NUMERICAL STUDIES OF AUTOROTATING MAGNUS CYLINDER SHAPES THAT AID THE STARTING OF MAGNUS VERTICAL-AXIS WIND TURBINES

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Abstract

The Magnus vertical-axis wind turbine (M-VAWT) is a variant of the articulating straight-bladed version (Giromill). The articulating straight blades have been replaced by rotating Magnus cylinders which produce powerful lifts that could exceed by an order of magnitude those produced by standard aerofoils. These Magnus vertical-axis wind turbines are ideally suited for operation in hostile wind environments because of their special features. However, for the wind turbines to be self-starting, the Magnus cylinders need to possess the property of autorotation. The aerodynamic characteristics of autorotating Magnus cylinders have been investigated.

Introduction

Magnus-effect based small, vertical-axis wind turbines (M-VAWT) are being developed to address the urgent Indian need for small, rugged wind turbines for electric power generation and battery charging. M-VAWTs can operate in complex terrains and can effectively harness turbulent gusty winds blowing from any horizontal direction as well as non-horizontal winds, within limits. An M-VAWT (Fig 1) consists of a multiple rotating Magnus cylinder array, which itself rotates about a common aligned vertical axis, driving a rotor/power shaft through a planetary gear arrangement.

The Magnus lift effect is an aerodynamic phenomenon resulting from the rotation of an object in a flowing air stream. The Magnus effect is often explained using theoretical hydrodynamics as the superposition of the flow field from an ideal vortex in the cylinder with a uniform free stream flow. This is for inviscid flow with no viscosity, even though this is the real cause of the circulating flow (Ref 1). Like in an aerofoil, the Magnus lift is caused by circulation. This powerful Magnus lift could exceed that caused by a standard aerofoil by even an order of magnitude. The Magnus lift can be shown, within limits, to vary linearly with the spin ratio as can be derived from the Kutta-Joukowski law. However, the Magnus effect occurs only if the cylinder is rotating. Then the question arises as to how a Magnus wind turbine can start unless the cylinders start rotating independently. Vertical axis wind turbines are notorious for their starting difficulties. A Magnus wind turbine fitted with autorotating cylinders would solve the problem of self-starting.

Autorotation is essentially associated with vortex shedding and hence there are considerable theoretical difficulties in the analysis. For bodies autorotating parallel to the flow, the rate of autorotation is essentially constant whereas for autorotation at right angles to the air stream, the rate is periodic (Ref 2). There are indeed cylinder shapes (Fig 2) that do possess this property because of their advantageous wake flow structures (Refs 2-6). Circular cylinders cannot autorotate. A computational and experimental study of the autorotation of promising Magnus candidates was carried out. The specific issues addressed were whether the shape could autorotate and if so what would be its lift, drag and moment co-efficients.

Keywords: Vertical-axis wind turbine, Magnus effect, Autorotation, Torque co-efficient, Smoke-flow visualisation.

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Results and Discussions

Numerical and Experimental Studies

Numerical simulations were carried out using the commercial code ANSYS FLUENT 14. The geometry was modelled in design modeller and meshed in ANSYS Workbench meshing. Pressure based coupled solver was used to model the flow with k-ε as the turbulence model. The rigid body motion of the autorotating body was modelled using 6 DOF model with dynamic meshing. Triangular meshing was used inside the deforming zone adjacent to the body. The time step was chosen carefully to facilitate the re-meshing algorithm to adjust with a change in rigid body motion. The solution was run till a constant angular velocity of the body was achieved. The results were processed in CFD Post. 2D-LES simulations were carried out for computing the Riabouchinsky curve (Ref 4).

The time lapsed (azimuthal angle variation) streamline contours for a self-starting Savonius rotor and a biconvex aerofoil are shown in Figs 3 & 4. The non-dimensional time \( t = t/(D/V) \) where \( t \) is the actual lapsed time since starting from rest, \( D \) the characteristic length (60 mm) and \( V \) the approach velocity (5 m/s). As envisaged, the clear vortical structures that enable the starting ability are seen. Fig 5 shows the aerodynamic characteristics of typical Magnus candidate cylinders. The near linear variation of the lift co-efficient with the spin ratio, as can be derived from the Kutta-Joukowski law is seen. The Kutta-Joukowski law states that the lift force per unit cylinder length is independent of the rotating cylinder size and shape. This too is seen to be borne out in the lift co-efficient graph. \( C_L/C_D \) is seen to peak at a spin ratio of 2 which was as expected.

Fig 6.a shows the variation of the crucial torque co-efficient (autorotation ability) with spin ratio for candidate Magnus cylinders, details of which are given in Fig 6.b. This gives a clear picture of the ability to self-start and this approach is due to Riabouchinsky (Ref 4). If a horizontal line is drawn depicting the cogging torque level of the wind turbine generator, the intersection of this line with the Riabouchinsky curve will indicate the regions of the spin ratio where self-starting is possible.

Complementary smoke flow visualisation studies (Fig 7) of the rotating Magnus bi-convex (Configuration 1 – Fig 6.b) cylinder were also carried out (\( \theta \) is the azimuthal angle from the start). The time lapsed pictures of the flow structures closely highlight those predicted computationally as shown in Figs 3, 4.

Concluding Remarks

This CFD approach has been shown to be powerful method to rapidly screen and assess aerodynamically promising candidates which have autorotation ability and which thereby would be suited for employment in Magnus vertical-axis wind turbines.

References

Fig. 1. Schematic of a Magnus Vertical-Axis Wind turbine (M-VAWT)

Fig. 2. Promising autorotating candidates

Hybrid Cylinder  Biconvex  3<No of Polygon sides<8

Triangular  Savonius  3 Cup Anemometer
Fig. 3. Time lapsed streamline contours of flow over a self-starting, autorotating Savonius rotor ($V = 5 \text{ m/s}, D_{\text{characteristic}} = 60 \text{ mm (Fig. 2)})$. 
Fig. 4. Time lapsed streamline contours of flow over a self-starting, autorotating biconvex (Configuration 1) shape (V = 5 m/s, D_{characteristic} = 60 mm (Fig.6.b))
Fig. 5. Aerodynamic characteristics of candidate Magnus cylinder profiles (V = 5 m/s, D_{characteristic} = 60 mm (Fig. 6b)).

Fig. 6. a) Variation of Torque coefficient per unit cylinder length with spin ratio (V = 5 m/s, D_{characteristic} = 60 mm (Fig. 6b))

Fig. 6. b) Geometries considered for the Riabouchinsky curve
Fig. 7. Time lapsed smoke flow visualisation pictures of the self-starting, autorotating biconvex Configuration 1 (Fig. 6.b) Magnus cylinder \( (V = 5 \text{ m/s}, D_{\text{characteristic}} = 60 \text{ mm}) \).

\( \theta = 0^\circ \)

\( \theta = 2\pi + 70^\circ \)

\( \theta = 100^\circ \)

\( \theta = 2\pi + 210^\circ \)

\( \theta = 260^\circ \)

\( \theta = 4\pi ^\circ \)

\( A \) – trailing edge vertex of the biconvex Magnus cylinder.