Ocean Engineering 37 (2010) 627–637

Contents lists available at ScienceDirect

Ocean Engineering

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

Modeling of twin-turbine systems with vertical axis tidal current turbines: Part I—Power output

Ye Li [a,*,1], Sander M. Calışal [a,b]

[a] Naval Architecture and Offshore Engineering Laboratory, Department of Mechanical Engineering, the University of British Columbia, 1051-6250 Applied Science Lane, Vancouver, BC, Canada V6T1Z4
[b] Piri Reis University Turkey, 34940 Tuzla Istanbul, Turkey

ARTICLE INFO

Article history:
Received 18 January 2009
Accepted 13 January 2010
Available online 20 January 2010

Keywords:
Tidal power
Tidal current turbine
Twin-turbine system
Discrete vortex method
Hydrodynamic interaction

ABSTRACT

Recent interest in the tidal current industry has driven development of the prototype from the stand-alone turbine to the twin-turbine system. In this paper, we develop a numerical model to systematically analyze the relationship between the power output and the configuration of a twin-turbine system. First, we present the design principle of the twin-turbine system. We then develop the numerical model for simulating the operation of the system, and validate the model by conducting towing tank experimental tests. We then use the model to predict the power output of the system. The results of this study show that the total power output of a twin-turbine system with optimal layout can be about 25% higher than two times that of a stand-alone turbine. We also discuss the hydrodynamic interaction between the two turbines under different configurations of the system. We conclude that the optimally configured counter-rotating system should be a side-by-side system, and that the optimally configured co-rotating system should have the downstream turbine partially in the wake of the upstream turbine, depending on the detailed configuration of the turbine.

1. Introduction

Tidal current energy is regarded as one of the most promising alternative energy resources for its minimal environmental footprint and high-energy density. The device used to harness tidal current energy is the tidal current turbine, which shares similar working principle with wind turbines. According to the principle, tidal current turbines can be classified as either horizontal or vertical axis turbines. In the past few years, tidal current energy industry has been rapidly evolving. Many investigations of stand-alone turbines have been reported, e.g., Li and Calisal (2010a) and Batten et al. (2008). Several pre-commercial prototypes have been deployed in the sea by some vendors, e.g., Marine Current Turbine, Verdant, and Archimide. Unlike the wind energy industry, stand-alone is not the only format for the tidal current turbine. Informed by the design of the marine twin-propeller system in the marine industry, many tidal current turbine designers have suggested that a twin-turbine system is a better format. A few studies of the twin-turbine system with horizontal turbines have been reported, e.g., VanZwienten et al. (2006) and Clarke et al. (2007). Moreover, the world's first twin-turbine system with horizontal axis turbines was deployed by Marine Current Turbine in 2008 (Fig. 1). On the other hand, no study on the twin-turbine system with vertical axis turbines has been reported, although vendors have released their concepts (e.g., Bluenergy 2008, Fig. 2). Practically, twin-propeller systems with vertical axis propellers have been used for many years (Jurgens and Fork, 2002). Nonetheless, the vertical axis turbine has its own unique advantages: (1) it is a uni-directional device, which means that it does not need to adjust direction to obtain optimal power output as with the horizontal axis turbine; and (2) most of the components are above water so that maintenance is easy. Thus, we decided to focus on the twin-turbine system with vertical axis tidal current turbines. In the rest of this paper, when we use "a twin-turbine system", we refer to a twin-turbine system with vertical axis tidal current turbines. Readers who are interested in a more detailed comparison of vertical and horizontal turbines can refer to Shikha et al. (2005).

To date, to the best of our knowledge, no systematic investigation of twin-turbine systems has been reported, mainly due to the complexity of the hydrodynamic interaction between the two turbines. Recently, preliminary studies have suggested that a twin-turbine system with an optimal configuration can noticeably increase power output at the two turbines (Li and Calisal, 2009). We therefore decided to proceed with a systematical numerical investigation validated by a prototype towing tank test; these efforts are summarized in this paper. After defining the

* Corresponding author. Tel.: +1 303 384 6988.
E-mail address: ye.li@nrel.gov (Y. Li).
[1] This work was conducted when Ye Li was with University of British Columbia. Now Ye Li is a senior research scientist at National Wind Technology Center, National Renewable Energy Laboratory. Present address: 1617 Cole Blvd, MS 3811, Golden, CO 80401, USA.

0029-8018/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2010.01.006

Fig. 1. Twin-turbine system with horizontal turbines (courtesy of Peter Frankel).

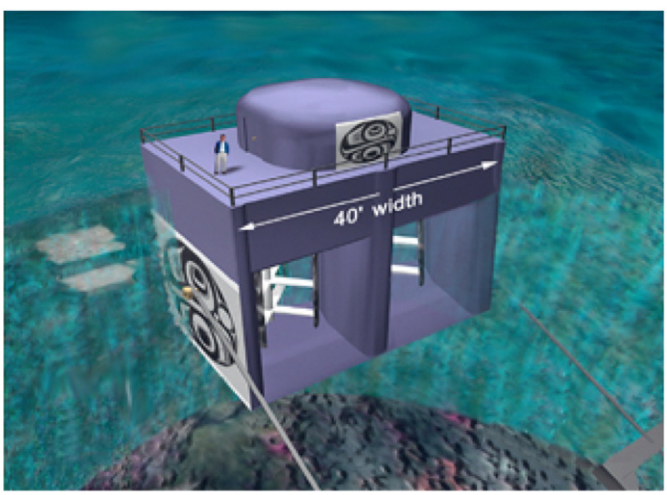

Fig. 2. Twin-turbine system with vertical axis turbine (courtesy of Bluenergy).

major dimensionless configuration parameters for characterizing the twin-turbine system, we formulate a numerical model for simulating twin-turbine systems. We then validate this twin-turbine model by conducting model tests in a towing tank. The comparison results suggest that the twin-turbine model can predict the performance of the system with acceptable accuracy. Then, using the twin-turbine model, we analyze the relationship between the configuration and power output of the system. Particularly, we find that the power output of a twin-turbine system with optimal layout can be 25% greater than two times that of a stand-alone turbine under the same operating conditions. Finally, we analyze the hydrodynamic interaction associated with the relationship between the configuration parameters and the power output of the system.

2. Design principle of the twin-turbine system

The primary design principle of the twin-turbine system is to maximize the power output of the system, i.e., to produce power greater than two times that of a corresponding stand-alone turbine. In order to compare the power output of a twin-turbine system with that of the stand-alone turbine, we define a dimensionless coefficient, the relative efficiency of a twin-turbine system, $\tilde{\eta}_{2T}$, as the ratio of the power output of the twin-turbine system to that of a stand-alone turbine, P_S, under the same operating conditions, given as Eqs. (1) and (2).

$$\tilde{\eta}_{2T} = P_{2T}/P_S \tag{1}$$

$$P_{2T} = P_1 + P_2 \tag{2}$$

where P_{2T} denotes the power output of a twin-turbine system, and P_1 and P_2 denote power outputs of the two individual turbines in the system. In general, the design principle is to let $P_{2T} > 2P_S$.

