA PIV 532-120-M	Spectra Physics Quanta-Ray PIV-400	Quantel Evergreen 200	Quantronix Darwin Duo 527-80-M
Wavelength [nm]	532	532	532	527
Energy per pulse [mJ/p]	18	300–400	200	50
Pulse repetition rate [Hz]	40×10^3	30	15	10×10^3
Laser head mass [kg]	31.5	84	7	31.5

Table 4.5: Key parameters taken from the datasheet of the BAW M18MI-UAC50B-S04G proximity sensor [74].

Parameter	Reported value
Rated operating distance, S_e	4 mm
Limit frequency (−3 dB)	500 Hz
Response time	1 ms
Output signal	0–10 V
Housing size	cyl. M18

4.4.3. Laser Selection

Four types of lasers are available within the FPT laboratories. These four and some of their main properties are shown in Table 4.4. All four lasers produce beams with a wavelength in the green light spectrum. Similar to the camera selection, a trade-off is performed on the other parameters of the lasers. The Continuum MESA PIV 532-120-M and the Quantronix Darwin Duo 527-80-M are high-speed lasers, reaching pulse repetition rates in the multi-kHz range. This is suitable for high-speed PIV applications, but comes at the cost of the energy per pulse, which will result in lower illumination of the particles. The pulse repetition rate of all four lasers is higher than the blade passing frequency, see section 4.2. In this regard, they are all still suitable, but the lower-speed lasers are preferred for their higher energy per pulse. Finally, a very practical requirement is considered. The laser head will be mounted on a traversing structure in the wind tunnel to facilitate easy movement of the measurement plane. For this, the weight of the laser head must be considered. It can be seen that the Quantel Evergreen 200 is then the clear winner, since it has the significantly lowest laser head mass. The energy per pulse and repetition rate are both less than those of the Spectra Physics Quanta-Ray PIV-400, but still sufficient.

4.4.4. Calibration Plate

To transform pixel coordinates into real-world coordinates, a calibration is needed. To do this, a calibration plate is placed in the measurement position, and a recording of 50 images of the plate is made. The calibration plate contains a dot pattern. Since the dimensions of the calibration plate and the locations of its dots are known, a transformation can be made from the pixel coordinates of the dots to real-world coordinates. A calibration plate of Type 30 was used. This plate is a 3D calibration plate meant for stereoscopic camera systems. This means the plate has two levels, separated by a depth of one millimetre. This type of plate does not have an origin, so the dot that forms the origin and the dots that define the x_a - and y_a -axes of the airfoil coordinate system are selected manually. After selection, the DaVis software ensures the origin and axes are aligned with the calibration plate dots. The size of the plate is 30 cm $\times$ 30 cm. The resulting FOV of the flow fields after stitching is approximately 31 cm $\times$ 27 cm.

4.4.5. Proximity Sensor and Adapter

A trigger needs to be sent to fire the laser and take images with the cameras. To send a trigger when the blade is in the vertically upward position, defined as 0° azimuth, a proximity sensor is used. The selected sensor is the BAW M18MI-UAC50B-S04G. A few key parameters of this sensor are reported in Table 4.5 [74].

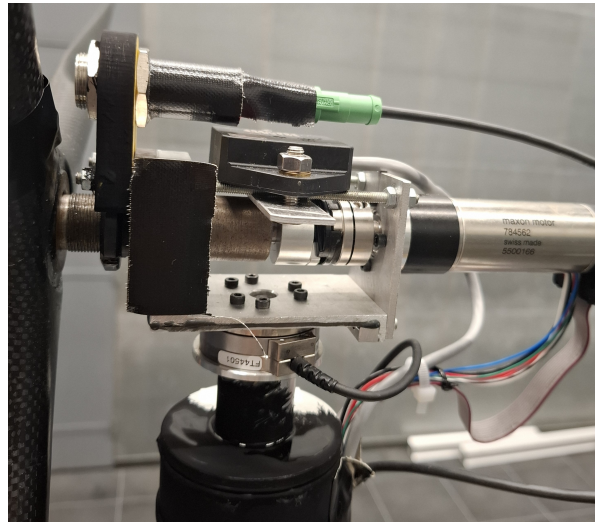


Figure 4.3: Turbine nacelle, including proximity sensor on top.

To mount the sensor, an adapter is designed and 3D printed. This adapter is attached to two threads that are already part of the turbine nacelle. The adapter is then clamped between two nuts and a plate on the rest of the nacelle. The nacelle, including the proximity sensor and adapter, is shown in Figure 4.3. This figure also shows the accelerometer, a motor that keeps the rotor at a constant rpm, and the load cell.

4.4.6. Data Acquisition System

In this subsection, the data acquisition (DAQ) system and how it is connected to the other measurement equipment is described. Figure 4.4. The DAQ system consists of four PC's and a dSPACE MicroLabBox II.

The dSPACE MicroLabBox II, referred to as 'dSPACE' from here on, is a real-time processing unit, which can run high-performance simulations and has both an analogue and digital I/O interface. In this experimental campaign, it is used both to output commands to several hardware systems and to receive analogue input from several sensors. The dSPACE is configured using ConfigurationDesk, where SimuLink models are connected to the dSPACE. During experiments, the dSPACE is controlled and monitored using the ControlDesk software.

The first PC is the Host PC. This PC runs the ControlDesk software. Recordings of the dSPACE data are started and stored here. In the ControlDesk software, the hexapod motion is also set, and the PIV trigger is sent. Furthermore, ControlDesk visualises important measured data in real-time, allowing the user to monitor the actual hexapod motion, the turbine loads, accelerations, motor rpm and wind speed. This allows the user to quickly identify if something goes wrong, whether this means a sensor is not connected or turned off, or to monitor if an overspeed event of the motor happens.

The second PC is the Hexapod PC. This PC runs SimuLink models related to the hexapod, allowing the hexapod to be enabled, calibrated, homed and run, see section 4.3.

The third PC is the OJF control room PC which commands the OJF fan and the traversing system. This OJF PC allows the user to command a setpoint for the desired wind speed in the tunnel. The monitor also displays measured wind speed, air temperature, atmospheric pressure, density, fan rpm, and fan vibrations. However, this data is not acquired automatically, so the measured wind speed is written down manually for each test, and the air temperature, atmospheric pressure and density when

The last PC, shown in Figure 4.5, is the PIV acquisition PC, which saves the recordings that are made by the cameras on its hard drive and commands the recording through the PTU.

Figure 4.5, shows the flow of in- and output of the PIV system. This system is connected to the previously presented DAQ system through a PIV trigger signal from the dSPACE.

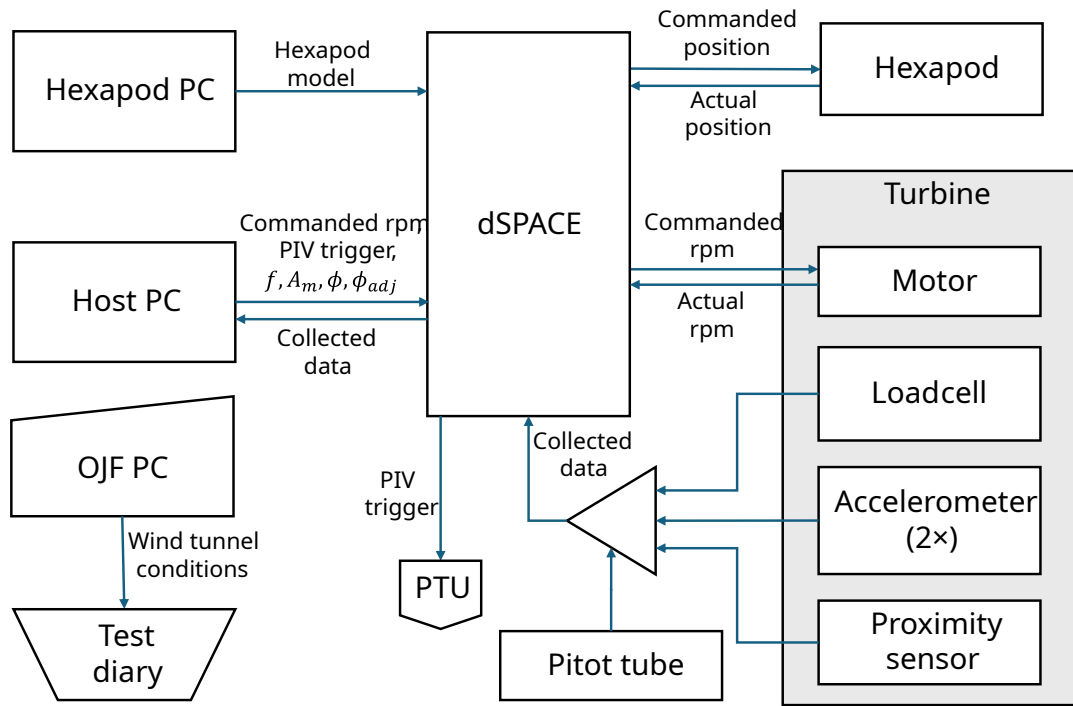


Figure 4.4: Flowchart describing the data transfer for the data acquisition system, excluding the PIV system.

A programmable timing unit (PTU) is used to trigger the cameras and laser after the PIV trigger input has been received from the dSPACE. The PTU used in this campaign is the PTU X 2015. The PTU receives the PIV trigger through the dSPACE. After a short delay of $10 \mu s$ the signal is sent to the lasers and cameras. This delay is accounted for in tuning the timings of the system.

4.5. Test Cases

Many suitable test cases are determined, with priorities assigned to each. In the campaign, the test cases with higher priorities were performed. For each radial section, a new static baseline needs to be included; for each motion, the four motion phases need to be included; for each case, both the pressure side (PS) and suction side (SS) need to be measured. This causes the test matrix to grow rapidly and requires a decision of when in the campaign to switch the laser head and measurements from one side to the other, as this requires a new calibration and is thus done only once. Due to technical, electrical

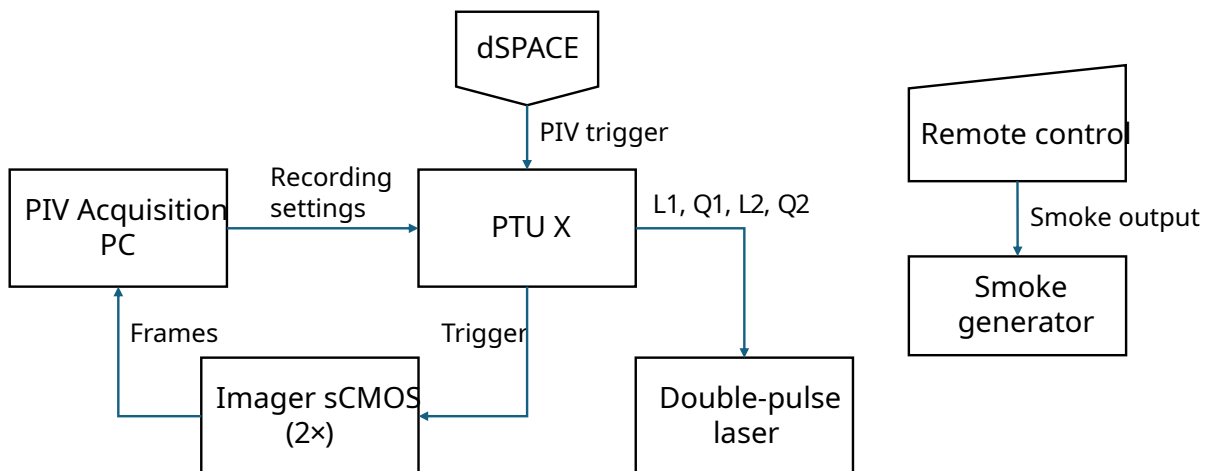


Figure 4.5: Flowchart describing the in- and output for the PIV system.

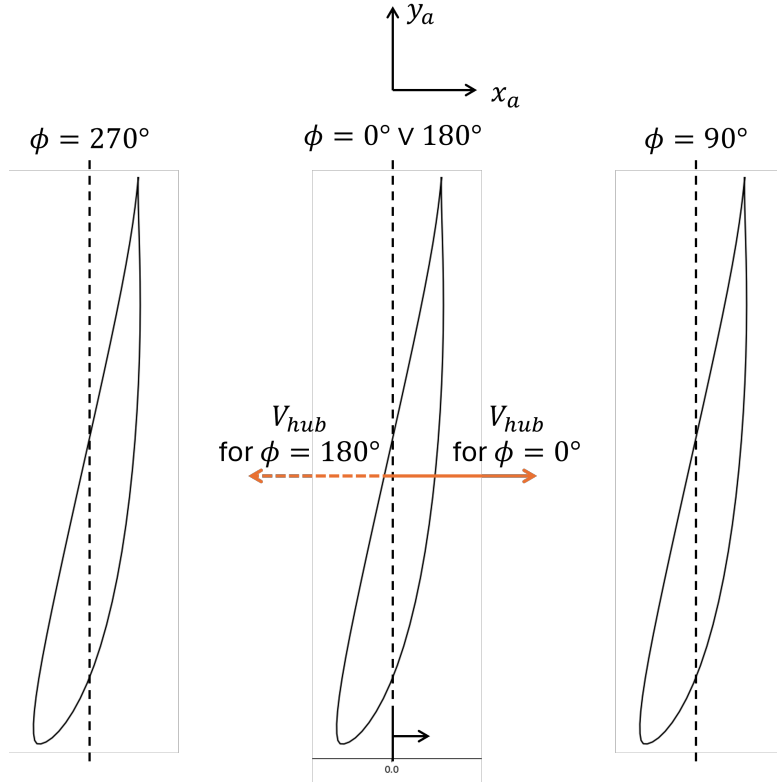


Figure 4.6: Schematic showing blade section position for the four considered phases. The airfoil coordinate system, (x_a, y_a) , is centred in the middle of the airfoil when the motion phase $\phi = 0^\circ$.

issues outside of the control of the campaign, the measurements for $r = 321 \text{ mm}$ could not be performed for the PS.

4.5.1. Determination of Cases

The measurement planes were chosen to be the aerodynamically interesting ones. This means three locations at 52%, 70%, and 84%. The exact points were also chosen to align with the OpenFAST model of the rotor. The phases are chosen to be the moments with the most positive and negative hub velocity at the motion phase, $\phi = 0^\circ$ and $\phi = 180^\circ$ respectively, together with the two moments when the hub velocity is at zero, to compare any unsteady effects over time at the most extreme hub position of $\phi = 90^\circ$ and $\phi = 270^\circ$, see Figure 4.6. For the surge, the motion amplitude is set such that $\Delta V^* = 10\%$. The rotor reduced frequency is $f_r = 0.60$. Under these conditions, the airfoil-based reduced frequency $f_a < 0.05$ over the whole blade, implying the flow around the airfoil may be considered locally quasi-steady. The reduced frequency is also too low for the returning wake effect to occur. To enable the returning wake effect, where the rotor reduced frequency is close to the tip-speed ratio, $f_r \approx \lambda$, under the hexapod limitations, the wind speed needs to be set close to 1 m s^{-1} , where reliable measurements are not realistically possible. Since $f_r \gg 0.05$, the dynamic wake effect is expected to be present, and the flow is not steady at the rotor level.

4.5.2. Test Matrix

The analysed test cases can be found in Table 4.6. These five cases can be summarised as the baseline static case and the 2 Hz surge cases, for $r = 421 \text{ mm}$, or $\frac{r}{R} = 70\%$. This radial section is in the outboard region, but without strong 3D effects. For each case, both the pressure side and suction side recordings are made. Each measurement contains 200 measurements. Each measurement contains four frames: a double frame for both the top and bottom camera. Many more cases were performed during the campaign, but due to time constraints, not all cases are presented. For the full test matrix, see Appendix B.

Table 4.6: Analysed test cases.

DoF	Frequency [Hz]	Phase [°]	Radial section, r , [mm]
static	-	-	421
surge	2	0	421
surge	2	90	421
surge	2	180	421
surge	2	270	421

The pitch motion has only a limited amplitude. This means, that using a small angle approximation, that the pitch motion can be approximated as a surge motion. Additionally, motion at higher frequencies, such as 5 Hz is limited by the hexapod acceleration limit, which reduces the normalized velocity variation, ΔV^* , that can be achieved to less than 10 %. Therefore, the surge motion at 2 Hz was chosen to be analysed.

Using Equation 2.6, the airfoil-based Reynolds number including the rotational velocity component at $r = 421$ mm, at an ambient temperature of 20 °C, is approximately $Re \approx 46\,000$. The flow is considered incompressible, as the Mach number $M \approx 0.06 < 0.3$.

