AERODYNAMICS LABORATORY

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Date: January 19, 2010

Classification:	Unclassified
Distribution:	Limited
For:	Ranger Innovations, Ltd.
Reference:	46AB-I008
Submitted by:	Dr. Steven J. Zan, **Laboratory Director**
Approved by:	Jerzy Komorowski, **Director General**

Pages:	17
Figures:	
Tables:	

Abstract

Ranger Innovations, Ltd. is in the process of developing two novel concepts for wind energy conversion systems. As part of the development, the NRC Institute for Aerospace Research (NRC-IAR) has been asked to conduct an evaluation of the aerodynamic feasibility of the concepts. This report contains that analysis, and shows that both concepts can be expected to perform in a manner similar to traditional vertical axis wind turbines, from a first-order theoretical point of view. This report also covers many operational and practical considerations that must be addressed as the designs progress.

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Nomenclature

Symbols:

a	acceleration of the cart and blade
A	wind turbine swept area
c	blade or wing chord length
C_D	drag coefficient based on freestream wind speed (Equation 2.2)
C_{DD}	drag coefficient based on disc speed, V_D (Equation 2.1)
C_P	power coefficient (Equation 2.6)
D	total drag force in the WECS resolved in a direction parallel to the freestream wind
F	driving force acting on the blades resolved tangential to the track
F_gen	force applied to the cart and blade by the generator/wheel system
h	wind turbine height
k	reduced frequency
L	track length
m	mass of the cart and blade
N	number of cart-and-blade assemblies
P	theoretical aerodynamic power (Equations 2.4 and 2.5)
R	radius of the LCD
t	time
V	translational speed of a blade and cart along the track
V_D	disc speed, or wind speed as seen by the blades
V_{inf}	freestream (atmospheric) wind speed
$\tilde{\mathbf{V}}_\mathbf{l}$	total local wind vector at a given blade at a given moment
V_{max}	maximum translational speed of a blade for the TWD
α	angle of attack
λ	blade tip speed ratio (Equations 2.7 and 2.8)
ρ	air density
σ	WECS solidity (Equations 2.9 and 2.10)

τ	blade setting angle
ω	angular rotational speed of the blades of the LCD
Ω	blade oscillation frequency

Acronyms:

IAR	Institute for Aerospace Research
IRAP	Industrial Research Assistance Program
LCD	Large Circle Design
TWD	Translating Wing Design
VAWT	Vertical Axis Wind Turbine
WECS	Wind Energy Conversion Systems

1. Introduction

The NRC Institute for Aerospace Research (NRC-IAR) conducts many wind engineering studies that require the simulation of Wind Energy Conversion Systems (WECS). Through the Industrial Research Assistantship Program (IRAP) for small consultation projects, Ranger Innovations, Ltd. has commissioned the NRC-IAR to perform an independent evaluation of two large-scale WECS. This report has two purposes: to provide a first-order analysis of the aerodynamic potential of the concepts and to indicate areas of consideration that must be addressed as the concepts are developed.

1.1 Description of Concepts

The two wind energy machines under development by Ranger Innovations, Ltd. are both large-scale WECS with the blades on the order of 100 m tall and 20 m in chord length. For both designs, the blades are mounted vertically on translating carts that are constrained to move along a track. The power is generated at the interface between the blades and the track. This interface will likely take the form of a cart with railway bogy, and the mechanism for power transmission is embedded in the track. The WECS are intended for implementation in large opens areas, deserts or plains, where tracks on the order of several hundred metres or kilometers can be constructed.

It will become obvious that this report has used the term "blade" and "wing" interchangeably, due to this study's aerodynamic analysis of Ranger Innovations' concepts using a technique associated with conventional WECS. Conventional WECS rely on rotating blades to extract energy from the wind; however, the blades of the Ranger Innovations concepts are analogous to one-half of an aircraft wing standing vertically and moving along a track on the Earth's surface. In this orientation, such blades are aerodynamically similar to the sail of a ship; however, for part of this report it was considered more appropriate to refer to the blade as a wing.

The difference between the two concepts is in the shape of the track. The two concepts are described here.

Large Circle Design consists of a circular track on which several evenly spaced cart-and-blade assemblies can travel. Assuming that each blade will sit on its own independent cart, the blades can be individually articulated in order to maximize aerodynamic output. Aerodynamically, this device resembles a large Darrieus Vertical Axis Wind Turbine (VAWT) that is mounted next to the Earth's surface.

