Ocean Engineering 127 (2016) 325–334

Contents lists available at ScienceDirect

Ocean Engineering

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

Frequency analysis of the power output for a vertical axis marine turbine operating in the wake

Amir Hossein Birjandi*, Eric Louis Bibeau

Department of Mechanical Engineering, University of Manitoba, Winnipeg, Canada R3T 0C4

ARTICLE INFO

Keywords:
Marine turbine
Wake
Turbulence
Fatigue load
Frequency analysis
Power output

ABSTRACT

Flow condition in rivers is highly turbulent and unsteady due to upstream structures or geometry of the river. In a hydrokinetic farm downstream turbines are subjected to the wake of upstream turbines. Operating in the wake not only affects the average power output of the turbine but also influences the quality of the power by imposing fluctuations to the power. The current study presents the water tunnel testing results of a vertical axis turbine operating in the vortex shedding behind a cylinder with various sizes located at different distances upstream the turbine. The vortex shedding from a circular cylinder has similar patterns with vortex shedding from blades of a vertical turbine. Results show that for certain sizes of upstream cylinder the maximum negative effect occurs when the upstream cylinder is 1.5 turbine diameters away. At closer or farther distances the negative effect is limited. The frequency analysis of the power data shows that when the turbine operates in the wake, the frequency strength at the rotational frequency of the turbine and its multiples decreases. At the same time, new frequency peaks appear in the power spectrum as the result of the vortex shedding behind the cylinder.

1. Introduction

In February 1977 Sheldahl and Blackwell (1977) tested a 5-m diameter Troposkein Darrieus turbine in the free air condition at the Sandia Laboratories Wind Turbine Site. Later when they repeated the test in late July and early August, they observed maximum power coefficient reduction from 0.28 to 0.24, as seen in Fig. 1. They investigated the source of this phenomenon by looking at the wind speed distribution and wind quality for these two tests. They found that the wind speed distribution for the February test, test a, is much smoother than the wind speed distribution for the August test, test b, Fig. 2. They attribute the high fluctuations in the wind speed for the power coefficient reduction in test b. Therefore it can be concluded that the power coefficient not only is a function of the average wind velocity but also is affected by the wind distribution pattern.

Birjandi et al. conducted a series of field measurements upstream of a 5 and 25 kW vertical hydrokinetic turbines in the Winnipeg River at Pointe du Bois (Birjandi et al., 2012) and founded that the river flow carries large eddies with the order of magnitude of the turbine's diameter. Large eddies break into smaller size eddies as they approach the turbine. Small size eddies are still comparable with the chord length of the blade. These eddies are able to trigger temporal flow separation on the blade surface and cause dynamic stall to occur (Birjandi et al., 2012). Yokosi (1967) measurements in the Uji River and the Sosui canal show that the depth and width of the river determine the order of magnitude of the largest eddies in the river. The large-scale eddies cascade energy from the mean flow velocity to the smaller eddies and they are created mainly in the wake zones or in regions with high velocity gradient. In rivers large-scale eddies are created in following circumstances:

- rapid changes in the profile of riverbeds or banks,
- presence of large boulders or ice floes,
- man-made obstructions like a bridge pier or upstream turbines, and
- rapid river level changes leading to hydraulic jumps.

In most cases the wake and eddies are smaller than the cross-section of the turbine; therefore, different parts of the turbine experience dissimilar inflow conditions due to different sizes of eddies and wake intensity. The large eddies and regional wakes create non-uniform inflow condition for the turbine that imposes higher power output fluctuations and higher fatigue loads on the structure of the turbine. There is little information available in the literature about regional wake and large-scale eddy interaction with hydrokinetic turbines. The National Renewable Energy Laboratory is currently doing a comprehensive investigation for better understanding the effects of unsteady inflow on horizontal wind turbines (Sutherland and Kelley, 1995; Hand et al., 2001; Kelley et al., 2002; Sheng et al.,

* Corresponding author.
E-mail address: amir.birjandi@gmail.com (A.H. Birjandi).

http://dx.doi.org/10.1016/j.oceaneng.2016.09.045
Received 12 August 2015; Received in revised form 16 July 2016; Accepted 29 September 2016
Available online 15 October 2016

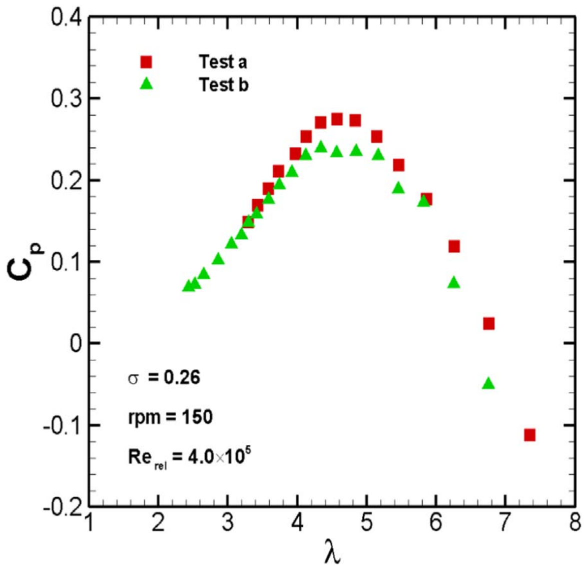

Fig. 1. Power coefficient data of the 5-m Troposkein turbine at 150 rpm for test a and test b (Sheldahl and Blackwell, 1977).