Results and Discussion

This chapter presents the results of the experimental campaign. The chapter starts out by showing the measured velocity fields in section 5.1. This contains separate velocity fields for both the pressure side and suction side measurements, a convergence study on the velocity in three representative points, and the stitched velocity field. Then, a convergence study for the computed aerodynamic parameters is presented in section 5.2. After a suitable number of control points is chosen, the final results of the aerodynamic parameters are shown and discussed in section 5.3. Finally, a frequency domain analysis is given in section 5.4.

5.1. Velocity Fields

In this section, the resulting velocity field as obtained using the PIV and subsequent post-processing is shown and discussed. Firstly, the separate fields as obtained for the pressure side (PS) and suction side (SS) are presented in subsection 5.1.1, together with the difference between these fields. Then, a convergence study on these flow fields can be found in subsection 5.1.2. The last subsection contains the stitched field, where the PS and SS are combined to obtain one full flow field, without shadow or optical occlusion, see subsection 5.1.3.

5.1.1. Separate Velocity Fields

In this subsection, the separate velocity fields for the PS and SS are shown for the static case, at $r = 421 \text{ mm}$, or $\frac{r}{R} = 70\%$. While the exact flow fields for the motion cases are not the same, they are similar enough that visual investigations of the fields are presented for only the single case.

Velocity Field Pressure Side

Figure 5.1 shows the velocity field of the static case, for $\frac{r}{R} = 70\%$ for the pressure side. This is the velocity field before adding the rotational and structural components, $-\Omega r$ and U_{hub} , to more clearly visualise the flow fields as captured by the PIV, since the differences are more defined without the large rotational component, $\Omega r = 21.1 \text{ m s}^{-1}$. The figure also includes the local coordinate system, x_a and y_a , defining the velocity components, u and v , respectively. This airfoil coordinate system is right-handed, which defines the z_a direction with the w -component.

The heatmap visualises the magnitude of the in-plane velocity, (u, v) . The quiver arrows visualise the direction and magnitude (in length) of the same in-plane velocity, for every 10th horizontal and vertical position. The dash-dotted vertical line shows the rotor plane, with the blade section visualised in the centre.

The u -component slightly upstream of and on the rotor plane is approximately $2\text{--}3 \text{ m s}^{-1}$. With a freestream velocity of $U_\infty = 4 \text{ m s}^{-1}$, this is expected, since $u_{\text{rotorplane}} = U_\infty(1 - a)$, and the axial induction factor, a , can be expected to be in the range of $a = 0.25\text{--}0.5$.

Starting from the blade section and going to the top right, the shadow caused by the blade results in a large portion of missing data. The missing data area also contains part of the optical blade occlusion.

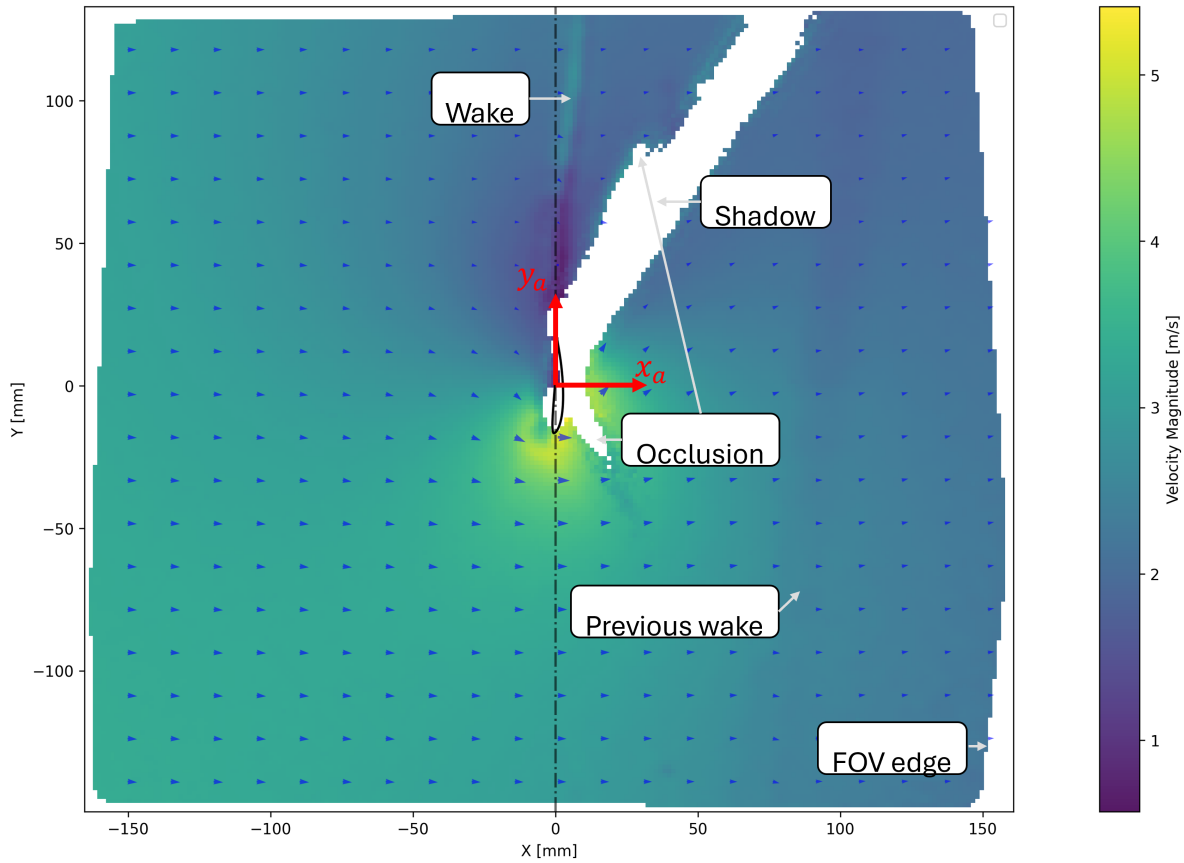


Figure 5.1: Flow field for the pressure side static case at $\frac{r}{R} = 70\%$ from the static reference frame.

Part of this occlusion, mostly on the top, caused by the bottom camera coincides with the shadow area.

Under the blade, the flow acceleration is visible in the higher velocity magnitude. It can be seen that upstream, the flow is mostly horizontal, but already lower than the far upstream wind speed. Just upstream of the blade, the flow is deflected in the negative y_a -direction. Just downstream of the blade, the flow is redirected in the positive y_a -direction. Farther downstream, the flow is mainly horizontal again, but due to induction it has slowed down further.

Above the blade section, the airfoil wake is visible. In this wake, the velocity direction and magnitude are non-uniform. The wake of the previous blade is also slightly visible in around $x = 100$ mm. The strong velocity gradients are more clearly seen in the vorticity, see Figure 5.2.

The flow field is contained in a non-rectangular area, due to the edges being cut off by the calibration deforming the rectangular FOV of the camera. In the combined field, a slight mismatch of the FOVs of the two cameras will result in edges where data for only one of the measurements is available. In all subsequent processing, a rectangular area is defined to trim off the edges where not both data fields are available.

To allow easier visual identification of the flow field characteristics, the z_a -component of the vorticity is plotted. Since the vorticity is dependent on the gradients of the u - and v -components, the local differences are shown more clearly. This is shown in Figure 5.2. While already present in the velocity plot, the wakes are more clearly defined in the vorticity plot. This is due to the fact that the wake increases the local turbulence, causing large local differences that do not converge rapidly, as will be shown in subsection 5.1.2. The wake caused by the photographed blade has strong negative vorticity on the left and positive vorticity on the right. The wake of the previous blade is already partially mixed with the rest of the flow field, causing the vorticity to spread out and decrease in local intensity.

Figure 5.3 shows the w -component of the flow for the PS. Here again, the wake and previous wake

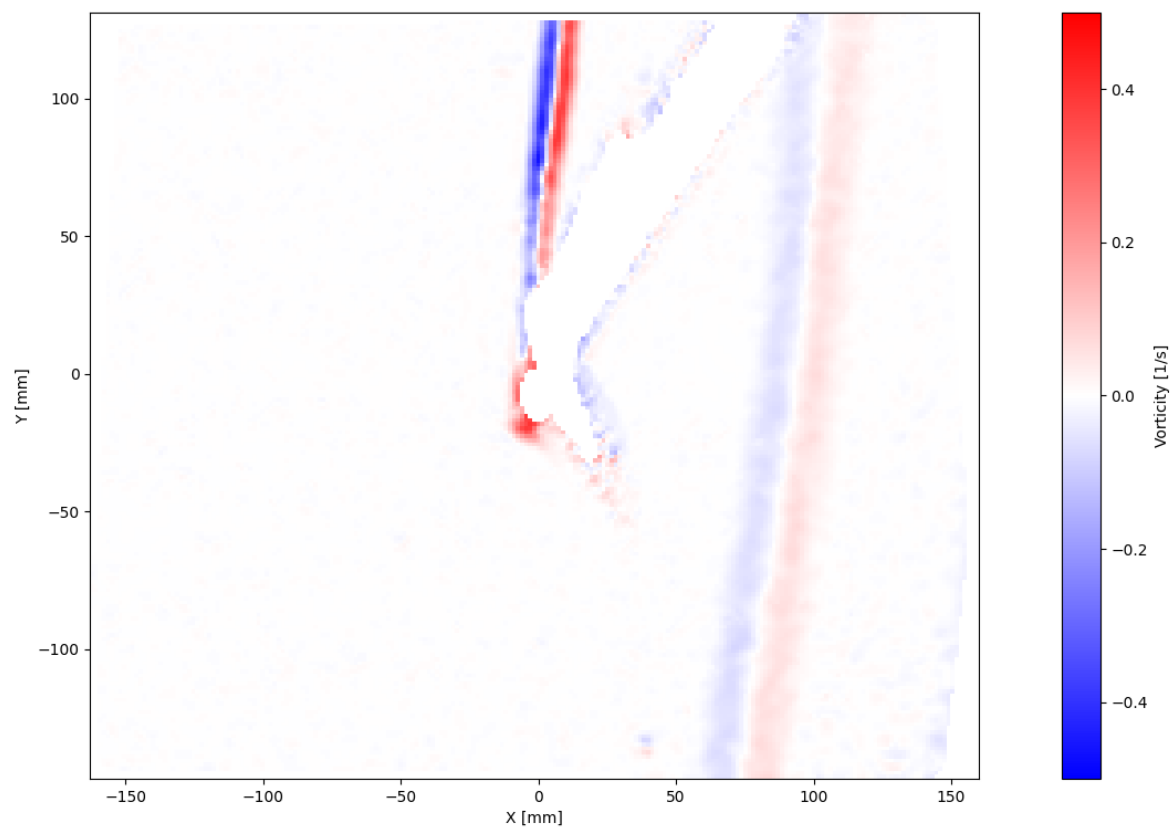


Figure 5.2: z_a -component of the vorticity field, ω_z for the pressure side static case at $\frac{r}{R} = 70\%$.

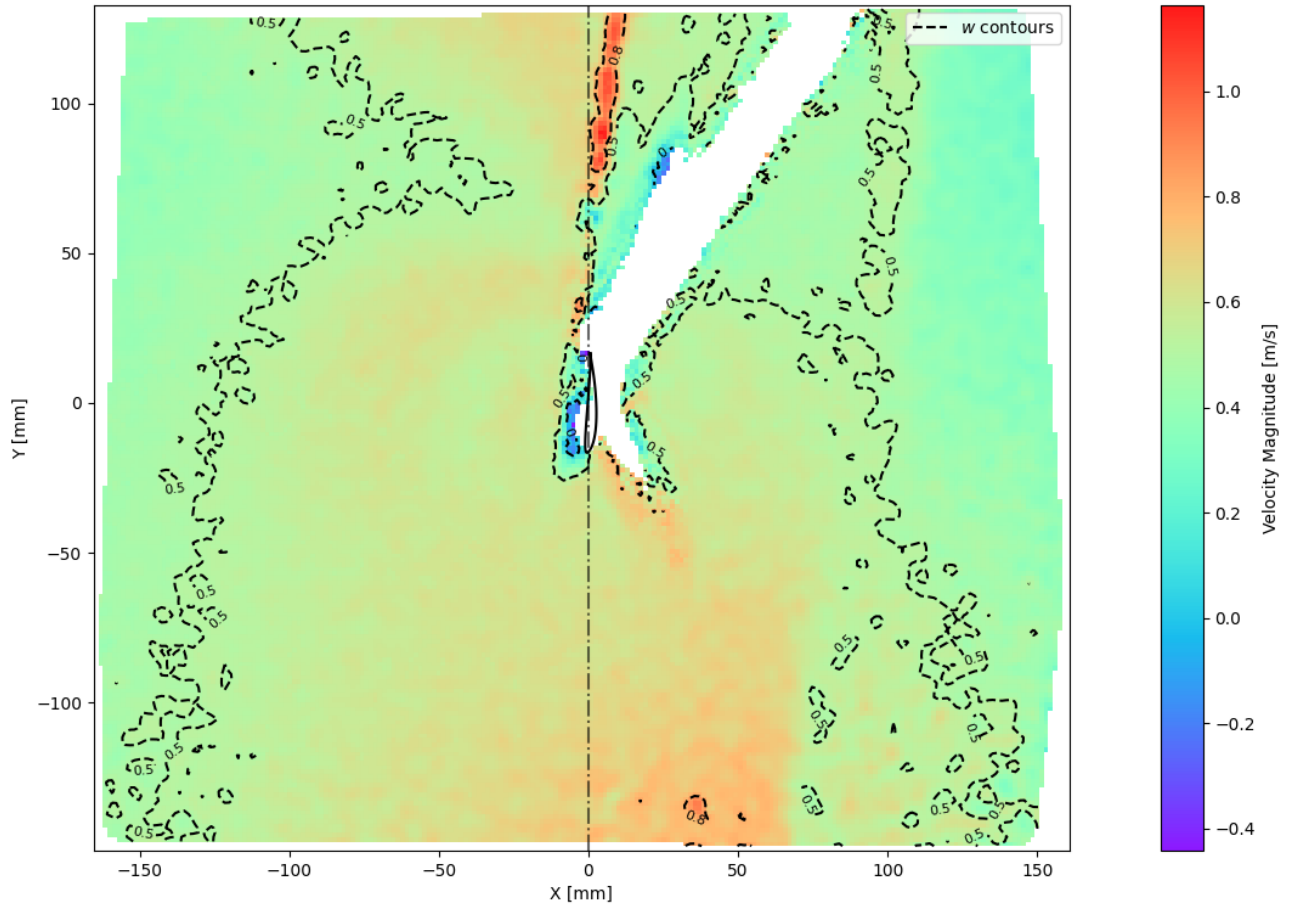


Figure 5.3: w -component of the flow field for the pressure side static case at $\frac{r}{R} = 70\%$.

are visible. Note that the colour bar is not symmetric. This is due to the fact that the flow moves mostly outboard for rotating turbines. This corresponds to the quasi-1D flow stream tube model that is often used for wind turbines. Locally near the pressure side of the airfoil, there appears to be a strong negative w -component. Overall, the magnitude of the w -component is considered to be sufficiently small that the cross-flow principle holds. This implies the necessary 2D assumption for the Ferreira-Micallef method should hold, but this might need to be challenged in future studies.

Velocity Field Suction Side

Figure 5.4 shows the velocity field in the static reference frame for the suction side static case at $\frac{r}{R} = 70\%$. Most features are the same as for the pressure side, just with the blade shadow flipped to the other side. However, two new observations can be made. Firstly, the area to the top-right of the blade contains a distinct region with lower velocity and even a few masked pixels. This is caused by the blade's trailing edge as seen by the top camera. Background filtering and vector validation removed a large part of the blade and its trailing edge, but it could not be filtered out completely. Secondly, on the bottom-left and -right, several vectors are missing as well. This is due to the higher velocity uncertainty in this region, which is filtered out by the vector validation after averaging. In general, although it cannot be seen easily in this image, the SS suffered from higher noise, or more accurately a lower signal-to-noise ratio, than the PS.