The power output of the system is mainly determined by the hydrodynamic interaction between the two turbines, and which is governed by the configuration of the system. Therefore, in addition to the typical configuration parameters of the stand-alone turbine, i.e., tip speed ratio (TSR) and solidity, we shall also study the dimensionless configuration parameters of the system. These latter parameters include the relative rotating direction of the two turbines, incoming flow angle, ψ, and the relative distance, D_r, the distance between the two turbines, as depicted in Fig. 3. The relative rotating direction of a twin-turbine system can be either co-rotating, which means that both turbines rotate in the same direction (either clockwise or counterclockwise), or counter-rotating, which means that the two turbines rotate in opposite directions. The incoming flow angle, ψ, and the relative distance of the system, D_r are used for quantifying the layout of the system, as given in Eqs. (3)–(5).

$$\psi = \tan^{-1}\left(\frac{Y_d}{X_d}\right) \tag{3}$$

$$D_r = \sqrt{(X_d^2 + Y_d^2)} \tag{4}$$

$$\begin{cases} X_d = \dfrac{X_1 - X_2}{R} \\ Y_d = \dfrac{Y_1 - Y_2}{R} \end{cases} \tag{5}$$

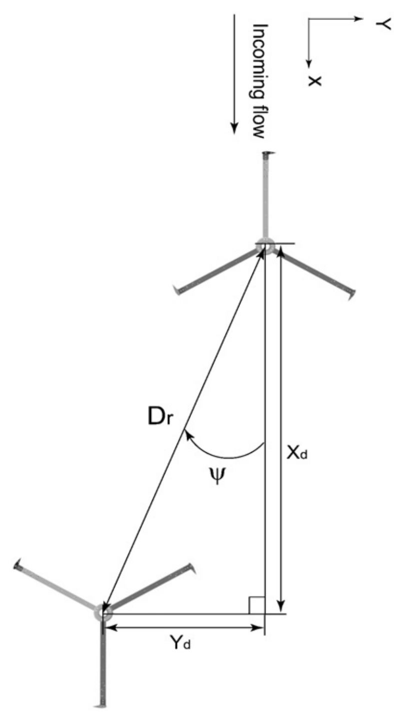

Fig. 3. An illustration of the incoming flow angle and the relative distance of a twin-turbine system.

where X_d and Y_d denote the relative distance between two turbines in the x and y directions, respectively, R denotes the radius of an individual turbine, and (X_1,Y_1) and (X_2,Y_2) indicate the respective positions of those two turbines.

3. The twin-turbine system model

We propose to develop a numerical model to approximate the operation of twin-turbine systems and the unsteady flow with all configurations with acceptable computational cost. This twin-turbine model is developed based on DVM-UBC, a well-validated numerical method for simulating tidal current turbines proposed by Li and Calisal (2007). Therefore, we review the basic theory of DVM-UBC before presenting the structure of the twin-turbine model.

3.1. Review on modeling blades using DVM-UBC

DVM-UBC is developed based on the traditional discrete vortex method (DVM), a potential flow method proposed by Rosenhead (1931). However, the traditional DVM cannot precisely simulate motions in marine applications due to the viscous effect (Wong, 1995). Using perturbation theory, Li and Calisal (2007) introduced the viscous effect into the traditional DVM and extended it to DVM-UBC by assuming that the viscous effect is limited to the near field where no-slip boundary condition exists. DVM-UBC uses Lamb vortices to replace potential vortices and introduces vortex decay, nascent vortex, and vortex shedding frequency into the formulation for describing the life cycle of vortices in approximating the physics of unsteady flow around the turbine.

DVM-UBC is a fully three-dimensional method. Each blade is represented by a set of vortices filaments with an accurate description of the blade curvature. One set of free vortices filaments together with uniform flow is used to represent the unsteady wake. These free vortices are shed from the blade trailing edge in each time step, as DVM-UBC is a time-dependent method. In each time step, DVM-UBC utilizes the relationship between the strength of free vortex and induced velocity to approximate the flow field and to predict lift, and uses this relationship together with viscous effect to predict drag. The lift and drag are then used to calculate instantaneous power. It is understood that the turbulence effect, the boundary layer effect, the free surface effect exist in a realistic turbine operating condition, especially the turbulence effect may be more noticeable in twin-turbine case than in the stand-alone turbine case due to the hydrodynamic interaction. In the initial design stage, however, these factors are not important because the designers are focusing on standardizing the configuration of the devices, and it will significantly increase the computational cost to simulate these effects. We found that even without considering these factors, DVM-UBC can predict the turbine's performance with acceptable accuracy; the deviation of the numerical results from the experimental test results is within 10% (Li and Calisal, 2010b) and the comparison in Section 4 of this paper also suggests that the deviation of numerical results from the experimental test results of the twin-turbine system is within 10% for most of scenarios. Thus, we decided not to consider these effects in DVM-UBC.

3.2. Structure of the twin-turbine model

The twin-turbine system model uses the stand-alone turbine model as a sub-module, so the two models share several similar principles. For example, a twin-turbine system is modeled by simulating the behavior of blades. If one turbine has three blades, the twin-turbine system is modeled by simulating the behavior of six blades, while the stand-alone turbine is modeled by simulating the behavior of three blades. In order to formulate a rigorous mathematical model to describe the hydrodynamics of a twin-turbine system and the unsteady flow, we made the following assumptions:

- There are no auxiliary structures (such as ducts and anchors) or other turbines around the studied twin-turbine systems.
- Each turbine blade is divided into several finite segments (elements) along the span of a blade with a given geometry.
- In the wake, the velocity at a single point is simplified by superimposing all the induced velocities upon the undisturbed incoming flow velocity.
- Shafts and arms are not being considered in this formulation.

Two sets of bound vortices are employed to represent the two turbines in the system. Each turbine is represented by one set of vortices. Similarly, two set of free vortices are employed to represent the wake vortices shed from the two turbines. Fig. 4 presents a flowchart of the computational procedure for the twin-turbine model. After the initialization of the positions and the strengths of bound vortices and the parameters of a twin-turbine system, the main program of the twin-turbine model checks the positions and relative rotating directions of the two turbines to make sure that there is no physical overlap between the mechanical components of the two turbines.[2] In this study, we define that the relative distance of a co-rotating twin-turbine system should be more than 2.25 while the relative distance of a counter-rotating twin-turbine system can be as small as 1.5. If there is no overlap, the main program calls the stand-alone turbine model to predict the bound vortices and the wake vortices of each of the turbines. Then, the wake vortices generated by each turbine are used to calculate the new strength of the blade-bound vortices of each blade. With the new strength of blade-bound vortices and the free vortices in the wake, the main program calls the stand-alone turbine model again to calculate the power output of each turbine, and a loop is formed. This loop is the main process for calculating the hydrodynamic interaction between the two turbines, which ends when the convergence criterion is satisfied. Here, when the deviation of the current value of the strength of the blade-bounded vortex from the value in the last loop is less than the critical convergence value, we say that the convergence criterion is satisfied. In this study, we set the critical convergence value at 0.02. Then, the program calculates the blade force and wake of the system, and ends when a critical number of revolutions is achieved. Selection of this critical number depends on the configuration of the system. For example, if the relative distance is ten, the critical number is sixteen. Additionally, the power output is calculated by time averaging the instantaneous power. In order to maintain the accuracy and stability of the prediction, we use the power output of the fifth to the third last revolutions. For example, if the critical revolution number is sixteen, the relative efficiency of the system can be written as follows:

$$\tilde{\eta}_{2T} = \frac{1}{10}\sum_{i=5}^{14}\tilde{\eta}_{2T,i} \tag{6}$$

[2] In this model, the arm and shaft of the turbines are not simulated. Thus, the program still works even if there is an overlap between some of the components (e.g., arm) of the two turbines. In order to avoid this overlap, we check the possible overlap between the components of the two turbines at the beginning.

