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Fluid dynamic performance of a vertical axis turbine for tidal currents☆

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ABSTRACT

This paper is concerned with the study of a novel design of turbine for tidal currents or fast-flowing streams, called the 'Hunter Turbine'. The turbine consists of several flapping blades that are hinged on a revolving drum. Flow visualization experiments on a small model were conducted to provide some basic rules from which the movement of every flapping blade at every drum position could be determined. Two-dimensional quasi-steady CFD was then used to obtain detailed information about the flow field, including pressure and velocity contours, and the pressure distribution on the surface of the blades. It was found that the Hunter Turbine gives very satisfactory performance over a restricted range of flow coefficient. Under these conditions, the kinetic energy of the incident flow can be effectively transferred into the movement of the rotor, so that the average power coefficient (based on the projected area with an open blade) reaches a value of 0.19. Using the CFD results, a polynomial function is fitted to the dependence of an effective force coefficient for all blades on the rotational angle and the flow coefficient. The net forces acting on the surfaces of the blades can thus be interpolated between the calculated data points.

1. Introduction

It has only recently been recognized that the kinetic energy stored in tidal currents around our coasts has significant potential as a source for power generation, even though it has a low energy density compared to fossil fuels [1]. Several turbine designs are now operating at a potentially commercial scale, notably the Marine Current Turbines propeller-type design (a horizontal axis turbine) [2]. Meanwhile, vertical axis turbines (or cross-flow turbines) where the axis is perpendicular to the incident flow are also being developed. Vertical axis designs are attractive because they respond to flow from any direction, and allow the generating equipment to be located clear of the water, driven by the vertical shaft.

One of the best-known examples of a vertical axis tidal turbine is the Darrieus turbine, which has three or four thin, straight blades with hydrofoil cross-section mounted vertically at the end of radial arms. Some stand-alone prototypes have been tested under laboratory conditions by Takamatsu [3] and Takenouchi [4]. By means of a 2D CFD simulation, Dai [5] succeeded in predicting the performance of a Darrieus turbine. In order to estimate 3D effects, as well as the effect of the arms on the performance of the Darrieus turbine, Li [6] developed a novel vortex method which had been validated in a series of towing tank tests. Ponta [7] introduced a channeling device for a Darrieus turbine to increase the flow velocity around the rotor and amplify the turbine output at a specific size. A related kind of vertical axis turbine is called Gorlov's turbine [8,9], in which the blades are designed with a helical twist relative to the axis of rotation. Shiono [10] reported that a turbine with helical blades had quite a small rate of pulsation, and its starting characteristic was more favorable than other vertical axis turbines with straight blades.

The Savonius turbine is also a type of vertical axis tidal turbine with great development potential. Yaakob [11] studied the effect of overlap ratio on the performance of a Savonius turbine with a 3D computational model, while Kyozuka [12] showed that a combined Darrieus and Savonius turbine improved turbine performance with high starting torque.

This paper considers a rather different concept for a vertical axis machine, although somewhat related to the Savonius design, that could have operational and economic advantages. This is the design of the late John Hunter, whose patent (No.GB9524439.8) describes a turbine concept by which the power can be extracted from a river or ocean current. Fig. 1 illustrates Hunter's concept for his vertical axis machine. It consists of several flapping blades, which are all

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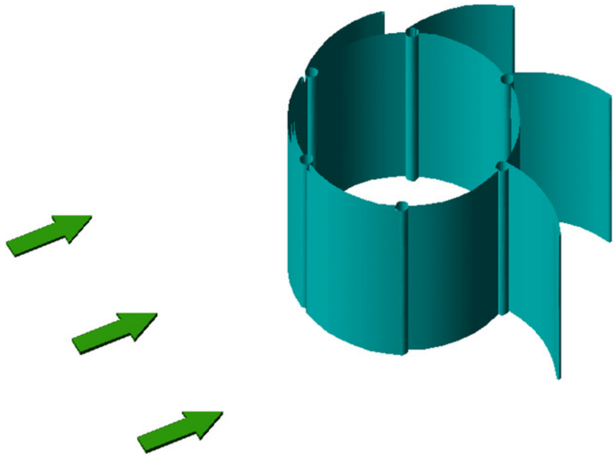

Fig. 1. The Hunter Turbine.

