# Numerical simulation on hydrodynamic performance of parallel twin vertical axis tidal turbines

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***Abstract*— The single and parallel twin vertical axis hydro turbines were numerical simulated by open code-OpenFOAM, emphatically studied on the interference effect such as torque and load of turbine as well as hydrodynamic performance influenced by the distance and rotation forms between twin turbines and analyzed the wake flow field to show the velocity profile distribution. Results show that average power of parallel twin turbines is always higher than the power of a single turbine, the closer the lateral distance between turbines, the higher the power. At the same time, opposite outward rotation is the best arrangement form for twin turbines to get more power and counteract the lateral force.**

***Keywords*— Tidal current energy; vertical-axis hydro-turbine; hydrodynamic performance; parallel twin turbines; wake flow**

## I. Introduction

As a renewable energy, tidal current energy is a kinetic energy generated by regular flow, which is caused by steady flow and tide in benthonic channel and strait. Compared with other kinds of ocean energy resource, tidal current energy has a higher energy density, steady period, steady load and abundant reserves. It's estimated that the total theoretical reserves of tidal current energy around the world is about $10^8$ kW[1,2]. Therefore, the large-scale development and utilization of tidal current energy can relieve energy supply and environmental pollution problem at local area.

Hydro-turbine is one of the main energy capture device of tidal current energy. At present, for large-scale tidal power station, power generation capacity of traditional single turbine system is completely limited, large scale of turbine array can improve economic benefits of power station better[3]. Multi-unit tidal power station not only can obtain more energy in limited tidal current field but also greatly reduce the cost of single turbine owing to mass-produced manufacture. Moreover, it is more convenient to maintain and operate power station. Therefore, multi-unit turbine array tidal power station research has great advantages and development prospect.

Many researchers have studied on vertical axis tidal turbine array. Li Ye[4,5] studied twin-turbine array by free vortex method and found that the decisive factor of turbine energy efficiency was flow direction distance between parallel vertical axis turbine arrays. Ander Goude et al.[6] studied on the energy efficiency of five groups of vertical axis turbine array by using two-dimensional vortex method, after comparing and analyzing the advantage and disadvantage of parallel arrangement scheme as well as staggered arrangement scheme, the total output power of staggered arrangement turbine array was higher than that of parallel arrangement scheme. Guo Fengshan[7] systematically studied on multi-unit vertical axis tidal turbine array arrangement by CFD, the research revealed that smaller lateral distance of parallel turbine array can efficiently improve turbine's power coefficient and the rotation direction of turbine had little effect on turbines total output power. Wang Kai and Sun Ke[8] numerical simulated on parallel twin-turbines by transient CFD method, emphatically researched on the influence of the initial position angle between two groups of two blades turbine on turbine's hydrodynamic performance, results showed that the total output power of twin-turbines was more than twice the output power of the single turbine, especially at medium high speed ratio working condition. Eduard Dyachuk[9] studied on single-row parallel turbines, analyzed the influence of the distance between turbines and the inlet angle on the output power of each turbines, results showed that the output power of turbine was sensitive to the inlet angle variation. Jeong Ki Lee[10] studied on the influence of the rotation direction as well as the distance between turbines on the output power of turbine sets, the research result showed that the output power of twin-turbine of opposite inward rotation direction was higher, and its energy efficiency was about 9.2% higher than that of the single turbine.

In this paper, single and parallel twin vertical axis hydro turbines were numerical simulated by OpenFOAM, emphatically studied the influence of the distance between turbines and rotation forms on turbine array interference effect as well as hydrodynamic performance characteristics in order to optimize the layout scheme of twin vertical axis tidal turbines.

## II. NUMERICAL SIMULATION

In this article, an H-type straight blade vertical axis hydro turbine with NACA airfoil is selected as the research model. Due to it has the same shape of the cross-section of wing span direction, compared with three-dimensional simulation method, two-dimensional simulation will not only save calculation time by greatly reduce grid numbers but also keep an accepted calculation accuracy. Hence two-dimensional simulation method is adopted to numerical simulation based on the following simplification: (a) Neglect the three-dimensional effect of blades; (b) Neglect the influence of free surface and water bed; (c) Neglect the influence of main shaft, spoke and the other additional structures; (d) Assume the incoming flow is an uniform flow. The geometry of the physical model is listed in Table I.

