The influence of axial gusts on the output of low-inertia rotors

Adnan M. El Makdah *, Sacha Ruzzante, Kai Zhang, David E. Rival

Department of Mechanical and Materials Engineering, Queen’s University, Kingston, Canada

HIGHLIGHTS

• The unsteady response of a generic low-inertia rotor is investigated experimentally.
• The vortex dynamics in the rotor’s wake is examined using time-resolved 2D-PIV.
• Insights on the bound circulation were gained using a vortex model of the wake.
• Compared to steady operation, the rotor model produces higher power during the gust.
• The circulatory forces are the source of the increased power output during the gust.

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ABSTRACT

Wind and hydrokinetic turbines are designed for steady operation, and hence their efficiency suffers in unsteady environments. In this study, the response of a low-inertia rotor model to axial gusts is investigated experimentally. Gust profiles are modelled as ramp functions with differing slopes, and are simulated by accelerating the rotor model in a towing-tank facility. Rotor speed and torque are recorded during the system’s response to the variation in freestream velocity. Furthermore, time-resolved particle image velocimetry (PIV) is carried out in the rotor’s wake to gain insights on the change of bound circulation. The power produced is observed to be higher during the gust than during steady operation. For instance, the power output of the rotor during the fastest gust is, at maximum, 27% higher than during steady operation. Using the PIV data, the circulation of the tip and trailing vortices is estimated as a proxy for the bound circulation, and is found to have higher absolute magnitudes during the gust. As a result, the increase of the circulatory forces is concluded to be the source of the increased power performance. The current findings are relevant to rotor systems with directly coupled generators and no speed control.

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1. Introduction

The energy-extraction mechanisms of rotor systems have been the subject of wind and hydrokinetic energy research for almost a century. A large corpus of literature has explored, using numerical and experimental tools, the performance of rotor systems operating in steady environments (Lignarolo et al., 2014; Akay et al., 2013; Krogstad and Adaramola, 2011). As a result, most rotors are designed using steady flow assumptions, augmented by empirical formulations to account for unsteady operation (Leishman, 2002). Consequently, the performance of wind and hydrokinetic turbines can suffer in unsteady environments unless these turbines are equipped with sophisticated control mechanisms (Milne et al., 2013). In order to design rotors with better performance in unsteady conditions, there is a need to replace these
empirical formulations with a physical understanding of the rotor's response to gusts (Vermeer et al., 2003). Unsteady environments, especially gusts, are particularly problematic for the operation of small wind turbine rotors, which have low rotational inertia (Lubitz, 2014). Furthermore, small wind turbines often operate in urban environments where the wind is expected to be unsteady most of the time (Emejeamara et al., 2015). Meanwhile, tidal stream turbines, and more generally hydrokinetic turbines, are also sensitive to unsteady fluctuations of currents (Winter, 2011). Most small wind turbines have their rotors directly coupled to the generator, while tidal turbines often have a heavy drivetrain in between the rotor and the generator. However, the equivalent inertia of the rotor and the drivetrain of a typical small tidal turbine is still low compared to the hydrodynamic loads acting on the rotor, while this is not the case for large tidal turbines that have large and heavy drivetrains. The current study aims to characterize the effects of axial gusts on the response of a low-inertia rotor model with a horizontal axis, as shown in Fig. 1.

Unsteady environments are characterized by rapid fluctuations of both magnitude and direction of the turbulent wind or stream. A better understanding of the dynamic loads acting on rotor systems operating in unsteady environments is crucial for designing reliable and safe turbines. Zhang et al. (2015) investigated the effect of microburst-like winds on the dynamic loads experienced by a wind turbine model. This type of wind was found to produce dynamic loads at least four times higher than conventional Atmospheric Boundary Layer (ABL) wind. Gusts are common in unsteady environments, and are defined as sudden fluctuations of the wind speed with amplitudes of 30% to 50% of the average wind speed (Scelba and Consoli, 2010). In some previous studies (e.g. Lubitz, 2014; Emejeamara et al., 2015), small-scale gusts were quantified by the statistically averaged turbulence intensity of the incoming flow. Previous investigations have explored the kinetic energy present in the wind resource. Van der Hoven (Van der Hoven, 1957), for instance, found that wind speeds with high-frequency fluctuations contribute through a strong peak in the wind-energy spectrum. In a recent study, Emejeamara et al. (2015) assessed the available energy of urban gusts using high temporal measurements of the wind. They found that the gust’s available energy is underestimated by averaging the wind speeds over relatively large time periods. To accurately estimate the energy present in the gusts, Emejeamara et al. (2015) emphasized the need for proper modelling of the turbulence intensity of the wind. Thus, they proposed an empirical formulation to estimate the gust energy from the inflow turbulence intensity. This empirical formulation indicates that the available energy present in a gust decreases as the averaging time period increases, and therefore, suggests that rotors with faster responses would be more effective in extracting the energy within a gust (Emejeamara et al., 2015).

