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Shroud Design Criteria for a Lighter than Air Wind Energy System

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Abstract. Airborne Wind Energy (AWE) is a novel form of wind energy research looking to utilize the greater wind resource at higher altitudes. This paper focuses on a lighter than air system developed by Altaeros Energies. Using two force ratios the relationship between the buoyancy and aerodynamic force is related to the geometric parameters of the shroud. A dependence on a so-called area ratio is also shown relating the shrouds area to the shrouds throat area used as a reference for aerodynamic calculations. This ratio was varied in simulation and was found to have a marked effect on the driving forces over the shroud. Finally, an investigation into whether helium or hydrogen should be used for this application is shown. It is found that the design of the shroud has to be aerodynamically optimized for successful operation and that the choice of which gas to employ becomes one of safety rather than enhanced performance.

1. Introduction

In 2012, wind energy had increased its overall installed capacity to 11% up from 2% in 2000 [1]. As conventional horizontal axis turbines continue to mature, a greater understanding is developed of key components and operational strategies of the system. However, on a smaller scale (2kW – 200kW) there exists an opportunity to develop a bespoke system that will alleviate the dependence on both the tower and foundations. This new field of wind energy research is known as Airborne Wind Energy (AWE). These systems use tethers to attach an aerofoil to ground and are designed to attain heights varying between 100 – 600m depending on tether length. At these higher altitudes the wind profile is more consistent and less turbulent than at lower altitudes. A recent study demonstrates this as the measured wind power density was 4 times greater at a height of 500-1000m than that taken at ground level [2].

This paper will focus on one key design challenge associated with a lighter than air wind energy system. The challenge is to characterise the interaction between the buoyancy and aerodynamic forces on the shroud and rotor through the development of two force ratios that relate the buoyancy and aerodynamics to the parameters of the shroud. Over the operating envelope there is a change in dynamics from buoyancy driven behaviour at low wind speeds to aerodynamic driven behaviour at high wind speeds. This force ratio helps to characterise these transition points and allows an assessment as to whether there is any advantage to using a particular type of buoyant gas. This differs from existing literature in Airborne Wind Energy, which is predominately based on kite and rigid body applications and extends the work of Chris Vermillion in [3] to further characterise the main driving forces on a lighter than air system. The paper is broken up as follows. **Section 2**, will introduce the lighter than air system developed by Altaeros Energies. Two force ratios will then be developed in **Section 3** which relates the geometric parameters of the shroud to the three main driving forces. **Section 4** will examine the stability of the shroud as a consequence of these driving forces and a conclusion and summary will then be provided in **Section 5**.

2. A Lighter than Air Concept

The new lighter than air system developed by Altaeros Energies, substantially differs in design and operation from other types of AWE systems [4]. The Altaeros system is comprised of three main components. A buoyant shroud with a standard turbine rotor fixed within its shell, 3 tethers connecting the system to ground and a rotating base station that has 3 independent motor winches regulating tether length [3]. One tether is made with an electrically conducting material to facilitate energy transfer to ground. An illustration of the system is shown in Figure 2. During normal operation the shroud remains stationary and altitude, pitch and roll control is employed to regulate the shrouds position and facilitate optimum energy capture. Currently, the system operates whilst stationary in the air i.e. the flight path is not cyclical. This compares favourably with the rigid body and kite applications as dynamic control is not required [4]. However in a general sense, there are still major challenges to address with each system to make it competitive within the wind industry. This is fundamentally a cost of energy consideration, as the material for both the tethers and the aerofoil will have to be as light-weight as possible as well as considering the potential fatigue of mechanical fixings and bearings holding the rotor in place. This will add to the operation and maintenance expense and means the overall expense of the system may be greater compared with a standard wind turbine in its current form.

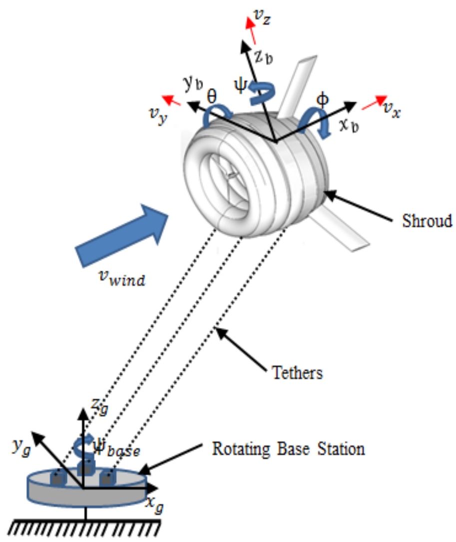

Figure 2. Altaeros Energies System [3]

Figure 2, depicts the Altaeros Energies System showing the shroud and three tethers located at the fore and aft, linking the shroud to the base station. For information on how the system is modeled, please see [3]. This paper focusses on the rationale behind why the shroud will have to be aerodynamically designed to generate lift and what effect this may have on stability and control design. In addition, this paper compares two types of buoyant gas that could be used to fill the shroud. In this case, helium and hydrogen were compared.