Translating Wing Design consists of a straight track on which a single blade-and-cart assembly translates back and forth. This concept requires coordinated articulation of the blade angle of incidence with respect to the cart such that the angle of attack and resulting aerodynamic forces can be maximized as the cart travels back and forth. In order to maximize annual energy output, the track of the TWD must be set perpendicular to the prevailing wind direction at the specific geographic location of installation. Furthermore, when deciding on the orientation of the track, consideration must also be given to the prevailing direction of the winds that contain the most annual energy (if this is different from the prevailing wind direction).

Clearly, the sheer size of these devices calls for some clever engineering. Ranger Innovations, Ltd. is in the process of determining appropriate materials and off-the-shelf components to make the machines light, inexpensive and feasible. The structural and electrical design of these devices is not the focus of this analysis. However these concerns, called "practical considerations" throughout this report, can have a direct impact on the aerodynamics. Some of the most important are listed here.

- The mass of the blades, particularly as is relates the the amount of energy required to actuate them should be considered. Also, the maximum acceleration the blades can undergo during start-up and shutdown of the wind energy devices will affect the operational characteristics, especially during acceleration at the track ends for the translating wing design. The durability, stiffness and cost of the materials to be used in construction will all have an effect on the final mass of the blades. As a general rule of thumb, the cost and mass of any object varies as the cube of variation in its reference dimension.
- The size, added mass, location, and control of the actuators required to articulate the blades must all be considered during the design.
- The size, optimum speeds, and added mass of the power generating units is of importance, including whether or not these units can be used to drive the blades as well and extract power from their aerodynamically-driven motion.
- Maintenance considerations and longevity will affect the marketability of the devices.
- Methods for the collection, storage, and conditioning of electrical power must be considered carefully.
- The maximum practical size of the track must be determined, which includes the definition of spaces that are large enough to accommodate the design and whether or not these spaces are close enough to existing electrical infrastructures.

These considerations are all critical to the success of the proposed concepts. However, they are not the focus of this analysis and it shall be left to Ranger Innovations to demonstrate their feasibility.

2. Concept Evaluation using Single Streamtube Theory

The aerodynamic potential of the two concepts was evaluated using single streamtube and blade element theory. This level of analysis represents a first-order estimate of the relative performance of the concepts. Once design is underway and some of the practical concerns have been addressed, a more detailed analysis and/or wind tunnel testing of scale models is required. The following idealizations are inherent in this analysis.

- One-dimensional momentum theory (single streamtube theory) is used to calculate the local wind speed as seen by the blades. This is standard practice in wind turbine analysis, although more complex analyses use multiple one-dimensional streamtubes to analyze a single wind turbine (Paraschivoiu, 2002).
- Blade element methods are used to calculate the aerodynamic forces on the blade. The airfoil data used here is shown in Figure 2.1, where the equations used were originally determined by Wall (2009), based on experimental data presented in Critzos *et al.* (1975). It is based on a NACA 0012 operating at a Reynolds number of 1.8×10^6, which is lower than Reynolds number for the proposed concepts (in the range of 1×10^6 to 1×10^8), however as a first order estimate, these values are considered representative. This analysis does not include optimization for airfoil, tip losses, robust stall modelling, or unsteady effects. While these issues are often included in wind turbine analysis, the demonstrative nature of this work allows their exclusion.
- The importance of blade aspect ratio (blade length divided by mean blade chord) has not be considered in this design. This parameter is of importance because tip losses are lower for blades with longer aspect ratios. From an aerodynamic point of view, it is desirable that the aspect ratio be as large as possible. However, this parameter must be optimized in concert with structural considerations and is therefore not considered in this analysis.
- Boundary layer flows are not modelled. The tendency of the wind to slow near the earth should be considered carefully before installing turbines next to the surface. The speed gradient will affect the available power negatively, and also the aerodynamic loading. Here, the flow is modelled as a one-dimensional uni-directional constant speed flow. Because this analysis feature non-dimensional results, turbines at altitude and near the surface are analyzed equally, however appropriate wind speeds at the altitude of turbine installation should be considered when comparing individual devices. The variation in wind speed and direction over time for a given turbine site are also neglected.
- The energy and momentum analyses have been completed for idealized systems. Therefore, frictional losses, power requirements to articulate the blades, generator inefficiencies, and flow irregularities have all been neglected.

