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Marine kinetic turbine operation in the wake zone

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ABSTRACT

Marine hydrokinetic turbines experience non-uniform inflow conditions due currents, geometrical changes in water boundaries, objects located upstream in the flow, and flow disturbances from other marine turbines when multiple units are installed. This paper reports on a series of water tunnel testing to investigate the performance of a two bladed squirrel cage vertical marine kinetic turbine that more closely simulates an array of turbines with one diameter center to canter spacing operating in the wake zone. It provides general results how their performance is affected by wake structures. In this study wakes are created by different sizes of circular cylinders placed at various longitudinal and lateral upstream locations. Results show that a cylinder placed 1.5 diameters upstream of a turbine and centered with the turbine rotational axis has the most power reduction effect. However, moving the cylinders laterally moderates the negative effect of an upstream cylinder and can even improve the performance of a turbine by up to 35% in a laboratory setting due to velocity enhancements on the high torque region of the rotating blade.

1. Introduction

Unlike the uniform and low turbulence conditions of flow in computational simulations, water tunnels and tow tanks, the actual flow in rivers, channels and oceans is highly turbulent and non-uniform due to the eddies, with the size comparable to the diameter of the turbine, as shown in Fig. 1. This condition accentuates in hydrokinetic farm applications where multiple turbines operate in eddies shed by upstream turbines; however, this condition is expandable to other disturbance sources like:

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

In this study, we use a water tunnel and install cylinders with different sizes upstream of a scaled vertical axis turbine to simulate the field wake condition. We try to not limit the results to any particular object by focusing on wake pattern and size rather than emphasizing on geometry of the upstream object. Since there are significant studies available on circular cylinder wake we decide to use this geometry to create the non-uniform flow condition. Although circular cylinder might not be able to mimic the exact wake dynamic behind a vertical turbine it has the closest counter-rotating vortex pater to a vertical turbine wake. This research methodology is supported by studies of Medici and Alfredsson (2006) and Fujisawa and Shibuya (2001). Medici and Alfredsson (2006) measured the velocity field behind a two-bladed horizontal wind turbine model with 18 cm diameter in a wind tunnel test. In the frequency domain, they found that the velocity signal shows velocity peaks at frequencies much lower than that of the rotational frequency. The Strouhal number ($St=fD/U$) of these low frequency peaks decreases with increasing tip speed ratio ($\lambda=\omega r/U$), and when it exceeds a specific tip speed ratio it levels out. Here, f represents the frequency of the peak, D is the diameter of the turbine, U is the free-stream velocity, ω is the angular velocity of the blade, and r is the radius of the turbine. This Strouhal number definition is similar to the Strouhal number of a solid disc with the same diameter as the turbine. Therefore, the vortex shedding behind the horizontal turbine has the same characteristics as the vortex shedding behind a bluff body.

In another study, Fujisawa and Shibuya (2001) investigated the wake behind a vertical axis turbine. They observe two pairs of counter-rotating vortices developing in the wake of the blade in the upstream path. The first pair of vortices forms between the azimuth angles of 45° and 90°; between the azimuth angles of 90° and 135°, forms the second pair. The reference for the azimuth angle is the position in which the blade velocity makes 180° angle with the free stream velocity. In the pair of counter-rotating vortices, the first vortex is the result of the flow separation from the leading edge of the blade due to the high angles of attack. The roll-up flow motion from the pressure side of the blade to the

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suction side through the trailing edge creates the second vortex pair. The second vortex pair rolls up and re-attaches the flow to the blade. These two vortex pairs are similar to vortices in the Von Karman vortex street behind a cylinder. Fig. 2 illustrates the vortex formation behind a vertical axis turbine. This pattern also was visualized in the water tunnel testing by Birjandi et al. (2013) using high speed camera.

Even with no turbine in the upstream, still hydrokinetic turbines experience non-uniform inflow due to other sources mentioned earlier. Birjandi et al. (2012) conducted comprehensive series of measurements in Winnipeg River upstream a prototype vertical axis turbine and reported non-uniform inflow and the existence of eddies comparable with the order of magnitude of the turbine blade chord size. In this study we simulate different non-uniform inflow condition