TABLE I

GEOMETRIC PARAMETERS OF THE TURBINE MODEL

| **Parameter** | **Symbol** | **Value** |
|---|---|---|
| Hydrofoil | - | NACA0022 |
| Number of blades | Z | 3 |
| Turbine diameter | D | 6 m |
| Chord length | C | 0.7 m |
| Blade deflection | $\varphi$ | -3° |
| Incoming flow velocity | $V_A$ | 3 m/s |

### A. Coordinate and Parameter Definition

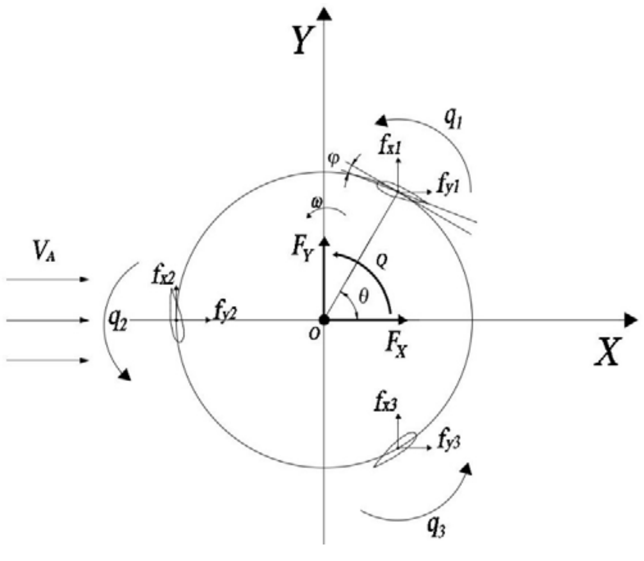



Fig. 1 Vertical axis hydro turbine coordinate system

The Cartesian coordinate system of vertical axis hydro-turbine is shown in Fig.1. The origin of global coordinate system is located at the center of turbine, the *X* axis direction is the same as the direction of incoming flow, and the *Y* axis direction pass the origin and is perpendicular to the direction of incoming flow. $\theta$ is the position angle of blade, which anticlockwise rotation is positive while taking positive *X* axis as starting point. The origin of local coordinate system is at the center of every blade, the *x* axis direction and *y* axis direction are the same as the direction of global X and Y direction. The deflection angle $\varphi$ is defined by the angle between the chord length direction of blade and the tangential direction of blade's circular locus, and the angle $\varphi$ of fixed angle vertical axis hydro turbine remains -3° in this model.

In order to analyze calculating data conveniently, several dimensionless parameters are definition as follows:

$$\lambda = \frac{\omega R}{V_A} \tag{1}$$

$$C_{F_X} = \frac{F_X}{0.5\rho {V_A}^2 DH} \tag{2}$$

$$C_{F_Y} = \frac{F_Y}{0.5\rho {V_A}^2 DH} \tag{3}$$

$$C_q = \frac{q}{0.5\rho {V_A}^2 DHR} \tag{4}$$

$$C_P = \frac{Q\omega}{0.5\rho {V_A}^3 DH} \tag{5}$$

$$\eta = \frac{Cp1+Cp2}{2} \tag{6}$$

Where $\lambda$, $C_{F_X}$, $C_{F_Y}$, $C_q$, $C_P$ and $\eta$ are respectively the tip speed ratio (TSR), thrust coefficient, lateral force coefficient, blade torque coefficient, power coefficient of the single turbine and average energy efficiency of twin turbines. *R*(m) is turbine radius, which is half of the turbine diameter *D*; $\omega$(rad/s) is turbine angular velocity; $V_A$(m/s) is uniform incoming velocity; *H*(m) is wing span, which is unit length in 2D model; $\rho$(kg/$m^3$) is fluid density, which chooses 1025 for sea water; *q*(N·m) is the torque of a single blade on the main shaft; *Q*(N·m) is the total torque of turbine, $Q = \sum_{i=1}^{3} q_i$;$F_X$(N) is the overall thrust of turbine, $F_X = \sum_{i=1}^{3} f_x$; $F_Y$(N) is the overall lateral force of turbine, $F_Y = \sum_{i=1}^{3} f_y$; $\eta$ is the average energy efficiency of turbine1 and turbine2 in Fig.2.