Difference Velocity Field

Figure 5.5 shows the difference in the two velocity fields by subtracting the u - and v -components of the SS from the PS and then visualising the magnitude of resulting in-plane flow field. Upstream, there are only very small differences between the two fields. Larger differences can be seen near the shadow, in the wakes and near the edges. The colour bar is capped at 0.2 m s^{-1} to show the areas with large

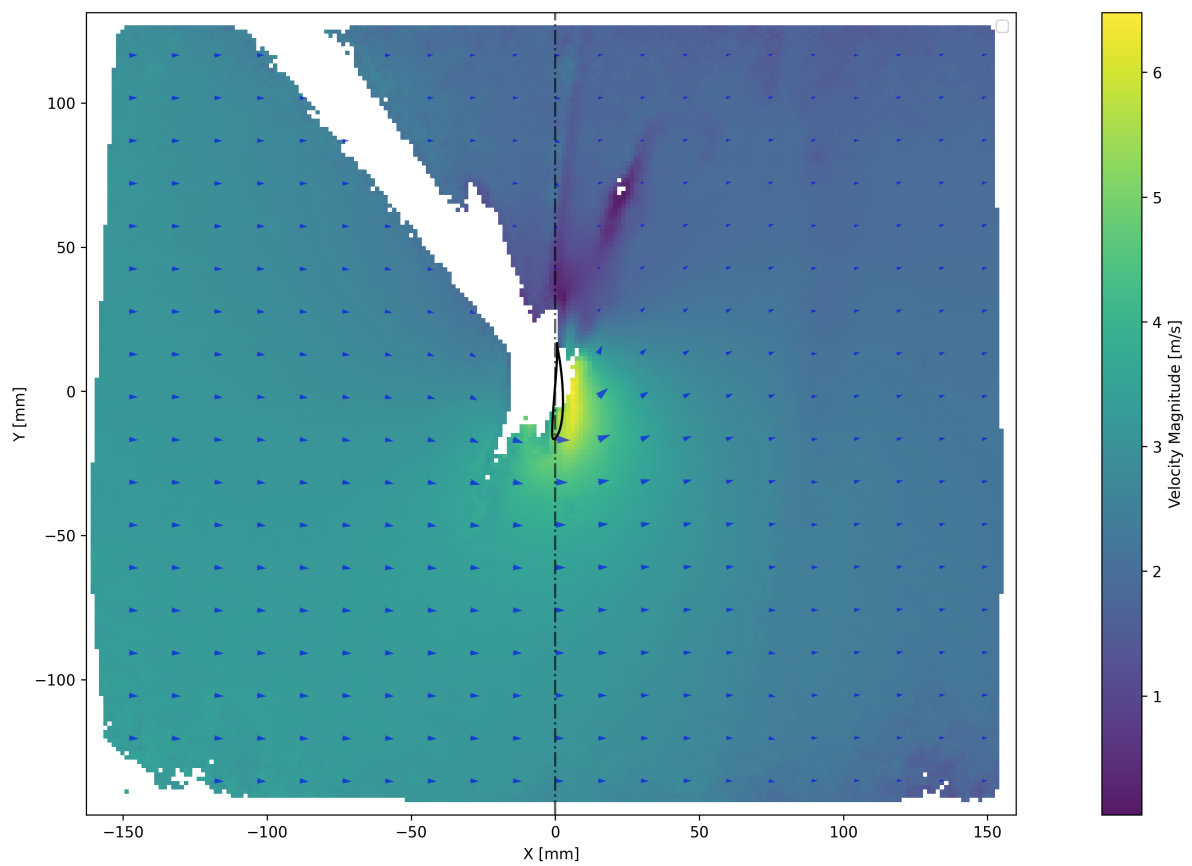


Figure 5.4: Flow field for the suction side static case at $\frac{r}{R} = 70\%$ from the static reference frame.

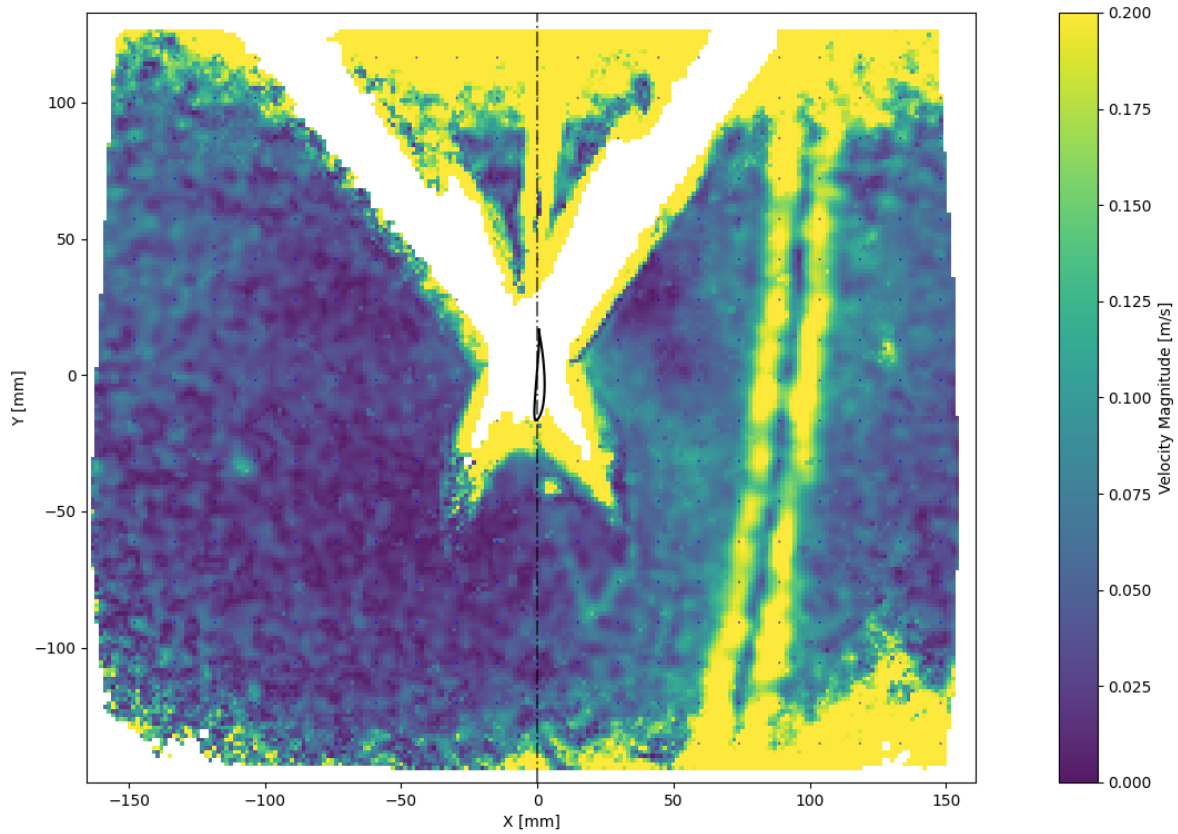


Figure 5.5: Difference in in-plane velocity magnitude between PS and SS fields for the static case at $\frac{r}{R} = 70\%$.

differences, but even most of the yellow area does not significantly exceed this threshold. In a handful of pixels, the difference exceeds 1 m s^{-1} . Most pixels with truly large differences also contain a larger uncertainty of the same magnitude as the difference, which is filtered out before the fields are stitched.

5.1.2. Velocity Vector Convergence

Three representative points were chosen: point 1 - upstream of the blade; point 2 - in the blade wake; point 3 - downstream of the blade. Figure 5.6 shows the locations of these points, and the rectangle that is used to normalise PS and SS with respect to each other, see subsection 3.6.1. Point 1 is expected to have the least standard deviation and converge the fastest, since fewer flow perturbations are caused here by the blade. Since point 2 is located in the wake, the standard deviation is expected to be high and lower convergence is achieved for the same number of vector fields. Point 3 is not in the direct wake of the blade or the previous blade, but does experience significantly lower u -velocities due to the induction. The induction, which is caused by the entire rotor, acts on the whole field, but most strongly downstream. Point 3 is located in the near wake of the rotor instead of the airfoil wake.

The convergence of the u -component of the three representative points for the static case at $r = 421 \text{ mm}$, or $\frac{r}{R} = 70\%$, for both PS and SS is shown in Figure 5.7. Figure 5.8 shows the convergence of the standard deviation of the absolute velocity $|V|$ for the same three representative points for the same case. While the absolute velocity also includes the v - and w -components, for most of the field the u -component is the dominant flow direction. It can be seen that point 1, the circle in the plot, converges the fastest. In the upstream region, while already slowed down by the rotor-wide induction, there is little perturbation caused directly by the passing blade. This results in a relatively low standard deviation, and thus convergence is reached already after 25 to 50 vector fields. Contrast this with point 2, the square in the plot, which seems to converge only when approaching 200 vector fields. This is coupled with its high standard deviation, which is on the same order of magnitude as the velocity component

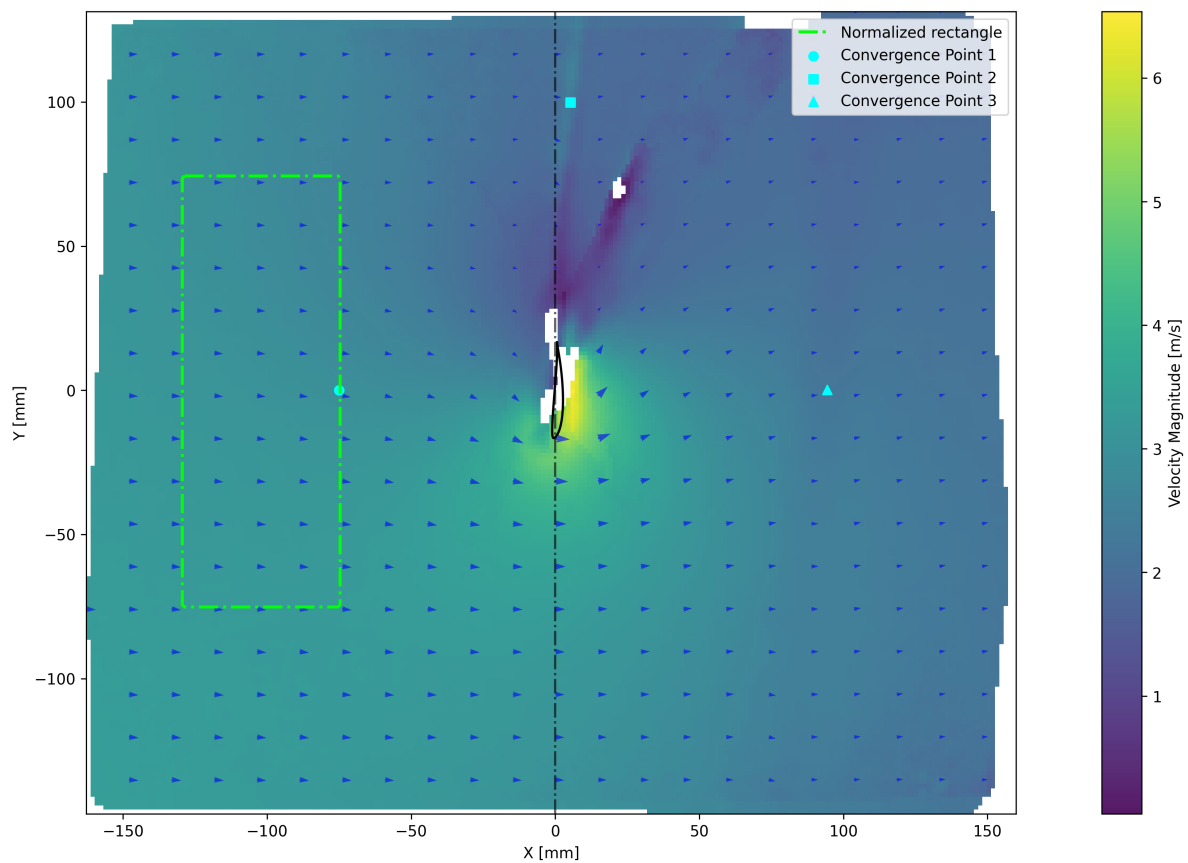


Figure 5.6: Locations of the three velocity convergence points and the rectangle on which the pressure side and suction side are normalised. The flow field is presented in the static reference frame, at $\frac{r}{R} = 70\%$.

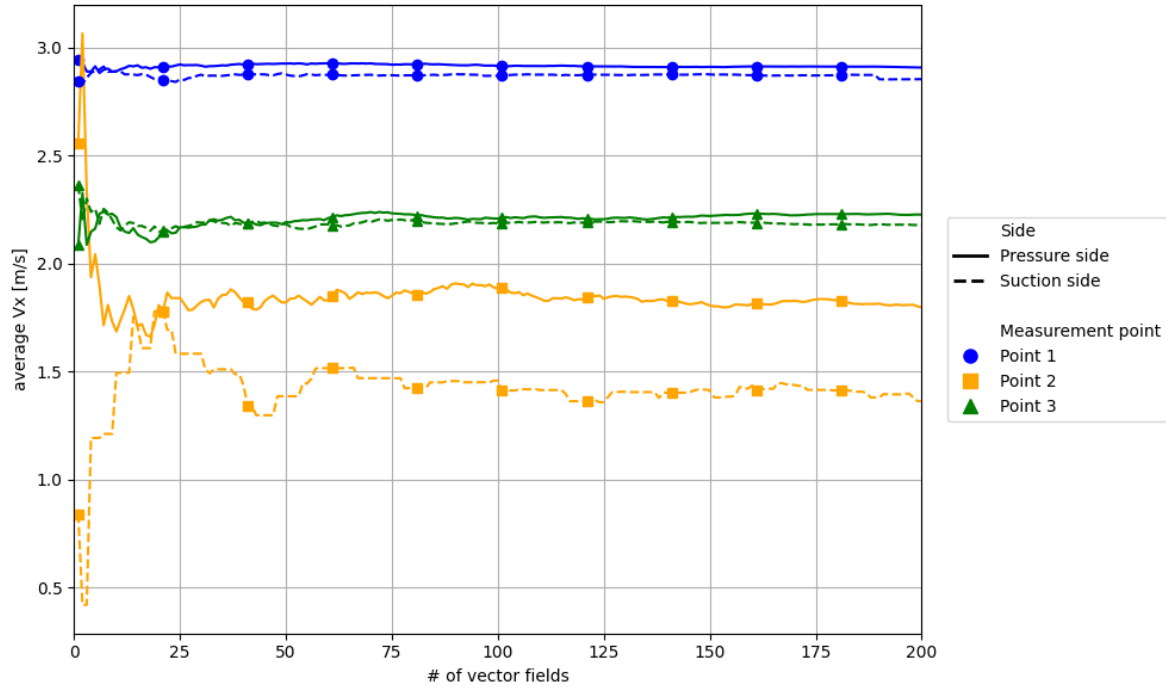


Figure 5.7: Convergence of the u -component in three reference points: upstream; in the wake; and downstream for the static case, both pressure side and suction side.

itself. This indicates that the flow is highly turbulent in the wake, which is seen previously in the high vorticity in the wake.

Note that the number of vector fields is the number of analysed pairs of PIV images. In some instances, this vector field may not produce a valid vector, and no contribution to the average velocity is made for an increased number of vectors. In one clear case, a vector is produced, but clearly non-physical. This happens in point 1 at image 189, where one of the cameras produced a faulty frame, which contained noise in the form of horizontal lines. This image reduced the average u -component and increased the standard deviation significantly. A filter was made to filter out these noisy frames as an early step in DaVis, but was not implemented in the final results due to time constraints.

Finally, point 3 sits in between point 1 and 2 in terms of average velocity and standard deviation. As the point is downstream, induction has slowed the flow down. However, unlike in point 2, the flow is still aligned mostly downstream, with significantly lower turbulence than point 2, but due to the perturbations, higher turbulence, and thus standard deviation than point 1.

For all three points, it can be observed that the velocity in the suction side measurement was lower. For points 1 and 3, this difference was only slight. Comparing the test diary, it can indeed be seen that the registered wind speed in the OJF for the SS recording was 3.96 m s^{-1} , while it was 4.01 m s^{-1} for the PS recording. This small difference of $\sim 1.2\%$ in wind speed probably caused the difference in the calculated wind speeds at these points. However, the effect for the point in the wake seems to be intensified, as the difference in average wind speed and standard deviation is around $\sim 30\%$ to 40% .

Convergence plots for the other cases show similar results, with convergence after a similar amount of vector fields. Thus, for brevity, these plots are not presented again. For all future velocity fields, the full 200 measurements for each case for both PS and SS are used. So, each point in the stitched field can have anywhere between 10 and 400 data points. If a point has data for less than 10 velocity fields, it is not used, as the data in that point will likely not be converged.

