Journal of Fluids and Structures 48 (2014) 487–496

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Experimental study of the aerodynamic characteristics of a low-aspect-ratio flat plate array in a configuration of interest for a tidal energy converter

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ARTICLE INFO

Article history:
Received 7 March 2013
Accepted 13 April 2014
Available online 10 May 2014

Keywords:
Cascade
Tidal energy converter
Aerodynamics

ABSTRACT

Wind tunnel experiments were conducted for the flow around a single flat plate and through an array of three parallel flat plates at different angles of incidence to compare their lift and drag coefficients for several values of the Reynolds number around 10^5 and for three aspect ratio values. The selected cascade configuration is of interest for a particular type of tidal hydrokinetic energy converter. The main differences in the lift and drag forces are discussed, finding that for a plate in a cascade the maximum lift coefficient takes place at a quite different angle of attack, depending on the aspect ratio. The optimal conditions for extracting power from a tidal current are analyzed.

1. Introduction

The study of the flow through cascades (or lattices of airfoils) is of great practical interest for the aerodynamics of turbines and compressors, and much theoretical and experimental effort was expended, mainly during the development of the axial turbines and compressors in the first half of the 20th Century, to characterize the aerodynamic forces exerted on the blades of a cascade (see, e.g. Hawthorne, 1964). As a consequence, a large amount of experimental data for the aerodynamic characteristics of very different types of cascades, many of them obtained in specially designed wind tunnels, have been accumulated over the years, both for low speed (incompressible) and high speed (compressible) flows (see, e.g. Gostelow, 1984, Chapters 2 and 4, Hodson and Howell, 2005, and references therein). However, no experimental data exist, to the best of our knowledge, for the aerodynamic characteristics of a cascade of low-aspect-ratio blades at moderate or relatively low Reynolds numbers, being perhaps the most similar configuration for which there exists experimental data that of a vertical axis wind turbine (e.g. McLaren et al., 2012). The incompressible flow through such a cascade is of current interest for a particular device to extract kinetic energy from tidal currents, consisting of a cascade of underwater sails or blades that travel carried by the tidal current in a given direction, which in turn drive an electric generator ('Tidal Sails AS', 2012). It is also of basic aerodynamics interest to find out how the lift and drag forces on a blade in a cascade are affected by the adjacent ones, in relation to the forces on an isolated blade, when the aspect ratio is varied for moderate and low Reynolds numbers. This problem is even more topical now because of the growing interest in the aerodynamics of low-aspect-ratio wings at low Reynolds numbers aimed at the development of fixed-wing micro aerial vehicles (e.g. Mueller et al., 2007), so that new experimental data for low-aspect-ratio wing aerodynamics at low Reynolds numbers are becoming

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http://dx.doi.org/10.1016/j.jfluidstructs.2014.04.001
0889-9746/

available in recent years (Pelletier and Mueller, 2000; Torres and Mueller, 2004), complementing older experimental data aimed at the understanding of the enhanced lift in short span rectangular wings (e.g. Winter, 1936).

We consider in the present work a cascade of flat plates with different values of the aspect ratio (AR), measuring in a wind tunnel the lift and drag forces on a plate in the cascade for increasing values of the angle of attack (α) and for different Reynolds (Re) numbers (these nondimensional quantities are defined in the next section). The aerodynamic forces are compared with those on an isolated flat plate for the same values of AR, α and Re. The simplicity of flat rectangular airfoils has also been the reason for its selection as a reference blade in the above-mentioned works for low-aspect-ratio wing aerodynamics (Pelletier and Mueller, 2000; Torres and Mueller, 2004), whose experimental results will be used here to check our single flat plate results and thus to validate the experimental measurements. In addition, the blades in the actual arrays used in the device for extracting hydrokinetic tidal energy that motivates the present work are symmetrical thin airfoils ('Tidal Sails AS', 2012) that can be assumed to be rectangular flat plates in a first approximation. Of course, subsequent experimental studies on the aerodynamics of these devices have to take into account the effect of the blade profiles.

In the experiments reported in the present work we use flat plates with three different values of the AR, namely 1, 2 and 6, and several values of the Reynolds number around 10^5. Actually, we take advantage of the flow symmetry about the middle plane and consider flat plates anchored in the base of the wind tunnel test section with values of the semispan aspect ratio (sAR) of 0.5, 1, and 3. These values of the aspect ratio are within the range of interest in the mentioned tidal energy converters, and coincide with some of the ones considered by Pelletier and Mueller (2000) for a single flat plate, used to validate our experimental results.

In relation to the cascade configuration, we used an array of three stationary flat plates forming an angle of 45° with the wind tunnel flow direction in the test section, and measure the aerodynamic forces on the central plate in the cascade as the angle of attack α is varied for different values of sAR and Re. This configuration corresponds, for instance, to a cascade moving perpendicularly to the current with the same speed as the current (see the next section). Some other arrays could have been tested, but this seems to be one of the optimal configurations in actual tidal current devices (Mayorga, 2012). A similar configuration, but for the aerodynamic study of a linear oscillating cascade, was used by Buffum and Fleeter (1991).

2. Experimental set-up

For the experiments we used a low-speed closed circuit wind tunnel with a test section of $1 \times 1\ \text{m}^2$ cross section. Either a rectangular flat plate or an array of three of them was mounted in the test section of the wind tunnel (see Fig. 1, where it is shown the array of three plates). The main objective of this experimental study was to compare these two configurations in terms of the aerodynamical forces for one (isolated or central) plate mounted on a platform force balance. However, to check that the extent of the cascade with just three blades was enough for obtaining relevant results, we also used an array of five flat plates. No significant differences for the forces exerted by the flow on the central plate in the cascade were observed (see Section 4).

The plates were made of steel with 2 mm thickness and 15 cm chord length (i.e., a thickness-to-chord ratio of 1.33%). Several values of the aspect ratio were used. The leading and trailing edges of these steel plates were both tapered on a length of about 2.5 times its thickness, and identical plates were used in both the single plate configuration and the array of three plates, so that the effect of the adjacent plates in the cascade on the aerodynamic characteristics of a plate could be analyzed.

The array of three flat plates was mounted with an angle of 45° in relation to the wind tunnel current (see Fig. 1). As commented on above, this configuration corresponds to a cascade moving perpendicularly to a tidal or river current with the same speed as the current (see Fig. 2, where the cascade speed U is equal to the current speed V). The wind tunnel speed $W=\sqrt{V^2+U^2}=\sqrt{2}V$ corresponds to the relative air velocity to the plates in a reference frame moving with the cascade. We used this speed W and the chord length c (=15 cm) as the reference velocity and length scale, respectively, to define the Reynolds number,

$$\mathrm{Re}=\frac{Wc}{\nu}, \tag{1}$$

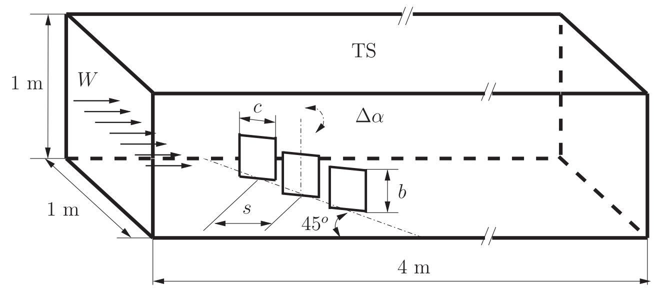

Fig. 1. Sketch of the wind tunnel test section with the array of three flat plates.