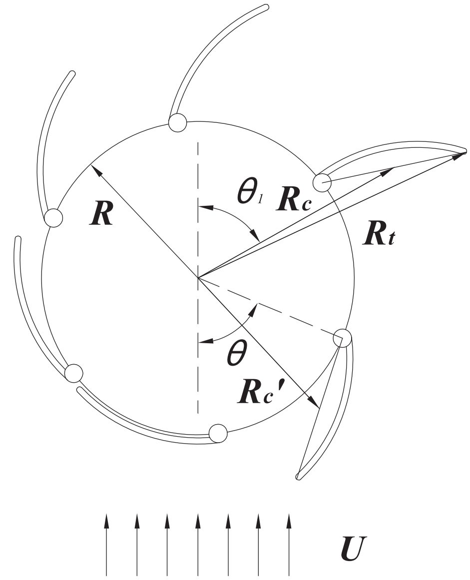

Fig. 2. Definition of parameters.

hinged on a revolving drum. The turbine works upon the principle that the flapping blades are opened by the incident flow on the working side of the revolving drum until they are restrained in the fully open position by stops, whilst the blades on the opposite side are closed by the flow to allow the water past the drum with minimum resistance. The resultant torque drives the turbine, producing power that can be converted to electricity by a geared or direct-drive generator.

Over the last 12 years, some project students in Queen Mary University of London have investigated various aspects of this design at small scale in a laboratory water-tank. These investigations included flow visualization and fluid mechanical performance measurement [13], and examination of some effects, such as the introduction of ducting and the suspension of the turbine below a floating vessel, on turbine performance. A larger version was also built and generated a few watts of power in the Thames. Moreover, some rudimentary computational fluid dynamics (CFD) calculations were undertaken to guide the design.

Thus, most of the knowledge of the Hunter Turbine still pertained to the machine's performance under laboratory conditions, and no systematic exploration had been carried out. However, for possible future practical applications, the problems of how to design a turbine and how to estimate power output under specific practical conditions have to be faced. In view of the present stage of development of the Hunter turbine, this research is focused on the prediction of power output by means of CFD, aided by flow visualization experiments, with a view to extrapolating to a commercial scale.

2. Experimental turbine test

2.1. General principles

Some important parameters are defined in Fig. 2. R is the diameter of the drum, R_c is the distance between the drum axis and the center of blade chord when the blade is opened completely, R_c' is this distance when the blade is in the opening or closing process, and R_t is the distance between the drum axis and the tip of the blade when it is opened completely. Rotational angle, which is used to describe the rotation of the trailing edge of one blade and measured from the point of closest approach to the incident flow, is designated θ. θ_1 is an included angle between the direction of the incident flow and the line from the drum axis to the centre of the blade chord.

To characterize behavior, the turbine performance should be related to some hydrodynamic and geometrical parameters. By dimensional analysis, some critical parameters are grouped into one dimensionless one, the flow coefficient.

$$\phi \equiv \frac{\omega R_c}{U} \tag{1}$$

where ω is the angular velocity and U is the velocity of the incident flow. It was assumed that the turbine performance would be greatly affected by the flow coefficient, with second order effects associated with the viscosity, represented in a Reynolds number.

2.2. Apparatus

Based on the considerations in the last paragraph, it is quite clear that every blade will experience two dynamic processes in a full rotation, i.e. the opening process and the closing process. But it is difficult to determine accurately when these two processes are triggered or finished with a given incident flow just by theoretical analysis. Fortunately, by means of flow visualization experiments, these two processes can be observed directly on a small scale model.

In these experiments, the turbine was submerged in a flume, so its size was limited by the cross-section of the flume. A converging section was installed upstream to speed up the flow incident on the turbine (Fig. 3). The turbine rotor in this instance was composed of six blades and a drum. The blades were curved and spaced equidistantly around the drum, which had a diameter of 51 mm. Each blade had a chord length of 25.5 mm and a height of 51 mm. All six blades were hinged on the drum and could open freely around a hinge pin before becoming perpendicular to the drum and hitting a stop. The turbine was connected to a load unit through a shaft. The load unit included a gear and a dynamometer (a 1 W motor driven in reverse) by which the shaft energy was converted into electrical energy. A floating barge may be adopted to suspend the submerged turbine in the sea. In this experiment, the model 'barge' was made of polystyrene, on which the load unit was mounted above water level. A variable resistor in series was used to adjust the electrical current through the dynamometer, while the voltage was determined by the rotational speed. An increase in electrical current in a loop increased the mechanical resistance of the