Small wind ram air turbine blade geometric modification for performance

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1. INTRODUCTION

Wind energy is one of the main pillars of renewable energy policy worldwide. Various installations of different size are used from small turbines in urban settings to large off-shore structure. The common with all of them that they fixed to the ground (on shore or seabed) or sometimes on floating platforms. Hence in terms of aerodynamic design extracting maximum power P from the incoming wind is the primary point. The drag experienced by the turbine which (due to historial reasons of being develop from the propeller design) is referred as thrust *T*. It is considered to be less crucial for stationary grounded application and is mainly required for the structural design of the turbine.

However, recently interest has grown at small airborne wind turbines as attached to aircraft or stationary airships in order to provide additional power to the air vehicle, which may transmitted to the ground in case of an airship. We will call this kind of turbine ram air turbine (RAT) [1]. On the face it, such turbine does not make sense as always it is efficiency will be less than one, meaning the loss of thrust for the aircraft due the drag caused by the small turbine will require power compensation from the engine higher than the power the turbine can give the aircraft. However, there are instances when power is so needed and/or slowing down the air vehicle is acceptable in order to get that additional power. Nevertheless, in this concept of extracting power from the wind the drag experienced by the turbine (which we note as *T*) has to be considered as important as the power P. We can normalise both to yield coefficients of power and thrust C_P and C_T respectively as follows:

$$C_P = \mathrm{P}/(0.5\rho \mathrm{AV}^3)\,, C_T = \mathrm{T}/(0.5\rho \mathrm{AV}^2), \tag{1}$$

where ρ is the air density, *A* is the cross-section area covered by the turbine's rotor, V is the incoming wind speed towards the turbine (taken as low enough for incompressible flow assumption).

There has been strong interest to increase C_P using passive or active aerodynamic control means. For example, we can use the simple installation of Gurney Flap (GF) illustrated in Fig 1 named after the F1 race car driver who introduced the flap in 1971 to increase the lift *L* produced by the spoiler of the car. Hence, this small modification has strong potential to increase the power production for a lift based turbine, as our group argued for a vertical axis wind turbine [2].

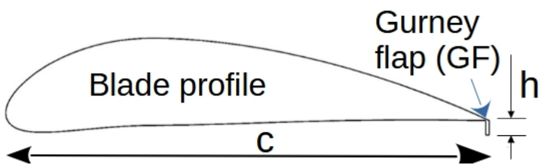

Figure 1, illustration of a Gurney Flap (GF) mounted perpendicular at the trailing edge of the blade profile, where c is the profile's chord length and h is the GF's height.

However, the GF will also increase the drag *D* caused by the profile as surely it will enhance flow separation around the trailing edge (T.E). This does not prevent the C_P to increase due to the GF demonstrated by the following blade element momentum (BEM) analysis and Fig 2 for a horizontal axis wind turbine (as commonly in RAT design). Taking that the resultant force acting in the rotation plane as caused the aerodynamic forces lift *L* and drag *D*: $F_Q = \mathrm{L} \cdot \sin\phi - D \cdot \cos\phi$. Assuming high tip speed ratio $TSR = \Omega R/V$ (see Fig 2 for definitions), linear aerodynamics and a simplistic model of constant drag coefficient C_D we get for the maximum possible C_P [3];

$$(C_P)_{\max} = \frac{\sigma(\mathrm{TSR})^3}{4}[2\phi_t C_{L_t} - C_D], \tag{2}$$

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where

$$C_L = L/(0.5\rho U^2 c)\,,\, C_D = D/(0.5\rho U^2 c)\,,\sigma = b\bar{c}/(\pi R). \tag{3}$$

The speed U is defined in Fig 2, b is the number of blades (b=2 for our RAT) and $\bar{c}$ is the mean geometric chord length of the blade. The subscript t relates to the blade's tip condition where we neglected tip losses in Eq (2).