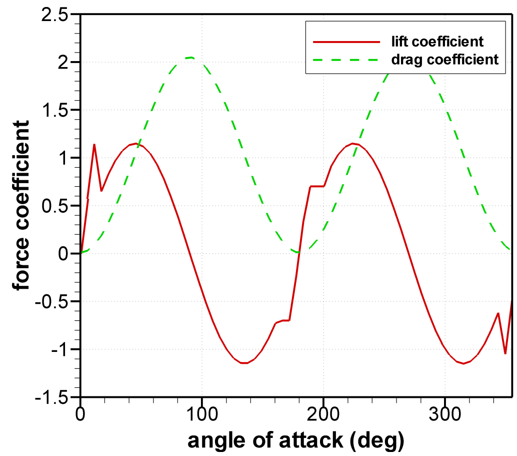

Figure 2.1: Lift and drag coefficients used in the simulation (lift perpendicular to relative airflow; drag parallel to relative airflow).

The numerical tools exist with which to consider many of these effects. Their exclusion is a reflection of the time constraints of this contract and the current design level of the concepts themselves. It is noted that accounting for the effects described above will reduce the performance of the turbine.

The reader should refer to Templin (1974) and Paraschivoiu (2002) for details on the VAWT aerodynamic analysis and the single streamtube approach in particular, however the following brief overview of the method is presented.

- First, the parameters of the WECS are defined, including the size, geometry, operational speed of the blades along the track, V, and the speed of the freestream (undisturbed or atmospheric) wind, V_{inf}. If needed, the blades are divided into a finite number of discrete blade elements for which the local aerodynamic forces will be calculated. For Ranger Innovations' concepts operating in a uniform wind environment, the aerodynamic environment is uniform at any given moment along the length of each blade. Therefore this analysis considers only one element per blade.
- Single streamtube theory considers a one-dimensional streamtube of air that begins in the free-stream, encounters an actuator disc that extracts energy from the flow, and ends with the final wind speed in the wake of the turbine. Figure 2.2 shows this schematically. Analyses in the references cited above show that the wind speed at the actuator disc, V_D, is the average of the free-stream and final wake speeds. This analysis uses an idealization where the whole VAWT is considered to be represented by the actuator disc and all the blades encounter the disc speed, V_D.
- An iterative process to determine the disc speed, V_D, begins by assuming that its value is equal to the freestream speed, V_{inf}. The first estimate of the local relative wind vector with respect to the blade, $\tilde{\mathbf{V}}_1$, is therefore the vector sum of V_D and the blade speed along the track, V. Blade element theory is then used to calculate a first estimate for the aerodynamic loads on each blade using the local relative wind, $\tilde{\mathbf{V}}_1$, and the local

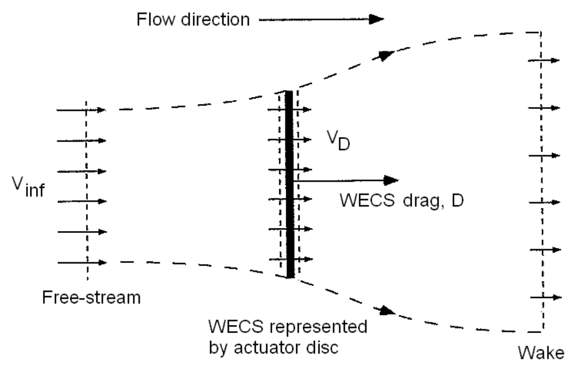

Figure 2.2: Theoretical representation of WECS used in single streamtube theory (modified from Leishman (2006))

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blade setting angle, τ. The local angle of attack depends on the disc speed, V_D, the blade incidence angle, τ, that can be modified on a schedule that optimizes blade driving force. This calculation requires a look-up table of aerodynamic coefficients for the wind turbine airfoil as a function of angle of attack and Reynolds number. This is done for each blade for one complete rotation or cycle of the turbine. By taking the appropriate coordinate transformations and summing the contributions from each blade, an average wind-wise drag coefficient based on the disc speed, V_D can be calculated as

$$C_{DD} = \frac{D}{\frac{1}{2}\rho V_D^2 A} \tag{2.1}$$

where D is the total average turbine drag force resolved in a direction perpendicular to the wind (resulting from the lift and drag forces originally calculated in blade coordinates), and ρ is the density of air. The parameter A is the swept area of the wind turbine, given by the diameter of the track, $2R$, times the blade height, h for the LCD, and the track length, L, times the blade height, h for the TWD. This definition for drag coefficient should not be confused with the more conventional drag coefficient

$$C_D = \frac{D}{\frac{1}{2}\rho V_{inf}^2 A} \tag{2.2}$$

which is based on ambient dynamic pressure.

