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Experimental Study on the Wake Structure behind a Cylindrical Rotator with Asymmetric Protrusions in a Unidirectional Flow

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Abstract

Wake structures behind a cylindrical rotator with asymmetric protrusions were investigated through a laboratory experiment. Such a cylindrical rotator could prevent a flood disaster due to the accumulation of driftwood at bridges. In this study, a rotator composed of a cylinder with five quarter-cylindrical protrusions was placed in a unidirectional flow. The rotator could rotate freely under hydrodynamic forces. The results indicate that vortices shed from the rotator affected flow structures behind the rotator. The transverse distribution of the time-average longitudinal velocity of the flow with respect to the rotator was asymmetric about the longitudinal centerline. In the accelerating area with rotation of the rotator, five vortices were obviously shed from each quarter-cylindrical protrusion in each period. Where the flow and rotation were in opposite directions, vortices formation was disrupted. A longitudinal series of vortices merged downstream, ultimately becoming a single vortex. Therefore, the wake flow becomes asymmetric in an area behind the rotator where a significant torque acts.

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1. Introduction

In recent years, the frequency of torrential rains resulting in slope failure, bank erosion, and other problems has been increasing. In particular, there are many cases where driftwood flowing in medium and small rivers builds up against bridges that span the river, damming the river because the span length of the bridge is too small in some cases. As a result, overflow occurs that inundates nearby houses, shore areas, and other places resulting in massive damage, even when the flow discharge does not exceed the design high-water discharge.

Research into driftwood and measures for dealing with it have therefore become a pressing issue [1]. However, although there are examples of research into the accumulation of driftwood at bridges and houses [2-7], there are few examples of investigation into specific measures for reducing the damage caused by driftwood [1]. A detachable parapet of a bridge was proposed as a countermeasure to reduce the accumulation of driftwood and refuse during flooding [8].

Against this background, we previously proposed a method for preventing the buildup of driftwood and refuse at bridges by installing a rotating cylinder called the "rotator," which is an asymmetric structure set in front of the bridge piers, and a similar method for preventing the buildup of driftwood and refuse at bridges by wrapping the bridge piers in a rotating caterpillar fitted with an asymmetric structure [9]. These methods use the massive energy of the water flow during a flood to turn the flow direction of driftwood around a bridge pier by the rotator or the caterpillar and to promote the washing out of driftwood that would otherwise build up against the bridge pier. If there is no torque around a bridge pier without the rotator or the caterpillar, driftwood and refuse are likely to balance and accumulate there.

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In that research [9], we investigated the effectiveness of the rotating bodies for preventing driftwood from getting caught on the bridge by flowing driftwood models in an open water channel where a rotator was installed in front of a bridge model and comparing the results with those from other cases, such as when a non-rotating cylinder was installed. However, there is little research that treats water flow around a cylindrical rotator with an asymmetric shape, and there are almost no examples of research that can serve as references for the aim of putting this technology into practical use.

Accordingly, in this study we first experimentally investigated the basic wake structure of rotating bodies with the aim of understanding and improving the effectiveness of installing rotators to prevent the buildup of driftwood at bridge piers. Note that this investigation is also applicable to the flow around a cylindrical bridge pier wrapped in a rotating caterpillar of the type mentioned earlier [9].

Research related to this work, which treats cylinders rotating due to flow, includes research into vertical-axis wind turbines such as those of the Darrieus and Savonius types [10-14]. The shape of the Savonius wind turbine in particular is relatively similar to the shape of the rotator examined in this research. Although the knowledge gained from these previous studies will serve as a useful reference in some ways, the wake structure of the rotator examined in this research is greatly different than that of the wind turbine because the wind is a fluid introduced into and emitted from the interior of the cylinder in the wind turbine.

Furthermore, in recent years, spiral Magnus wind turbines, which utilize the Magnus effect, have increasingly come to be used in practice [15-18]. These wind turbines generate electricity in a highly efficient way, by applying electric power to rotate cylinders that have spiral-shaped fins attached, which makes the entire wind turbine rotate from the aerodynamic lift produced. However, it may be possible to generate power even more efficiently, using natural energy alone, by using the rotator from this research instead of the impermeable spiral cylinder blades corresponding to the fins in regular wind turbines. An experimental study was conducted by Ito et al. [17] on the technology for rotating spiral Magnus wind turbines without motors by combining them with the aforementioned Savonius wind turbines.

2. Methods

A linear open channel of length 1400.0 cm, width 60.0 cm and height 60.0 cm, as shown in Fig. 1, was used in the experiments. The experimental conditions are shown in Table 1, where Q is the flow rate, h is the water depth at a point A (refer to Fig. 1, 50.0 cm upstream of the lateral center of the cylinder), U is the cross-sectional mean flow velocity at the vertical cross-section containing the point A, Re is the Reynolds number, and Fr is the Froude number. Re is defined as UD/ν, where ν is the kinematic viscosity coefficient of water and D the cylinder diameter. Note that D for the rotator is the diameter of the cylindrical part. Fr is defined as $U/(gh)^{1/2}$ for a given h where g is the gravitational acceleration.

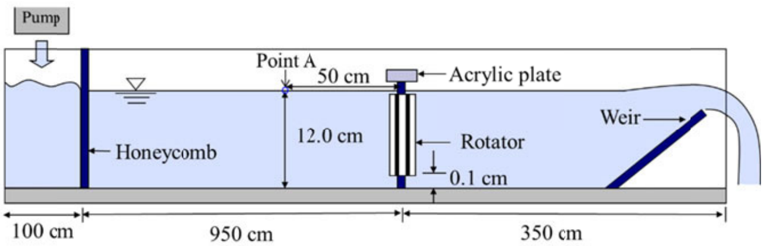

Fig. 1. Side view of the experimental apparatus

Table 1. Experimental conditions

Q (m^3/hr)	h (cm)	U (cm/s)	Re	Fr
75.0	12.0	29	1.4×10^4	0.27

The rotator is a cylinder of diameter D = 5.0 cm and length 12.0 cm, to which five quarter-cylindrical protrusions formed by dividing a cylinder of radius k = 1.0 cm into four equal parts have been attached at equal spacing (refer to Fig. 2), and the support post of the rotator, which is an axle of rotation, is fixed by an acrylic plate installed spanning the water channel. A cylindrical structure was installed laterally in the middle of the channel with longitudinally 950 cm downstream from a honeycomb to control water surface disturbance (refer to Fig. 1). The cylindrical structures used in the experiments were a rotator that is not controlled and rotates freely depending on the current and, for comparison, a non-rotating cylinder of the same size without the quarter-cylindrical protrusions attached.