### B. Computational Domain

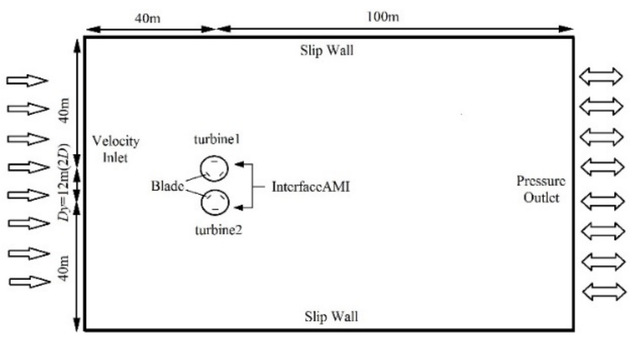
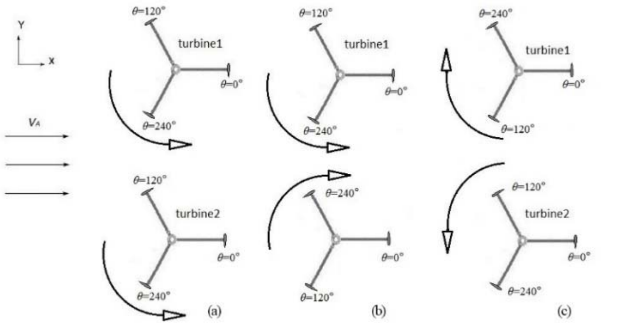



Fig. 2 Computational domain of parallel turbines

The twin turbines are placed parallel from lateral direction, the absolute value of turbine axis relative position angle $\Psi$ is 90°. Fig.2 shows the computational domain of parallel turbine and boundary condition. The lateral distances $D_y$ are set 1.25D, 1.5D, 1.75D, 2.0D, 3.0D, 4.0D respectively.

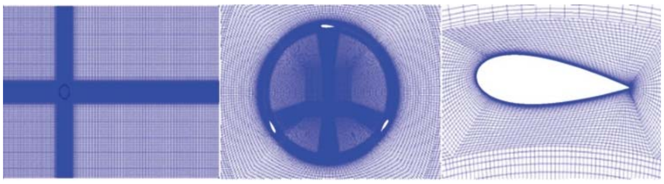
For studying on the influence of the rotation direction of parallel turbines on hydrodynamic performance, numerical simulation of three kinds of turbine rotation forms are carried out, which are the same rotation, opposite inward rotation and opposite outward rotation, as shown in Fig.3.




(a) Same rotation (b) Opposite inward rotation (c) Opposite outward rotation

Fig. 3 Rotation forms illustration of twin turbines

## III. Single Turbine Model Validation



(a) Grid in outer domain (b) Grid in rotating domain (c) Grid near the blade

Fig. 4 Grid of the single turbine model

Grid of the single turbine model is shown in Fig.4. The whole calculation model is divided into two parts, rectangular outer flow field and circular rotating field containing blades. The single turbine model size and parameters of flow field are the same as parallel turbine model.

TABLE II

Parameters of CFD analysis

| Parameter | Value |
|---|---|
| Total grid number | 121000 |
| Rotation domain grid number | 85000 |
| $y^+$ | 5 |
| Time step | 0.001 s |
| Solver | PimpleDyMFoam |
| Turbulence model | *k-ω* SST |
| Turbulence intensity of velocity let | 5% |

Parameters of OpenFOAM calculation for the single turbine model as well as parallel turbine model are selected, including grid, time step, turbulence model, turbulence intensity of velocity inlet and so on[11]. Table II lists parameters of CFD analysis.