- Single stream tube theory, which considers the conservation of energy and momentum for an actuator disc acting on a streamtube of air that flows through the wind turbine, gives a relationship between the disc drag coefficient and a new estimate for disc speed through

$$V_D = \frac{V_{inf}}{1 + \frac{1}{4}C_{DD}} \tag{2.3}$$

This newly calculated value of V_D, is used with blade element theory to re-evaluate the aerodynamic loads on the each blade, and through the procedure just described, arrive at subsequent an estimation for the local velocity at the rotor disc. This iteration is continued until convergence at some acceptable level is reached. For this study, convergence was considered achieved when the value of V_D changed by less than 0.01 m/s.

- Once the final value for disc speed and the blade forces at a discrete number of track positions have been determined through iteration, the aerodynamic power can be determined. This is done by first resolving the blade forces into a component that is tangential to the track. This driving force component is denoted as F. For the LCD, the power, P, is given by

$$P = FR\omega \tag{2.4}$$

where ω is the angular rotational speed of the blades and R is the radius of the track. In the case of the TWD, power is given by

$$P = FV \tag{2.5}$$

An estimate for the WECS power is given by summing the instantaneous power contributions for each discrete track position for which aerodynamic forces were previously determined (one rotation for the LCD or one full track-travel for the TWD), summing the contributions for each blade on the device, and taking the average of the instantaneous power contributions over all discrete track locations. Finally, the power is converted into non-dimensional state by normalizing by the power that is available in the wind. This is given by the power in the streamtube of air of cross-sectional area, A, as

$$C_P = \frac{P}{\frac{1}{2}\rho V_{inf}^3 A} \tag{2.6}$$

which represents a standard measure of the efficiency of wind energy generation.

Wind turbines are traditionally analyzed by completing the analysis described above for a range of operational speeds and computing the theoretically available power at each. That available power is then expressed as a function of the specified speed; this is called the turbine power curve. If the non-dimensional power, C_P, is plotted versus tip speed ratio, λ, given by

$$\lambda = \frac{\omega R}{V_{inf}} \tag{2.7}$$

for the LCD and

$$\lambda = \frac{V_{max}}{V_{inf}} \tag{2.8}$$

for the TWD, then the resulting power curve is non-dimensional and can be compared with other turbines of different size, shape, and speed. In this report, only non-dimensional performance is shown to allow the results to be compared easily with other WECS, and to allow the predicted power output to be estimated for different geometries as the designs are advanced.

2.1 Large Circle Design

The Large Circle design resembles a VAWT with straight vertical blades in its aerodynamic behaviour; the differences between the two are largely structural and operational. With this in mind, it is possible to extract a wealth of information on the the aerodynamic potential of the LCD from the existing body of research that has already been conducted on traditional VAWTs. Using the analysis method described in the previous section, the LCD was analyzed for the case where the blades do not articulate. This was done in order to allow comparison with typical VAWT performance, as shown by Templin (1974).

Figure 2.3 shows the predicted performance curve for the LCD. Turbine solidity, defined as

$$\sigma = \frac{Nc}{R} \tag{2.9}$$

where N is the number of blades, c is the chord length, and R is the radius has been shown to be a parameter of importance for the determination of performance. Therefore, the analysis presented here shows the performance at various solidities. To put the results in context, dimensions of the LCD that could correspond to each solidity are given in Table 2.1. The values are just examples; the analysis holds valid for any size of turbine with the same solidity, provided the airfoil coefficients are valid for the resulting Reynolds numbers.

Table 2.1: Representative dimensions for the LCD.