When dealing with the unsteady response of rotor systems, researchers have focused on studying the effects of turbulence intensity on the power output and loads experienced by the rotor. Lubitz (2014) found that the energy production of small wind turbines is affected by the turbulence intensity of the wind. This conclusion was obtained by grouping the incoming wind according to the turbulence intensity into three arbitrary groups: low, medium, and high. Lubitz (2014) found that the impact of turbulence intensity was dependent on the average wind speed. At low wind speeds within the operating range of the turbine, the increase of the turbulence intensity appeared to improve the energy production of the turbine. Lubitz’s (Lubitz, 2014) findings are in line with previous wind resource investigations. However, these findings are sensitive to the predetermined grouping criteria, and in turn, cannot be generalized to other small wind turbines operating in different environments. Tian et al. (2014) also grouped the incoming wind based on the turbulence intensity to investigate the unsteady loads experienced by the turbine. They found that higher inflow turbulence intensity led to larger fatigue loads. The findings of these studies highlight the importance of estimating turbulence intensity for turbine design, although they do not specify the exact impact of the turbulence intensity on the energy-extraction mechanism. Moreover, the metric of turbulence intensity masks the frequency component of wind-speed fluctuations,
and thus does not fully describe the coherence of the unsteady incoming flow. The current study considers the response of rotor systems to large-scale gust encounters as opposed to the aforementioned studies.

Several studies on tidal turbines investigated experimentally the effects of unsteady flow on the hydrodynamic loads acting on the rotor’s blades. Milne et al. (2013, 2010, 2015) investigated the blade loading on tidal turbines for uniform oscillatory flows. In their experiments, the rotor speed was held constant throughout the tests, while measuring the bending moments at the blades roots using strain gauges. They found that the unsteady blade loads are approximately 15% higher than the steady blade loads. Whelan et al. (2009) studied the effects of the added mass forces on the loads acting on tidal turbines encountering unsteady flows. They concluded that axial added mass forces acting on the rotor subjected to passing waves are small. In addition to the experimental studies, McNaë (2013) developed an unsteady vortex lattice method to analyse the circulatory and non-circulatory forces acting on tidal rotors operating in unsteady flows.

A fundamental understanding of gust response is crucial for modelling the performance of rotor systems operating in unsteady environments. An accurate model of the gust response will thus help to develop control systems in order to extract the available energy of the flow, while reducing the unsteady loads experienced by the rotors (Scelba and Consoli, 2010; Bernhammer et al., 2016). In the case of fixed-wing aircraft and rotorcraft, 2D linear unsteady airfoil theories, such as those developed by Theodorsen (1949) and von Kármán and Sears (1938), are commonly used to model the aerodynamic response of profiles in unsteady flows (Leishman, 2006). Sequeira and Miller (2014) numerically investigated the limitations of 2D unsteady airfoils theories in predicting tidal-turbine response to gusts. They showed that Theodorsen’s theory, for instance, underpredicts the unsteady lift amplitude with nearly 18% error at high reduced frequencies. This error can be reduced to 8% by using a calibrated version of Loewy’s theory (Sequeira and Miller, 2014).