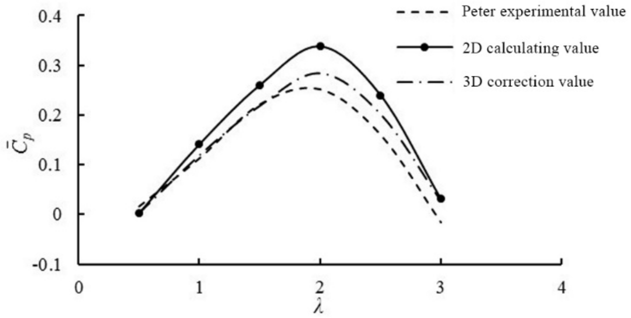



Fig.5 Average power coefficient comparison

For validating the availability of two-dimensional numerical model based on OpenFOAM code, a single vertical axis hydro turbine tested by Peter Bachant is selected as verifiable example. Fig.5 is the comparison curves of calculated value and experimental value of turbine average power coefficient $\overline{C_P}$. 2D calculating value is from two-dimensional numerical model by OpenFOAM. Peter experimental value come from test data in reference[12]. Considering the three-dimensional effect including tip of blade and support structures, we corrected the 2D calculation data referring some conclusions by Li Ye[13]. Blade tip effect will decrease average power coefficient about 8% and support structure will reduce average power coefficient about 9% when the turbine wing span-diameter ratio is 1.0. The 3D correction value is corrected by the 2D calculating result according to the reduction above. It can be seen from the graph that the changing trend of the simulated value has a good agreement to that of the experimental value, both of them reach the maximum $\overline{C_P}$ at TSR 2.0. The maximum absolute error between 3D correction value and experimental value of power coefficient is 4.16%, which proves that the accuracy of the numerical model for vertical axis hydro-turbine is acceptable in this article.

## IV. Results and Discussions

### A. Single Turbine

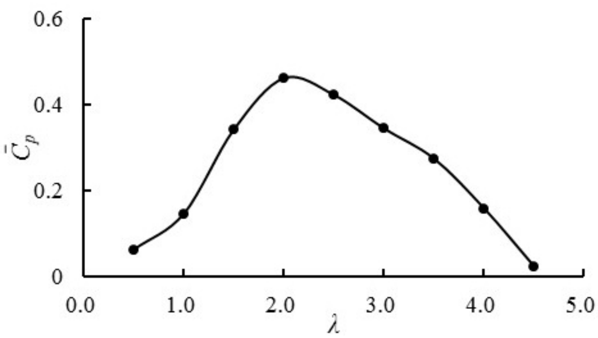


Fig. 6 Average power coefficient of the single turbine

The most important parameters which measure hydrodynamic performance of vertical axis hydro turbine are average power coefficient $\overline{C_P}$ and blade torque coefficient $C_q$.

The average power coefficient at different speed ratio of a single turbine can be seen in Fig.6. It is shown that turbine power coefficient is highest at TSR 2.0. Therefore, we assume the following two parallel turbines rotate at the same angular speed and both TSR at 2.0.

Fig.7 shows the changing curve of single blade torque coefficient $C_q$ with different blade position angle when TSR is 1.0, 2.0, 3.0 and 4.0. It is shown that blade torque is higher when blade position angle range from 120° to 240°, and the torque peak around 180°. Therefore, the main area which provide torque is at upstream disk of the turbine.

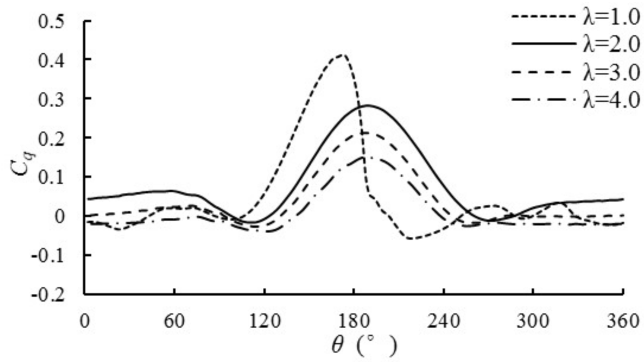



Fig. 7 Single blade torque coefficient

### B. Parallel Turbine

Lateral distance $D_y$ and different rotating forms of parallel turbines are studied for exploring the turbine hydrodynamic performance.