σ	N	c (m)	R (m)	h (m)
0.24	3	4	50	100
0.084	3	1.4	50	100
0.048	3	0.8	50	100

For a solidity of σ = 0.24, the LCD gives a power maximum of about C_P = 0.34 at a tip speed ratio of about λ = 3.1, and for a solidity of σ = 0.084, C_P = 0.23 at a tip speed ratio of about λ = 5.2. This compares well with Templin's analysis for a Darrieus turbine where for a solidity of σ = 0.25, C_P = 0.37 at a tip speed ratio of about λ = 4.3, and for solidity of σ = 0.083, C_P = 0.25 at a tip speed ratio of λ = 6. Differences between the two studies are due to a combination of factors, including different airfoil characteristics and the fact that Templin analyzed a turbine with parabolic blades. The discontinuous nature of the power curves in Figure 2.3 are due to the peaky qualities present in the airfoil characteristics model shown in Figure 2.1. Airfoil optimization and dynamic stall models, which should be incorporated in future analyses, will likely smooth the discontinuities.

As a matter of practicality, the tip speed at a tip speed ratio of 3 at a wind speed of 6 m/s is 18 m/s, which is equivalent to 65 km/h. The blades must be able to withstand the radial acceleration loads at this speed. Any WECS site having an annual average wind speed of 6 m/s at 10 m above the ground is considered good for wind energy production. Also, the final blade chord must be sufficient to support a blade 100 m tall. This could be optimised using tapered blades, which would allow stronger blade roots without adding to the overall solidity.

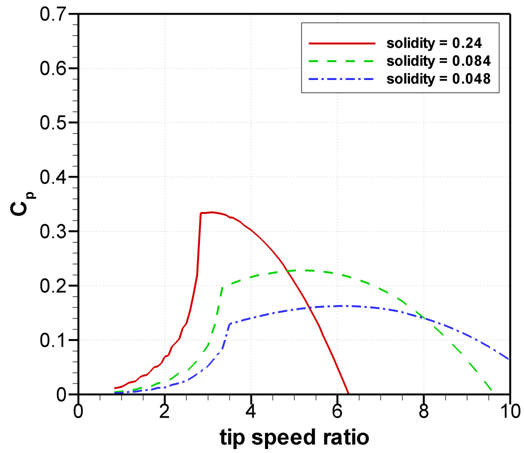

Figure 2.3: Non-dimensional power curve for a non-articulated VAWT (equivalent to a non-articulated LCD).

The articulated LCD can be expected to produce more power than a traditional vertical axis wind turbine, owing to the fact that aerodynamic output can be optimized using the blade articulation capability of the device. Articulated vertical axis turbines have been previously considered by Staelens *et al.* (2003) and so his work, summarized in this paragraph, offers a good reference on the relative benefits and drawbacks of blade articulation. Three different control strategies were tested. The first involved keeping the angle of attack optimized around the entire rotation. This produced the greatest peak in C_P, but caused problems in that a step-function change in angle of attack was required to maintain the optimum angle of attack. This presents practical problems with attempting to realize these rapid angular changes, such as with sizing the blade actuators. The second control strategy involved actuating the blades only when they move beyond the stall angle in order to maintain attached flow throughout turbine rotation. This modification showed only minor loss in power compared to the fully optimized case, with the advantage of being physically realizable. The third control strategy involved varying the blade angle in a continuously varying sinusoidal fashion around the circumference of the turbine. This strategy also shows improvements in performance over the fixed-bladed VAWT, but not as high as either the first or second control strategies. However, being cyclic in nature, it has the advantage that it could be realized through mechanical means. Part of the detailed design of Ranger Innovations' concepts must include determination of the best control strategy to meet Ranger Innovations' needs, and this optimization can draw on the information in the previously referenced work.

As a matter of practicality, the blades of VAWTs are not constantly in a state of producing positive thrust. With the possible exception of the first control strategy described above, the cart and blades of the LCD must be capable of driving themselves through the part of each rotation wherein they are not producing positive thrust. Either their momentum must be sufficient for this purpose or power from the grid must be used to drive the blades. In either case, assuming perfect efficiency of the entire system, this will not subtract from the expected total power to be generated by the device, however it presents some design challenges to be overcome.

This limited analysis indicates that LCD has the potential to produce electricity with efficiencies similar to standard VAWTs, from an aerodynamic theoretical point of view. Based on the actuator sizing and control capabilities, the exact blade articulation strategy will likely be the subject of a future optimization study.