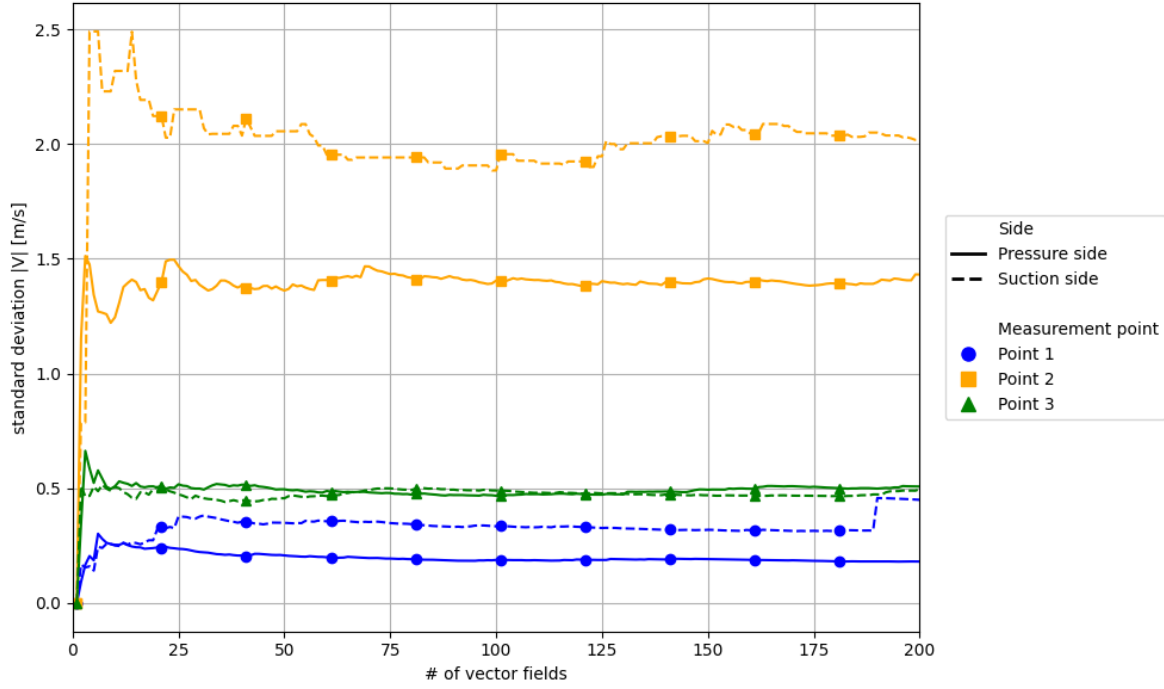


Figure 5.8: Convergence of the standard deviation of the absolute velocity $|V|$ in three reference points: upstream; in the wake; and downstream for the static case, both pressure side and suction side.

5.1.3. Stitched Velocity Field

Figure 5.9 shows the stitched velocity field for the static case for $\frac{r}{R} = 70\%$. In contrast to the earlier velocity plots that were shown in a static frame of reference, here the rotational component $-\Omega r$ has been added. Since this is the static case, U_{hub} is not present. The stitched field shows the same flow features that could be defined in the PS and SS separately, such as the wake and previous wake. However, with the rotational component, it can be seen that from the frame of reference of the blade, the flow is not accelerated under the blade, but to the positive x_a side of the airfoil. This makes the distinction between pressure side and suction side that has been referenced already many times clearer, since these are normal concepts to talk about in e.g. a normal wing in flight.

It can be seen that due to the stitching, the shadow area disappears, and the regions with missing data are the overexposed blade section itself, the part that is both in the trailing edge for the SS and in the blade shadow for the PS and some vectors near the FOV edges. As mentioned, the further analysis cuts of these edges slightly further to work within a clean rectangle wherein both PS and SS FOV edges are available.

Further visualised in the stitched field is the rectangle used to normalise the velocity fields based on the average in-plane velocity magnitude in this rectangle for both PS and SS; the control points used to calculate the angle of attack (AoA) for the blade; and the resulting AoA as the orange arrow.

Figure 5.10, 5.11, 5.12 and 5.13 show the same stitched flow fields for the surge 2 Hz cases for motion phases $\phi = 0^\circ, 90^\circ, 180^\circ, 270^\circ$, respectively. Overall, the same things can be seen here as for the static case. For the cases of $\phi = 90^\circ, 270^\circ$, the rotor plane has moved to the new position.

5.2. Aerodynamic Parameter Convergence

For the aerodynamic parameters that have been presented before, a convergence study is also performed to show the method is stable, and that the number of control points chosen has a negligible impact on the error compared to the presented confidence interval. The number of control points used to determine the induced wind contribution of the field is varied from 10 to 160 in steps of 10. Additionally, the control point circle radius is varied using $r_{scale} = [1, 1.5, 2, 3]$. The 95 % confidence interval, as

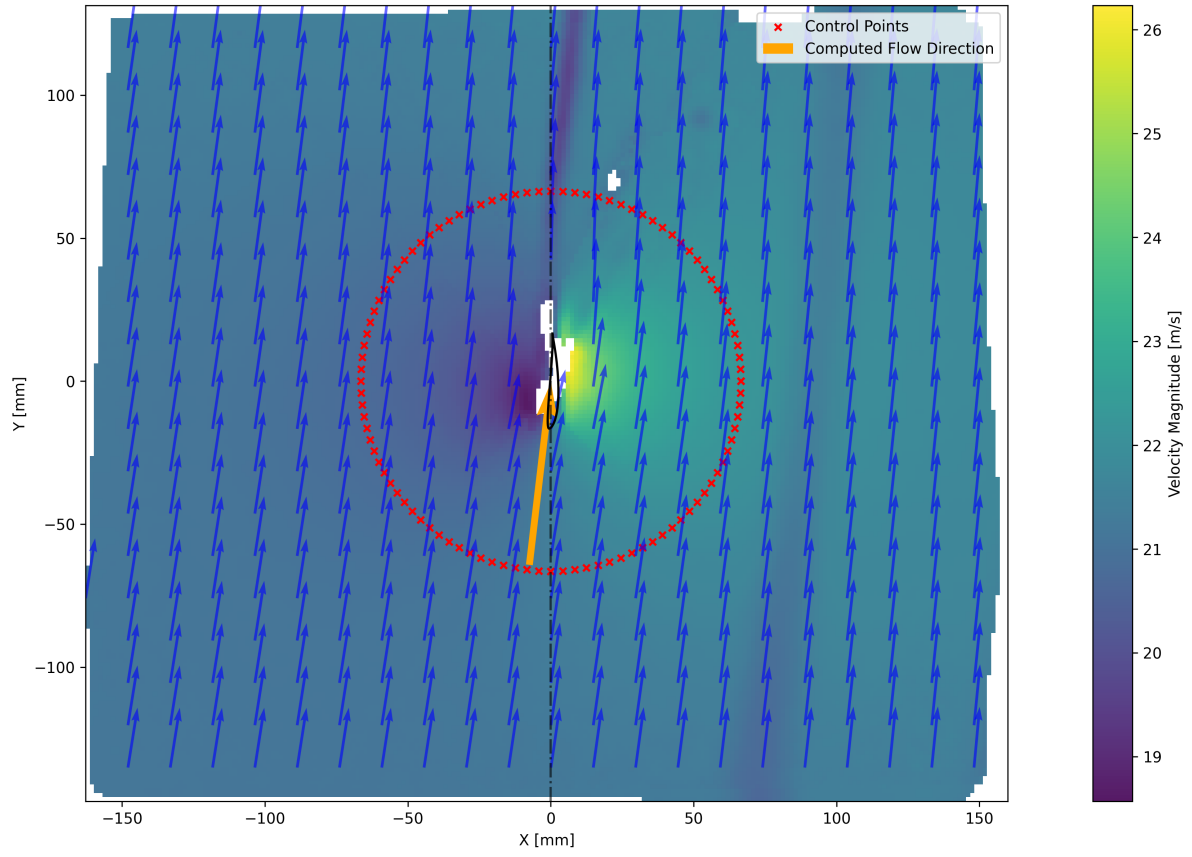


Figure 5.9: Full velocity field for the static case for $\frac{r}{R} = 70\%$, including the control points with $r_{scale} = 2$ and $N_{cp} = 100$.

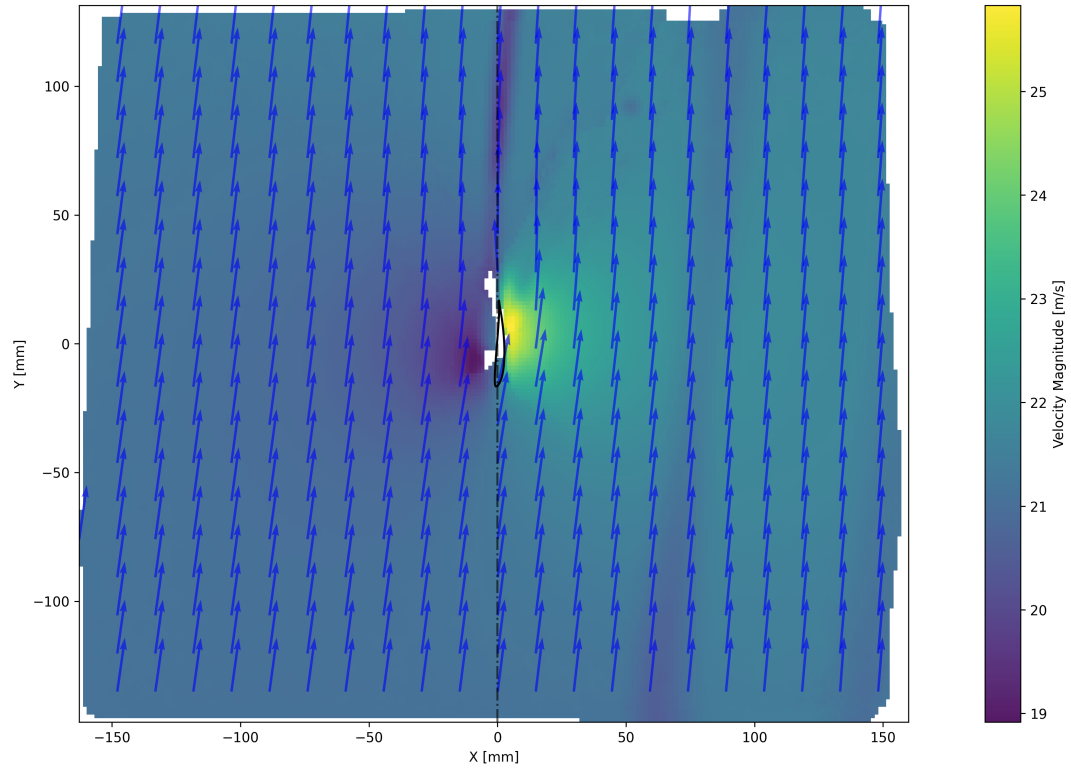


Figure 5.10: Full velocity field for surge 2 Hz case, with $\phi = 0^\circ$, for $\frac{r}{R} = 70\%$, with $r_{scale} = 2$ and $N_{cp} = 100$.

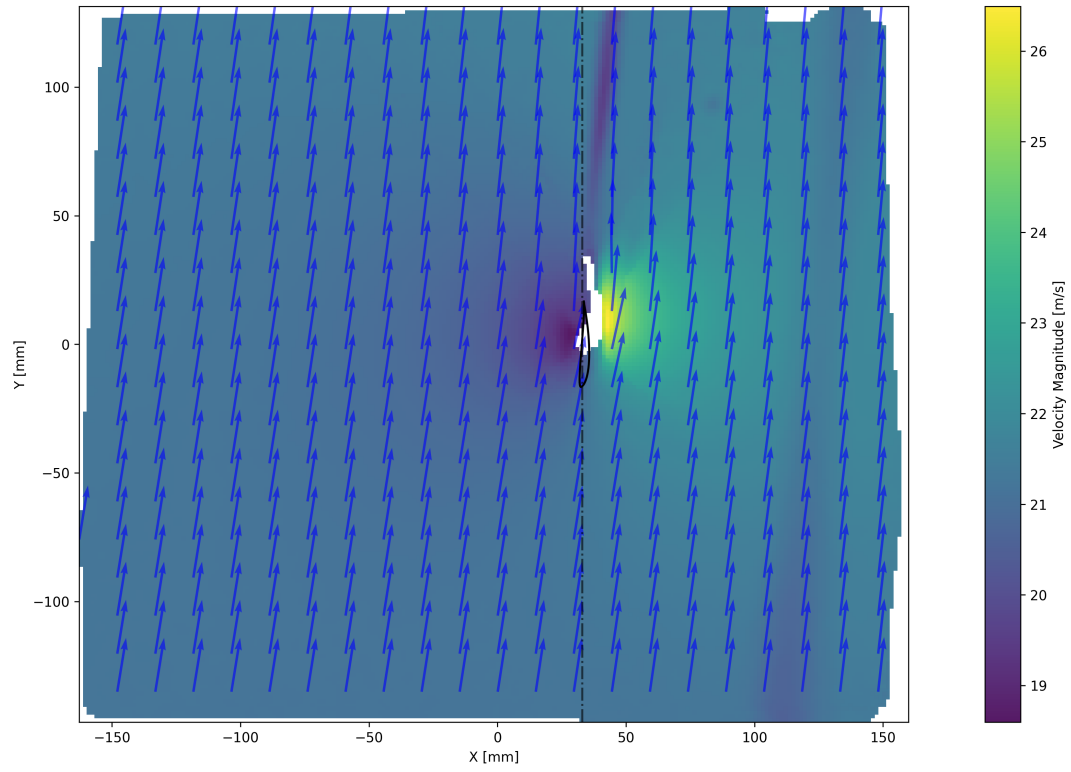


Figure 5.11: Full velocity field for surge 2 Hz case, with $\phi = 90^\circ$, for $\frac{r}{R} = 70\%$, with $r_{scale} = 2$ and $N_{cp} = 100$.

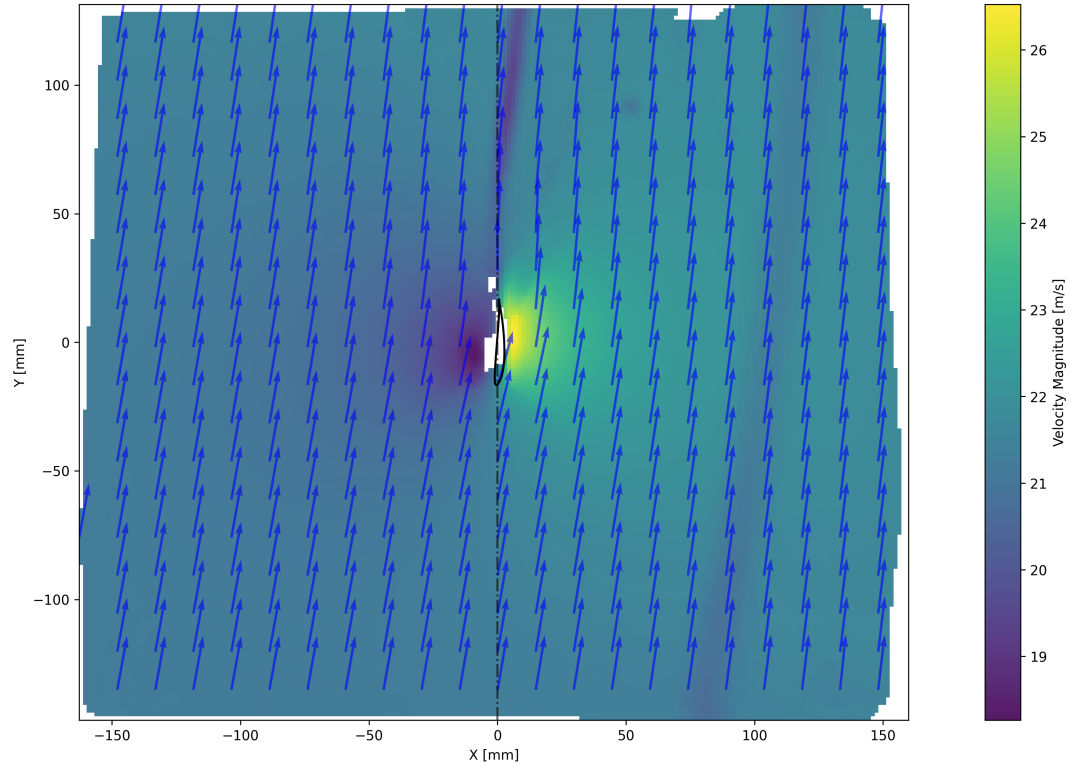


Figure 5.12: Full velocity field for surge 2 Hz case, with $\phi = 180^\circ$, for $\frac{r}{R} = 70\%$, with $r_{scale} = 2$ and $N_{cp} = 100$.

