Numerical analysis of Coriolis effect on low-head hydraulic turbines

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Abstract. For the low-head hydropower station, the operating head is low, and the turbine intake channel is relatively short. The turbine internal flow behaviour can be influenced by fluid flows in the upstream reservoir easily, then it would influence the turbine hydraulic performance. Water flows in the upstream reservoir can be influenced by the Coriolis force by the Earth rotation, and it differs at the different Rossby number. In this paper, the Coriolis effect on the approach flows and the turbine performances are investigated numerically for the low-head units. Firstly, the Coriolis effect (under the different latitudes and the same characteristic length scale) on reservoir flows was predicted. Secondly, the prototype performance of a bulb-type turbine was simulated including the reservoir flow with the Coriolis effect, and then the effect on the turbine performance is be discussed. Results show that the flow field in the upstream reservoir at the low Rossby number, the ratio of inertial force to Coriolis force, can sufficiently influence the turbine intake flows and the turbine performances. Adjusting the side-wall distance can reduce the Coriolis effects.

1. Introduction

Ocean energy, such as the ocean waves and tides, represents a high energy density source [1]. The tidal energy by tidal movements is one of them, and it can be classified into the tidal current units and the tidal barrage units, which utilize the kinetic energy and the potential energy of the tides respectively. At present, for the tidal barrage units, only a few of power stations are operating commercially, such as the Rance tidal power station in France, Kislaya Guba tidal power station in Russia, Jiangxia tidal power station in China, Annapolis Royal generating station in Canada and Sihwa Lake tidal power station in South Korea. The tidal power units are classified as the low-head turbines.

For the low-head hydraulic turbine, the operating head is low, and the flow rate is relatively small. The interaction between water and air in a reservoir could influence on the turbine performance due to the short turbine intake. The two-phase flow including the free surface in the reservoir, the surface vortices and the surface fluctuations, can cause the non-uniformity of the velocity and pressure distributions in turbine units. It can increase vibration by additional radial forces [2]. Furthermore, Froude number is low relative to high-head hydraulic turbine, so the gravity force sufficiently influence the flow characteristics in turbine units. In this reason, the pressure fluctuation and the cavitation in a rotating runner are governed by the gravity effect [3-5].
The different power station sites are in the different oceanic environment and are at the different latitudes. Flow velocities in the ocean near tidal power stations are relatively low, and the surrounding sea has the large and wide areas. These parameters can be defined as the Rossby number, which is the non-dimensional number the ratio of inertial force to Coriolis force. For the above mentioned power stations, the latitudes are about 30 degrees for the Jiangxia power station in China, 50 degrees for the Rance power station in France and 70 degrees for the Kislaya power station in Russia. If the velocity in the sea side is low in the same specific capacity, the approach flow characteristics near the tidal power units could be influenced by the Coriolis force by the rotating Earth and also vary at the different latitudes. The Rossby number is defined as \( R_0 = \frac{U}{fL} \), where \( U, f \) and \( L \) are the approach flow velocity, the Coriolis parameter and the length scale. The Coriolis parameter \( f = 2\Omega \sin \varphi \) where \( \Omega \) and \( \varphi \) are the rotational speed of the Earth and the latitude. In this paper, the rotational speed is assumed to be constant of \( 7.292 \times 10^{-5} \) s\(^{-1}\). The Coriolis effect at the southern hemisphere is opposite to one at the northern hemisphere, and the effect at the equator is equal to zero.

In this paper, the effect of the Coriolis force of the rotating Earth on the approach flows is investigated under the different latitude conditions, and then the effects of inflow with Coriolis force effect on the turbine performances for the low-head units will be discussed.

2. Numerical method

2.1. Governing equations

In order to investigate the effect of the Coriolis force on the approach flow and the turbine performance, numerical simulations are performed with simplified calculation models. The incompressible continuity equation is

\[
\nabla \cdot (\rho u) = 0
\]

(1)

where \( \rho \) is the water density. The momentum equations with the Coriolis and gravity forces are the following:

\[
\frac{Du}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x} - fw + \nu \nabla^2 u - S
\]

(2)

\[
\frac{Dv}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + g + \nu \nabla^2 v - S
\]

(3)

\[
\frac{Dw}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial z} + fu + \nu \nabla^2 w - S
\]

(4)

\[
S = \frac{\partial}{\partial x_j} \left[ \nu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right]
\]

(5)

where \( f, \nu \) and \( S \) are the Coriolis parameter, the kinematic viscosity and the stress tensor. The momentum source terms are used for taking the gravity force and the Coriolis force into account. In this simulation, the Coriolis effect is assumed to be very small relative to the gravity effect, therefore, the Coriolis force is ignored in the gravity direction.

2.2. Calculation domains and boundary conditions

The water level is assumed to be stable and constant, so the single-phase N-S equations are used, and the air-water interactions are ignored in this paper. The simplified reservoir models are used to predict flow fields with the Coriolis force, so the complex topography and water depth change are not considered. At the reservoir inlet, the inflow velocity and the flow direction are assumed to be uniform and have only normal direction component. For the Rossby number, the length scale is defined as the distance between the reservoir inlet to the reservoir outlet, which corresponds the turbine channel inlet, and the distance is 100 m in this paper. The inlet boundary condition is set as the constant velocity of 0.1 m/s.
The SST-CC (Curvature Correction) turbulence model [6] is used for predicting well the rotating flows in the turbine. The initial conditions are set as the velocity of 0.1 m/s and the hydrostatic pressure distribution depending on the water level for the 3D calculation domain. The commercial CFD code CFX-solver was used. The two-case simulations will be performed in this paper.