#### 1) Average energy efficiency

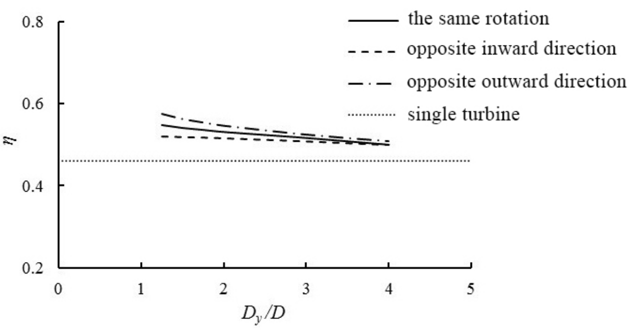
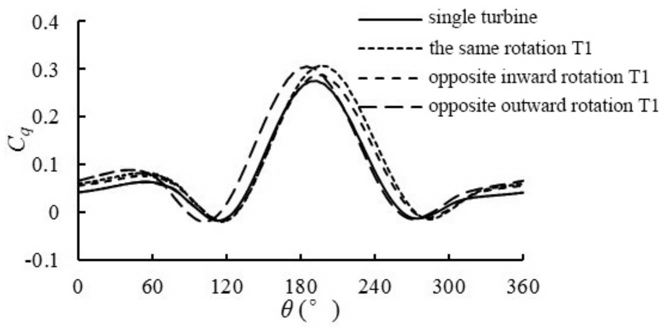



Fig. 8 Average energy efficiency comparison at three rotating forms with different lateral distance

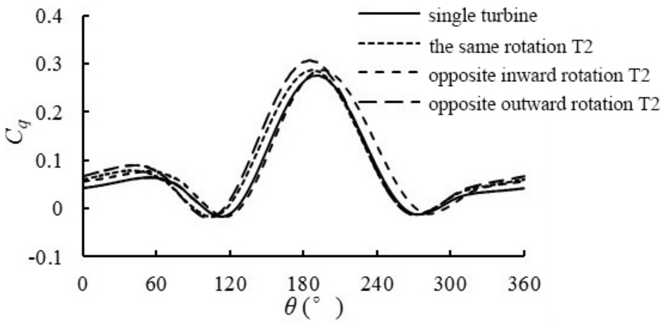
Fig.8 shows average energy efficiency changing curves of parallel turbines in three rotating forms with different lateral distance $D_y$. When the lateral distance between turbines are from 1.25D to 4.0D, average energy efficiency $\eta$ of twin turbines is higher than that of the single turbine at any rotating forms caused by the blockage effect of turbines. The highest is opposite outward rotation direction, the second high is the same rotation direction and the lowest is the opposite inward rotation direction. The average energy efficiency decreases with the increase of lateral distance. Therefore, theoretically the smaller distance, the more power output. But too small lateral distance between turbines will make difficulty of the installation and daily maintenance of equipment.

#### 2) Blade Torque Coefficient

For studying blade mechanical characteristics in the running process of parallel turbine, three lateral distances of turbine are set $D_y$=1.5D, 2.0D and 4.0D. Here T1 and T2 represent the blade torque on turbine1 and turbine2 as shown in Fig.2.