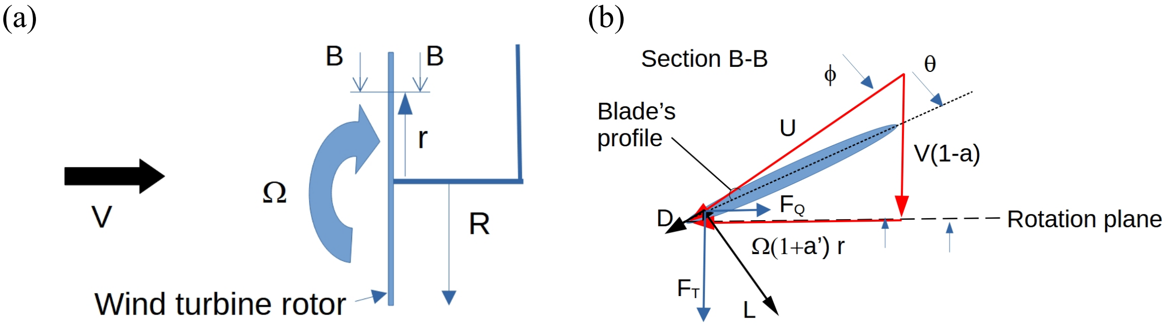

Figure 2, illustration of a blade element method analysis of a horizontal axis ram air turbine (RAT) configuration, where a and a' are the axial and tangential induction factors.

Since the aerodynamic efficiency of a profile C_L/C_D is so high (above 10) then even when the GF causes a higher percentage increase in C_D than in C_L, it will still lead to an increase in C_P by Eq. (2) as long as the flow angle ϕ_t does not change much (it relates to the pitch angle θ_t through a quadric equation). However, the force contributing to the thrust T of the turbine is F_T=L · cosϕ+D · sinϕ by Fig 2 and for TSR>>1, $\phi \ll 1$ rad and thus $F_T \simeq L$. Hence T will increase due an increase in the profile's lift caused by the GF. Nevertheless, if we manage to keep the ratio C_P/C_T as similar to the (clean) configuration without the GF, then increasing C_P using a GF (or any other blade) modification will still be highly useful. This is the aim of this paper. We started looking at this using a combination of 2D computational fluid dynamics (CFD) and BEM for a generic RAT, showing that it is possible to achieve such improvement if the GF is implemented only partly near the blade's hub [1]. Here, we extend this study by using additional wind tunnel test results and known optimisation procedures for the blade's twist angle to maximise C_P.

2. METHODOLOGY

The methodology follows the BEM approach. The aerodynamic forces acting on the blade profile due to the incoming wind were studied using three methods and then were fed into the freeware qblade that calculated the turbine's coefficients C_P and C_T using the BEM method [4]. For the 2D profile aerodynamic calculations we used Xfoil as implemented in qblade [4], computational fluid dynamics (CFD) based on RANS and wind tunnel tests. Xfoil proved itself sufficiently accurate for the clean profile (i.e. with no GF) in pre-stall conditions, while the flow separation around the profile's T.E. caused by the GF led to distortion in the Xfoil's results. The 2D CFD-RANS calculations were pursued using the Ansys software, where a structural C grid was used along with the SST k-omega RANS model. Second order upwind and central schemes were used for the convection and diffusion terms respectively. A velocity inflow condition was used along with a pressure outlet as an outflow condition. The overall computational domain size was (26x26)c, where symmetry conditions were used on the upper and lower sides of the computational domain. Grid point clustering was used near the profile, leading to a y^+<1 for the first grid point above the profile's skin. For further details on this CFD approach, the reader is referred to Ref [2].

The wind tunnel tests were pursed in the open suction wind tunnel AF100. As in the CFD and Xfoil calculations, the Reynolds number was matched with that experienced by the blade's profile. The incoming velocity was measured through a pitot tube and the blade model was put on a balance to measure the lift and drag. The model stretched from wall to wall of the work section, but cautiously it did not touch the walls. This led to a very minor secondary flow through the less than 1 mm gap between the wall and the model (as compared to the model's chord length of 127 mm), which mildly increased the drag. Measurements were averaged along a period of time and repeated several times to remove any temporary fluctuations.

3. RESULTS AND ANALYSIS

A two-blade RAT was studied with the profile NACA8318 [1, 5]. Its geometry and twist angle are illustrated in Fig 3. The chord length *c* was uniform along the blade's span yielding a Reynolds number Re_C (as based on c) varying from about 218k 25% away from the hub to close to 700k near the tip at mid range TSR of about 4. This means the blade exhibits laminar aerodynamics near the hub, while turbulent aerodynamics near the tip.