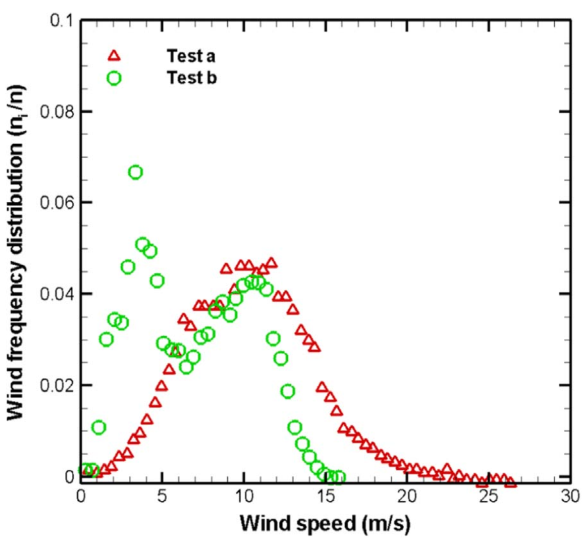

Fig. 2. Wind frequency distribution for the test a and test b in Sheldahl and Blackwell (1977).

2010).

In laboratory testing, the turbulence intensity of the flow is increased by employing a screen upstream the model. When flow passes through the screen, small vortices are shed off the screen wires and increase the turbulence intensity of the flow. The size of the generated vortices is in the order of magnitude of the screen wires' diameter. This technique increases the turbulence intensity homogeneously in entire flow. Compared to the low turbulence intensity flow, a high turbulence intensity flow postpones the stall phenomenon to higher angle of attacks thus increases the maximum lift coefficient of the blade. Therefore, the performance of the turbine is enhanced in turbulent flows and results in higher power output. This statement is true as long as the vortices in the turbulent flow are much smaller than the chord length of the blade. Unlike water tunnels and towing tanks where flow is uniform and turbulence is low, in rivers, channels and oceans the flow is highly turbulent and non-uniform and contains large-scale structures exceeding the diameter of the turbine. This condition will be accentuated in hydrokinetic farm applications where some turbines operate in eddies shed by upstream turbines.

1.1. Modeling the regional wake

It is impossible to reconstruct or scale down actual river conditions for lab testing. In traditional water tunnel settings, an upstream screen increases the turbulence intensity of the flow by introducing small eddies to the flow; however, this technique is unable to simulate localized wakes, wakes smaller than the diameter of the turbine, and create large-scale eddies which are common phenomena in hydrokinetic turbine farms in rivers and oceans. Medici and Alfredsson (2006) measured the velocity field behind a two-bladed horizontal wind turbine model with 18 cm diameter in a wind tunnel. They measured all three velocity components using a two-component hot wire. In the frequency domain, they found that the velocity signal shows peaks at frequencies much lower than that of the rotational frequency of the turbine. The Strouhal number ($St=fD/U$) of these low frequency peaks decreases by increasing the tip speed ratio, and when the turbine exceeds a specific tip speed ratio, the frequency peaks level out. Here, f represents the frequency of the velocity peaks, D is the diameter of the turbine, and U is the free-stream velocity. This Strouhal number definition is similar to the Strouhal number of a solid disk with the same diameter of the turbine. Therefore, the vortex shedding behind the horizontal turbine has the same characteristics as the vortex shedding behind a bluff body.

The operating condition for vertical turbines is different than horizontal turbines; therefore, they create different wake pattern behind them. Blades in vertical turbines are subjected to an oscillating angle of attack condition as the blade travels on the circumference of the turbine. Assuming no momentum loss when the flow passes through the actuating disk of the turbine, the angle of attack of the blade, α, can be defined as:

$$\alpha = \tan^{-1}\left[\frac{\sin(\theta)}{\lambda + \cos(\theta)}\right] - \alpha_p, \quad (1)$$

where $\lambda=\omega r/U$ and is known as the blade speed ratio or tip speed ratio, θ is the azimuth angle of the blade, and α_p is the preset pitch angle of the blade. Fujisawa and Shibuya (2001) showed that the vortex shedding behind the vertical axis turbine blade has the similar pattern as vortices in the Von Karman vortex street. The vortex shedding behind a two-dimensional circular cylinder is known as Von Karman vortex street. Consequently the vortex shedding behind a vertical axis turbine can be modeled by the vortex shedding behind a cylinder. In vertical axis turbine, two counter-rotating vortices are developed due to the flow separation from the leading edge and roll-up flow motion from the pressure side of the blade. The first pair of vortices forms between the azimuth angles of 45° and 90°. The second pair forms between the azimuth angles of 90° and 135°, as shown in Fig. 3. The flow visualization technique around the blade in a vertical turbine, depicted in Fig. 4, verifies the results obtained by Fujisawa and Shibuya (2001).

Based on the results obtained from studies conducted by Medici and Alfredsson (2006) and Fujisawa and Shibuya (2001) and our team in the water tunnel, the wake behind a vertical turbine consists of two pairs of counter rotating vortices shed from the blade. This vortex shedding can be modeled by placing circular cylinders in the water tunnel. The size of the vortices and frequency of the vortex shedding can be controlled by the Reynolds number and the diameter of the cylinder. Cylinders with different diameters are placed upstream the scaled turbine to create vortex shedding. In this study, the upstream cylinder is aligned with the rotational center of the turbine with no lateral offset. The cylinder is placed at various longitudinal distances to assess the proximity effect. The torque, rotational speed and the azimuth angle of the turbine are recorded with high frequency sampling rate during the test. Then the average and instantaneous power output and of the turbine are calculated and plotted for different inflow conditions. The power output quality is investigated by analyzing the power data in the frequency domain.