The specific profiles of a gust add to the complexity of characterizing the rotor response (Scelba and Consoli, 2010). Because of the difficulty of simulating the complex gust profiles in wind and water tunnels, previous experimental studies resorted to either time consuming outdoor experiments on full-scale models, or implementing complicated and expensive control systems in wind tunnels (Yang et al., 2017). In the current study, gust profiles are modelled as ramp functions with differing slopes, and are simulated by accelerating the rotor model in an optical towing-tank facility at Queen’s University. For investigating turbine response, the towing-tank facility is equivalent to a circulating tank facility (Gaurier et al., 2015). Using a towing tank allows one to easily simulate transient flows, such as gusts, through acceleration of the model rather than the flow (Granlund et al., 2014). Investigating simplified gust profiles will be a benchmark for understanding more complicated gust profiles later. Throughout the paper, we use the term “gust” to refer to the incoming flow speed ramp function. The towing acceleration of the rotor model is normalized and referred to as “gust duration” denoted by $t_g^*$. The tested gust profiles are defined in detail in Section 2.

The objective of this study is to experimentally investigate the effects of gust duration (ramp-up only), i.e. incoming flow acceleration, on the performance of a generic rotor model. The rotor model, used in this study, has a simplistic design to study the effect of the gust on the rotor’s response without the influence of more complex (real-life) rotor geometries. Furthermore, particle image velocimetry (PIV) is carried out in the rotor wake to investigate the flow mechanisms responsible for the observed gust response. Using the PIV data, the behaviour of the bound circulation over the rotor blades during the gust is determined using a vortex model proposed by Mast et al. (2004). The findings of the current study apply only to rotor systems with low-inertia rotors, such as small wind turbines and tidal turbines. The purpose of this study is to fundamentally understand the gust response of rotor systems such as small wind turbines. Although the findings of this study could potentially help in improving the performance of commercial small wind and tidal turbines, the main goal of the study is to explore the flow physics associated with the gust response on a generic, low-inertia rotor. The following section presents the experimental methods used to investigate the power output of the rotor model. The results of the current study are then presented and discussed in Sections 3 and 4, respectively. Finally, the conclusions and outlook are presented in the last section.

2. Methodology

2.1. Rotor model and turbine rig

The generic three-bladed rotor model was designed and 3D-printed out of Acrylonitrile Butadiene Styrene (ABS) plastic with a printing resolution of 0.127 mm. The diameter of the rotor model was chosen to be 30 cm thus producing a blockage ratio of 7.1%, based on swept area, in the towing tank. SD7003 airfoil profile was chosen because its lift–drag coefficients are independent of Reynolds number, calculated according to the chord, over the operating range of $60,000 < Re < 300,000$ (Selig, 1995), in addition to the availability of the literature on this profile’s aerodynamic behaviour (Ol et al., 2009; Rival et al., 2009). The blades were designed with a constant chord, an aspect ratio of three, and with twist such that an effective angle of attack of $10^\circ$ was achieved at $\lambda = 4$ assuming negligible induction factor, where $\lambda$ is defined as tip speed ratio. The rotor model was designed to operate optimally at incoming flow velocity of 1 m/s. Accordingly, the Reynolds number of the rotor model, calculated according to the rotor’s diameter, is 330,000, which is in the operating range of commercially available small wind turbines that have rotor diameters between 3 to 5 metres (e.g. Britwind® R9000 5 kW). The performance of the rotor model was tested at 1 m/s at $3.89 \leq \lambda \leq 4.53$. The maximum recorded power coefficient ($C_p$) was 0.29 at $\lambda = 3.89$. It should be noted that modern wind turbines with horizontal axis operate at a tip speed ratio range of $4 \leq \lambda \leq 8$ (Burton et al., 2001). Hydrokinetic turbines, however, were tested at...
different tip speed ratios in the range of $3 \leq \lambda \leq 8$ (Milne et al., 2013; Sequeira and Miller, 2014; Birjandi et al., 2013; Luznik et al., 2013).

An experimental turbine rig designed and built at Queen's University, shown in Fig. 2a, was used to study the unsteady response of the rotor model itself. The rig comprises an assembly for the sensors and a sting set-up where the rotor is attached. The rotation of the rotor is coupled to the sensor assembly via a 1:1 stainless steel chain drive. The rotary shafts are made of stainless steel (grade 316), and have a diameter of 1.27 cm. The rotor has the largest inertia of all the rig's components, which is double the inertia of the frictional brake. The inertias of the rotary shafts and the sensors are negligible compared to the rotor and the frictional brake.