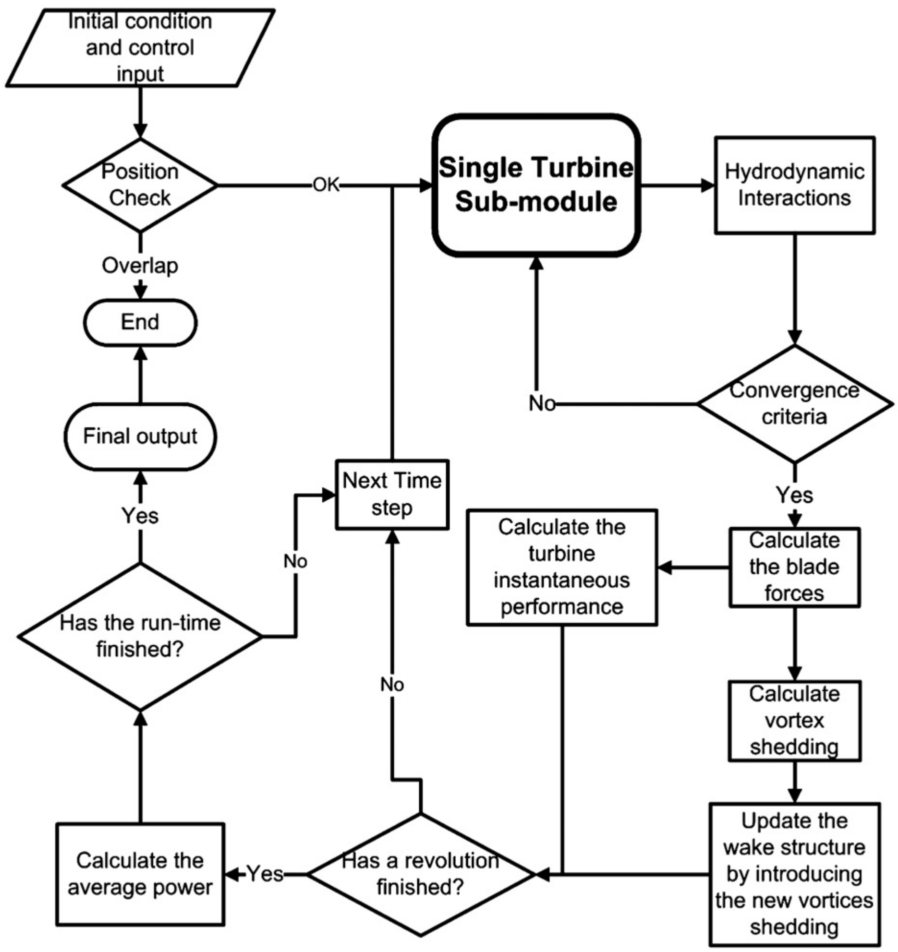

Fig. 4. Flowchart of the computational procedure for the twin-turbine model.

4. Validation of the twin-turbine model

Although DVM-UBC, the cornerstone of the twin-turbine model, has been validated with the stand-alone turbine model, it is still necessary to validate the twin-turbine model before we use it for simulating the operation of the twin-turbine system. As there is no previous study of the twin-turbine system, we decided to conduct a towing tank test to validate the numerical model.

4.1. Experimental setup

The towing tank test of twin-turbine systems was developed following the same principle used for the UBC towing tank test described in Li and Calisal (2010b). As the UBC towing tank is not big enough for the twin-turbine system test, we decided to conduct the test in the in the towing tank[3] at the Institute of Ocean Technology, Canadian Research Council. The length, width, and the depth of the tank are 90, 12, and 3 m, respectively. There is a manned carriage with a four-wheel or rack-synchronous motor drive (Fig. 5a). The original carriage is adjustable for model weights up to 80,000 kg mass, with 745 kW of power for a drive force of 60 kN. The speed range is 0.0,002–4.0 m/s, but it cannot support the twin-turbine system directly because of the demand for flexibility to represent different system configurations. In order to test the twin-turbine system, we designed a new frame to provide maximum flexibility for all tests we needed to do (Fig. 5b). The two beams that the two frames are mounted on were connected to the carriage but had the ability to move towards/away from each other as well as up and down.

When we installed the twin-turbine system, the two turbines were installed one by one similar to the stand-alone turbine configuration described in Li and Calisal (2010b). The upper shaft bearing of each turbine was mounted above the water surface onto a force balance consisting of two parallel plates capable of translating forces relative to each other and connected via load cells. The load cells were used to measure the drag force exerted on the turbine as it was towed through the water. The turbine speed was controlled using an AC motor controller. An optical encoder was used to measure the speed and position of the shaft of each turbine. When we installed the first turbine, i.e., the main turbine, we moved the two beams towards each other until the two frames came close enough together to be bolted. Having the two frames bolted together provided a very rigid support for the turbine. Then, the secondary turbine was installed accordingly. In order to ensure that the turbines always spun at the same revolution per minute (rpm), we powered both turbines using the same motor by adding a long shaft that was mounted off of the main gearbox of one turbine and then connected to the gearbox on the other turbine. It was very important to have the turbines spinning at the same rpm for consistency with regards to optimal operating condition; furthermore, the turbines were so close together that the blades could hit each other if they were rotating at different rpms. To move the turbines toward/away from each other, we simply moved the beams apart. To change the relative rotating direction of the

[3] This towing tank is locally known as ice tank as it has the capability to test marine structure with ice effect.