2.2.1. **2D free-stream flow simulation**
In order to investigate the effect of the Coriolis effect on the reservoir flow field, the 2D simulation is performed with a rectangular calculation model of 100 m x 100 m as shown in figure 1. The boundary conditions are set to the uniform velocity of 0.1 m/s for the inlet, the average pressure of 0 Pa for the outlet and the periodic conditions for the two side-walls. The number of grids is 10,000, which is of 100 x 100. The simulations are performed at the different latitudes of 0, 30, 60, 90 degrees.

![Figure 1. Computational domain for 2D simulation.](image)

2.2.2. **3D flow field simulation with a prototype bulb-type turbine**
The 3D flow field, with a prototype bulb-type turbine, is simulated to predict the effect of the approach flow with the Coriolis effect on the turbine performance for the low-head units. The calculation domain consists of a simplified reservoir model and a prototype turbine, and it is illustrated in figure 2. The height of the reservoir is about 8 m from the intake center, which corresponds the upstream water level, and the width is the four times of the intake diameter, with about 1.6 million structured grids. The prototype consists of 3 blades and 16 guide vanes and two channels, with about 3.5 million structured grids. The runner diameter is 2.5 m with the rated rotational speed of 125 rpm and the rated head is 3 m. The generated calculation grids are shown in figure 3. In the reservoir model, the boundary conditions are the translational periodic conditions for the two side-wall, the symmetry condition for the top-wall and the no-slip conditions for the others. The inlet boundary condition was set to the uniform velocity in the normal to the inlet, and the outlet boundary condition was set to the average pressure depending on the downstream water level at the rated head condition.

![Figure 2. Computational domain for 3D simulation.](image)
3. Numerical results

3.1. Effect on the flow fields in the reservoir

2D free-stream flow simulation result is illustrated in figure 4, where $\alpha_{rel}$ represents the flow angle relative to the inflow direction. From the simulation result, the relative flow angles increase as the latitudes increase with decreasing the Rossby number. At the latitude of 0 degrees, the Coriolis parameter is equal to zero, so the Rossby number cannot be defined, in this reason, the relative flow angle is zero. Figure 4 shows that the Coriolis force of the rotating Earth sufficiently influences the flow field at the low Rossby number. Rossby numbers are 13.7 for the latitude of 30 degrees, 7.92 for 60 degrees and 6.86 for 90 degrees. The relative flow angles are 4.17, 7.20 and 8.30 degrees for the different latitudes of 30, 60, 90 degrees, respectively in this simulation. The difference of the relative flow angles between the latitudes of 30 and 60 degrees is larger than one between 60 and 90 degrees, it is due to sin-curve characteristic.

![Graph showing relative flow angle and Rossby number](image)

**Figure 4.** Relative flow angle and Rossby number.

3.2. Effect on the turbine performances

3D flow fields were simulated with a prototype bulb-type turbine. The calculation conditions are as followings: the inflow velocity of 0.1 m/s at the different latitudes (0, 30, 60 degrees) for the reservoir; and the guide and runner vane openings, the rotation speed of the runner, the water level difference are based on the site-test results for the rated head and power operating condition. Figure 5 shows the streamlines on the top-wall in the reservoir, the streamlines have the different characteristics due to the Coriolis effect. At the low Rossby number, the approach flows have asymmetric structures as shown in figure 5. Figure 6 shows the Rossby number in the reservoir and the flow angle relative to the axial direction at the turbine inlet, for the low Rossby number, the relative flow angle is much larger than the high Rossby number. It means that the approach flow to the turbine intake under the Coriolis force effect could sufficiently influence the turbine internal flows.
Figure 5. Streamlines on the top-wall at the different Rossby numbers.

Figure 6. Rossby number and relative flow angle.

Figure 7 shows the simulation results at the different latitudes. Those results are under an assumption that the flow rate is constant in this paper, where the turbine net head and efficiency are to be divided by one for the latitude of zero. The effective head between the turbine inlet and outlet decreases as the latitude increases with decreasing the Rossby number. It means that the head losses vary at the different Rossby numbers under the same water level difference. Nevertheless, the efficiency at the low Rossby number is higher than the Coriolis parameter of zero. It might be due to the increase in the tangential velocity component in the turbine flow passage.

But, it should be noted that this simulation result is to be only at an operating condition (strictly, the operating points at the three latitudes vary in performance curves) and an inflow velocity in the reservoir. If the inflow velocity is much lower or the latitudes are negative values, the losses might have the different tendency. Unfortunately, at present, it is difficult to validate the simulation results. However, this study can help further turbine unit and reservoir designs.
3.3. Effect of side-wall on Coriolis forces

In order to study the effect of two side-wall on the Coriolis effects, the 2D simulations were performed. Calculation domains are based on the model in figure 1, and the boundary conditions are also the same with them in section 2.2.1 excluding the side-wall. Figure 8 shows the relative flow angle at the outlet with the different widths between the two side-wall at the same Rossby number. In this result, the $\alpha_{rel}$ decreases increasingly as the width decreases, for the outlet averaged values, at the width of the ten times of the length the flow angle is still influenced by the side-wall effect slightly, whereas for the point of outlet center, the relative flow angle is much influenced below the ratio of the width to the length of 5.0. From the simulation results, the side-wall can sufficiently influence the Coriolis effects, furthermore, it can reduce the Coriolis effects.

4. Conclusion

In order to predict the Coriolis effect by the Earth rotation on the approach flows and the prototype turbine performances for the low-head unit, the 2D free-stream flow and the 3D flow fields including a turbine unit were simulated with N-S equations with the gravity and Coriolis forces. From the numerical results, for the low-head unit, the Coriolis forces can influence the approach flows to the turbine units and the operating conditions, sufficiently. Adjusting the distances between two side-wall can reduce the Coriolis force effect. The effects could vary at the different Rossby number (at the different latitudes or with the reservoir characteristic lengths).

Acknowledgments

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