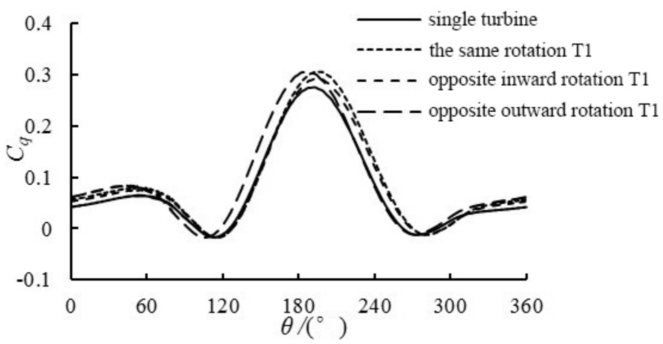



(a) Tubrine1-blade

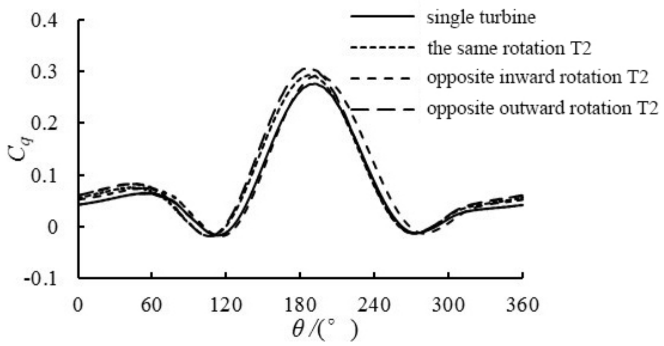



(b) Turbine2-blade

Fig.9 Blade torque coefficient with different rotation forms ($D_y$=1.5D)

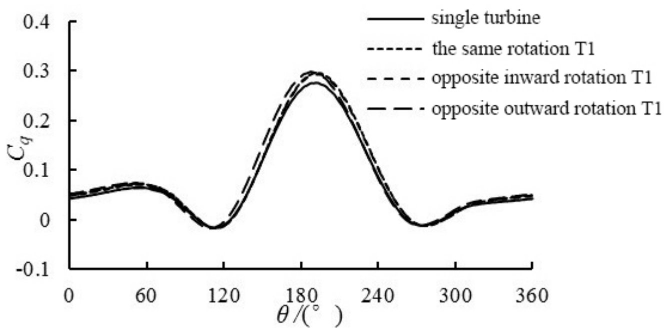



(a) Tubrine1-blade

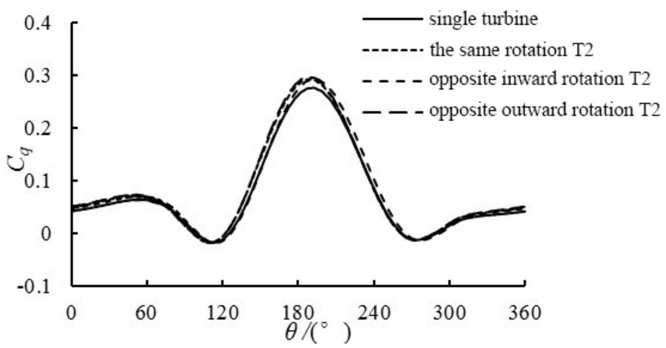



(b) Turbine2-blade

Fig.10 Blade torque coefficient with different rotation forms ($D_y$=2.0D)




(a) Tubrine1-blade




(b) Turbine2-blade

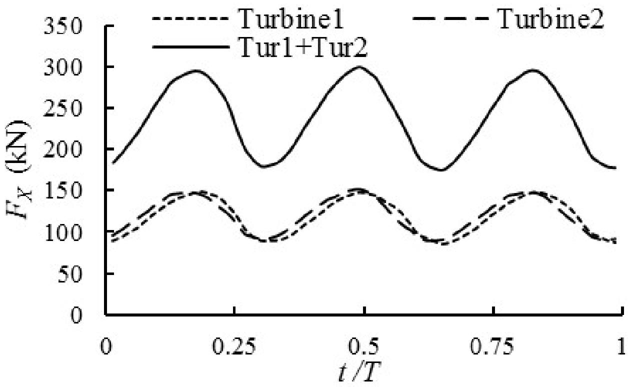
Fig. 11 Blade torque coefficient with different rotation forms ($D_y$=4.0D)

Fig.9 to Fig.11 are individual blade torque coefficient of each turbine with three rotation forms at three lateral distances, which can be seen that each blade torque of parallel turbine is clearly higher than single turbine blade when the position angle range from 120° to 270°. The lateral distance is smaller, the average value and the maximum value of blade torque coefficient are higher. With the increasing of lateral distance, the blade torque coefficient gradually become smaller and close to that of the single turbine.