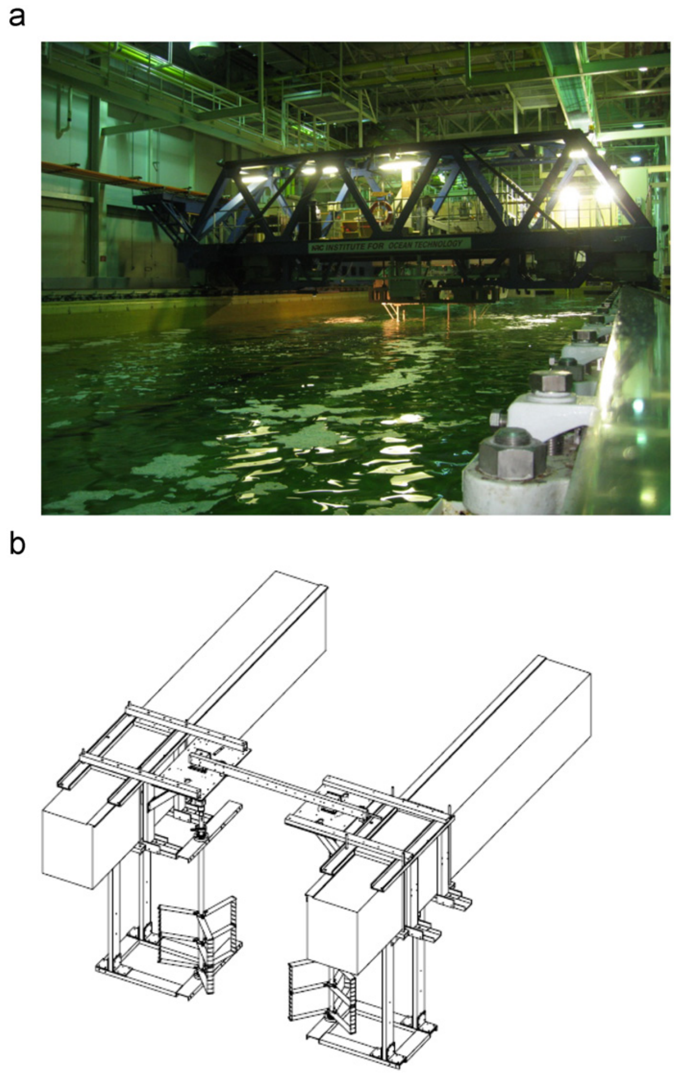

Fig. 5. Experimental setup. (a) A snap shot of IOT towing tank. (b) An illustration of the twin-turbine system with the mounting frame).

two turbines, we flipped the turbine gearbox. To conduct the tests with one turbine behind the other, we brought the frames together to the point where one turbine was directly behind the other and adjust the beam to get the right distance apart. In general, the primary turbine was held in place, while the secondary turbine was positioned using a combination of sliding the turbine along the beam and moving the beam itself. Additionally, we slid the frame up and down to lower/raise the turbines from the water whenever we need to make adjustments.

4.2. *Validation of the numerical model*

We validated the twin-turbine model by comparing the relative efficiency of the twin-turbine system obtained with the numerical model with that obtained with the experimental test (Fig. 6). Two scenarios were used for validation: (1) the incoming flow angle of the system was fixed at 90° while the relative distance was varied, and (2) the relative distance of the system was fixed at 3.5 while the incoming flow angle was varied. In both scenarios, we compared the results when the TSR was equal to 2.5 and 2.75. For each turbine, the blade type was NACA $63_{(4)}$-021, the solidity was 0.435, and the Reynolds number was 160,000.

The comparison shows that the most of the results obtained with the twin-turbine model are higher than those obtained with the experimental test. This is mainly caused by the mounting frame effects. Yet, the deviation between the numerical model results and the experimental test results is mostly less than 10% for scenario 1 and for most situations in scenario 2. The one exception occurs when the incoming flow angle is less than 20° and the relative distance is 3.5. In this exceptional situation, the mounting frames of both turbines are in line with the incoming flow direction. Therefore, the hydrodynamic interactions between the frames of the turbines are significant given that their relative distance, i.e., 3.5, is considerably short. The hydrodynamic interactions that occur when one structure is behind the other have significant negative impacts on the power output (Li and Calisal, 2010b). Thus, the experimental test results in this particular situation are much lower than the numerical results. When the incoming flow angle is larger, the hydrodynamic interactions between frames are reduced, and the difference between the numerical results and experimental results is significantly less. In the future, we will conduct experimental tests, to find ways to reduce the hydrodynamic interactions between the frames when the incoming flow angle is less than 20°.

Compared to our experience at the UBC towing tank, the experimental setup in the IOT towing tank was much more sophisticated and the deviation is less. However, in addition to the hydrodynamic interactions between the frames, there are three setup processes worth noting: (1) In the DC motor, the turbine's angular velocity controller was unable to maintain a constant angular velocity during the turbine's rotation, a high-end angular velocity controller is expected; (2) although there is no blockage effect, the free surface and bottom effects still amplify the asymmetry of the wake; (3) we did not have an opportunity to conduct a precise dynamic calibration on the sensor system; consequently, the signal amplification may occasionally shift the result with respect to the recorded phase angle.

Overall, the above validation shows that the twin-turbine model can predict the performance of twin-turbine systems with acceptable accuracy. In the next section, we shall use the twin-turbine model to conduct a systematical analysis.

5. Numerical prediction

In this section, we study the relationship between the configurations/operational parameters (i.e., TSR, relative distance, incoming flow angle, and relative rotating direction) and the relative efficiency, i.e., power output of the twin-turbine system. In order to conduct a systematic comparison, we used a typical turbine for the system, and this turbine is well-discussed in Li and Calisal (2010a); some of the description provided in that paper will be restated here. The basic specifications for this turbine are that (1) it has three blades, (2) the blade type is NACA 0015, (3) the solidity is 0.375, and (4) the Reynolds number is 160,000.

Fig. 7 shows the relationship between the relative efficiency and the relative distance of the system at various incoming flow angles when the TSR is 4.75, i.e., the design TSR of the corresponding stand-alone turbine of the system.[4] In general, the relative efficiency of the counter-rotating twin-turbine system

[4] The design TSR refers to the TSR where the power output of the turbine is close to its maximum value and this value does not fluctuate too much when the TSR fluctuates. That is, value of the power output at design TSR may not be the maximum. For example, the maximum power output of above turbine can be obtained when TSR is equal to 4.05 while the design TSR is 4.75. Interest readers can refer to Li and Calisal(2010a) for details about the definition.

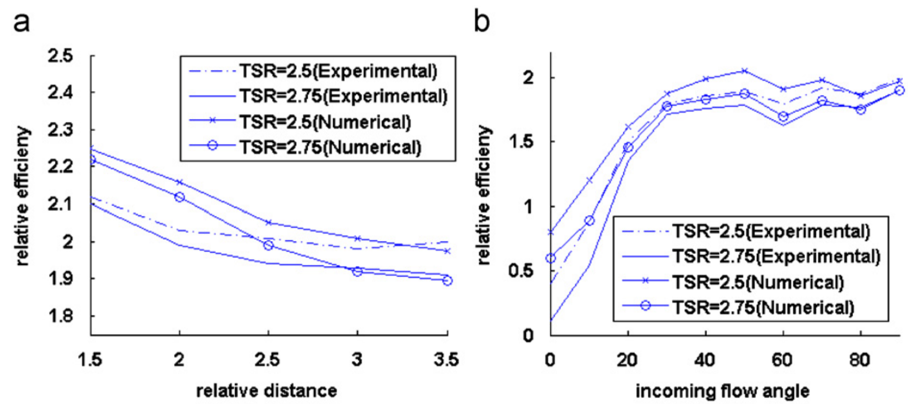

Fig. 6. Comparison between the results of experimental test and numerical prediction.

