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Computational study on novel circulating aerofoils for use in Magnus wind turbine blades

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In most efficient aerofoil sections used in wind turbine blades, the maximum lift to drag ratio hardly reaches 200. Our research obtained higher lift by employing the Magnus effect obtained by circulating symmetrical geometries. First the research study reviews the literature of Magnus effect for circulating cylinders, presents recent progress on BEM (blade element momentum) modelling, and highlights the importance of lift to drag ratio in both Magnus and conventional aerofoil type wind turbine blades. Magnus effect can be produced by a circulating surface of symmetrical aerofoils. However, neither experimental nor computational studies are found in literature for circulating aerofoils. Subsequently, this text presents, a high-resolution computational solver, based on finite-volume TVD (total variation diminishing) scheme, to solve fluid flows around symmetrical NACA0015 aerofoil, where the results are validated against a widely used experimental data. Finally, the circulating NACA0015 aerofoil with various surface treadmill speeds is investigated at different incident angles. The computational results reveal that the lift increases while drag decreases in all cases. The significant lift to drag ratio of 278 is obtained at dimensionless treadmill speed of 2 at incident angle of 10°. The flow features around this circulating aerofoil, along with the need for additional experimental research, is described.

1. Introduction

The first successful device based on Magnus effect returns to the year 1924, when Anton Flettner has manufactured his first ship, Buckau, operating with Magnus force with operating two vertical rotating cylinders [1]. The potential of producing high lift forces then attracted many researchers in aeronautics. Many reported patents were appeared in the areas of naval or aerospace applications based on using Magnus forces [1]. In parallel, many research works were conducted on determining aerodynamic forces from the rotating cylinders both experimentally and numerically [2–9].

The renew attention in the Flettner type rotor is becoming again a hot topic in naval engineering due to the increase in fuel costs and environmental concerns. Seifert [1] has extensively reviewed the application of Magnus forces in aeronautics who believes that there are no specific methods available for designing lifting devices using Magnus effects. This is particularly observed on works reported on Magnus wind turbines.

The purpose of this study is to introduce the circulating aerofoil for use in Magnus type wind turbine. The manufactured or experimented Magnus wind turbines are reviewed in Section 1.1. Then, the outcome of some numerous experimental and computational results on lift and drag forces of rotating circular cylinders are summarized in Section 1.2. Next in Section 1.3, the power capture of the Magnus wind turbines is presented based on the extended BEM (blade element momentum) analysis for rotating cylinders. Section 2 deals with the concept of circulating aerofoil-Magnus type wind turbine. In Section 3, the CFD (computational fluid dynamics) method is described and the corresponding CFD results for the circulating symmetrical NACA0015 aerofoil are presented in Section 4. Section 5 concludes discussion of the results.

1.1. Manufactured Magnus type wind turbines

Bychkov [10] reports on an experimental methodology for optimising a Magnus wind turbine with rotating cylinders. Bychkov

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[10] believed that the optimal Magnus type wind turbine should possess 6 rotating cylinders with high aspect ratio of 15 and with high rotational speeds of 8000 rpm. He also believed that his Magnus wind turbines can compete with the conventional wind turbines at low air speeds below 8 m/s. Moreover, his findings suggest that Magnus wind turbines can operate at low cut-in wind speeds of 1–2 m/s which is advantageous for sites with low wind speeds.

More recently, Murakami and his co-workers in Japan [11,12] have patented two Magnus type wind turbines with 6 and 5 rotating cylinders. These wind turbines use some spiral ribs along the cylindrical blades. The wind turbines have been manufactured in Japan by Mecaro Co. [13]. In the new design patented in 2010, Murakami indicated that their 5 bladed Magnus wind turbine now produces 3 kW electrical power at the rated wind speeds of 8 m/s and operate at cut-in wind speeds of above 4 m/s. No data were given for higher wind speeds than 8 m/s; although, the rotational speed is given to be 1080 rpm [12].

Giudice and Rosa [14] has also designed and prototyped a chiral blade system. Their experimental testing of low velocity flow is combined with some simple analytical approach based on the ideal two-dimensional potential flow solution. They suggested that their chiral blade system can be efficiently used in micro hydro or aero generation.

Komatinovic [15] has extensively investigated several Savonius-type Magnus wind turbines both using CFD and experiment. By studying various Savonius configurations using 2D CFD simulations, Komatinovic has manufactured five most promising prototype blade models. Wind tunnel tests then were performed to measure torque and rotational speed of the wind turbines using different sets of 2, 3, 4, and 5 bladed wind turbines. Experiments were performed extensively over various ranges of wind speeds; however, no measurements were reported to express the lift to drag ratio of each blade section. The power capture of all tested wind turbines was very low and usually less than 0.1.