Only the three main driving forces will be considered namely; Lift force, Drag Force and Buoyancy Force. These are formulated in equations (1) – (4) below:

$$F_D = \frac{1}{2}\rho_{air}{v_{app}}^2 A_{throat} C_D \tag{1}$$

$$F_L = \frac{1}{2}\rho_{air}{v_{app}}^2 A_{throat} C_L \tag{2}$$

$$F_B = \gamma V(\rho_{air} - \rho_g)g \tag{3}$$

$$\gamma = \frac{\left(V\left(\rho_{air} - \rho_g\right) - m\right)g}{V\left(\rho_{air} - \rho_g\right)g} \tag{4}$$

Equations (1) – (3) show how the drag, lift and net buoyancy force are calculated for the shroud. v_{app} is the apparent wind speed derived as a function of oncoming wind speed and shroud velocity in the x, y and z direction. A_{throat} is the characteristic throat area of the shroud used in the calculation of aerodynamic coefficients through CFD simulations in [3]. C_L and C_D are the aerodynamic drag and lift coefficients respectively, calculated as a function of the inflow angles and turbine angular momentum. For more information on how these coefficients are calculated, see [3]. The buoyancy force is calculated as a function of enclosed volume of gas V and the relative difference between the air density, ρ_{air} and gas density ρ_g, where g is the acceleration due to gravity. It should be noted that in this analysis the density of gas is treated as constant as it is assumed the shroud is fixed at a certain altitude in the air and at a constant temperature. However, in real time the density will fluctuate as a function of both altitude and temperature and this will alter the buoyancy force accordingly.

In equation (3) the buoyancy force is calculated as a function of a so called buoyancy reduction factor γ given in equation (4). This factor relates the total buoyancy force to the total mass of the system m including the mass of the shroud, rotor, mechanical fittings and tethers. This results in F_B being computed as the net buoyancy force acting on the system.

3. Shroud Design

As the wind turbine rotor is fixed within the shrouds structure, the shroud must be stable during the standard wind speed range for electricity generation, typically 3.5 – 25 m/s. What is analysed here is how the design of the shroud will directly impact the captured energy in a positive or adverse manner depending on the aerodynamic design. This analysis will determine where in the shrouds operating envelope the buoyancy to aerodynamic transitions take place. This is important from a control perspective as it will help to quantify where in the operational envelope the physical dynamics are likely to change. This is advantageous as the controller could then be designed to mitigate any negative effects this could have on the system.

To do this, let us introduce the concept of two force ratios, one that relates buoyancy to lift and the other that relates buoyancy to drag. The ratio is calculated as a function of either C_L or C_D which is calculated at a fixed angle of attack that can be varied for each calculation. The fixed angle of attack is assumed to be the pitch angle of the shroud θ shown in Figure 2. The shroud is assumed to be cylindrical so that the volume is calculated as a function of the shrouds area and length. Although, this does not exactly match the physical design, it is seen as a good approximation. The two force ratios are shown in equations (4) and (5).

$$\frac{F_B}{F_L} = \frac{2l\gamma g}{{v_{app}}^2 C_L}\left(1 - \frac{\rho_{gas}}{\rho_{air}}\right)\left(\frac{A_{shroud}}{A_{throat}}\right) \tag{4}$$

$$\frac{F_B}{F_D} = \frac{2l\gamma g}{{v_{app}}^2 C_D}\left(1 - \frac{\rho_{gas}}{\rho_{air}}\right)\left(\frac{A_{shroud}}{A_{throat}}\right) \tag{5}$$

It can be seen from equations (4) and (5) the ratio of buoyancy to drag/lift will vary inversely with the apparent wind speed squared. It can also be deduced that the amount of buoyancy force produced will be directly proportional to the relative difference between the density of gas used and the density of air, in addition to the length of the cylinder l. There is also a dependency on total system mass shown through the buoyancy reduction factor γ. If the mass of the tethers, rotor and mechanical fittings is large then the net buoyancy force will suffer as a consequence. This indicates why the system mass must be kept to an absolute minimum. This is done by using lightweight materials for the tether such as kevlar or vectran composites and high tech material for the shroud. The compromise is that these newly manufactured materials for the shroud and tethers tend to be expensive because of their mechanical properties and thus the overall system cost is increased.