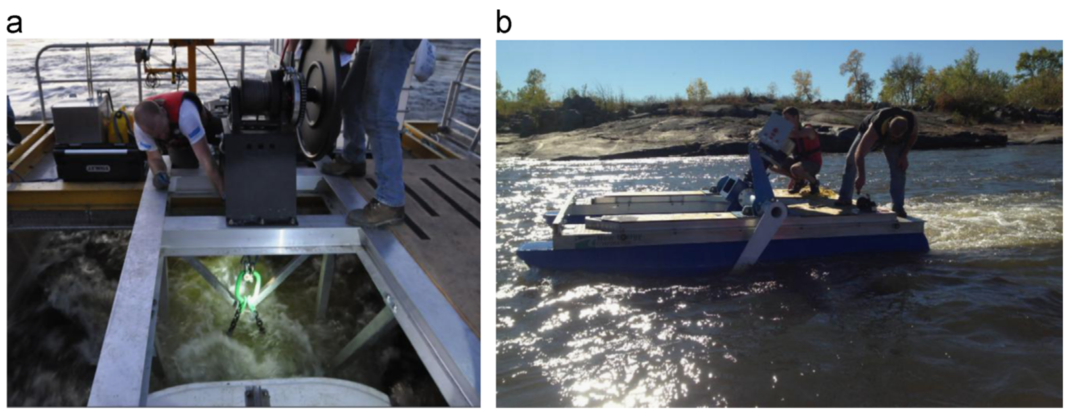

Fig. 1. (a) Bottom mounted Clean Current hydrokinetic turbine before being lowered to the riverbed, and (b) New Energy hydrokinetic turbine with pontoon floats. Pictures show the river surface flow conditions during installation of these turbines at Seven Sisters on the Winnipeg River at the Canadian Hydrokinetic Turbine Test Centre (CHTTC).

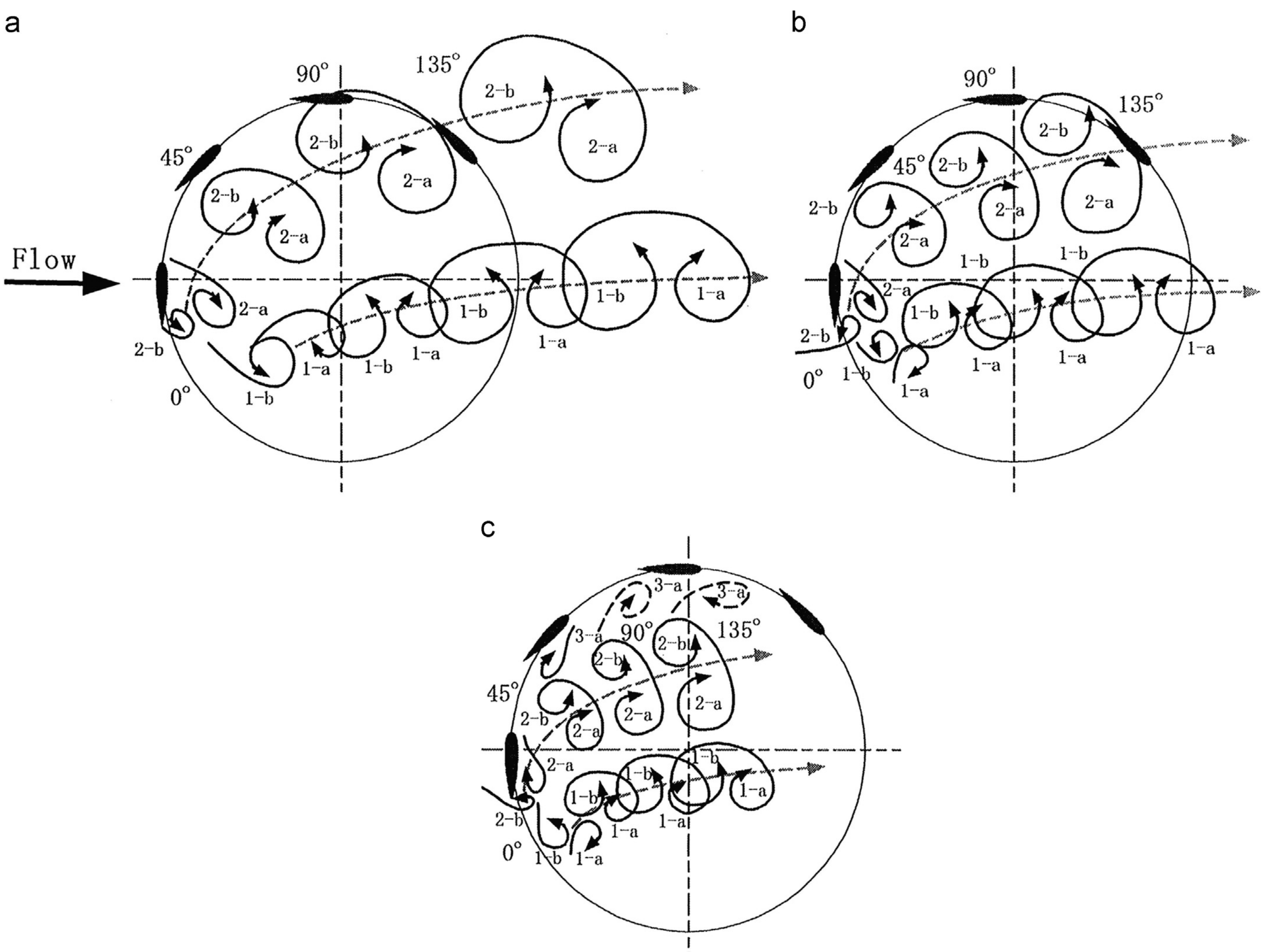

Fig. 2. Schematic illustration of counter-rotating vortices from Reference (Fujisawa and Shibuya, 2001).