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Modeling of twin-turbine systems with vertical axis tidal current turbine: Part II—torque fluctuation

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ABSTRACT

We recently showed the advantage of using a numerical system to extract energy from tidal currents by developing a new twin-turbine model (Li and Calisal, 2010a). Encouraged by this result, we decided to use this model to study another important characteristic of the turbine system, torque fluctuation. This effort is summarized in this paper. The torque fluctuation is expected to reduce the fatigue life of tidal current turbines, though potentially it also may deteriorate the power quality of tidal current turbines. In this paper, after reviewing the twin-turbine model, we use it to predict the torque fluctuation of the system with the same configurations as we used to study the power output in Li and Calisal (2010a). Specifically, we investigate the torque fluctuation of twin-turbine systems with various turbine parameters (e.g., relative distance between two turbines and incoming flow angle) and operational condition (e.g., tip speed ratio). The results suggest that the torque of an optimally configured twin-turbine system fluctuates much less than that of the corresponding stand-alone turbine, under the same operating conditions. We then extensively compare the hydrodynamic interaction's impact on the torque fluctuation and the power output of the system. We conclude that the hydrodynamic interactions pose more constructive impacts on the torque fluctuation than on the power output. The findings indicate 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 turbines. Furthermore, one must balance the optimal torque fluctuation against the optimal power output.

1. Introduction

Informed by the design of the marine twin-propeller system in the marine industry, tidal current turbine designers such as Marine Current Turbine, Underwater Electric Kite and Bluenergy have suggested that a twin-turbine system is a better format to extract energy from tidal current flow. This advantage is analyzed in Part I (Li and Calisal, 2010a)[2] where the relationship between the power output and configuration of the twin-turbine system with vertical axis tidal current turbines are extensively discussed. By utilizing the wake vortices interaction, an optimally-configured twin-turbine system is expected to have a better overall performance than that of two corresponding stand-alone turbines. Particularly, the results in Part I show that the power output of a system, with optimal configuration, is 25% more than two times that of the corresponding stand-alone turbine. More importantly, a twin-turbine numerical model is developed in Part I. Encouraged by the promising findings in Part I, we decided to proceed with a study of other characteristics of twin-turbine systems using this model.

For tidal current turbine systems with vertical axis turbines, power output and torque fluctuation are the most important performance characteristics (Li and Calisal, 2010b). Torque fluctuation refers to torque variation on the shaft during the turbine rotation. A turbine's blade azimuth angle changes with the rotation of the turbine. Consequently, the blade angle of attack changes, and the torque on the blade fluctuates as a function of the angle of attack. Torque fluctuation poses an unsteady load on the blades and the shaft of a turbine, which significantly affects the reliability of the turbine and can lead to severe failure. Moreover, the unsteady load on the shaft of a turbine may affect power quality. Poor power quality could lead to electricity intermittency when integrating power into the electrical grid.

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[2] Because this research is highly related to Part I (Li and Calisal, 2010a), Part I will be cited several times in this paper. Thus, we cite the paper as Part I rather than Li and Calisal, (2010a).

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Nomenclature

ψ	Incoming flow angle
c	chord length
C_{RTF}	Relative torque fluctuation coefficient
$C_{TF,S}$	Torque fluctuation coefficient of a stand-alone turbine
$C_{TF,Twin}$	Torque fluctuation coefficient of a twin-turbine system
C_{TF}	Torque fluctuation coefficient
D_r	Relative distance
$f_{peak,1}$	Frequency corresponding to the first peak of torque PSM
$f_{peak,2}$	Frequency corresponding to the second peak of torque PSM
R	Turbine Radius
$T_{peak,1}$	First peak of torque PSM
$T_{peak,2}$	Second peak of torque PSM
X_d	Relative distance between two turbines in x direction
X_{down}	x-coordinate of the downstream turbine
X_{up}	x-coordinate of the upstream turbine
Y_d	Relative distance between two turbines in y-direction
Y_{down}	y-coordinate of the downstream turbine
Y_{up}	y-coordinate of the upstream turbine

The working principles of tidal current turbines and wind turbines are similar and impacts from torque fluctuation have been observed for wind turbines when they harness energy (Takada et al., 2003; Piegari et al., 2007 and Manwell et al., 2010). In the wind power industry, researchers and practitioners suggest using advanced control devices to reduce torque fluctuation (Kumano, 2006; Lin et al., 2005; Takata et al., 2005; Wakui and Yokoyama, 2007). However, these kinds of advanced components often are expensive for underwater applications. Given that the operations and maintenance costs of offshore renewable energy devices are high, it is not cost-effective to use these components to reduce torque fluctuation for tidal current turbines (Li and Florig, 2006). Seeking alternative solutions, we found that an optimal design may reduce the torque fluctuation of the turbine (Li and Calisal, 2010b). In this paper, we study the possibility of optimizing a twin-turbine system to reduce the torque fluctuation of tidal current turbines.