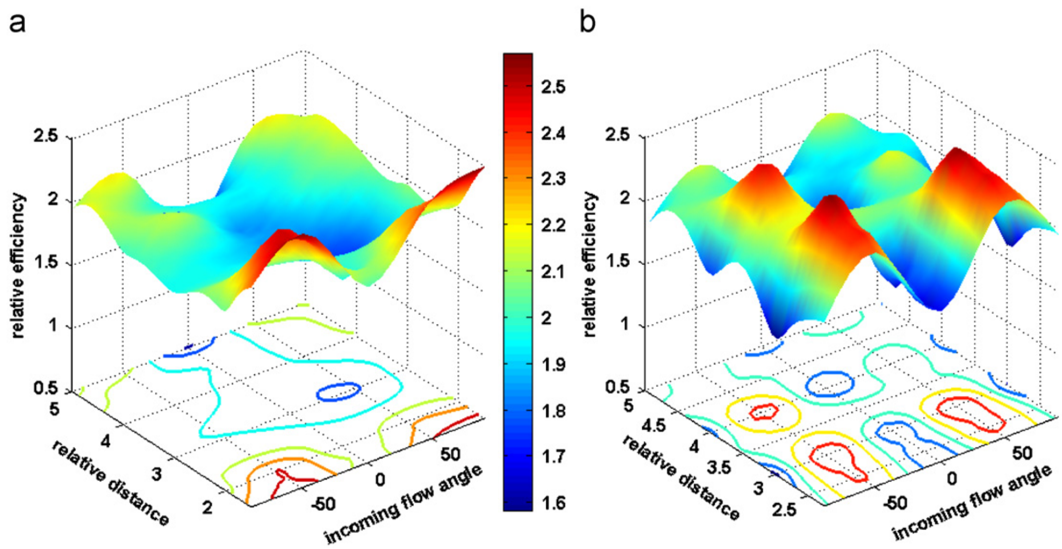

Fig. 7. The relative efficiency of twin-turbine systems when TSR=4.75 (a) counter-rotating and (b) co-rotating.

achieves its maximum value when the incoming flow is 90° and achieves its minimum value when the incoming flow angle is around 0°. The system with the former incoming flow angle as well as the system with the incoming flow angle of −90° are called canard systems, while the system with the latter incoming flow angle is called a tandem system; these two systems are the two typical systems (Li and Calisal, 2009). If the incoming flow angle is constant, it is noticed that the maximum relative efficiency can be achieved when the relative distance is equal to 1.5. Then, as the relative distance increases, the relative efficiency will significantly decrease until it reaches its minimum value when the relative distance is around 3. After that, the relative efficiency will increase as the relative distance slowly increases. For the co-rotating system, the relative efficiency achieves its maximum value when the incoming flow angle is 45° and its minimum value when the incoming flow angle is around 0°. If the incoming flow angle is constant, the relative efficiency increases with some fluctuation as the relative distance increases until it reaches its maximum value when the relative distance is around 3. After that, the relative efficiency decreases slowly with some fluctuations as the relative distance increases. One may note that all above relative distance and incoming flow angle corresponding to the maximum or minimum relative efficiency are dependent on the turbine configurations as well as the TSR, and this will be discussed in Section 6.1 in greater details.

When the relative distance is constant, one can note that the results are asymmetric with respect to the plane where the incoming flow angle is zero, although the difference between the values in the negative plane (i.e., the plane where the incoming flow angle is negative) and those in the positive plane is rather small. For example, for the counter-rotating twin-turbine system, when the relative distance is equal to 1.5, the relative efficiency is 2.34 when the incoming flow angle is equal to 45°, and the relative efficiency is 2.47 when the incoming flow angle is equal to −45°. The relative deviation is 5.3% when the relative distance is equal to 1.5 and the incoming flow is equal to ±45°. Tables 1 and 2 summarize the deviations of the relative efficiency in the whole domain of the counter-rotating and the co-rotating systems; it is noted that the maximum relative deviation is less than 10%. Such a difference is primarily caused by the behavior of the wake of the system. It is understood that the strength of the wake vortices of a stand-alone turbine is asymmetric with respect to the middle line, i.e., the line where the incoming flow passes the shaft, although the difference of the wake in both sides is small (Fig. 8).[5] Consequently, when the two turbines come close to each other, the difference of the wake in the negative plane and

[5] We only show the wake of a one-blade-turbine for illustration purpose as the wake vortices are much less than those of a three-blade-turbine.

the wake in the positive plane of twin-turbine systems is much more significant than those of the stand-alone turbine with respect to the middle line. Furthermore, it is noted that the difference of the co-rotating system is much less than that of the counter-rotating system, because, theoretically, the distribution of the wakes of the co-rotating system with any given incoming flow angle of $\pm\psi^\circ$ are the same while those of the counter-rotating system are opposite. An example is given with the system with the incoming flow angle of 90° (Fig. 9). Therefore, the differences of the co-rotating system are due to the growth of the wake vortices and the computational stability, and the differences of the counter-rotating system are primarily caused by the opposite of the wakes of the system with opposite incoming flow angles. The physics of the wake of the system is beyond the scope of this as we try to focus on the performance of the two-turbine system for the engineering design purpose. From such a purpose, the 10% difference is quite acceptable, considering the highly steady wake. Of course, the physics of the wake of the system is very important for the purpose of understanding the flow. We intend to study the wake of the twin-turbine system in greater details in future as we did for the stand-alone turbine in Li and Calisal (2010b).

In general, we decided to regard the results as "quasi-symmetric" with respect to the plane when the incoming flow angle is zero. Here "quasi-symmetric" does not means that the results are physically quasi-symmetric. It means that the deviation between the values in the negative plane from those in the positive plane is less than a certain percentage. In this study, we set it as 10%. Mathematically, $-10\% \le (P(-\psi, D_r) - P(\psi, D_r))/P(\psi, D_r)) \le 10\%$. Because it is not purely physical quasi-symmetry, the signs of the difference are not half positive and half negative. This special feature indicates that the effects of hydrodynamic interaction between turbines are quasi-symmetric. More importantly, this feature can be used to help reduce the computational cost of studying the twin-turbine system. When studying the relationship between the relative efficiency and the relative distance of the system at various incoming flow angles, it is obvious that the finer the grid (the steps of relative distance and incoming flow angle in calculating the relative efficiency), the more precise the results are and the more costly the computation is. It takes the twin-turbine model more than thirty minutes to generate the relative efficiency of a twin-turbine system for one combination of the incoming flow angle, relative distance, and TSR using a standard PC. Hence, it requires significant computational effort to generate a fine chart of relative efficiency, which covers very detailed incoming flow angles and relative distance. In order to develop a cost-effective tool for system designers, one should balance the precision of the results against the computational cost. We can reduce the computational domain by calculating one part of the whole domain if the results of this part can represent the results in the other part. Therefore, we can reduce the computational cost while maintaining the precision of the results. In the above discussion, we showed that the deviation of the relative efficiency in the negative plane from that in the positive plane is quite small, i.e., the result in one half plane can represent the results in the other half plane. In the following analysis, we choose to calculate the relative efficiency in the positive plane, i.e., when $0^\circ \le \psi \le 90^\circ$.