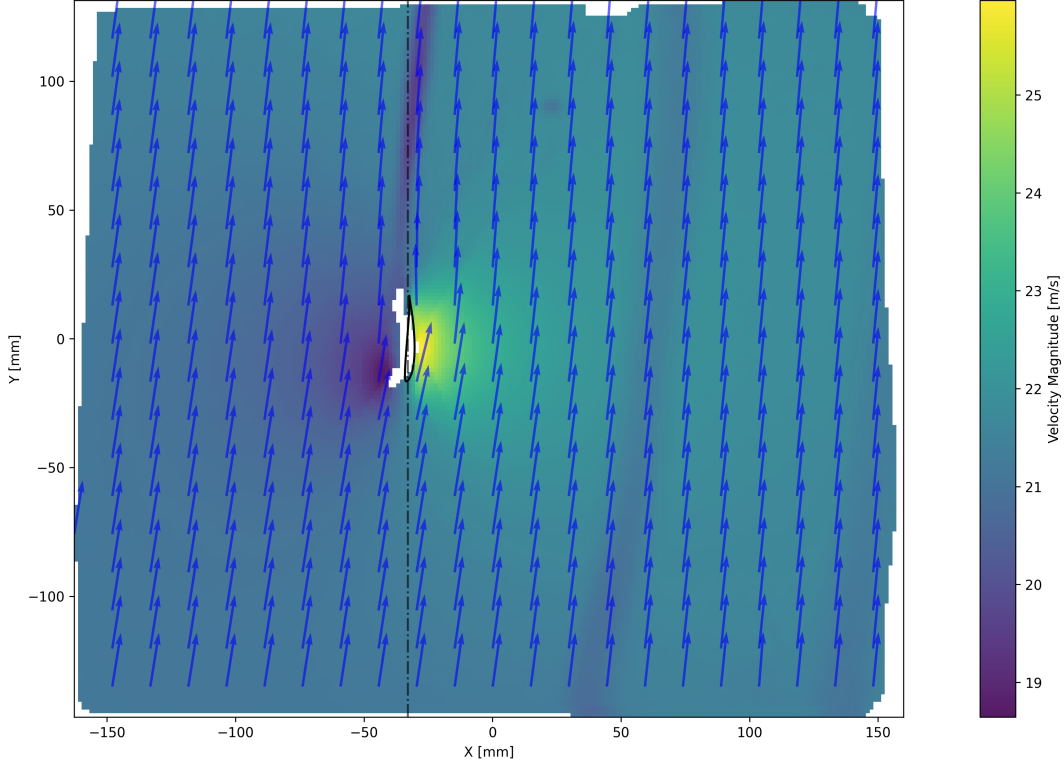


Figure 5.13: Full velocity field for surge 2 Hz case, with $\phi = 270^\circ$, for $\frac{r}{R} = 70\%$, with $r_{scale} = 2$ and $N_{cp} = 100$.

defined before, is included in the plots too. The convergence is shown for the static case. Similar to the flow fields, the surge cases behave the same, but with different associated values.

From the convergence study, $n_{cp} = 100$ and $r_{scale} = 2$ were chosen to be most suitable. This number of control points gives converged results, without the additional computational cost of more points. If the scale were increased to $r_{scale} = 3$, the control points would overlap with the previous wake as well.

5.2.1. Angle of Attack Convergence

Figure 5.14 shows the convergence for the angle of attack, α , including the 95% confidence interval. For fewer than 30 control points, the AoA is unconverged, and the change due to control points is larger than the change due to the scale. Adding more points increases the AoA to a converged value above 60 control points. While the AoA is converged for a given scale, there are still differences between the scales. However, these differences are small, less than 0.1° . Furthermore, the mean value of the angle of attack falls within the confidence intervals of each other scale. The line with $r_{scale} = 2$ falls in the middle, close to the values of $r_{scale} = 1.5$. For the smaller scale, the control points are close to the airfoil, where the uncertainties and errors are higher. For the large scale, the control points fall partly in the previous blade wake, again where uncertainties are higher.

5.2.2. Axial Induction Factor Convergence

Figure 5.15 shows the convergence for the axial induction factor, a . Since the axial induction and angle of attack are calculated from the same induced velocities, the convergence plots behave similarly. Only now, the larger scale results in smaller induction values, but this is expected when taking into account the velocity triangle, Figure 3.10.

5.2.3. Tangential Induction Factor Convergence

Figure 5.16 shows the convergence for the tangential induction factor, a' . The small peaks appear near $n_{cp} = 30$ and at $n_{cp} = 110, 120$. This is likely due to the placement of the control points in the blade wake. By changing the number of points in the circle, the number of points inside the wake changes.

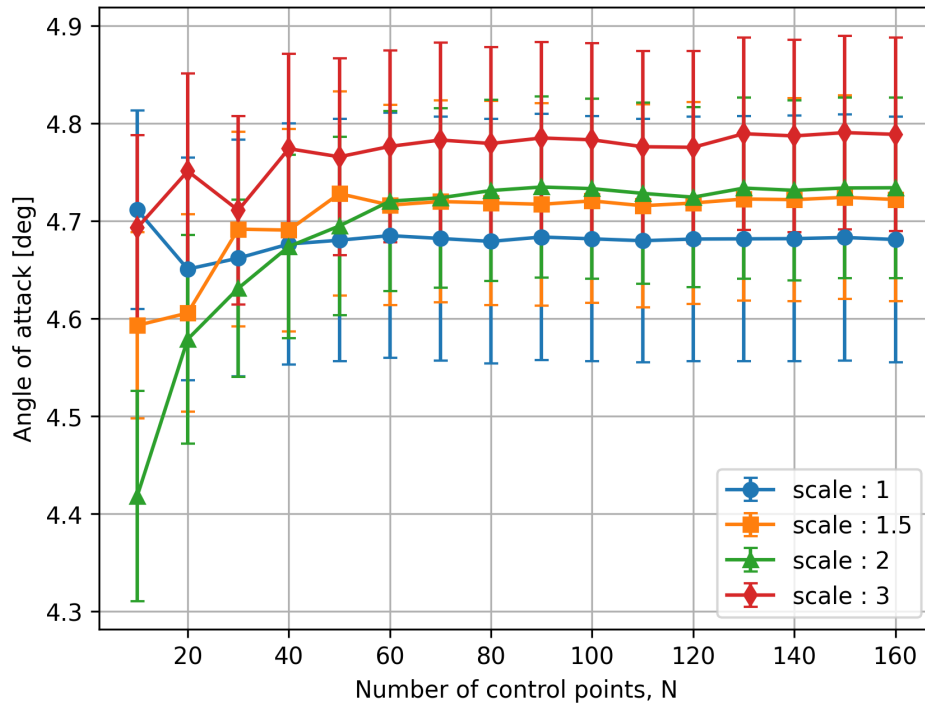


Figure 5.14: Convergence of the angle of attack, α , for the static case at $\frac{r}{R} = 70\%$ for the number of control points and various scales.

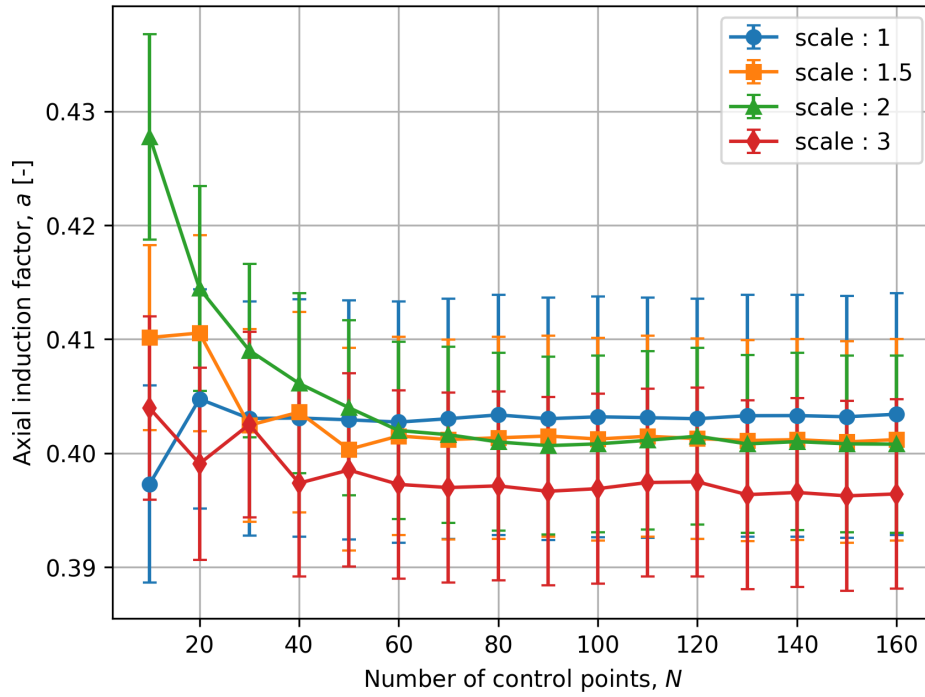


Figure 5.15: Convergence of the axial induction factor, a , for the static case at $\frac{r}{R} = 70\%$ for the number of control points and various scales.

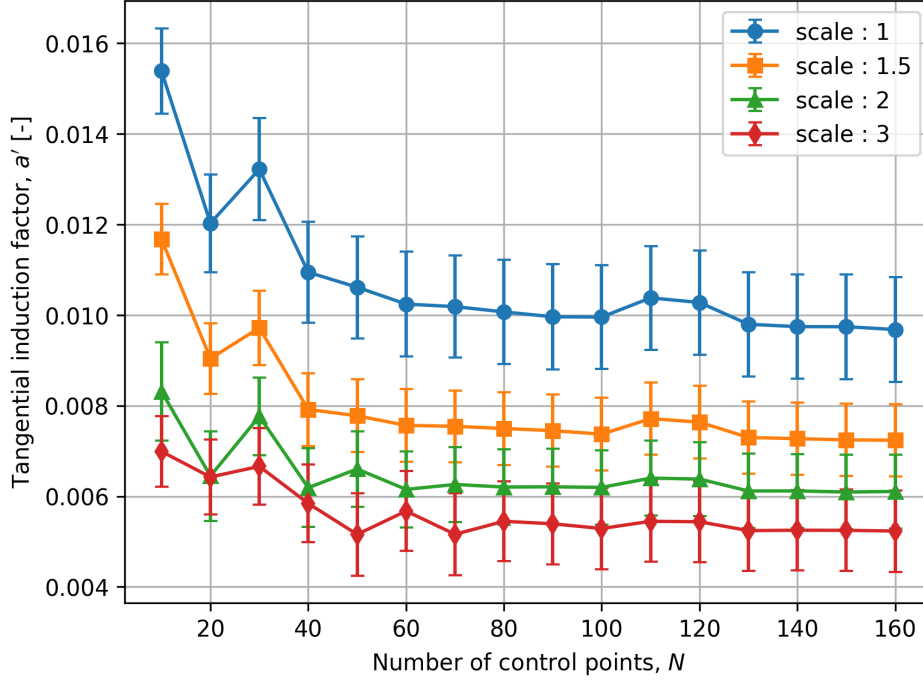


Figure 5.16: Convergence of the tangential induction factor, a' , for the static case at $\frac{r}{R} = 70\%$ for the number of control points and various scales.

The wake contains a large portion of the tangential induction. The wake is where the airfoil 'drags' the air with it to create both the vorticity in the wake and the tangential induction caused by the drag force acting on the air in the opposite direction to the drag force on the blade section. When adding more points, the points redistribute more evenly, and the number of points in the wake with respect to the total number of points is representative of the size of the wake with respect to the full field again.

The tangential induction factor is calculated to be larger with a smaller scale, so when the control points are closer to the airfoil. This is likely due to the fact that the tangential induction is caused by that drag force, which acts on the airfoil surface. This means the flow near the airfoil has a locally stronger tangential induction than the overall rotor-averaged tangential induction. The larger scales notice this local airfoil perturbation less and look more at this rotor-averaged induction.

Relatively, the spread in the tangential induction factor is large. The confidence interval is relatively spread out, and the effect of scale is relatively large ($a' \approx 0.005$ for $r_{scale} = 3$, while $a' \approx 0.010$ for $r_{scale} = 1$). However, the absolute value of a' is small, and a value of $a' < 0.01$ means it causes less than 1% contribution to the v -component compared to the rotational velocity Ωr .

5.2.4. Local Thrust Coefficient Convergence

Figure 5.17 shows the convergence for the local thrust coefficient, C_t . This is the non-dimensional value of the sectional normal load, F_N . A clear peak is visible at $n_{cp} = 30$ and at $n_{cp} = 110, 120$. Similar to the tangential induction, this is likely due to the placement of the control points in the blade wake. By changing the number of points in the circle, the number of points inside the wake changes. Since the normal load is sensitive to the circulation, adding an extra point in the wake will change the circulation, depending on where in the wake the point is located, since the vorticity goes from negative to positive in the positive x_a direction. When adding more points, they redistribute more evenly, and the positive and negative vorticity cancel out again, and the load converges.

5.2.5. Tangential Load and Local Power Coefficient Convergence

Figure 5.18 shows the convergence for the local tangential force coefficient, C_{tan} . This is the non-dimensionalised sectional tangential load, F_T . Since the tangential load is calculated with the same

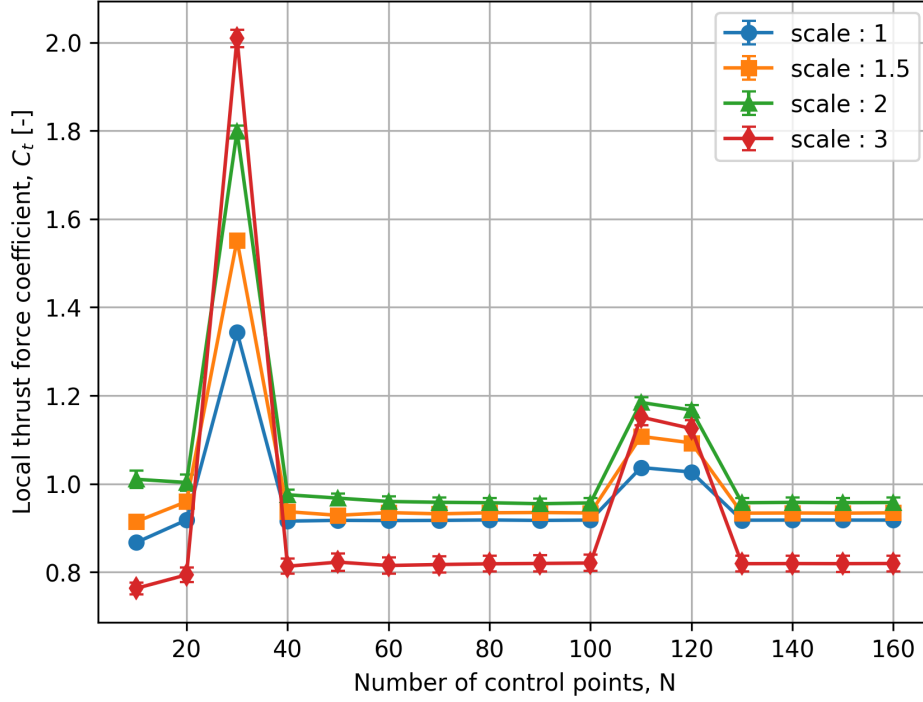


Figure 5.17: Convergence of the local thrust coefficient, C_t , as determined by the KJ method for the static case at $\frac{r}{R} = 70\%$ for the number of control points and various scales.

circulation as F_N , the same peaks are shown. Although the tangential load is not calculated with a reliable method, it is insensitive to the standard deviation in the flow, as the 95 % confidence interval is small. Compared to the normal load, the relative spread of the interval is smaller. When referring back to Equation 3.10 and 3.11, both F_N and F_T use the same circulation and density. However, F_T uses $U_\infty(1 - a)$, whereas F_N depends on $\Omega r(1 + a')$.

Figure 5.19 shows the convergence of the local power coefficient, C_p , as calculated from C_{tan} , using Equation 3.14. This is a linear scaling from C_{tan} , so the same shape can be seen. The Betz limit for maximum power extraction, $C_p = 16/27$ achieved at $a = \frac{1}{3}$, is also shown. Here it can also be clearly seen that the peaks at $n_{cp} = 30, 110$ and 120 , are physically incorrect. For the values at the other control points, it can be seen that the local C_p is under the maximum power coefficient. The axial induction factor, a , is already shown to be larger than $\frac{1}{3}$, explaining the lower value of C_p .