First, we define the geometric parameters of a twin-turbine system as we did in Part I, and we also introduce a new definition, relative torque fluctuation coefficient to quantify the torque fluctuation of the system. After that, we review the numerical model used to simulate the behavior of the twin-turbine systems. Then, we use this twin-turbine model to analyze the relationship between the geometric configuration and the torque fluctuation of the system. Specifically, we find that the torque of an optimally configured twin-turbine system fluctuates much less than that of the corresponding stand-alone turbine, by comparing the hydrodynamic interaction's impact on the torque fluctuation and that on the power output of system. Finally, we discuss the effect of the choice of the blade profile on the torque fluctuation of the system, and discuss the limitation of the definition of the relative torque fluctuation coefficient.

2. Twin-turbine system and twin-turbine model

This section presents the important parameters of the twin-turbine system and the twin-turbine model. The major parameters for characterizing the configuration of a stand-alone turbine include tip speed ratio (TSR) and solidity (Nc/R). The parameters for characterizing the configuration of a twin-turbine system include the incoming flow angle, ψ, and relative distance, D_r, which is the distance between the centerlines of the two turbines (Fig. 1), and can be obtained with Eqs. (1)–(3).

$$\psi = \tan^{-1}\frac{Y_d}{X_d} \tag{1}$$

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

$$\begin{cases} X_d = \dfrac{X_{up} - X_{down}}{R} \\ Y_d = \dfrac{Y_{up} - Y_{down}}{R} \end{cases} \tag{3}$$

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_{up}, Y_{up}) and (X_{down}, Y_{down}) indicate the positions of the upstream turbine and the downstream turbine, respectively. Additionally, the turbines can rotate in two directions, either co-rotating, where both turbines rotate in the same direction (either clockwise or counterclockwise), or counter-rotating, which means that the two turbines rotate in the opposite direction (one clockwise and the other counterclockwise). The torque fluctuation of a turbine is quantified using the torque fluctuation coefficient

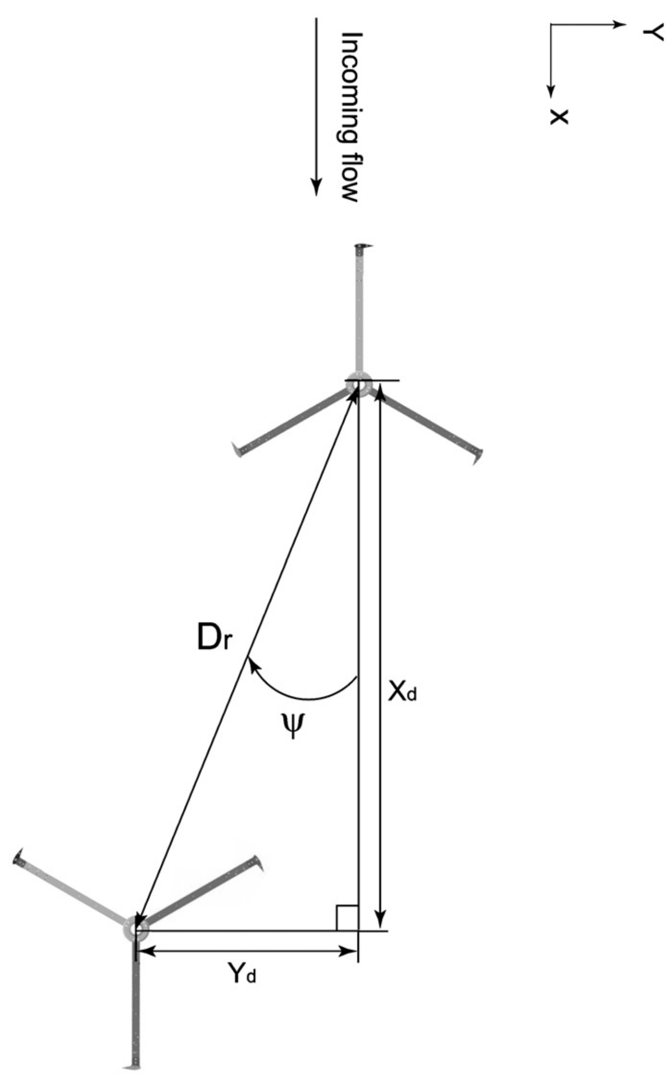

Fig. 1. An illustration of the parameters for characterizing the configuration of a twin-turbine system (a top view).