2.2. Measurement of the rotor's output

All the experimental tests were performed in an optical towing-tank facility at Queen's University, which has a 15-metre long test section and a $1 \times 1$ m cross-section. The towing tank is enclosed by a roof along its length to minimize the free-surface effects, with a 50 mm wide opening in which the test article can be mounted and towed, as shown in Fig. 2b. The experimental rig was mounted such that the rotor's axis of rotation is aligned with the centre axis of the tank. The rotor speed and torque were measured using a magnetic encoder (Baumer® ITD69H00) and a torque sensor (HBM® T22), respectively. Both sensors were sampled at a frequency of 1 kHz. Constant load of 0.42 N m was applied on the rotor model using a frictional brake to achieve approximately $\lambda = 4$ at a towing speed of 1 m/s for all test cases.

As mentioned in the introduction, gusts are defined as sudden fluctuations of the wind speed with amplitudes of 30% to 50% (Scelba and Consoli, 2010). Therefore, in this study, gusts were modelled as ramp functions of the wind speed, and they were simulated by accelerating the rotor model from 1 m/s to 1.5 m/s with different towing accelerations to represent extreme gust events. In the present study, the dimensionless time and gust duration are denoted by $t^*$ and $t^*_g$, and they are defined by:

$$t^* = \frac{t(U_2 - U_1)}{D},$$

$$t^*_g = \frac{1}{a} \frac{(U_2 - U_1)^2}{D},$$

where $t$ is the dimensional time, $U_1$ is the steady towing speed before the start of the gust, $U_2$ is the steady towing speed after the end of the gust, $D$ is the diameter of the rotor model, and $a$ is the dimensional towing acceleration. Four gust
profiles (ramps) were tested as follows: $t^*_g$ = 0.5, 1, 2, and 4 (see Fig. 3). For a typical rotor with a diameter of 16 m, the slowest and the fastest tested gusts ($t^*_g$ = 4 & $t^*_g$ = 0.5) are equivalent to the change of wind speed from 12 m/s to 18 m/s in 10 and 1.3 s, respectively. Therefore, a real rotor-system cannot react (changing the applied load or controlling the pitch) quickly enough to mitigate the effects of the tested gusts. Therefore, in the current experiments, the applied torque by the brake must be held constant to simulate the behaviour of real rotor systems experiencing gusts. The dimensionless time, $t^*$, for each case was further normalized by the gust duration, $t^*_g$, in order to be able to compare directly over the same period for all gust cases, $0 < t^*/t^*_g < 1$. For each tested gust profile, the recorded rotational speed and torque were averaged over 50 independent runs. The data were filtered and smoothed using a low-pass Butterworth filter and a Savitzky–Golay filter, respectively.

In Section 3, the power output during the gust is compared to the equivalent steady power, $P_{steady}$. The steady data were produced by measuring power output at steady speeds of 1.0 m/s, 1.1 m/s, 1.2 m/s, 1.3 m/s, 1.4 m/s, and 1.5 m/s. Each speed was tested 10 times to obtain statistical convergence.

2.3. Particle image velocimetry (PIV) measurements

Time-resolved planar particle image velocimetry (PIV) was conducted in the rotor’s wake. Two high-speed cameras (Photron®, SA4), with a resolution of 1024 $\times$ 1024 pixels, were used to capture the flow field. Both cameras have a field of view (FoV) of 1D $\times$ 1D, with an overlap of 5 cm to allow proper stitching of the resultant vector fields. The combined FoV was situated in the lower half of the horizontal midspan of the rotor’s plane (Fig. 4). The coordinate system was placed at the centre of the rotor’s plane such that the x-axis is aligned with the rotor towing velocity, and the r-axis is pointing radially downwards, as shown Fig. 4. A high-speed laser (Photonics® DM40-527) was used to form a vertical laser sheet 3 mm in thickness to illuminate the wake of the rotor, as depicted in Fig. 4. The laser sheet was shifted by 1.5 cm from the rotor’s central axis to reduce the reflections caused by the sting. The tank was seeded by neutrally buoyant, 100-μm silver-coated hollow-glass spherical particles (Potters® AGSL 150-30TRD). The triggering of laser and cameras was synchronized, and they were operated at 500 Hz. The PIV measurements were repeated and recorded 50 times for each case, and the results were phase-averaged according to both the rotor’s angular position ($\phi$) and the gust-phase ($t^*/t^*_g$). The resultant velocity fields were filtered and smoothed by median and Gaussian filters, respectively.