In order to conduct a sensitivity analysis with respect to the TSR, we investigated such a relationship by studying the scenarios when the TSR is equal to 4.25, which is lower than the design TSR, and at 5.25, which is higher than the design TSR (Fig. 10). The results show that the relative efficiency of the counter-rotating system when the TSR is equal to 4.25 can hardly exceed two, no matter the system is counter-rotating or co-rotating. That is to say, the hydrodynamic interaction always poses destructive impacts. Comparing with the relative efficiency of the system when the TSR is equal to 4.75 at the same incoming flow angle and relative distance, the relative efficiency when the TSR is equal to 4.25 is lower. Comparing the relative efficiency of the counter-rotating system and that of the co-rotating system, it is noted that the relative efficiency of the co-rotating system is greater than that of the counter-rotating system except when the incoming flow angle is 90°. The results also suggest that with other

Table 1
The relative deviation of the relative efficiency in the negative plane from the corresponding value in the positive plane (TSR=4.75, counter-rotating).

ψ	D_r					
	1.5	2	2.5	3	4	5
$\pm\pi/8$	4.0%	6.9%	9.6%	9.9%	8.7%	−2.1%
$\pm\pi/4$	5.3%	9.4%	9.8%	9.9%	7.9%	−1.1%
$\pm 3\pi/8$	7.1%	−3.5%	3.2%	8.1%	4.1%	5.2%
$\pm\pi/2$	−9.6%	−7.0%	−7.4%	6.1%	6.0%	−1.1%

Table 2
The relative deviation of the relative efficiency in the negative plane from the corresponding value in the positive plane (TSR=4.75, co-rotating).

ψ	D_r				
	2.25	2.5	3	4	5
$\pm\pi/8$	1.3%	0.7%	0.3%	3.5%	0.3%
$\pm\pi/4$	−0.4%	−0.9%	0.8%	8.8%	−0.9%
$\pm 3\pi/8$	0.6%	−0.7%	0.1%	6.8%	3.1%
$\pm\pi/2$	0.4%	−1.1%	−1.3%	1.7%	1.5%

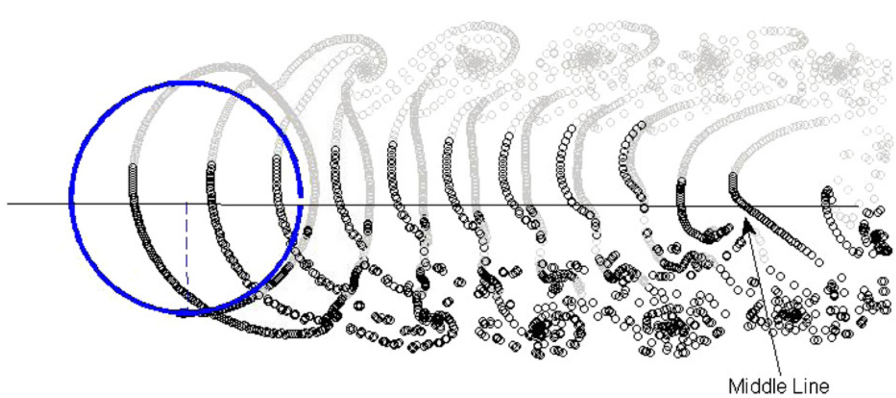

Fig. 8. Wake of an example one blade turbine, Black (positive), Grey (negative).

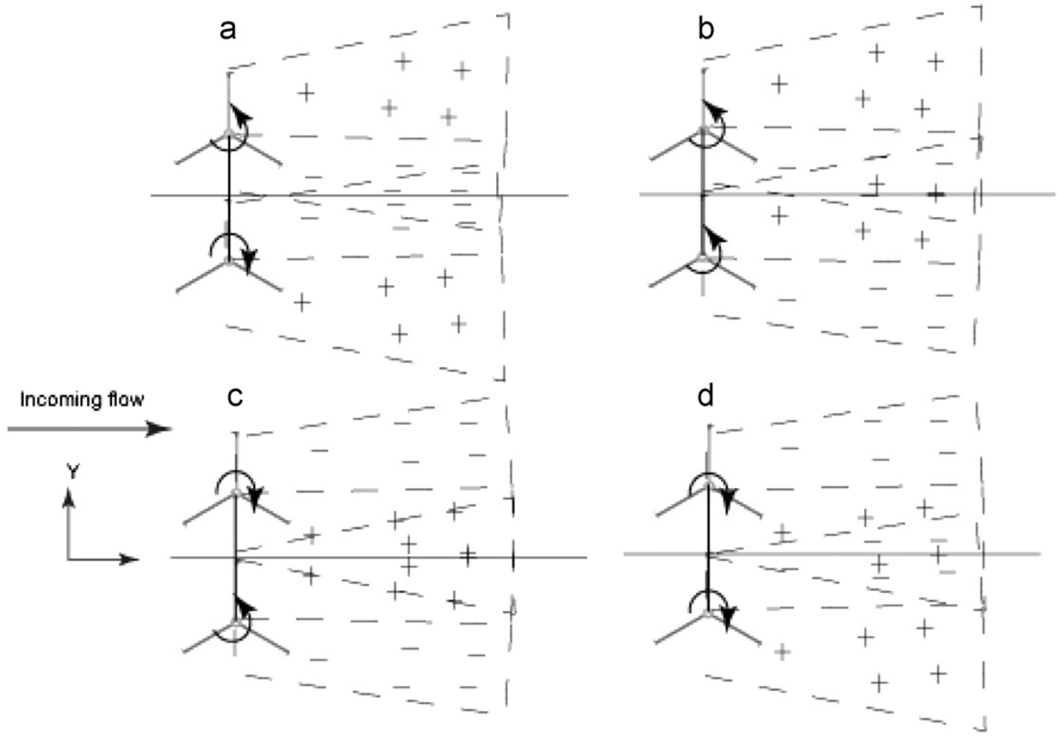

Fig. 9. Illustration of the wake of canard systems. (a) Counter-rotating and $\psi=90^\circ$, (b) co-rotating and $\psi=90^\circ$, (c) counter-rotating and $\psi=-90^\circ$, and (d) co-rotating and $\psi=-90^\circ$. *Note*: This figure is for illustration purpose and does not represent the physics.

conditions being the same, the relative efficiency when the TSR is equal to 5.25 is much higher than that when the TSR is equal to 4.25, but similar to that when the TSR is the design TSR (4.75).

6. Discussion and conclusion

This paper explains the development of a numerical model to simulate the operation of a twin-turbine system and an unsteady flow around the system, by fully taking into consideration the hydrodynamic interactions involved in harnessing tidal current energy with the system. This model is validated with a recent towing tank test. Then, the numerical model is used to predict the relative efficiency (dimensionless power output of the system) with various combinations of key parameters of the systems. In this section, we provide some further insight and conclusions of our findings.

6.1. Discussion

The power output of a twin-turbine system is determined by the hydrodynamic interaction between the two turbines. The main design philosophy is to take advantage of the hydrodynamic interaction; we try to increase the constructive hydrodynamic interaction so that the power output can be more than two times that of a stand-alone turbine. We change the hydrodynamic interactions by adjusting the configuration of the system. As the turbine is lift-dominant, a turbine can produce more power by gaining more lift, i.e., either by shedding more negative vortices into the wake or by augmenting the local velocity seen by the blade; these two ways are both affected by the hydrodynamic interactions.