2.2 Translating Wing Design

Compared to traditional WECS, the unique consideration for the TWD comes from oscillating nature of the blade motion. This introduces unsteady loads which may affect the quality of the power generated and will surely require careful structural design against fatigue. Although the TWD differs in operational requirements compared to the LCD, the concept can be analyzed using the same tools. First, a velocity schedule for one complete traverse of the track is defined as blade speed, V with respect to time, t. During this single traverse, the blade starts from rest, achieves some maximum speed, V_{max}, and comes to rest at the end of the track. In order to avoid large accelerations that the structure must withstand while changing direction, the velocity schedule during acceleration and deceleration was assumed sinusoidal. The track acceleration fraction, a concept introduced for this analysis, is defined as the fraction of the total track length during which the blade is accelerating or decelerating. For this analysis, the time to reach full speed from rest at the end of the track was taken to be 10 seconds. The time to rotate the blade from 0 angle of attack, α, to the optimum angle for constant-speed operation was also taken to be 10 seconds, although this quantity can have an independent value and should be optimized in future studies. The target full speed and the track acceleration fraction are prescribed, and these two quantities define a total required track length, L, and final velocity and acceleration profiles. The specified solidity, given by

$$\sigma = \frac{c}{L} \tag{2.10}$$

for the TWD, is used to calculate a resulting blade chord length, c. Then a single track run is analyzed using blade element theory in combination with the single streamtube theory as described in Section 2. This analysis gives the average available power and drag for given target schedules.

Figure 2.4 shows the operational characteristics assigned to the TWD with track acceleration fractions of 40% (left side) and 100% (right side). In the top panels, the blade velocity and acceleration profiles are shown, along with the resulting total relative flow magnitude, assuming the the freestream wind, V_{inf}, is 6 m/s and is perpendicular to the blade track. The exact velocity schedule including the maximum speed, track length, and time to reach full speed, will be a matter of future consideration, and must include practical as well as aerodynamic considerations. The middle panels in Figure 2.4 show the target angle of attack, α, and the resulting blade setting angle, τ, relative to the track required to achieve the angle of attack, where 0 degrees has the blade pointing into wind. The bottom panel shows the total force, mass times acceleration, required to accelerate the blade (assuming a mass of 50000 kg, which is an approximate value taken from an overview document provided by Ranger Innovations), plotted with the resulting aerodynamic force, F, available from the motion of the blade through the wind. Assuming that adequate driving force can be provided to the blades, the mass affects the magnitude of the driving force and the stresses the blade must withstand, but not the performance. The difference between the inertial "force" and the system and the available aerodynamic force, given by

$$F_{gen} = ma - F \tag{2.11}$$

is the force that must be either provided (in the case of blade acceleration) or extracted from the system (in the case of constant speed and deceleration) by the generator/motor system. In this equation, friction and other system losses are neglected. This analysis assumes that any energy added to the system during acceleration can be recuperated during deceleration by regenerative braking, which leads to the result that the difference in power generated is equal to the available aerodynamic power. The optimization of this requires a more complicated analysis, however in an ideal sense, it is safe to say that the faster the blade is accelerated to V_{max}, the better, since this maximizes the available aerodynamic power. This is one reason why the blades are assumed to be driven rather than allowed to accelerate passively to driving speed by aerodynamic forces alone. Another reason is that passive acceleration requires a longer track to achieve the same performance.

Figure 2.5 shows how the power curve varies with effective solidity and track acceleration fraction. The top panel, which shows the effect of solidity, demonstrates that high solidity (σ = 0.25) turbines can potentially achieve power coefficients on the order of C_P = 0.45 at tip speed ratios that are on the order of λ = 2. This condition has traditionally offered two challenges. First, the peakiness of the power curve makes the turbine very sensitive to tip speed ratio, which can change rapidly and often with turbulence and gusts in the wind. Therefore a turbine with lower solidity and lower theoretical efficiency is likely to outperform on a the basis of total energy extract from the wind. Secondly, the rotational speeds required by standard generators are typically much higher than those given by rotational wind turbines operating at tip speed ratios around 2. For this reason, modern horizontal and vertical axis wind turbines are designed to operate at tip speed ratios on the order of λ = 6 or 7. Whether this presents an operating challenge for the TWD remains to be seen. The bottom panel in Figure 2.5 shows the variation in the non-dimensional power curve as a function of track acceleration fraction. As might be expected, the smaller the track acceleration fraction, the higher the maximum power coefficient. This is because maximum power is generated during more track travel. The fact that this maximum occurs at a lower tip speed ratio is a function of the fact that lower track acceleration fractions have higher average drag across one track cycle, and therefore through the single streamtube theory, the flow deceleration at the disc due to the flow momentum change is manifested at slower blade speeds relative to the oncoming wind.