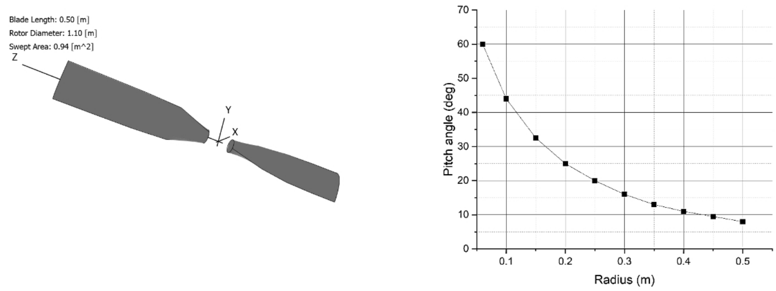

Figure 3, the RAT's studied geometry and its pitch angle variation along the blade's span.

The lift and drag coefficients variations with the angle of attack (AoA) for Re_C=218k which corresponds to the condition of the blade profiterole about 25%*R* away from the hub are shown in Figure 4 for the clean profile and those with GF (where *h*/*c* is noted by its percentage). These are the CFD results. All configurations show a region of linear aerodynamic followed by a stall. The slope of the lift coefficient is mildly below the familiar one for high Reynolds number (~0.1 1/deg) but also the wind tunnel test for the model with GF3% yielded a similar lift coefficient (although mildly higher, pointing to a deficiency of the RANS model at low Reynolds numbers). As Re_C was increased above 400k (making the profile dominated by turbulent aerodynamics) the C_L slope got very close the 0.1 1/deg value. The installation of the GF increases the lift coefficient but also increase the drag. This occurs due to the enhanced flow separation near the profile's trailing edge. It also hastens the occurrence of stall, as relative to the geometric AoA (i.e. as relative to the chord line) shown in Fig 4.

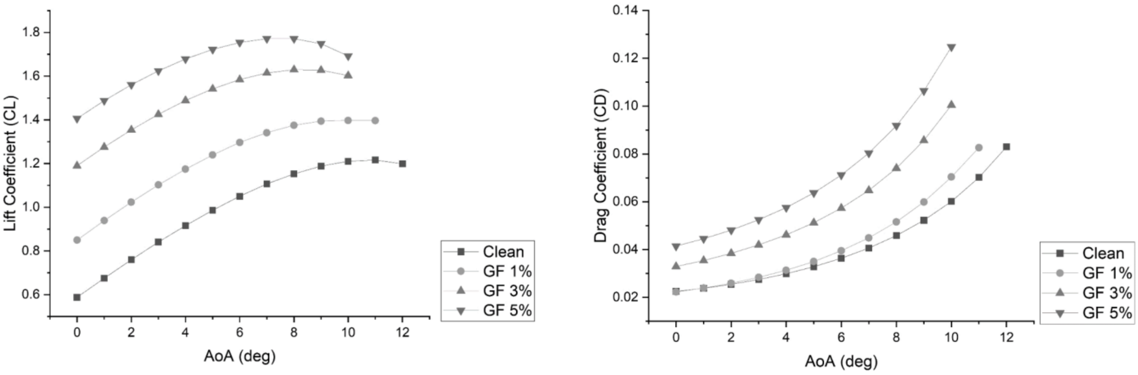

Figure 4, the variations of the lift and drag coefficients with the angle of attack (AoA) for the clean NACA8318 profile and its modifications with installed GF, where the GF height to chord length ratio (h/c) is noted in percentages and Re_C=218k. The results were produced using CFD-RANS.

To better understand the effect of the GF, we show the flow contours around the clean profile and its modified version with GF 3% at AoA=9 deg. Both profiles show noticeable flow separation near the trailing edge, but the one with the GF has a larger flow separation above the upper surface and also a small flow separation on the lower surface just in front of the GF. This results in a longer wake of flow separation beyond the profile and hence the higher drag coefficient, and earlier stall caused by the GF. Nevertheless, one should note that at low AoAs < 4 deg, all the profiles with GF modification showed higher aerodynamic efficiency (C_L/C_D) than the clean profile (i.e. no GF modification)

Finally, we present in Fig 6 the variations of C_P and C_P/C_T with TSR. It is seen that when using GF of 3% the TSR of the maximum C_P increases as well as the value of C_P. Hence, the ratio of C_P/C_T can also increase. Furthermore, the original configuration of the RAT [5] as illustrated in Fig 3, seems to have been

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optimised for its twist angle (yielding a variation close to $1/r$ as seen in Fig 3), but not for its chord length variation. Using the Betz BEM optimisation algorithm [4] we managed to further improve the C_P and C_P/C_T behaviours for TSR around 4.