5.3. Aerodynamic Parameter Results

The angle of attack, α ; the axial induction factor, a ; the tangential induction factor, a' ; and the local thrust coefficient, C_t are the main aerodynamic parameters being investigated. For the five analysed cases, the average of these values and their 95 %-confidence level values are plotted in Figure 5.20. This plot shows how these aerodynamic characteristics of the flow are the same, or change, for the different cases. The baseline for each parameter is the static case, which is then compared to the different phases of the surge case. All cases are analysed using $N_{cp} = 100$ and $r_{scale} = 2$, as these values came positively from the convergence study, see section 5.2.

Each parameter is discussed, starting with the AoA in subsection 5.3.1, followed by the axial and tangential induction factors in subsection 5.3.2. The local thrust coefficient is discussed in subsection 5.3.3. The local power coefficient C_p is not included in Figure 5.20. The C_p can be computed in two ways. One method is from the axial induction factor, using BEM theory, such that $C_p = 4a(1 - a)^2$. Since the rotor is heavily loaded, as $a > \frac{1}{3}$, a correction such as the Glauert correction is needed. However, C_p in that method still depends fully on the axial induction factor, which is already presented. The other method is as used in subsection 5.2.5. It was shown that the C_p using this method does converge. However, since C_p in this method depends on the local tangential force, F_T , as computed by the Kutta-

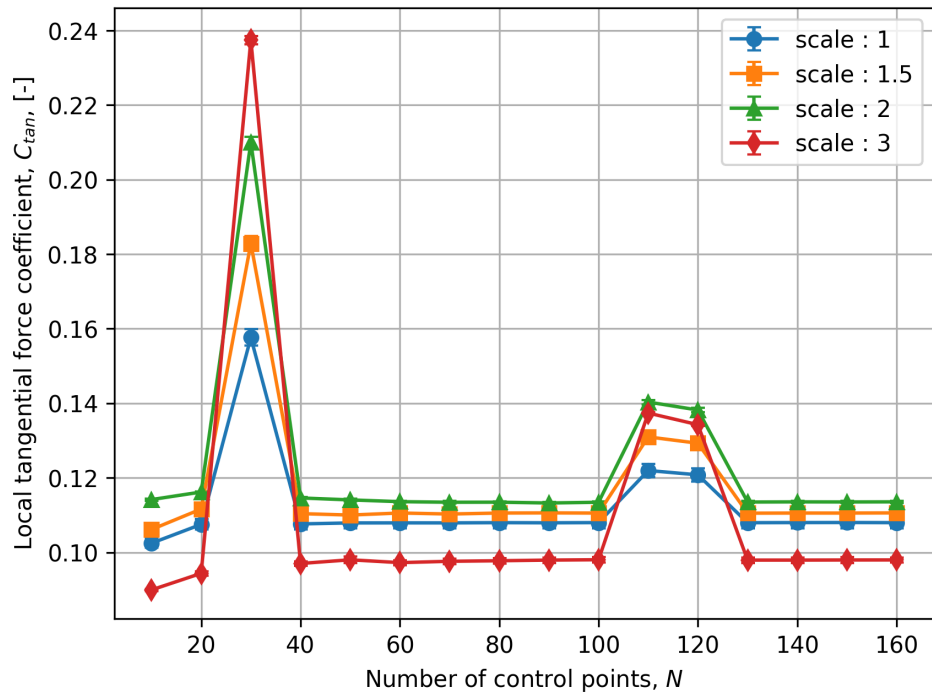


Figure 5.18: Convergence of the sectional tangential load, F_T , as determined by the KJ method for the static case at $\frac{\tau}{R} = 70\%$ for the number of control points and various scales.

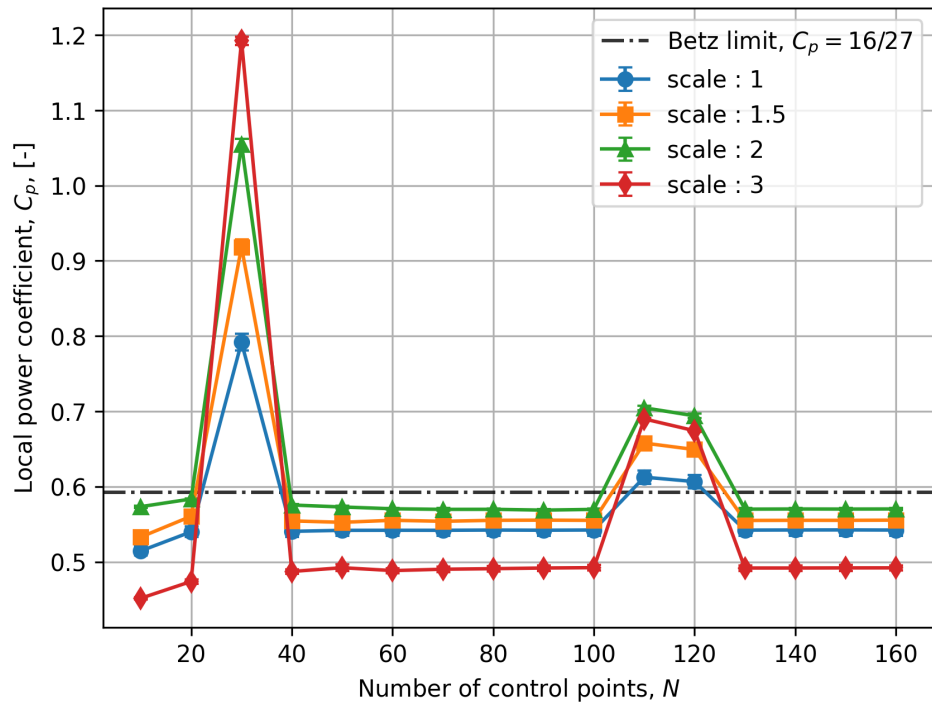


Figure 5.19: Convergence of the local power coefficient, C_p , calculated from the sectional tangential load, F_T , as determined by the KJ method for the static case at $\frac{\tau}{R} = 70\%$ for the number of control points and various scales.

Joukowski theorem, it is not reliable. The KJ-method does not take viscous forces into account, which can contribute approximately a third to F_T . Therefore, the C_p is not presented in this section.

5.3.1. Angle of Attack Results

Firstly, the AoA is compared. The static case gives a baseline of 4.73° , with a 95 %-confidence level of 4.64° to 4.83° . Expectedly, the angle of attack is significantly lower for the case of $\phi = 0^\circ$ and higher for the case of $\phi = 180^\circ$. This is mostly due to the addition of the structural velocity component U_{hub} in either direction. When the motion phase is zero, the blade moves in the positive x_a direction, and the horizontal u -component as seen by the blade decreases, decreasing the flow angle made by the relative velocity. Vice versa, the flow angle and thus AoA are increased for the negative hub motion when the motion phase is 180° .

If the change in AoA is solely due to the addition of the U_{hub} component, so no change in induction occurs, then adding the hub component to the static case and constructing the AoA using the calculated induction and new hub velocity, as in Equation 5.1, should give the same result as the angle of attack calculated directly from the flow fields of the $\phi = 0^\circ$ and $\phi = 180^\circ$ cases. This has been investigated. For $\phi = 0^\circ$, this results in a reconstructed AoA of $\alpha = 3.67^\circ$. This value is very slightly lower than the calculated mean for the real case, but falls well within the 95 %-confidence level interval. For the case of $\phi = 180^\circ$ however, the reconstructed AoA using $U_{hub} = -0.4 \text{ m s}^{-1}$, is $\alpha = 5.79^\circ$, which nearly 0.3° lower than the mean of the real 180° case, and falls out of the confidence interval by 0.22° , implying a physical effect of the motion, stronger than the measurement noise to a certain level of confidence. The observed effect is higher than expected angles of attack under surge motion, compared to the static motion.

$$\alpha = \arctan \left(\frac{U_\infty(1 - a) - U_{hub}}{\Omega r(1 + a')} \right) - \theta \quad (5.1)$$

While a linear average is an oversimplification of this non-linear system, the average of the mean for the four surge cases is 4.93° with a 95 %-confidence level of 4.86° to 5.00° , which falls completely outside of the range of the static case. To draw a more definitive conclusion, the AoA in more phases should be measured. However, if the AoA over time follows a continuous sinusoid-like function (in this context meaning with limited noise or deviation of a sinusoid), this also suggests that overall the angle of attack is increased due to the FOWT surge motion.

5.3.2. Axial and Tangential Induction Factor Results

In Figure 5.20, the axial and tangential induction factors, a and a' , are also shown. When looking at the axial induction factor for the zero-phase case, it is remarkably similar to the fixed case. This indeed aligns with the fact that a reconstructed AoA from the static case with added motion was shown to produce almost the same AoA as the real measurement. However, for the other motion phases, the story is different. A lower induction factor means that the freestream velocity has been slowed down less than in the baseline case.

Induction is a rotor-wide phenomenon. However, in this experiment it is calculated based on a snapshot of a 2D plane of a part of the rotor flow field. This might bring some systematic error to the exact value of the induction factor, but should not change the outcome of comparison between different cases. Since the surge motion happens at a four times longer time scale than the rotor rotation, 2 Hz against 8 Hz, the induction has one full rotation of the blades to change between the 90° interval of the PIV measurements.

While no previous studies have analysed the local blade for a surging FOWT, previous studies on the wakes of FOWTs have found faster wake recovery under motion cases. Faster wake recovery means the flow downstream of the rotor has a larger velocity, which is true of a rotor with lower axial induction.

An axial induction factor of $a = 0.40$ causes a velocity deficit of 1.6 m s^{-1} when compared to the 4.0 m s^{-1} upstream wind speed, giving an average u -component of 2.4 m s^{-1} at the rotor plane, which closely matches the observed flow field.

The tangential induction factor has relatively large error bars, but the overall magnitude of this factor

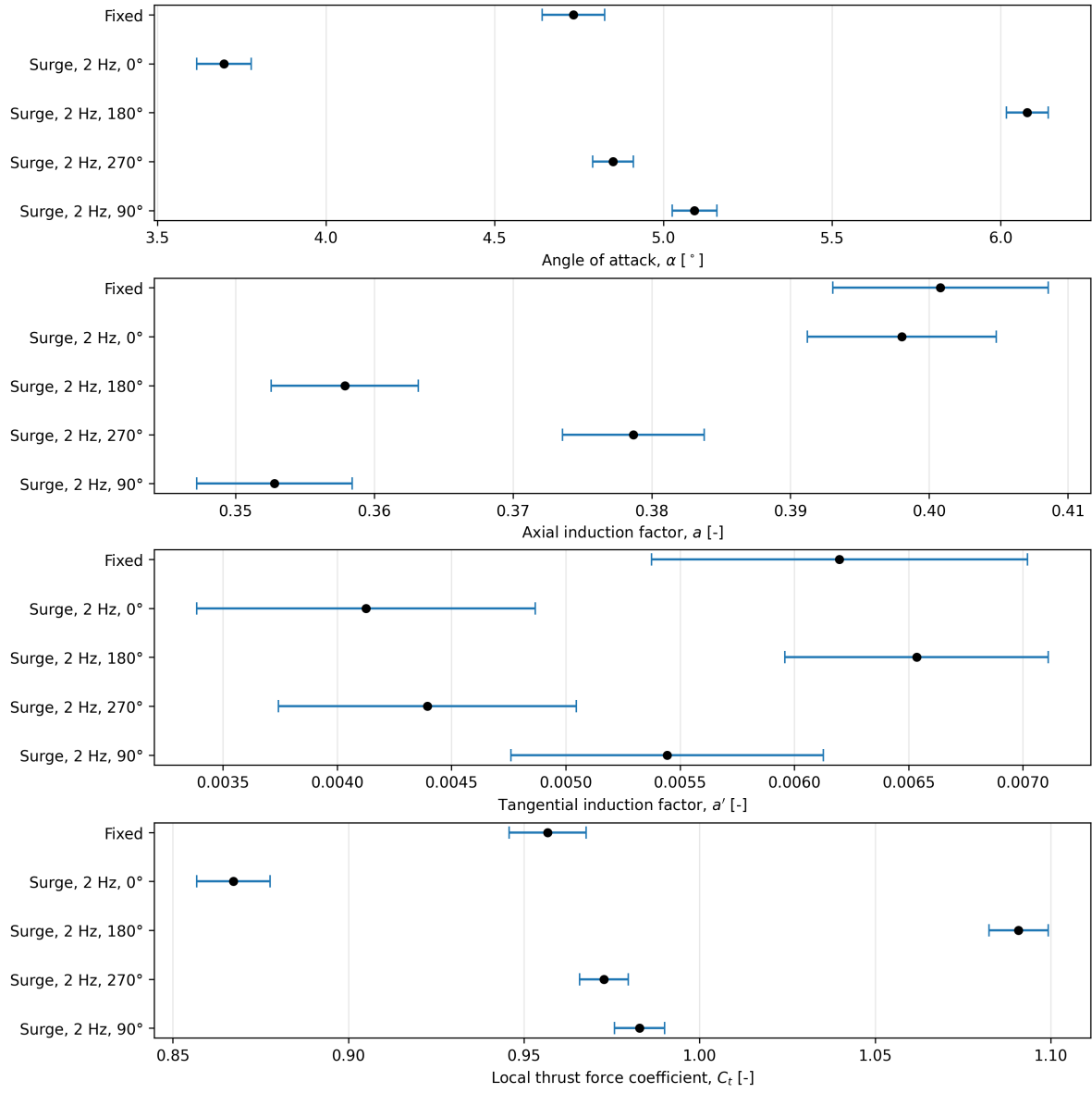


Figure 5.20: The angle of attack and axial and tangential induction factors and the local thrust coefficient for the five analysed cases at $\frac{r}{R} = 70\%$, using $N_{cp} = 100$, $r_{scale} = 2$.

Table 5.1: Local thrust coefficient, calculated lift coefficient and polar lift coefficient for the mean fields for each of the analysed surge cases at $\frac{r}{R} = 70\%$.

Case	Local thrust coefficient, C_t , [-]	Lift coefficient, C_L , [-]	According to polar, C_l , [-]
Static	0.957	0.944	0.8571
Surge, 0°	0.867	0.860	0.7146
Surge, 180°	1.09	1.07	1.0116
Surge, 270°	0.973	0.959	0.8571
Surge, 90°	0.983	0.968	0.8820

is small, dwarfing this contribution to the flow with respect to the rotational velocity component itself. Even at the highest tangential induction factor, the magnitude of the tangentially induced velocity will be less than 0.15 m s^{-1} . This is not a negligible contribution, but it is clearly less than the axial induction effect.

5.3.3. Local Thrust Coefficient Results

The mean local thrust coefficient, C_t found for the static case is 0.957. This aligns closely with BEM theory without correction, where $C_T = 4a(1 - a)$, and $a = 0.4008$ as per the fixed case, giving $C_t = 0.9606$. The mean sectional normal load, F_N , for the static case at $\frac{r}{R} = 70\%$ is 9.16 N m^{-1} . Since the angle of attack is small, small angle approximation and the fact that $F_T \ll F_N$ can combine to approximate $C_t \approx C_l$, the thrust coefficient can be compared to the lift coefficient from the SD7032 polar with a close Reynolds match of $Re = 50\,000$, where the value to the closest AoA available is chosen, with $\Delta\alpha = 0.25^\circ$. Alternatively, the lift coefficient can be calculated without these assumptions using $C_L = C_t \cos \alpha - C_{tan} \sin \alpha$, which would then use the tangential force coefficient C_{tan} , which cannot be accurate, as the Kutta-Joukowski theorem ignores the viscous drag term, but can be more accurate than not including it at all. The local thrust coefficient, C_t , the lift force coefficient, C_L , and the polar lift force coefficient, C_l , for the mean velocity fields for each case are shown in Table 5.1. The value for C_L is smaller than C_t , due to the negative contribution of $-C_{tan} \sin \alpha$.