Optimization of the many operational parameters is a task yet to be completed, however the forgoing analysis shows the range of power coefficients available in a typical manifestation of the concept. For context, dimensions of the TWD that could correspond to representative values of solidity, track acceleration fraction, and tip speed ratio at a wind speed of 6 m/s are given in Table 2.2. Each row corresponds to the system geometry at the operating condition given by the maximum of each curve shown in Figure 2.5. Of particular interest should be the track length that is required to meet the specified solidity, track acceleration fraction, and tip speed ratio. In many cases, tracks on the order of 1 km are required; the feasibility of this will need to be demonstrated. Additionally, the feasibility of the required tip speed should be

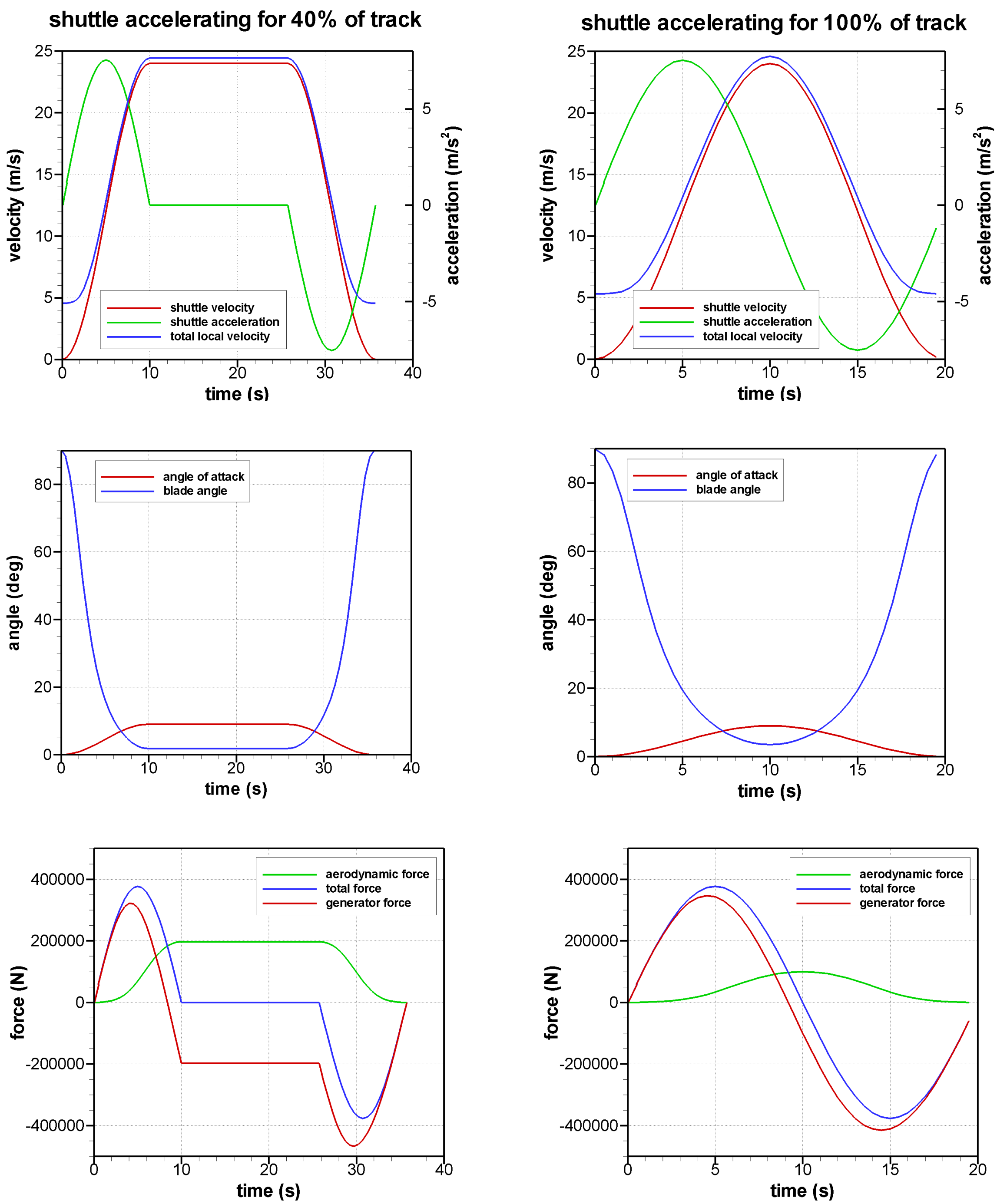

Figure 2.4: Operational characteristics for one cycle of blade travel.