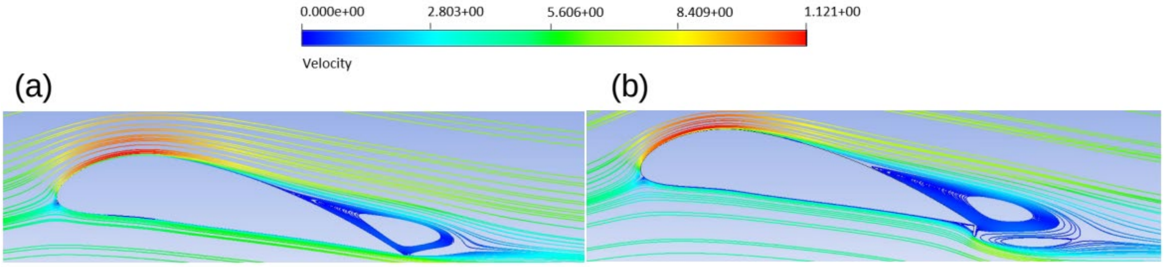

Figure 5, the flow regime around (a) the clean NACA8318 and (b) its modification with GF h/c=3% at AoA=9 deg as computed by the CFD-RANS and where the rest of the conditions are as in Fig 4. The velocity magnitude values have been normalised.

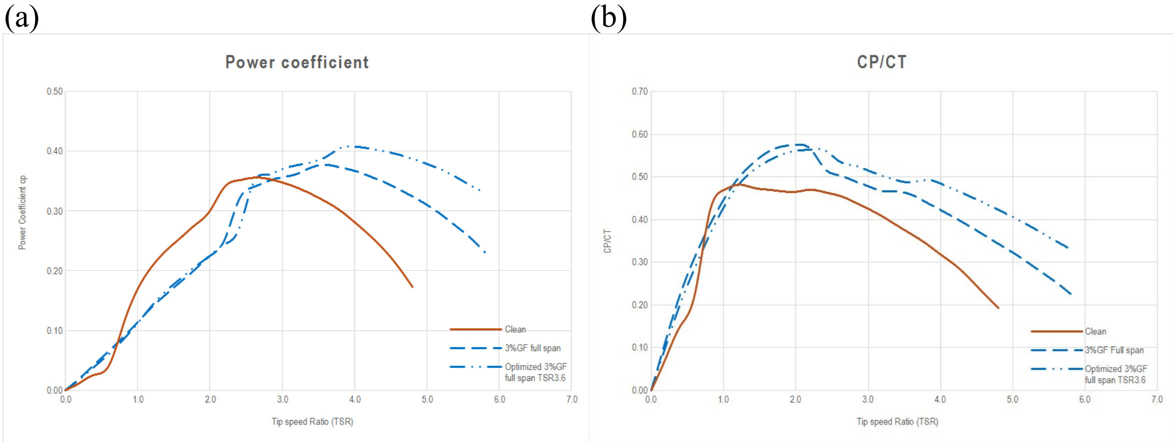

Figure 6, the variations of (a) C_P (b) C_P/C_T ratio with TSR for the original RAT configuration and its modification with GF installation of h/c=3% along with a Betz-BEM optimisation around TSR=3.6.

4. CONCLUSIONS

A small horizontal axis wind turbine was studied for its aerodynamic performance in context of its power P production and also thrust T (i.e .the actual drag it causes). It was argued that while in terrestrial implementations the importance is usually put on P and T is mostly important for structural considerations, T becomes as important as P for performance in airborne installation. It was also argued that enhancing P by increasing the lift produced by the blade will also very likely increase T. Hence, the focus of the aerodynamic design should be on the coefficient C_P and the coefficients ratio of C_P/C_T. It was shown that a Gurney flap (GF) installation has the potential to increase C_P and also C_P/C_T which can be attractive for further design. Further experimental tests and computations will be carried out to verify these results and also study other variations of GF as slotted ones.

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