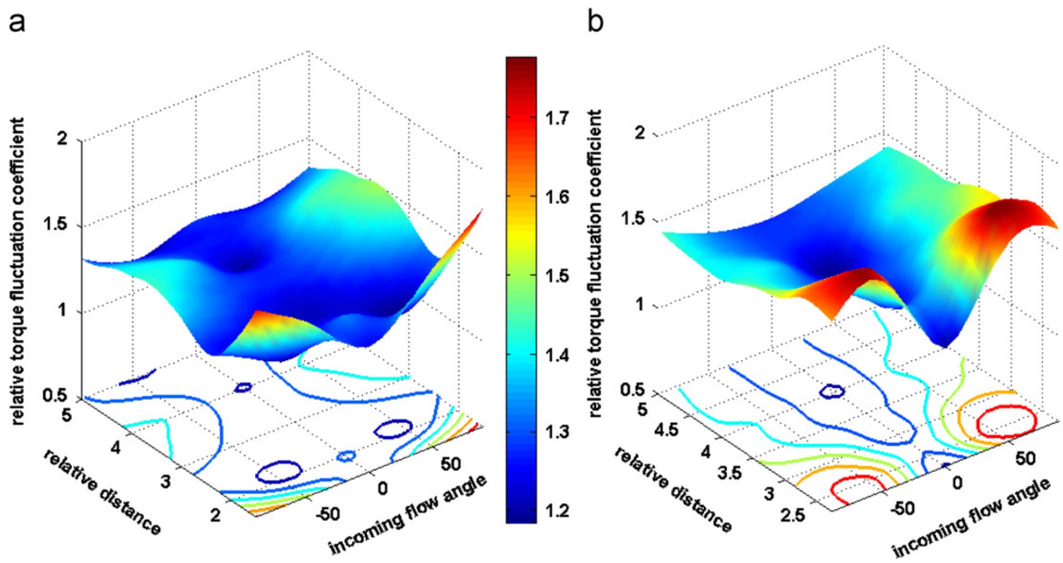

Fig. 2. Relative torque fluctuation coefficient of twin-turbine systems when TSR=4.75 (a) counter-rotating and (b) co-rotating.

(See Appendix A for the formulation). To compare the torque fluctuation of the twin-turbine system with that of the corresponding stand-alone turbine, we define a dimensionless coefficient, relative to the torque fluctuation coefficient of the twin-turbine, C_{RTF}, as the ratio of the torque fluctuation coefficient of the twin-turbine system, $C_{TF,Twin}$, to that of the a stand-alone turbine, $C_{TF,S}$ under the same operation conditions, given in Eq. (4)).[3]

$$C_{RTF} = \frac{C_{TF,\ Twin}}{C_{TF,\ S}} \tag{4}$$

In Eq. (4), the torque of a twin-turbine system fluctuates less than that of the corresponding stand-alone turbine, if the relative torque fluctuation coefficient is greater than one. This situation also suggests that the hydrodynamic interaction between the two turbines pose constructive impacts on the torque fluctuation of the system. If on the contrary, the relative torque fluctuation coefficient is less than one, the torque of the twin-turbine system fluctuates more than that of the corresponding stand-alone turbine, and the hydrodynamic interaction between the two turbines poses destructive impacts on the torque fluctuation of the system. This is discussed with the applications in Section 3.

2.1. Twin-turbine model

The numerical model for simulating twin-turbine systems (also called the twin-turbine model) in this paper was developed based on the discrete vortex method with a free wake structure formulated by Li and Calisal (2007, abbreviated DVM-UBC). The DVM-UBC was developed for unsteady flow and operation of tidal current turbines without turbulence. It was extensively validated for its prediction capability of various characteristics (e.g., power output, wake trajectory, and torque fluctuation) of the stand-alone turbine, in Li and Calisal (2010c). The stand-alone model is also used to study the characteristics of a generic turbine including power output, torque fluctuation, noise emission, and wake fluctuation (Li and Calisal, 2010b), and to quantify both the three-dimensional effect and the arm effect in modeling turbines (Li and Calisal, 2010d). The twin-turbine model proposed by Li and Calisal (2009) was validated and used to analyze the power output of the system in Part I (See Appendix B for further review). Since a model based on DVM-UBC can predict power output of a stand-alone turbine, it also can predict its torque fluctuation (Li and Calisal, 2010c). Thus, the twin-turbine model based on DVM-UBC that can predict power output of a twin-turbine system also can predict the torque fluctuation of the system.