These force ratios provide an opportunity to assess the impact of a particular shroud geometry on the driving forces over the shroud in relation to a fixed system mass. This is quantified in the area ratio $\frac{A_{shroud}}{A_{throat}}$ which relates the shrouds outer area A_{shroud} to its characteristic area A_{throat}. Looking at equations (4) and (5) it can be seen that the ratio of areas will have a direct impact on the aerodynamics. A large ratio will imply poor aerodynamics as the throat area A_{throat} is reduced in comparison to the shrouds area A_{shroud}. This is compared to good aerodynamic performance which would mean that A_{throat} is large compared to A_{shroud}. Therefore, equations (4) and (5) can be used to investigate how varying the different physical parameters of the shroud could impact the three main driving forces. The parameters that were used for this simulation study are shown in **Table 1**.

Table 1. Simulation Parameters

Parameters	Value
ρ_{helium} – density (kg/m^3)	0.1664
$\rho_{hydrogen}$ – density (kg/m^3)	0.0899
l – shroud length (m)	10
m – System Mass (kg)	400
θ – Angle of Attack (degrees)	10

The angle of attack (or pitch) of the shroud was fixed at 10 degrees, considered to be optimum for the shroud [3] and the lift and drag coefficients were calculated as a function of this angle [5]. In addition, the type of gas used to fill the shroud was varied to investigate the difference in performance. This will give an indication as to what improvement can be made with a particular gas and what the main factors are behind the choice of a particular gas. The two gases compared were hydrogen and helium and the gas density ρ_{gas} in equations (4) and (5) was changed to investigate its impact.

The simulation was conducted for 3 different area ratios to illustrate how the geometry of the shroud will affect performance. **Figure 3** shows the force ratios for both hydrogen and helium taken at different values of area ratio. When the force ratio is equal to 1, the buoyancy and aerodynamic force are balanced. This is indicated by the constant black line and the following relationships hold when interoperating the figure.