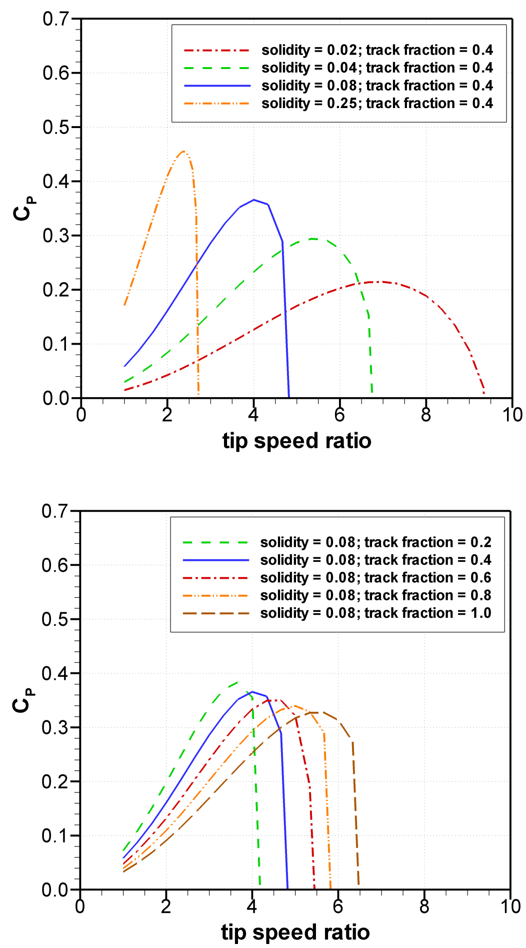

Figure 2.5: Non-dimensional power curves for the Translating Wing design.

Table 2.2: Representative dimensions for the TWD.

solidity	track accel fraction	tip speed ratio	tip speed (m/s)	track length (m)	chord (m)	height (m)
0.02	0.4	7	42	1051	21	100
0.04	0.4	5.3	32	801	32	100
0.08	0.2	3.7	22	1101	88	100
0.08	0.4	4	24	601	48	100
0.08	0.6	4.7	28	467	37	100
0.08	0.8	5	30	375	30	100
0.08	1	5.6	34	340	27	100
0.25	0.4	2.3	14	350	88	100

demonstrated.

The rotating nature of the blade introduces the possibility that dynamic stall effects can be used to slightly increase the total available aerodynamic lift. This phenomenon has been the focus of other oscillating wing WECS (McKinney and DeLaurier, 1980). In the case of the TWD, the reduced frequency, which is given by

$$k = \frac{\Omega c}{2V_{inf}} \tag{2.12}$$

where Ω = 0.314 rad/s based on 20 seconds to complete one cycle giving a reduced frequency on the order of 0.5 for a blade chord of 20 m and a freestream wind speed of 6 m/s. This reduced frequency (above 0.05) implies that unsteady effects could be at play. The use of this phenomenon must be considered in combination with the track acceleration fraction, since this unsteady effect cannot be sustained at constant angles of attack.

This limited analysis shows that the TWD has the potential to produce power at levels and at tip speed ratios that are comparable with theoretical VAWTs for a given turbine swept area.

3. Conclusions

Based on a first-order single streamtube analysis, both the Large Circle Design (LCD) and Translating Wing Design (TWD) variations of Ranger Innovations' large scale track-mounted WECS concept have the potential to produce electricity. Both concepts are based on sound aerodynamic principles that have been proven at smaller scales than those proposed by Ranger Innovations, Ltd. This report also provides design information for both concepts. For both concepts, non-dimensional power curves have been provided, along with example turbine sizes that could correspond to each performance curve. This information is intended to aid in the design optimization by providing a starting point for design, especially from the point of view of feasibility. Additional information is provided for the LCD by referencing work that has already been completed on VAWT blade articulation that is applicable to the LCD. For the TWD, an additional design parameter, the track acceleration fraction, that is not traditionally used in the analysis of WECS has been proposed. Incorporation of this parameter into the design process will aid in the development and optimization of the concept. Finally, when the practical issues listed in this report are addressed and a detailed design has been determined, then a more detailed aerodynamic analysis should be completed.

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