This study shows that, we understand that the hydrodynamic interaction is affected by four main factors, the incoming flow angle, the relative rotating direction, the relative distance, and the TSR. The TSR and relative distance will affect the interaction possibilities of the vortices from each turbine. The higher the TSR is or the closer the relative distance is, the higher the interaction possibility is. According to the physics of the vortex shedding, the vortex shedding frequency increases with the TSR (Li and Calisal, 2010b). Therefore, the number of the wake vortices of the scenario with a higher TSR is much more than that of the scenario with a lower TSR; the velocity of vortices of the former scenario is also faster than that of the latter scenario. Consequently, the possibility of vortex interaction of the former scenario is much higher than that of the latter scenario. Among the scenarios with all three TSRs in Section 5, it is noted that the maximum relative efficiency can be obtained when the TSR is around 5.25. However, from a cost-effective point of view, one cannot just decide to let the system operate at such a TSR because this result does not mean that the total power output of a system (i.e., the total power coefficient of the system, $C_{P1}+C_{P2}$, *where* C_{P1} *and* C_{P2} *denote the power coefficient of turbine 1 and turbine 2, respectively*) obtained its maximum value when the TSR is 5.25. One should also check the total power coefficient of the system before designing a twin-turbine system, since the total power coefficient can obtain its maximum value when the TSR is equal to 4.75 (Table 3). Furthermore, although the maximum relative efficiency of the system when the TSR is equal to 4.25 is much lower than those when the TSR is equal to 4.75 or 5.25, the maximum total power coefficient of the system when the TSR is equal to 4.25 is almost the same as the other two scenarios.

When two turbines are very close to each other, their wake vortices are very close to each other as well. Therefore, they will have a higher chance to interact with each other. Unlike the TSR, this does not mean that the shorter the relative distance, the higher the relative efficiency is. The impact of the relative distance on the relative efficiency still depends on the incoming flow angle and relative rotating direction. Also, the relative efficiency of the system with a relative distance around two is often much lower

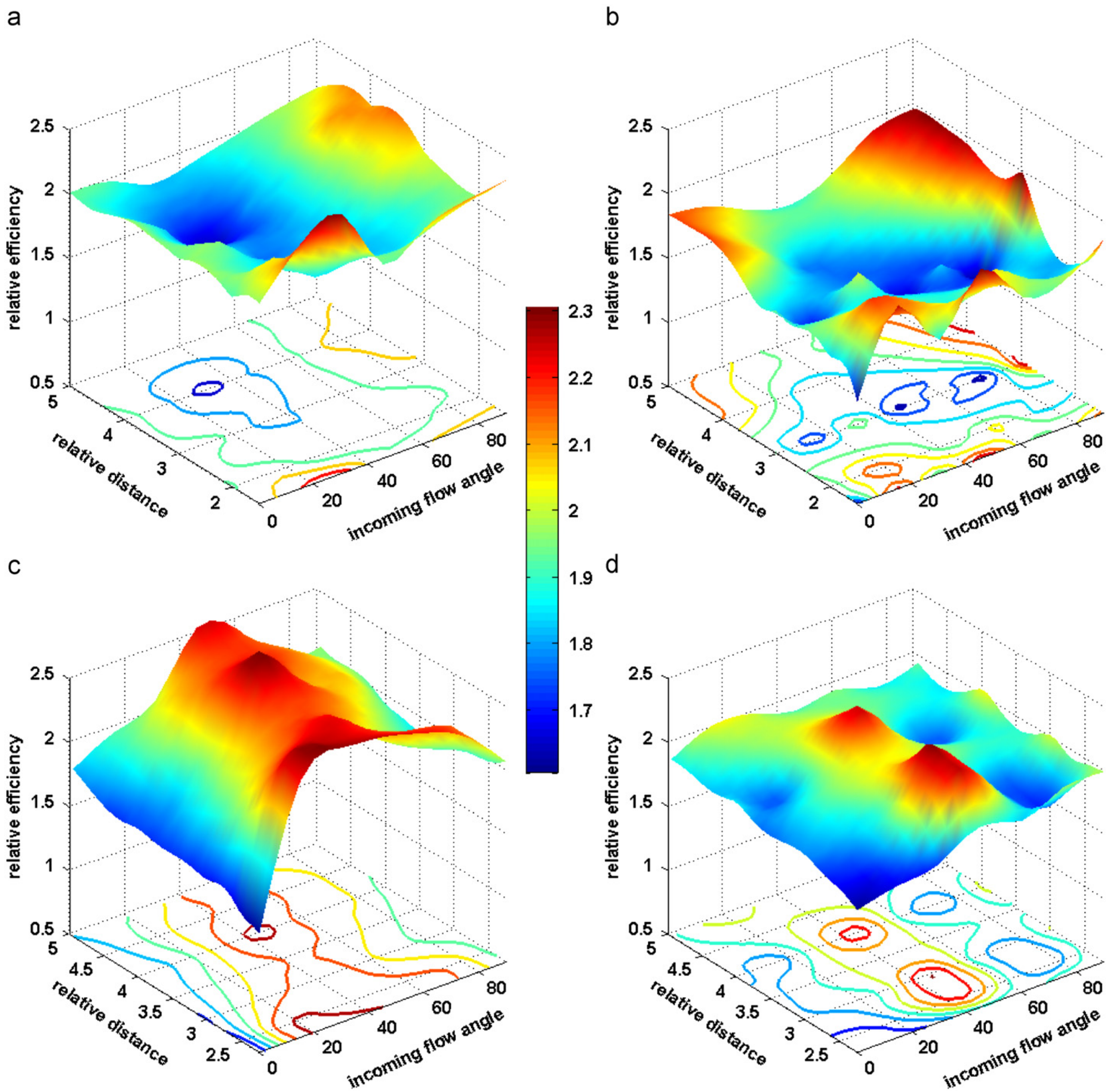

Fig. 10. The relative efficiency of the twin-turbine systems: (a) TSR=5.25, counter-rotating, (b) TSR=4.25, counter-rotating, (c) TSR=5.25, co-rotating, and (d) TSR=4.25 co-rotating.

Table 3
Summary of the maximum and minimum relative efficiencies.

TSR	Relative rotating direction	Max $\tilde{\eta}_{2T}$ (D_r, ψ)	Min $\tilde{\eta}_{2T}$ (D_r, ψ)	Max ($C_{P1}+C_{P2}$)	Min ($C_{P1}+C_{P2}$)
4.25	Counter-rotating	1.98 (3,90°)	1.26 (3,15°)	0.82	0.52
4.25	Co-rotating	2.29 (3.5, 45°)	1.61 (2.25,0°)	0.94	0.66
4.75	Counter-rotating	2.49 (1.5, 90°)	1.28 (5, 0°)	0.92	0.47
4.75	Co-rotating	2.61 (3, 45°)	1.41 (2.25,0°)	0.95	0.52
5.25	Counter-rotating	2.47 (4, 90°)	1.53 (4,30°)	0.84	0.52
5.25	Co-rotating	2.64 (2.5, 45°)	1.49(2.25,0°)	0.90	0.51

than those of the systems with a higher or a lower relative distances. When the relative distance of the system is around two, the blades of the two turbines are tangential with each other; the effects of boundary layer separation and turbulence are very strong, and the vortices are deformed so that the relative efficiency is very low.