$$\frac{F_B}{F_{L,D}} < 1 \; - \; Aerodynamics\ dominate \tag{6}$$

$$\frac{F_B}{F_{L,D}} > 1 - \; Buoyancy\ dominates \tag{7}$$

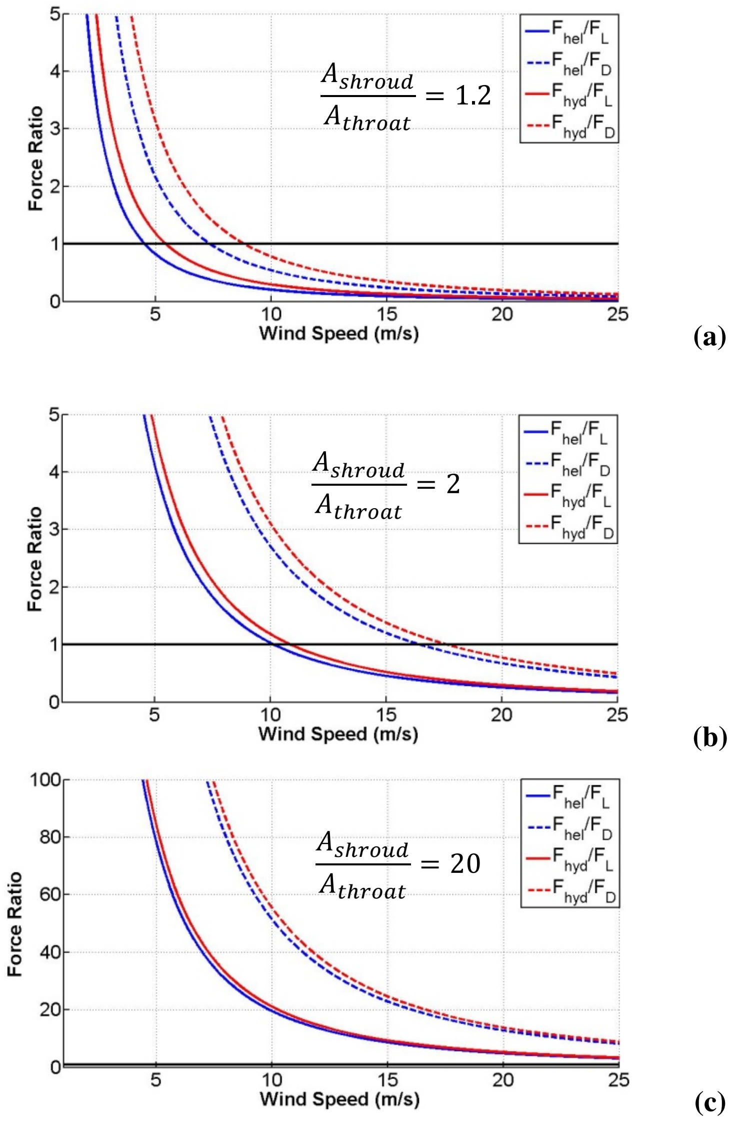

Figure 3. Force Ratio vs Wind Speed (m/s) with varying Area Ratio

Figure 3 (a,b,c) shows three separate scenarios showing the impact that a particular type of gas will have on the system along with a varying area ratio $\frac{A_{shroud}}{A_{throat}}$. The results are listed compactly in Table 2 for comparison:

Table 2. Helium and Hydrogen Shroud Transitions with varying Area Ratio

	Helium	**Hydrogen**
Area Ratio = 1.2		
Buoyancy – Lift Transition	4.55 m/s	5.44 m/s
Buoyancy – Drag transition	7.36 m/s	8.8 m/s
Area Ratio = 2		
Buoyancy – Lift Transition	10.15 m/s	10.88 m/s
Buoyancy – Drag transition	16.47 m/s	17.63 m/s

Table 2 shows the transition points for a hydrogen and helium filled shroud at two different area ratios. At an area ratio of 20 (**Figure 3c**) it is seen that there is no transition point between buoyancy to aerodynamic behaviour therefore it has been excluded from **Table 2**. This implies the area of filled gas is now 20 times greater than the reference area used for aerodynamic calculations. This means that the lighter than air structure is now dominated by buoyancy, with the aerodynamics rendered inconsequential to the overall driving force on the system. If the ratio $\frac{A_{shroud}}{A_{throat}}$ were to increase even further the buoyancy force will become even more dominant and move increasingly away from the transition point defined at $\frac{F_B}{F_{L,D}} = 1$.

From Table 2, the transition points for hydrogen are seen to be marginally higher than those for helium. Hydrogen will produce approximately 7% more buoyancy force per volume than helium therefore this difference is to be expected. The aerodynamic lift force begins to dominate at low wind speeds because the shroud is fixed at its optimum angle of attack of 10 degrees and the aerodynamic force increases with square of the apparent wind speed v_{app}. Comparing **Figures 3a** and **3b** shows that at a ratio of 2 the shroud is dominated by buoyancy for longer. There is a shift in transition points of 5.6 m/s for lift and 9.11m/s for drag in the case of helium compared with similar shifts of 5.44 m/s and 8.33 m/s for hydrogen. This analysis illustrates that the geometric design of the shroud will have an impact on the driving forces within the operating envelope of the shroud. This is quantified through a defined area ratio relating the area of the shroud and the characteristic area used for aerodynamic calculations. Altering the shroud geometry will therefore have a significant influence where the transition points between buoyancy and aerodynamic behaviour take place.

4. Stability

If the physical design of the shroud is considered without the influence of an aerodynamic design i.e. $F_L = 0$, then the impact of on system stability could be severe. From the analysis above, the shroud would become susceptible to drag within a wind speed range of 7.34 m/s up to 17.63 m/s if the area ratio was fixed at any point between 1.2 and 2. These winds speeds are within the operational range of the wind turbine rotor fixed within the shroud. Therefore, if the system is dominated by aerodynamic drag then it will adversely affect energy capture and move the system to an inefficient and unstable position.

To emphasise this point lets introduce a blowdown angle shown in **Figure 4**, which relates the total drag force to lift force from the zenith position this is calculated using equation (8).

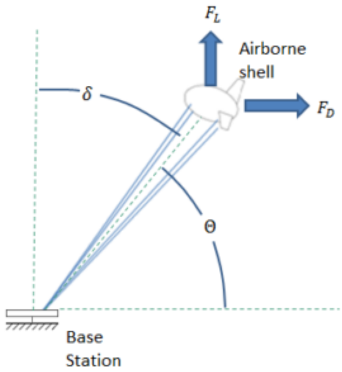

Figure 4. Blowdown Angle as a result of net lift and drag force [6]