The raw images were processed by DaVis® 8.4. The velocity vectors were computed using a two-pass cross-correlation algorithm with 50% overlap with a final interrogation window of 32 $\times$ 32 pixels. The particle positions were calculated within sub-pixel accuracy of ±0.1 pixel. The average pixel displacement was approximately 7 pixels, resulting in an estimated velocity error of 1.4%. Therefore, the maximum uncertainties for the normalized vorticity and circulation were estimated as 3.3% and 4%, respectively (Raffel et al., 2013).

The lift distribution can be estimated from the blade’s bound circulation using the Kutta–Joukowski theorem. Estimating the bound circulation over the rotor’s blades provides insight into the rotor’s performance during the gust. However, measuring the flow field around the blades to estimate the bound circulation is virtually impossible due to the rotation of the blades themselves. For that reason, Mast et al. (2004) proposed a vortex model to estimate the distribution of the bound circulation over a rotor’s blade from the detailed near-wake velocities. In their model, the rotor’s blades and the wake are modelled by infinite helical horseshoe vortex filaments of unknown circulation strength to be determined, as shown in Fig. 5b. Subsequently, the circulation distribution of the vortex system is related to the induced near-wake velocity field. However, the circulation distribution is determined from the near-wake velocity field which is also an unknown in the model. Therefore, the circulation is treated as a model parameter and is estimated with the objective of simulating the measured lift distribution.
velocities using the Biot–Savart law. The circulation distribution is then calculated using an optimization scheme described in more details in Mast et al. (2004).

In the Mast et al. (2004) study, the authors estimated the positions of the tip and trailing vortices using hot-wire measurements of the wake. In contrast, time-resolved planar PIV measurements were used in the current study to obtain the detailed wake structure. Using the resulting wake flow field, the positions and the strength of the tip and trailing vortices are easily estimated. Therefore, the bound circulation over the rotor's blades can be directly estimated from the circulation of the tip and trailing vortices without the need for the Biot–Savart law or the optimization scheme proposed by Mast et al. (2004). Although Mast et al. (2004) estimated the distribution of the bound circulation over the blades,
in the current study, the total circulation of the trailing vortex sheet and the tip vortex is estimated as a proxy for the total bound circulation over the blades. Consequently, conclusions can be drawn on whether the circulatory forces are responsible for the rotor’s gust response without the need to estimate the distribution of the bound circulation. Similarly to the Mast et al. (2004) study, the root vortex was not detected by our PIV measurements. We speculate that the root vortex is weak and interferes with the sting. Therefore, only the trailing and tip vortices were examined in the present study.

3. Results

3.1. Measurement of rotor response

Fig. 6 shows the tip speed ratio of the rotor ($\lambda$) as a function of the dimensionless time ($t^*$) for the tested gust profiles. The tip speed ratio ($\lambda$) of the rotor model increases during all gusts. During the fastest gust, the rotor model experienced the highest increase in tip speed ratio, as seen in Fig. 6. Furthermore, an overshoot of the rotor’s tip speed ratio was observed at the end of the gust ($t^*/t_g^* \approx 1$) for all gust profiles. The observed overshoot was largest at the end of the fastest gust ($t_g^* = 0.5$), and was smallest at the end of the slowest gust ($t_g^* = 4$). It should be noted that the inertia of the entire system is negligible since the maximum resultant fictitious torque due to the inertia of the entire rig is approximately 9% of the applied torque during the fastest gust.