The incoming flow angle and the relative rotating direction affect how the vortices interact with each other. The wake of a turbine is partly positive and partly negative (See Fig. 8 for more discussion). For an optimally configured counter-rotating twin-turbine system, the wake vortices are likely to be destructed because two turbines are close to each other, especially when the incoming flow angle is 90° and the relative distance is around 1.5, i.e., the system is a canard system (See Fig. 9a and c). In this case, the wakes of both turbines are symmetric with respect to the middle plane between the two turbines. Then, the negative wake vortices from one turbine will interact with the positive wake vortices from the other turbine, and thus these vortices are destructed as long as they are close enough to each other. Therefore, the induced velocity on the blade is much less than that of the stand-alone turbine, the local velocity seen by the blade is considerably higher, and thus the power output of each turbine of the system is higher than that of the corresponding stand-alone turbine. For an optimally configured co-rotating twin-turbine system, i.e., when one turbine (the downstream turbine) is partially[6] in the wake of another turbine (the upstream turbine); the upstream turbine has the opportunity to obtain more lift. In this case, the signs of the gained vortices of the downstream turbine blade are the same as the upstream wake vortices, i.e., either positive or negative. Thus, the blade of the upstream blade can gain more lift and/or more local velocity. Therefore, the power output of the upstream turbine is much higher than that of the corresponding stand-alone turbine, and the power output of the system is also higher than two times that of the corresponding stand-alone turbine.

Above discussions only provide a generic guide for turbine system designers; the exact configuration parameters of a specific twin-turbine system must be determined according to the detailed profile of the turbine's blade. Overall, these results indicate that the impacts of the hydrodynamic interaction on the relative efficiencies are partly constructive and partly destructive, and that the portion of destructive impacts increases when the TSR decreases and when incoming flow angle decreases.

6.2. Conclusion

Following conclusions are drawn from both the numerical and experimental analyses of the twin-turbine system:

- The twin-turbine model developed in this paper can predict the performance of the system with acceptable accuracy.
- The hydrodynamic interactions between the mounting frames of the two turbines are significant when the system's incoming flow angle is less than 20° and when the relative distance is short. These interactions will noticeably decrease the power output of the system.
- The numerical simulation results suggest that the relative efficiency of a twin-turbine system could be at least 25% higher than two times that of a corresponding stand-alone turbine and the relative efficiency can be 35% less than two times that of a corresponding stand-alone turbine. Particularly, for the two typical systems (i.e., the canard system and the tandem system), the canard system can achieve maximum efficiency when it is a counter-rotating system and the maximum power output is more than two times that of the stand-alone turbine, while the power output of the tandem system is always less than two times that of the stand-alone turbine.

[6] Here "partially" means that less than half of the downstream turbine is in the wake of the upstream turbine, i.e., the incoming flow angle is from 30° to 45°.

7. Future work

The innovation of the twin-turbine system has been inspired by the design of the twin-propeller system. One reason for using the twin-turbine system is to maximize the thrust and minimize the torque. In turbine design, we would like to maximize the torque. In this paper, we only study the power output and will address the torque in out next study. Some preliminary discussion can be found in Li (2008).

Although they are not critical in the initial design stage, the turbulence effect, free surface effect and bottom effect play very important roles in realistic operating conditions. These effects may affect the relative efficiency of a system, given that the relationship between these effects and the turbine's relative efficiency are highly nonlinear. They need further investigation.

Another issue worth investigating is the vortex–blade interaction in a very close distance in some systems, e.g., in a tandem system with very high solidity, there is a chance that a vortex shed from the upstream turbine will hit the downstream rotor. In this study, the solidity is not high; with a Monte Carlo simulation, we found that the possibility of the vortex shed from the upstream turbine hitting the downstream rotor is very low (Li, 2007). Therefore, we did not describe the deformation of the vortex and other phenomenon related to a vortex hitting a blade. In the future work, we shall systematically study the vortex–blade interaction of the twin-turbine system, and this can also be helpful in understanding the asymmetry of the relative efficiency results in Fig. 7.

Acknowledgements

The authors would like to thanks Natural Sciences and Engineering Research Council, Society of Naval Architects and Marine Engineers, IEEE, ASME, and ISOPE for providing financial support for conducting this research. The authors would like to thank Fraser Windsor and all staff at IOT who were instrumental in the successful execution of the tests. We would also like to thank Voytek Klaptocz, Bill Rawlings, and Yasser Nabavi of Mavi Innovations Inc. for designing the prototype, managing the towing tank testing and analyzing the experimental data. We would also like to thank Mahmoud Alidadi from UBC for his help with conducting the experiments.

References

Batten, W.M.J., Bahaj, A.S., Molland, A.F., Chaplin, J.R., 2008. The prediction of the hydrodynamic performance of marine current turbines. Renewable Energy 33 (5), 1085–1096.

Clarke, J., Connor, G., Grant, A., Johnstone, C., 2007. Design and testing of a contra-rotating tidal current turbine. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 221, 171–179.

Jurgens, B., Fork, W., 2002. The Fascination of Voitch Schneider propeller. Hamburg Publish, pp. 115–120.

Li, Y., 2007. Note on hydrodynamic interaction between two turbines. Technical Note, Naval Architecture and Offshore Engineering Laboratory, the University of British Columbia.

Li, Y., Calisal, S.M., 2007. Preliminary results of a discrete vortex method for individual marine current turbine. Proceedings of ASME 26th International Conference on Offshore Mechanics and Arctic Engineering, vol. 5, pp. 589–598.

Li, Y., 2008. A Procedure of Predicting the Power Output from a Tidal-Current Turbine Farm. PhD dissertation, the University of British Columbia.
Li, Y., Calisal, S.M., 2009. Preliminary investigation of power output of two typical two-turbine tidal current system. ASME 28th International Conference on Ocean, Offshore And Arctic Engineering, Honolulu, Hawaii, USA, 31 May–5 June, 2009.
Li, Y., Calisal, S.M., 2010a. Numerical analysis of the characteristics of a vertical axis water current turbine. Renewable Energy 35 (2), 435–442.
Li, Y., Calisal, S.M., 2010b. A new discrete vortex method for simulating a stand-alone tidal current turbine modeling and validation. Journal of Offshore Mechanics and Arctic Engineering, 132 (3), in press, doi:10.115/1.4000499.
Rosenhead, L., 1931. Formation of vortices from a surface of discontinuity. Proceedings of the Royal Society London 134, 170–192.
Shikha, S., Bhatti, T.S., Kothari, D.P., 2005. Early development of modern vertical and horizontal axis wind turbines: a review. Wind Engineering 29 (3), 287–300.
VanZwienten, J., Driscoll, F., Leonessa, A., Deane, G., 2006. Design of a prototype ocean current turbine—Part I: mathematical modeling and dynamics simulation. Ocean Engineering 33 (11), 1485–1521.
Wong, H., 1995. Slender ship procedures that include the effects of yaw, vortex shedding and density stratification. Ph.D. dissertation, Department of Mechanical Engineering, the University of British Columbia, Vancouver, BC, Canada.