It can be seen that the calculated lift coefficient is larger compared to the polar lift coefficient. This can be due to a physical phenomenon increasing the circulation. For example, the surging airfoil may cause more eddies in the flow. But this can also be due to experimental and method errors. One source of method error is neglecting viscous drag. While drag is perpendicular to lift, it does contribute largely to F_T and somewhat to F_N , such that the lift coefficient becomes less accurate. Another error can be the limited resolution. The image resolution is approximately 8 pixels to 1 mm. With interrogation windows of $48 \text{ px} \times 48 \text{ px}$ and a 75%, this gives an approximate vector resolution of one vector every 1.5 mm. This means any sub-millimetre-scale velocity gradient cannot be captured, and this circulation is not calculated. When the control points are close to the airfoil, the gradients are large, and this resolution causes inaccuracies. However, when the control points are far away from the airfoil, the gradient becomes small, and the velocity uncertainty causes relatively large uncertainties and thus error in the gradient. In between, there is a sweet spot where these effects together give the smallest error. This can be seen in the convergence study by the scale effect in the previous section, 5.2.

5.4. Frequency Domain Analysis

This section contains the results and analysis of several captured parameters in the frequency domain. The main purpose of this section is to analyse and explain the peaks that can be observed in the frequency domain plots. For the measured loads, accelerations, turbine position and several operational parameters, a power spectral density (PSD) is estimated using Welch's method, with 64 000 samples per segment and an overlap of 50%. The recording frequency is 1000 Hz, so each segment consists of 64 s. The PSDs are made using a realisation of the flow in the case of surge at 2 Hz, for the measurements of the pressure side, for motion phase $\phi = 270^\circ$. The associated side and phase for the PIV measurement are irrelevant as the frequency domain is considered. Other recordings were analysed, and it is found that the different recordings for the same surge case indeed behave similarly.

In the plots, the black dashed lines represent the motion frequency, f_{motion} , and several of its multiples.

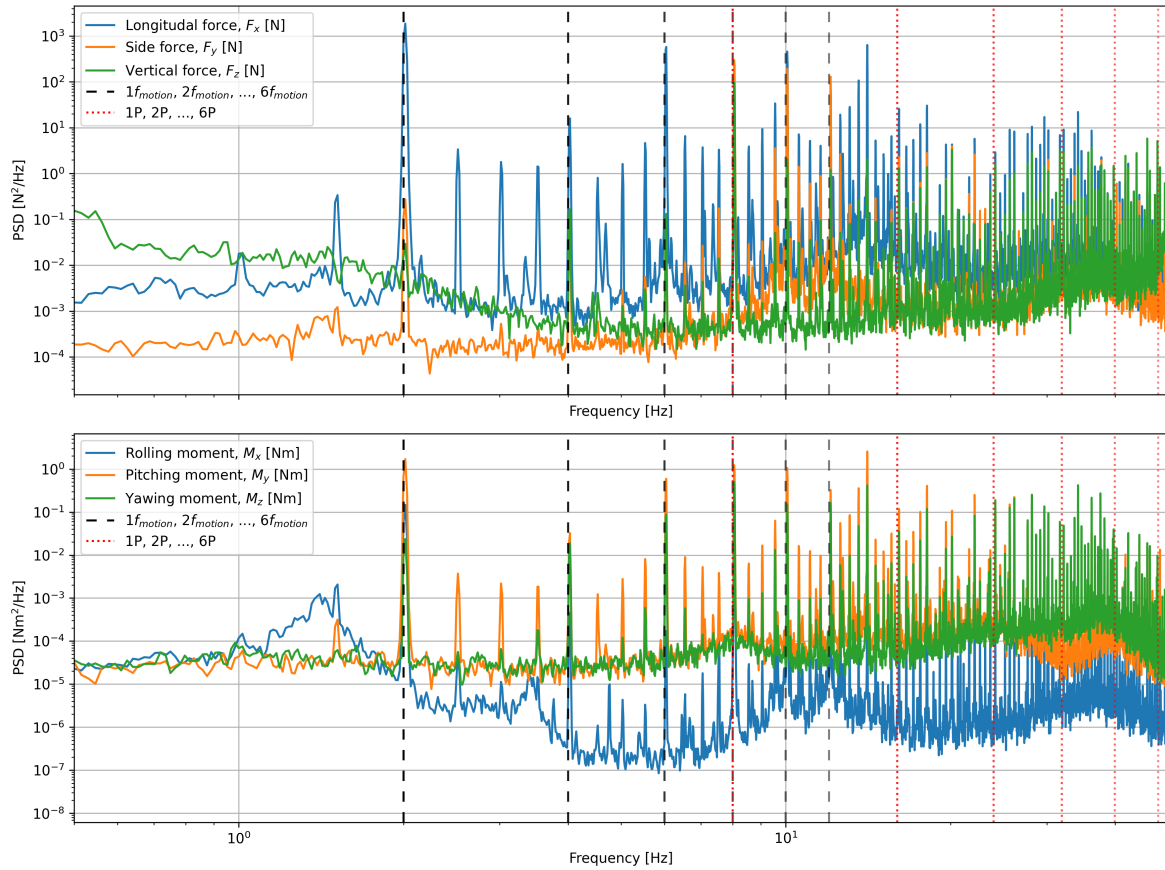


Figure 5.21: PSD of loads and moments from the load cell under a surge motion of 2 Hz.

Similarly, the 1P, 2P, 3P,... frequencies are represented by the dotted red lines. Since the 1P frequency is 8 Hz, the 1P aligns with $4f_{motion}$.

Figure 5.21 shows the PSD for the loads and moments measured by the load cell located under the nacelle. As expected, the main peaks are visible in the thrust force, as this is in the direction of the surge motion.

Figure 5.22 shows the PSD obtained using the two accelerometers. The top subplot shows the three accelerations of the top accelerometer, while the bottom subplot shows those of the bottom accelerometer.

Due to Newton's second law of $F = ma$, and the fact that the nacelle can reasonably be modelled as a rigid body, the peaks of the top accelerometer and the translational forces coincide very closely. A small difference can be seen in the 'baseline' below the peaks, where this line of noise is horizontal for the accelerometer and more curved for the load cell, but this can be explained by measurement accuracies and the very slow drift of the load cell measurements, whereas the accelerometers do not drift.

In general, the bottom accelerations exhibit the same peaks as the top accelerometer. There is a slightly more pronounced peak at 1 Hz, but this peak is still smaller than the intermediate peaks. At higher frequencies, the noise seems to slightly increase, whereas it decreased more for the top accelerometer.

Figure 5.23 shows the PSD of the actual turbine position, as determined by the dSPACE system from the output of the hexapod. The commanded signal was a sinusoid, with phase corrections where needed. For a pure sinusoid, the expected PSD is a horizontal line with a single peak at the imposed frequency. In the real-world measured signal, more peaks are visible.

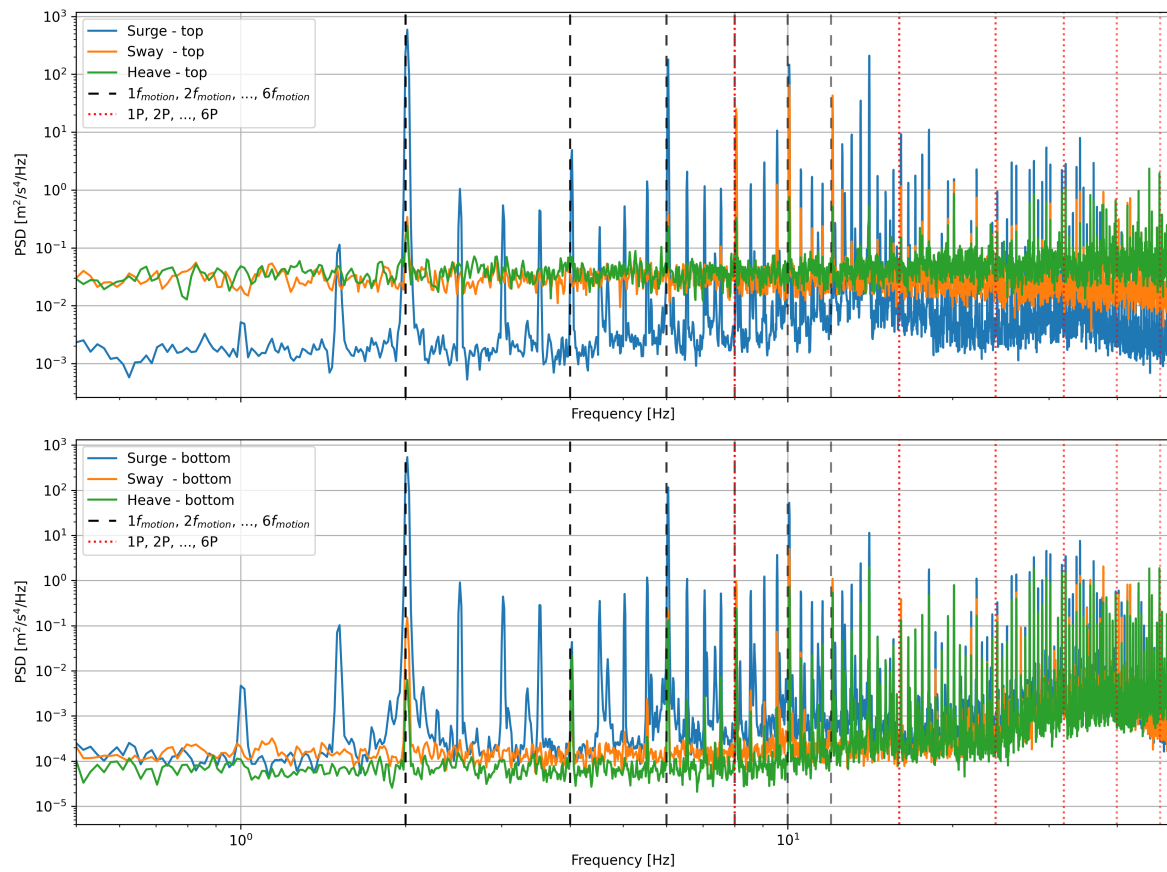


Figure 5.22: PSD of accelerations from the top and bottom accelerometer under a surge motion of 2 Hz.

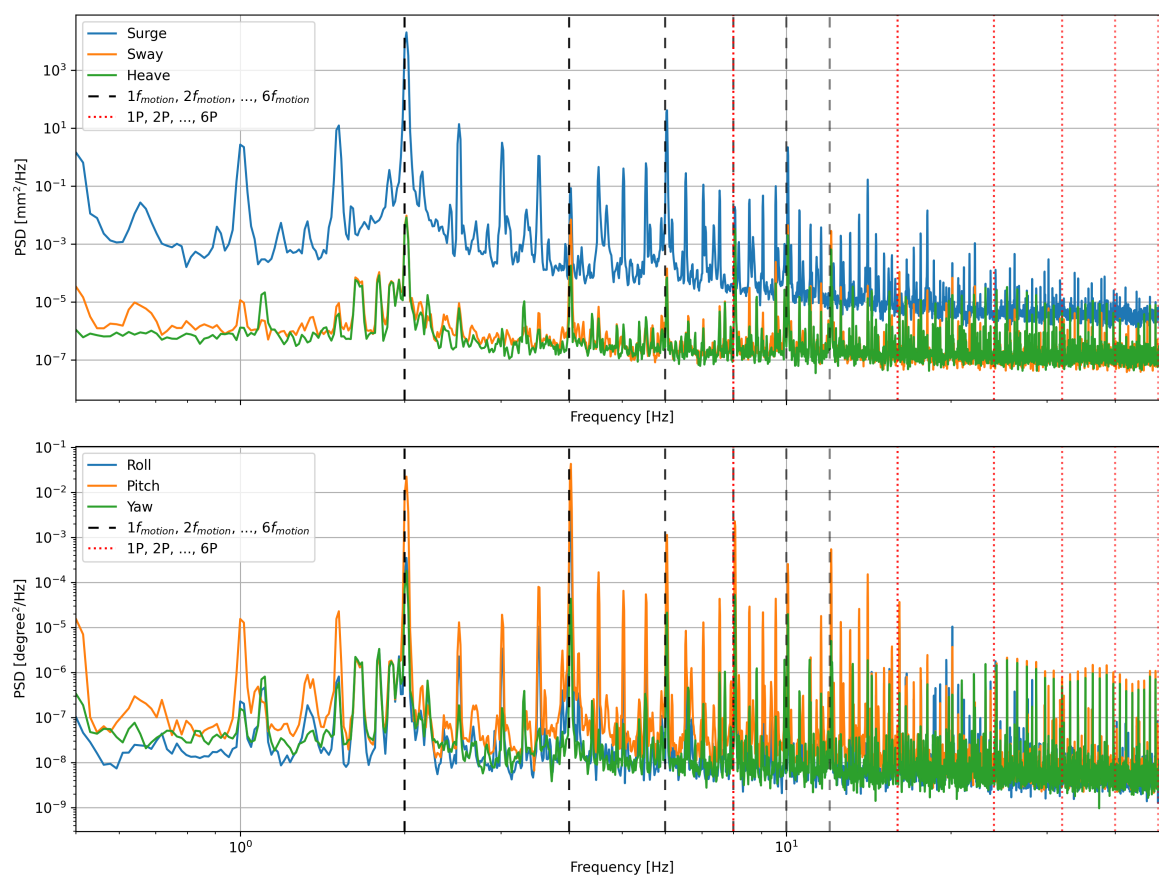


Figure 5.23: PSD of the actual turbine position as measured by the hexapod under a surge motion of 2 Hz.

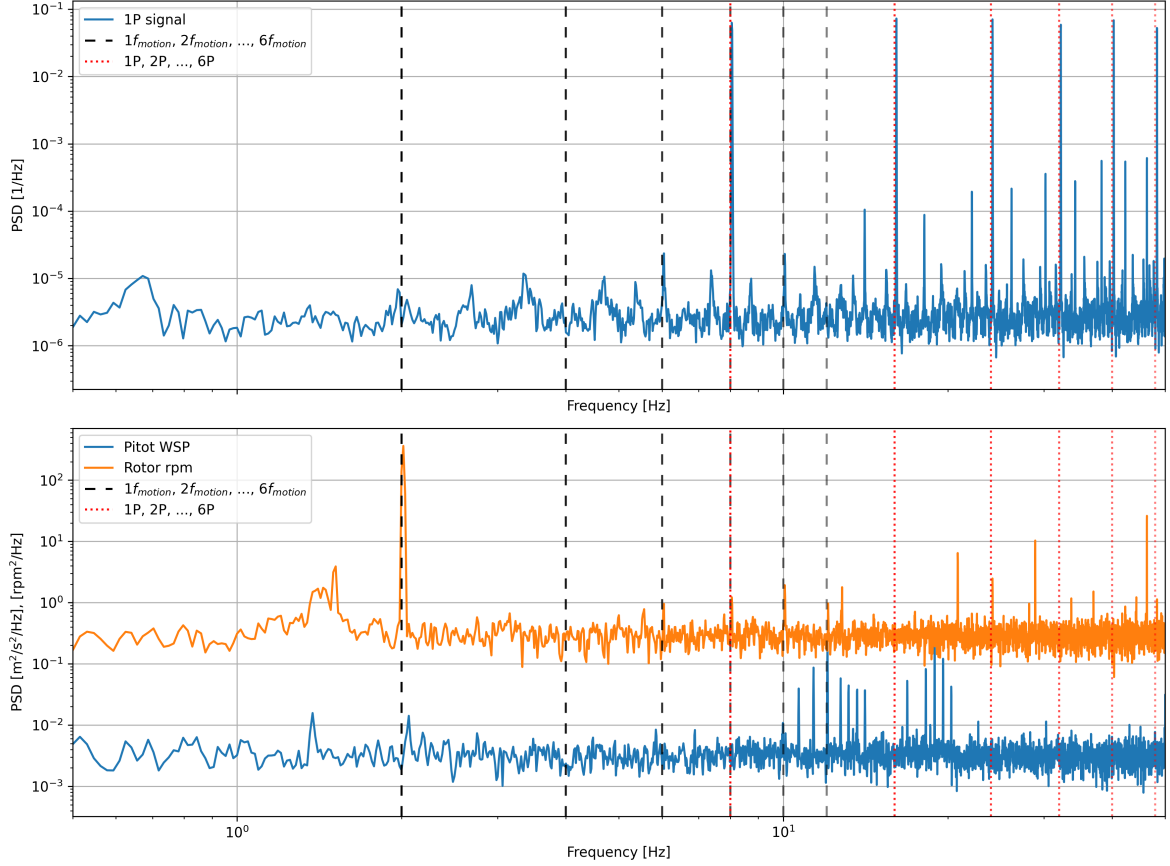


Figure 5.24: PSD of the 1P trigger signal, wind speed, and rotor speed under a surge motion of 2 Hz.