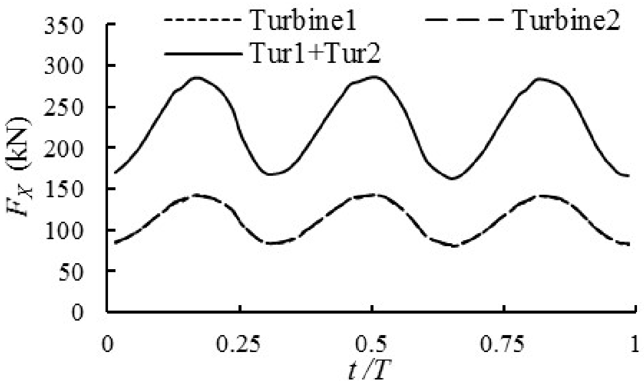
In addition, for rotating in the same direction, the average blade torque coefficient of turbine1 is higher than that of turbine2, and the position angle of turbine1 when blade torque reach the maximum is earlier than turbine2. This difference is caused by the asymmetry of flow field. For opposite inward rotation and opposite outward rotation, two turbines have nearly the same blade torque owing to its symmetric layout. The turbine's power derive from the torque of each blade. Therefore, the output power of two turbines are entirely same at two opposite rotation forms.

*3) Thrust and Lateral force of Turbine*

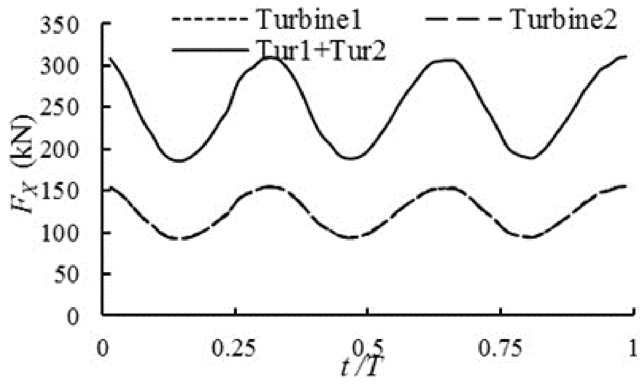
Because of twin turbines usually install on one carrier platform, the thrust and lateral force of turbines are vital importance for loads directly applied on the carrier platform. To study the influence of twin turbine rotation forms, we keep one fixed lateral distance $D_y$=1.5D. Thrust and lateral force of parallel turbines in one rotating period are shown in Fig.12 and Fig.13.