Sedaghat [16] has extended the potential and BEM theories for designing Magnus type cylindrical wind turbines. His extensive parametric studies revealed that the drag to lift ratio is the most crucial factor on developing any type wind turbine blades. The BEM theory requires lift and drag forces of two-dimensional aerofoil cross sections for each elemental constitute of the wind turbine blade. Hence, the theory is valid for any aerofoil shape because lift and drag coefficients are usually obtained from wind tunnel testing of two-dimensional aerofoil cross sections.

Likewise, the extended BEM theory [16] developed for Magnus type cylindrical wind turbine blades is also exactly valid for any shape cross section of circulating aerodynamic bodies. Experimental works on two dimensional circulating cylinders in wind tunnel test was reported in Ref. [16]; however up to this date, there is no evidence of testing two-dimensional aerofoil sections with surface circulation in wind tunnels nor any CFD simulation was reported.

There are vast literature on obtaining lift and drag of two-dimensional aerofoils either in wind tunnels or by CFD simulations; but, if the surface of the same aerofoil is circulated at different treadmill speeds then the results of lift and drag forces will be considerably different from the same aerofoil at fixed surface due to the Magnus effects. It is also difficult and expensive to measure lift and drag of symmetrical aerodynamic shapes with circulating surface in wind tunnels; therefore, it would be preferred to use reliable CFD methods for calculating lift and drag of two-dimensional circulating aerofoil cross sections at different circulating speeds and angle of attacks. Computation of circulating aerofoils is new and has not been reported elsewhere in literature. Moreover, the results of lift and drag of circulating aerofoil will be an input to the BEM extended theory to determine power performance of the Magnus type wind turbine blade.

1.2. Studies on flows over circular cylinders

Fluid dynamics of flows around spinning cylinders are fascinating due to many interesting features observed particularly in the wake region. It is understood that the most important factors influencing the flow regime are characterised by the Reynolds number $\mathrm{Re} = U_\infty D/\upsilon$ and the spinning ratio $\omega' = \omega D/2U_\infty$ [1]. Reid [2] conducted experimental research on rotating cylinders at the leading edge of wings for enhancing lift of wings in 1925. He observed that lift force was considerably increased at high rotational speeds of the cylinder up to 3600 rpm at various wind speeds. Perhaps it was Ingham [4] that reported the first computational solutions of flows over rotating cylinders in 1983. He studied the viscous effects of flows over rotating cylinders at very small Reynolds numbers. Later, Mittal and Kumar [5] studied two-dimensional incompressible flows over spinning circular cylinder at Reynolds number of 200. They defined a dimensionless spin ratio ω' varied between 0 and 5 to visualize flow features around the spinning cylinder. They observed vortex shedding at spinning ratio below 1.9; i.e. $\omega' < 1.91$. By increasing the spin rates, flow becomes steady until spin ratio of 4.34 where it becomes again unstable within the range of $4.34 < \omega' < 4.70$. High lift coefficients were obtained at high spin rates; but, the power consumption was rapidly increased too.

Historically, Prandtl believed that there is a limit, called as equilibrium state, which occurs at $\omega' = 2$, for spinning cylinders. At this limit, the maximum lift value of $C_{L_{\max}} = 4\pi \approx 12.6$ cannot be exceeded. However, Tokumaru and Dimotakis [6] conducted experimental and numerical research on spinning cylinders which suggested that unsteady effects can increase the maximum lift limit at higher aspect ratios and higher spinning speeds. In practical situations, further experimental and numerical works by Refs. [6,7] suggested a proper range of spinning rates, i.e. $2 < \omega' < 4$, at high range of Reynolds numbers $4 \times 10^4 < \mathrm{Re} < 6.6 \times 10^5$, to enhance lift while keeping drag coefficient low. Further studies on spinning cylinders revealed that the monotonic increase of lift coefficient over the rotating cylinders will be halted because of instabilities, 3D effects, or centrifugal forces at high Reynolds numbers and high spin rates [8,9].

It is well understood that the magnitude of the lift and drag forces and also friction torque depends on the Reynolds number and the spinning ratio [1,9]. A correlation based on a number of experimental and numerical results was introduced by Sedaghat [16] for lift to drag ratio of spinning circular cylinders at different spinning ratios as follows

$$\frac{C_L}{C_D} = \frac{-0.01355 - 0.4065\omega' + 1.2944\omega'^2 + 0.2249\omega'^3 - 0.09632\omega'^4}{1.0631 - 0.9137\omega' + 0.4694\omega'^2} \quad (1)$$

Here, lift and drag coefficients are defined as:

$$C_L = \frac{F_L}{\frac{1}{2}\rho_\infty A U_\infty^2}, \quad C_D = \frac{F_D}{\frac{1}{2}\rho_\infty A U_\infty^2} \quad (2)$$

In Equation (2), F_L is the lift force, F_D is the drag force, ρ_∞ is the air density, A is a reference area taken as the cylinder diameter, D, times the unit length, and U_∞ is the freestream wind speed. Relation (1) is compared with the experimental works [17] and numerical results of [8] in Fig. 1. As observed, the lift to drag ratio possess maximum value of $C_L/C_D = 4.3$ within the range of