Generally, the power coefficient ($C_p$) is dependent on the tip speed ratio during the steady operation of the rotor. The highest recorded power coefficient for our model was 0.29 at a tip speed ratio of $\lambda = 3.89$. Under steady operation, the high tip speed ratios associated with the gusts in Fig. 6 would be accompanied by lower $C_p$, and hence lower power. However, our results show that the rotor model displayed higher power output during the gust than during steady operation, as shown in Figs. 7 and 8. Therefore, there are fundamental differences in operation in unsteady conditions that steady formulations cannot accurately model.

The power output of the rotor model was obtained by multiplying the rotor’s rotational speed with the generated torque. The power output is plotted for all gusts in Fig. 7. It should be noted that the torque was held constant throughout all the experiments using the frictional brake. The power output increased during the gust with a shape similar to the tip speed ratio. Similarly, the power output also had an overshoot at the end of the gust before converging to the final power output at the towing velocity of 1.5 m/s. The rotor model had the highest power output and overshoot in the fastest gust ($t_g^* = 0.5$), while the overshoot was almost non existent in the slowest gust ($t_g^* = 4$).

Fig. 8 shows the rotor’s power output for all gusts, where the power is normalized by the steady power output. During the slowest gust ($t_g^* = 4$), the unsteady power output seems to be well matched by the steady power output with a
Fig. 7. Power production for each gust. In each case the power is normalized by the average power produced at 1 m/s \( (P_1) \). The fastest gust, \( t_g^* = 0.5 \) (blue) shows a considerable overshoot, settling to its final value well after the gust has ended. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Power production during gust. The shortest gust, \( t_g^* = 0.5 \) (blue), shows instantaneous power production almost 27% higher than the quasi-steady case. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

discrepancy of less than 5%, as shown in Fig. 8. However, during the faster gusts \( (t_g^* = 0.5, 1, \text{ and } 2) \), the rotor model produces higher power than the steady power output. For example, the unsteady power output during the fastest gust \( (t_g^* = 0.5) \) is approximately 27% higher than the steady power output. These results highlight the need for a proper model for the unsteady response of the rotors that takes into consideration the gust duration, or the equivalent incoming flow acceleration.

3.2. PIV Measurements of rotor wake

The flow field of the rotor’s wake during the gust \( (t_g^* = 1) \) was measured. This gust case was chosen for its relatively long gust dimensional time duration, which allowed the collection of enough time-resolved flow realizations during the gust. The flow field at the time instant \( (t^*/t_g^* = 0.6) \) was then chosen to compare the wake during the gust to that during
steady operation with similar incoming flow velocity ($U_\infty = 1.3$ m/s, $\lambda = 4.5$). The power output at the chosen time instant during the gust is 18% higher than the steady operation of the rotor.

The phase-averaged, normalized vorticity ($\omega_z/(U_\infty/D)$) contours for different phase angles are plotted in Fig. 9 for the gust and the steady cases. Vorticity was computed using the least square differentiation method described in Raffe et al. (2013). The structure of the wake in the gust case is similar to the steady case. However, the tip and the trailing vortices have higher vorticity magnitudes in the gust case compared to the steady case, as shown in Fig. 9.
Fig. 10. Average circulation of the tip and trailing vortices for the gust case at \( \frac{t^*}{t^*_g} = 0.6 \), and for the equivalent steady case \( U_\infty = 1.3 \text{ m/s} \). The error bars mark the precision error at a 95% confidence level. The average circulation of the tip and trailing vortices is higher than the steady circulation by 18% and 20%, respectively.

Being the least affected by viscous dissipation, the first tip and trailing vortices in the wake were chosen to estimate the circulation of the helical horseshoe vortices illustrated in Fig. 5. The vorticity integration areas used to estimate the tip and trailing vortices are shown by dashed rectangles shown in the first contour plot of Fig. 9. The integration areas used were of the same size for both the tested gust and steady cases. Fig. 10 presents the average circulation \( \Gamma / (U_\infty D) \) of the tip and trailing vortices for the tested gust at \( \frac{t^*}{t^*_g} = 0.6 \), and for steady case with similar incoming flow velocity \( U_\infty = 1.3 \text{ m/s} \). During the gust, the average circulation of the tip and trailing vortices is higher than the steady circulation by 18% and 20%, respectively. As a result, the bound circulation over the blades are similarly higher during the gust than during the steady operation. Therefore, it is clear that the circulatory forces are responsible for the increased power output during the gust.