(a) The same rotation



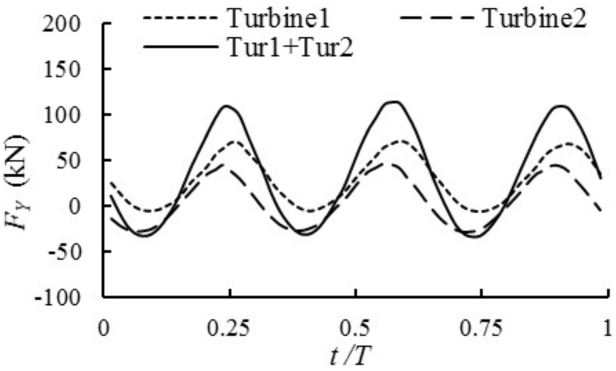

(b) Opposite inward rotation



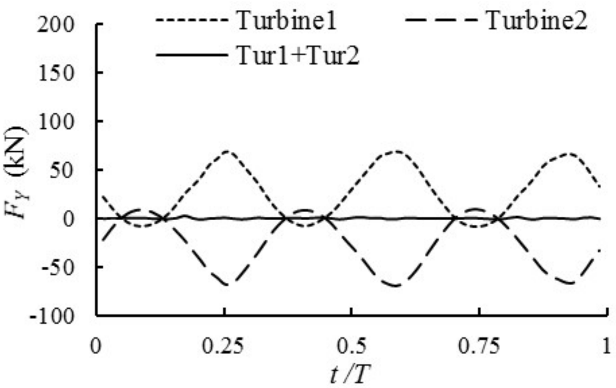

(c) Opposite outward rotation

Fig. 12 Thrust of turbines

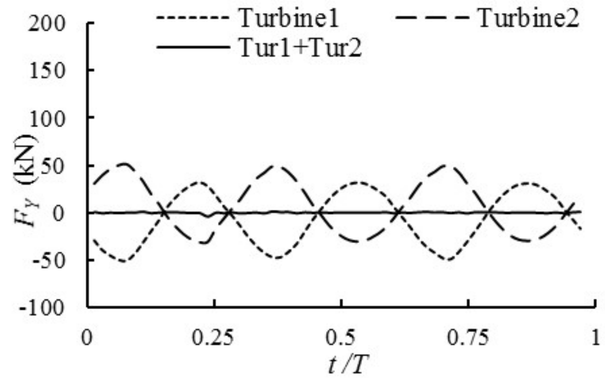
The total thrust of turbines with different rotating direction are given in Fig.12. For turbine rotating in the same direction, the thrust has three periodical fluctuations which equal to the blade numbers. Forces on turbine1 and turbine2 reach the peak almost simultaneously with large amplitude. For turbine rotating in opposite inward direction and opposite outward direction, turbine1 and turbine2 almost have the same thrust values, but have the opposite phase angle for inward and outward rotating direction. The average value of total force on two turbines nearly are the same, around 230kN, with the fluctuation amplitude 60kN, but phase angle of opposite outward rotation is different from the same rotation and opposite inward rotation.




(a) The same rotation




(b) Opposite inward rotation




(c) Opposite outward rotation

Fig. 13 Lateral force of turbines

The total lateral force of turbines with different rotating direction are given in Fig.13. For turbines rotating in the same direction, the lateral force of turbines has three periodical fluctuation which equal to the blade numbers. Force on turbine1 reach the maximum peak a little later and values are a little larger than that of turbine2, which caused by the flow field overlay. Total lateral force on two turbines are larger than that of each turbine in the same rotation direction, which is also larger than that of the other two rotation forms. For turbines rotating in opposite inward direction, lateral force on turbine1 and turbine2 nearly have the same value but an opposite phase angle. The similar results are suitable for opposite outward direction. At the same time, the total lateral force on two turbines is almost 0 at any time in one turbine rotating period which caused by the symmetry of flow field. The maximum fluctuation amplitude for turbine1 and turbine2 in opposite inward rotation is a tiny higher than that of opposite outward rotation.

Overall, according to the thrust and lateral force analysis, either opposite inward or outward rotation is a good scheme for parallel twin vertical axis turbines for cancelling the total lateral force and keeping acceptable trust force on the carrier platform.

## V. Conclusions

The hydrodynamic performance of parallel twin vertical axis tidal turbines are numerical simulated by using PimpleDyMFoam solver of open source fluid dynamic software OpenFOAM, including average energy efficiency, blade torque coefficient, thrust and lateral force on turbines. A single vertical axis turbine by Peter Bachant validate that the 2D numerical model with reasonable computational domain scale, grid density, *k-ω* SST turbulence model, PIMPLE algorithm and proper 3D correction can comparatively forecasted the turbine's average energy efficiency accurately. The average energy efficiency of parallel twin turbines is always higher than the single turbine and increases with the increase of the lateral distance between two turbines. Besides, within three kinds of rotation forms, average energy efficiency of opposite outward rotation direction is the best. When lateral distance approximates to 1.25D, the average energy efficiency value of parallel twin turbines is about 25% higher than that of the single one. Furthermore, comparing the power output efficiencies of three kinds of rotation forms, opposite outward rotation can get more power at the same lateral distance. For load comparison on turbines with different rotation forms, opposite rotation could cancel the lateral force effect of the total load on the twin turbines and carrier platform.

Therefore, for tidal energy generation platform with parallel twin turbines, opposite outward rotation is the best layout and the nearest distance between two turbines is the best to the extent permitted by equipment installation, operation and maintenance.


## ACKNOWLEGEMENT

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