$$\delta = \tan^{-1}\left(\frac{F_D}{F_B + F_L}\right) \tag{8}$$

If the shroud is not aerodynamic then $F_L = 0$ and the shrouds angle will only be related to the buoyancy and drag force on the shroud. However, if the shroud is designed to produce aerodynamic lift then $F_L \gg 0$, which will subsequently reduce the blowdown angle relative to the origin. A ratio of 1 will imply a force balance and this equates to an angle of 45 degrees from the zenith. Above 45 degrees, drag will dominate and the angle from the zenith will increase as a function of wind speed. Therefore, the system is considered to be unstable above 45 degrees and stable below 45 degrees. This is shown in **Figures (4)** and **(5)** where the effect of adding aerodynamic lift is investigated. The simulation was again been conducted for a shroud filled with helium and hydrogen and results are shown for an area ratio of 1.2.

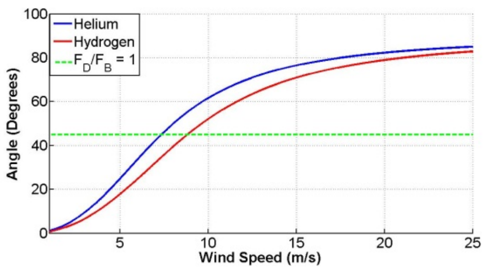

Figure 4. Blowdown angle with no Aerodynamic Lift relative to wind speed

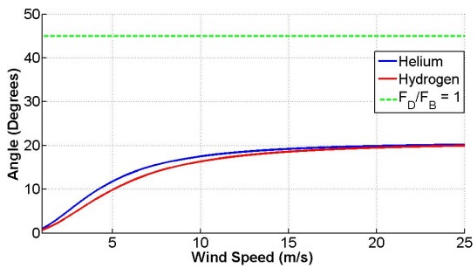

Figure 5. Blowdown angle with Aerodynamic Lift relative to Wind speed

From **Figures 4** and **5** the effect of including aerodynamic lift can be seen for systems filled with helium and hydrogen. **Figure 4** shows the lighter than air system relying purely on buoyancy force as support relative to drag. In the case of helium, at a wind speed of 7.36 m/s, the angle is equal to 45 degrees. Similarly, the transition point for hydrogen occurs at 8.8 m/s. This is verified by **Figure 3a** as it equals the point at which the buoyancy to drag ratio is 1.

The angle relative to zenith continues to rise beyond 45 degrees as a function of wind speed. It can be seen that at a wind speed of 25 m/s the shroud reaches a maximum angle of 85 degrees with Helium and 83 degrees with Hydrogen. This clearly indicates that the system has become severely unstable in both cases. Conversely, **Figure 5** shows that with the addition of aerodynamic lift the stability angle of 45 degrees is never reached in the case of either helium or hydrogen. The maximum angle that each system reaches is 20 degrees. This means that the system remains stable and gives a good stability margin in the operating region of the rotor.

5. Conclusions

This paper provides a brief introduction to AWE and focuses on the system dynamics of a lighter than air application developed by Altaeros Energies. From the results a few key conclusions can be drawn. In **Section 3**, the three main driving forces on the shroud, Lift, Drag and Buoyancy, were related through two force ratios showing a dependency on the shrouds geometric design and overall system mass. Transition points are then quantified to determine at what point across the operating wind speed range the equilibrium will change from being driven by buoyancy to being driven by aerodynamics. For a typical shroud design at an area ratio equal to 1.2 the buoyancy force will only dominate at low wind speeds. However, knowing where these transitions take place for a range of designs is important as the system scales up and from a control perspective. It is also shown in **Section 4**, that if the shroud design was not optimised to produce aerodynamic lift then the lighter than air system will succumb to drag moving the system into an unstable state. Therefore to offset this, the shroud design must produce aerodynamic lift although this this will come at a greater economic expense because the materials will not only have to be lightweight but will also have to be custom built to fit a bespoke aerodynamic design.

Throughout this paper a comparison was made between the impact of helium and hydrogen on system performance. A shroud filled with hydrogen gives higher transition points on account of its lighter density. However, because the system will still succumb to drag within the operating envelop of the rotor, the shroud will have to have an aerodynamic design. The benefit of using hydrogen is that it is much cheaper than helium and more readily available as the price of helium will increase as the resource becomes more and more scarce. However, there are significant safety issues associated with the use of hydrogen as it is highly combustible compared to the inert nature of helium. Unless absolute safety could be guaranteed using anti-static materials, helium would be the appropriate choice for a lighter than air application of this type. Future work will look to characterize the influence of transition points for a range of shroud geometries taking into account the variation in density as a function of altitude and temperature.

Acknowledgements

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