4. Discussion

Previous investigations of the wind resource showed a significant amount of kinetic energy stored in high-frequency fluctuations of the gusts. Van der Hoven (1957), using energy-spectral analysis, analysed the kinetic energy present in the horizontal wind as a function of the frequency of the wind-speed fluctuations. He used wind speed data obtained from Aerovane speed records located on the top of a 125-m high meteorological tower. The wind spectral analysis showed that unsteady gusts with periods of around 1 min contribute significantly to the energy spectrum of the wind. Furthermore, in a recent study, Emejeamara et al. (2015) showed that the estimated available energy present in a gust is sensitive to the sampling rate of the wind speed data. Therefore, they proposed an empirical relation to estimate the available energy of the gusts from the turbulence intensity.

Although Van der Hoven (1957), and recently Emejeamara et al. (2015), showed that unsteady gusts have excess available kinetic energy compared to steady wind, they did not discuss the effects of the unsteady gust on the performance of the small wind turbines. In contrast, we investigated the influence of the transient flows on the response of a low-inertia rotors. The findings of the current study suggest that rotor systems with low inertia are capable of extracting the excess energy of the gust.

The tidal turbines studies (Milne et al., 2013, 2010, 2015; Whelan et al., 2009; McNae, 2013) investigated the unsteady loads acting on the rotor’s blades, while in the current study, we analysed the unsteady performance of the rotor subjected to gusts in terms of the rotor’s power output and tip speed ratio. Furthermore, in the experiments of Milne et al. (2010, 2013, 2015), the rotor speed was held constant throughout the tests, which will make turbine rotor behave as if it had infinite inertia.

Assuming negligible induction factors \( a \) and \( a' \) for simplicity, the effective angle of attack \( \alpha \) is given by

\[
\alpha = \arctan \left( \frac{U_\infty}{\Omega r} \right) - \beta,
\]  

where \( r \) is the local radius, \( \beta \) is the local twist angle, and \( \Omega \) is the rotational speed. Manipulating Eq. (3), it can be written as

\[
\alpha = \arctan \left[ \left( \frac{1}{\lambda} \right) \left( \frac{R}{r} \right) \right] - \beta.
\]  

In the current study, the tip speed ratio of the rotor model increased during the gust, and therefore, the effective angles of attack of the rotor’s blades decreased during the gust (Eq. (4)). Consequently, the rotor’s blades experienced attached flow.
conditions during the gust. Furthermore, the vorticity contours of the rotor wake during the gust (Fig. 9a) do not show any sign of flow separation; the rotor had similar wake structure for the gust and steady cases. Our PIV measurements indicate that the circulatory forces experienced by the rotor’s blades were the source of the measured extra power output during the gust.

5. Conclusions

In this study, the response of a low-inertia rotor model to axial gusts was investigated experimentally. Time-resolved planar PIV was carried out in the rotor’s wake to estimate the bound circulation over the rotor’s blades. The gust was modelled as a ramp function of the incoming flow, and was simulated by accelerating the rotor model in a towing-tank facility. The transient output of the rotor model during the gust was then compared to the steady output during steady incoming flow.

The tip speed ratio and power output of the rotor model were higher during the gust compared to steady operation. The power output of the rotor was the highest during the fastest gust, and was 27% higher than the steady power output for this case. Using the PIV data, insights into the bound circulation over the blades were gained from the tip and trailing vortices using the vortex model proposed by Mast et al. (2004). During the gust, it was found that the circulation of the tip and trailing vortices was higher than the steady circulation, indicating higher bound circulation over the rotor’s blades. Therefore, the increase of the circulatory forces were found to be responsible for the increased power output of the rotor during rapid gusts.

To the best of our knowledge, no previous study has investigated the effects of the gust duration on the energy-extraction mechanisms of the rotor systems. Previous unsteady rotor investigations focused on empirically relating the turbulence intensity of the incoming flow to the energy extracted by the rotor and the loads experienced by the rotor’s blades. This study therefore presents a first step towards enhancing our understanding of the operation of rotor systems in unsteady environments and associated flow physics.

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