Figure 5.24 shows the PSD of the 1P trigger signal, wind speed and rotor speed. It can be seen that the 1P trigger signal has a large peak at 1P. Naturally, this is expected of a signal that should only trigger at that frequency. Interestingly, peaks of similar size can be observed at 2P, 3P, ..., 6P.

If the rotor speed were fully constant, as has been assumed, the PSD of the rotor speed should be a flat line, as there are no associated frequencies with a constant value. However, a single large peak can be observed at the motion frequency. This can be easily explained by the fact that the loads vary mostly at this frequency. The rotor is supposed to be kept at a constant rotational speed by the motor, but when aerodynamic loads due to the motion cause rotational accelerations, the motor control cannot respond infinitely fast, both due to control delay and the mass inertia.

The wind speed (WSP) as measured by the pitot tube situated in the OJF nozzle is mostly flat, will only small, noisy peaks. This proves that the measured wind speed was kept mostly constant during the tests. As the pitot tube is more than two rotor diameters upstream of the turbine model, there is no measurable effect caused by the rotor on the measured wind speed.

Table 5.2 contains a statistical summary for the longitudinal force, F_x , and the rolling moment M_x , both as measured by the load cell located under the turbine hub and for the actual x -position of the hub in the global coordinate system for the surge case. The statistics are made for a realisation of the static case and for the surge 2 Hz case. The blade section, motion phase and side are not relevant here, as those are used for the PIV measurements, not for the load cell and hexapod position.

The mean longitudinal force for the RNA-assembly in the static case is 9 N, which is the expected aerodynamic thrust under these conditions for a rotor thrust coefficient of $C_T = 0.8$. This means the local thrust coefficient at the analysed section is larger than the overall thrust coefficient. The standard deviation and maximum of the longitudinal force are much larger for the surge case. This is because the longitudinal force for the static case consists of the aerodynamic thrust on the rotor and nacelle, while

the measured longitudinal force for the surge consists for a large part of the inertial force caused by the surging mass. On average, the surging inertial force should cancel itself if the motion is symmetric. Indeed, it can be seen that the mean longitudinal force is close to the thrust from the static case.

Table 5.2: Statistical summary of selected signals for the static and 2 Hz cases.

Case	Signal	Mean	Std. dev.	Min.	Max.	1 st percentile	99 th percentile
Static	Long. force, F_x , [N]	9.065	1.418	4.167	14.226	6.139	11.998
Static	Roll. moment, M_x , [Nm]	0.171	0.078	-0.054	0.475	0.020	0.319
Surge 2 Hz	Act. x -pos. (surge) [mm]	0.062	22.164	-33.143	33.200	-33.031	33.097
Surge 2 Hz	Long. force, F_x , [N]	8.589	10.446	-13.536	39.888	-10.650	36.085
Surge 2 Hz	Roll. moment, M_x , [Nm]	0.143	0.156	-0.274	0.803	-0.110	0.559

6

Conclusion

The main aim of the study is to experimentally measure the local angle of attack for a floating offshore wind turbine. In this study, a wind tunnel campaign is performed to measure the local flow field around a blade section of a floating offshore wind turbine using a stereoscopic PIV system in a hybrid setup, using a hexapod to impose a sinusoidal surge motion. The angle of attack, axial and tangential induction factors, and local thrust coefficient are computed from the flow fields. A baseline bottom-fixed wind turbine case is compared to a surge motion case. The surge motion of 2 Hz gives a rotor reduced frequency of $f_r = 0.60$, and is measured at four motion phases. Measurements for both the pressure side and suction side are combined to obtain one full flow field per case.

Presented in the introduction, chapter 1, the two main research questions to be answered are RQ1 and RQ2, repeated here for convenience. The former relates to how the flow will be measured and is answered in section 6.1. The latter relates how the the flow behaves and is answered in section 6.2. Finally, recommendations for future research are given in section 6.3.

RQ1 How can the local aerodynamics of a scaled FOWT be measured in a wind tunnel?

RQ2 How does imposed sinusoidal platform motion of a FOWT influence the local aerodynamics?

6.1. How the Local Aerodynamics of a Scaled FOWT can be Measured in a Wind Tunnel

In this report, a system to measure and analyse several key aerodynamic parameters is shown. Advantages and drawbacks are presented in choosing and setting up this system. stereoscopic PIV was chosen, inspired by a previous study that analysed bottom-fixed wind turbines[47]. The system allows scientific analysis of the local aerodynamic field that has not previously been done in the floating wind environment. Apart from the SPIV setup, the system includes a traversing system to change the spanwise blade section being measured and a hexapod to impose the platform motion.

The blade position is kept locked in place by taking the PIV measurements only at the horizontal azimuth angle, coupled with a locked motion phase.

The angle of attack (AoA) is calculated using the Ferreira-Micallef method. This solution also gives the axial and tangential induction factors. The results are converged, and the spread in 95 % confidence interval is smaller than the changes between cases, so the method is deemed accurate enough for the current analysis. The normal load, and thus the local thrust coefficient, can be obtained using Kutta-Joukowski theorem via circulation. While this also gives an estimate for the tangential force, this is not accurate due to the lack of inclusion of viscous drag in this model.

6.2. The Influence of Imposed Sinusoidal Platform Motion of a FOWT on the Local Aerodynamics

Overall, it is found that the angle of attack is influenced most heavily by the direct movement of the FOWT hub. When the hub is surging with the wind, the AoA decreases. Vice versa, when the hub surges into the wind, the AoA increases. Between these motion phases, the mean AoA varies with almost 2.4° for $r = 421$ mm for the surge 2 Hz cases, with a 95 % confidence level spread for each case of less than 0.2° .

However, the hub movement itself does not fully explain the observed changes in AoA. If the variation in AoA were only due to the hub movement, then the axial induction factor would not change between cases. As the axial induction factor is shown to decrease under the surge motion there is an additional aerodynamic effect. A time lag between the surge motion and the resulting change in AoA may be present, hinting at the presence of the dynamic inflow unsteady effect, as expected for $f_r = 0.60$. This reinforces the limits on the use of quasi-steady theory. The reduced frequency is too low to trigger the unsteady airfoil or returning wake effect.

Overall, the computed AoA for the surge cases seems to increase due to surge motion, with the axial induction factor decreasing overall. In the analysed cases, the computed AoA is only lower for the motion phase of $\phi = 0^\circ$, due to the strong effect of the rotor moving with wind, decreasing the relative inflow in the freestream flow direction. When the motion phase is $\phi = 180^\circ$, the rotor is instead moving into the wind, and the largest angle of attack out of the four motion phases is measured. For the motion phases $\phi = 90^\circ$ and 270° , where the hub motion is zero, the AoA is slightly larger than in the fixed case, with the variation stronger for $\phi = 90^\circ$. The computed axial induction factor is largest for the fixed case, while the lowest value is computed for $\phi = 90^\circ$. Since the hub motion at that motion phase is zero, such as in the fixed case, this points to the presence of the unsteady dynamic inflow effect, where the rotor wake caused by the previous motion phases influences the axial induction factor, even when the hub is momentarily stationary.

Aerodynamic power was not measured in this campaign, but the increase in AoA and decrease in axial induction factor, while still heavily loaded with $a > \frac{1}{3}$, implies higher aerodynamic power can indeed be obtained under the surge motion. The lift coefficient was calculated to be higher than the lift as estimated by the polar, but here, the effect of measurement and method error may be as severe as physical effects.

6.3. Recommendations for Future Research

Several recommendations can be made for any future wind tunnel tests, or analysis of current data. Firstly, by far not all collected data was analysed, so more cases can be shown. Secondly, more analysis during future campaigns should be completed to allow more directed tests and improve the PIV conditions.

Another practical piece of advice is to cover the wall in the background with a black surface, such as a curtain. This will aid the post-processing. Painting the turbine black and placing black tape where paint was not possible also helped, so this should be done in future PIV studies where areas of high reflectivity can cause issues.

On a more scientific side, further research might take measurements at additional phases to more precisely see what happens to the flow when the surge velocity changes or direction is flipped. This will also show the time lag with which the angle of attack and induction factor respond to the surge motion.

Within the research group, the OpenFAST model of the model-scale turbine is being further developed. Running the same motion cases allows comparison of the numerical and experimental results. Any discrepancies may be due to measurement errors, numerical errors, or missing physics in the numerical setup. If a larger discrepancy is found in the surge cases than in the fixed case, an incorrect numerical model to account for the hub motion is likely to be the cause of this error.

More blade sections can be analysed. Sections closer to the blade tip may display different aerodynamic behaviour, due to the strong 3D effects. This can change the behaviour of the AoA and induction

due to surge motion. This can have a large effect on the magnitude and oscillation of the loads. These 3D effects do violate the 2D assumption of the FM method, so no reliable AoA can be calculated there using this method. Different methods to determine the AoA exist and may be tried. When multiple sections are analysed, a spanwise AoA-plot can be constructed and compared to the OpenFAST results. The root section is not aerodynamically significant for load generation compared to the outboard region, but may be physically interesting. In the root region, the rotational velocity component is smaller, so the angle of attack variation will be larger.

When multiple sections are analysed and the sectional loads are determined, the integral loads may be reconstructed. Especially the thrust, consisting of the integrated normal load, may be interesting to compare to the value measured by the load cell. The thrust is the main load of interest, since it is in line with the hub motion under surge and pitch and thus varies the most with the motion, and since it is the more reliable load that can be reconstructed. The thrust can be compared with a computed thrust using a load cell. In that case, the thrust can be extracted from the load cell, using a motion case with no wind, to mathematically remove the effect of the inertia loads[35]. By integrating the moments caused by the sectional loads, the blade root moments (BRMs) can be computed as well, see Appendix C. If the BRMs are measured independently, for example using strain gauges at the blade root, the computed and measured BRMs can be compared to determine a degree of reliability in the method. The BRMs can also be compared to the values computed by an OpenFAST simulation.

Ultimately, a good understanding of the instantaneous angle of attack for FOWTs will allow more complex control systems that can increase annual energy production (AEP), decrease fatigue loads, decrease ultimate loads, or a combination of these things. In the design and operation of floating offshore wind farms, a trade-off between AEP and the fatigue loads may be considered, to increase the expected life-time of the floating offshore wind turbines.

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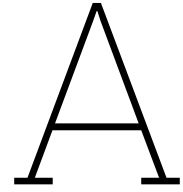
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Declaration of use of AI

This chapter declares the use of artificial intelligence (AI) during this study and while writing the report.

Limited use of GitHub Copilot was used in the writing of the code. Copilot was used for simple, menial tasks, such as but not completely limited to the generating of plot-layout and appearance. All Copilot suggestions have been manually reviewed. Limited use of ChatGPT was also used during the development of the code. All suggestions were again manually reviewed and adapted where possible. AI was not used to arrive at any of the presented conclusions in this report.

No generative AI was used in the writing of this report. ChatGPT provided one round of limited proofreading. The feedback from this proofreading is focused on structural parts of the report, not on the content itself.

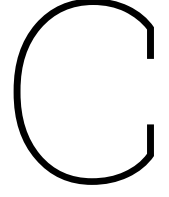
B

Test Matrix

Table B.1 contains the test matrix of all cases that were successfully tested during the wind tunnel campaign. For each case, the table includes the motion frequency, the motion amplitude, the motion phase, the spanwise radial section of the blade, the measured wind tunnel wind speed over the run, WSP_{OJF} , and the side on which the laser and cameras were positioned. All cases were performed with the turbine set at a rotor speed of 480 rpm. The table first shows all cases for the suction side (SS), then for the pressure side (PS). Trial runs that were performed during setup and tuning of the system are not included.

Table B.1: Test matrix of the completed cases, including motion frequency, the motion amplitude, the motion phase, the spanwise radial section of the blade, the measured wind tunnel wind speed over the run, WSP_{OJF} , and the side on which the laser and cameras were positioned.

DoF	Freq. [Hz]	Ampl. [mm/°]	Phase [°]	Radial section [mm]	WSP_{OJF} [m s ⁻¹]	Side
Fixed	—	—	—	311	3.99	SS
Surge	2	31.8	0	311	3.99	SS
Surge	2	31.8	180	311	3.99	SS
Fixed	—	—	—	421	3.96	SS
Pitch	2	2.25	0	421	4.03	SS
Pitch	2	2.25	180	421	4.03	SS
Pitch	2	2.25	90	421	4.02	SS
Pitch	2	2.25	270	421	4.02	SS
Surge	2	31.8	0	421	3.97	SS
Surge	5	6	0	421	3.96	SS
Surge	5	6	90	421	3.96	SS
Surge	5	6	180	421	3.95	SS
Surge	5	6	270	421	3.96	SS
Surge	2	31.8	90	421	3.96	SS
Surge	2	31.8	180	421	3.95	SS
Surge	2	31.8	270	421	3.96	SS
Fixed	—	—	—	505	4.01	SS
Pitch	2	2.25	0	505	4	SS
Pitch	2	2.25	90	505	4	SS
Pitch	2	2.25	180	505	4	SS
Pitch	2	2.25	270	505	4	SS
Surge	2	31.8	0	505	4.01	SS
Surge	2	31.8	180	505	4.01	SS
Surge	2	31.8	90	505	4.01	SS
Surge	2	31.8	270	505	4.01	SS
Surge	5	6	0	505	4	SS
Surge	5	6	180	505	4.01	SS
Surge	5	6	90	505	4	SS
Surge	5	6	270	505	4.01	SS
Fixed	—	—	—	421	4.01	PS
Pitch	2	2.25	0	421	4.01	PS
Pitch	2	2.25	180	421	4.01	PS
Pitch	2	2.25	90	421	4.01	PS
Pitch	2	2.25	270	421	4.01	PS
Surge	5	6	0	421	4.01	PS
Surge	5	6	180	421	4.01	PS
Surge	5	6	90	421	4.01	PS
Surge	5	6	270	421	4.01	PS
Surge	2	31.8	0	421	4	PS
Surge	2	31.8	180	421	3.99	PS
Surge	2	31.8	90	421	3.99	PS
Surge	2	31.8	270	421	3.99	PS
Fixed	—	—	—	505	3.9	PS
Pitch	2	2.25	0	505	3.91	PS
Pitch	2	2.25	180	505	3.91	PS
Pitch	2	2.25	90	505	3.91	PS
Pitch	2	2.25	270	505	3.91	PS
Surge	2	31.8	0	505	3.91	PS
Surge	2	31.8	180	505	3.91	PS
Surge	2	31.8	90	505	3.91	PS
Surge	2	31.8	270	505	3.91	PS
Surge	5	6	0	505	3.91	PS
Surge	5	6	180	505	3.91	PS
Surge	5	6	90	505	3.91	PS
Surge	5	6	270	505	3.91	PS



Integrated Load Validation

This following method is not used in the current study, but could be applied when multiple blade section are analysed. Therefore, it is included in the appendix of the report.

The local moment contributions due to the local loads can be integrated over the blades to calculate the blade root moment (BRM). The blades will also be equipped with strain gauges to measure the BRM directly. The BRMs that have been calculated can be compared to the directly measured BRMs to validate them against each other.

$$\text{BRM}_{\text{aero,integrated}} = \int_0^R f(r)rdr \quad (\text{C.1})$$

Here $f(r)$ is the spanwise load distribution. This will be f_n for the OoP BRM and f_t for the IP BRM.

The integrated aerodynamic blade root moment can then be compared to the integral blade root moment that can be extracted from the direct load measurements in the blade. The measured BRM in the blade consists of three parts: the aerodynamic, the inertial and the gravitational part, see Equation C.2. Both the inertial and gravitational part of the BRM can be expressed in general by Equation C.3.

$$\text{BRM}_{\text{meas}} = \text{BRM}_{\text{aero}} + \text{BRM}_{\text{inertial}} + \text{BRM}_{\text{grav}} \quad (\text{C.2})$$

$$\text{BRM}_{\text{inertial,grav}} = \int_0^R m(r)a(r)rdr \quad (\text{C.3})$$

Here, $m(r)$ is the spanwise mass distribution, and $a(r)$ the spanwise acceleration distribution. The acceleration needs to be taken in the same direction as the moment that is being calculated. Thus, the gravitational acceleration will be constant $a(r) = g$ for the IP BRM and $a(r) = 0$ for the OoP BRM. Similarly, the centripetal acceleration causes no contribution to the BRMs. Since the considered blade is rigid, the spanwise acceleration is also constant in translational motions, such as surge. For pitch, the acceleration over the blade is also constant when the blade is parallel to the pitch axis, so when the blade is horizontal.

Due to time constraints, only one radial section was analyzed and this subsection will not be represented in the results chapter.