3. Numerical prediction

This section discusses the relationship between the geometric configurations/operational parameters (i.e., TSR, relative distance, incoming flow angle and relative rotating direction) and the torque fluctuation. Specifically, we examine the use of the relative torque fluctuation coefficient to quantify the torque fluctuation of the system with respect to the corresponding stand-alone turbine. To conduct a systematic comparison, we used the same system as in Part I; therefore, some of the descriptions provided in that paper will be restated here. The basic specifications for the turbine in the system are the same: (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. As in Part I, the results are presented in a three-dimensional figure with respect to the relative distances and incoming flow angle. Consequently, we will investigate the symmetry of the results with respect to the plane where the incoming flow angle is 0°. "Symmetry" here means that the deviation between the values in the negative plane from those in the positive plane is less than a 10%. Mathematically, it means

$$-10\% \le \frac{C_{TF}(-\psi, D_r) - C_{TF}(\psi, D_r)}{C_{TF}(\psi, D_r)} \le 10\% \tag{5}$$

If the result is symmetric, we can reduce the computational domain by calculating one part of the whole domain. We can use the results in positive plane to represent the results in the negative plane. Therefore, we investigate the relative torque fluctuation coefficient in the whole domain first, i.e., $-90^\circ \le \psi \le 90^\circ$. Readers interested in the discussion of the physics related to asymmetry are referred to Part I.

Fig. 2 shows the relationship between the relative torque fluctuation coefficient and the relative distance of the system, at various incoming flow angles, when TSR is 4.75, i.e., the design TSR of the corresponding stand-alone turbine of the system. Tables 1 and 2 summarize the deviations of the relative torque fluctuation

[3] In order to keep the continuity of this paper, we only discuss the relative torque fluctuation coefficient and we left the definition of torque fluctuation coefficient in the Appendix A.

Table 1
Deviation of the relative torque fluctuation coefficient in the negative plane from the corresponding value in the positive plane (TSR=4.75, counter-rotating).

Incoming flow angle	Relative distance					
	1.5	2	2.5	3	4	5
$\pm 22.5^\circ$	6.5%	−0.8%	0.8%	3.1%	2.9%	2.8%
$\pm 45^\circ$	−3.1%	−1.8%	2.0%	3.5%	3.2%	−1.7%
$\pm 67.5^\circ$	6.5%	2.1%	2.0%	3.5%	3.2%	−3.1%
$\pm 90^\circ$	4.9%	3.3%	3.1%	3.2%	3.1%	6.7%

Table 2
Deviation of the relative torque fluctuation coefficient in the negative plane from the corresponding value in the positive plane (TSR=4.75, co-rotating).

Incoming flow angle	Relative distance				
	2.25	2.5	3	4	5
$\pm 22.5^\circ$	0.5%	−0.4%	2.1%	1.9%	1.4%
$\pm 45^\circ$	−0.9%	−0.8%	2.5%	2.2%	1.8%
$\pm 67.5^\circ$	2.5%	2.1%	3.5%	3.2%	−1%
$\pm 90^\circ$	3.8%	3.1%	3.2%	3.1%	−0.3%

coefficient in the whole domain, both the counter-rotating and the co-rotating systems. The maximum deviation is less than 6.7%, less than 10% given in Eq. (5). Thus, we decide to regard the results as "quasi-symmetric" with respect to the plane when the incoming flow angle is 0°.Consequently, to reduce the computational cost while maintaining the accuracy of the results, we only calculate the relative torque fluctuation coefficient for the positive domain, $0^\circ \leq \psi \leq 90^\circ$, and in a finer grid in the following investigation.

Additionally, one can observe that the relative torque fluctuation coefficient of the counter-rotating twin-turbine system achieves its maximum value where the incoming flow is 90° and achieves its minimum value where the incoming flow angle is around 0°. If the incoming flow angle is kept constant, the maximum relative torque fluctuation coefficient can be achieved when the relative distance is equal to 1.5. As the relative distance increases, the relative torque fluctuation coefficient significantly decreases until it reaches its minimum value when the relative distance is around 2.25. Beyond that, the relative torque fluctuation coefficient will increase as the relative distance slowly increases. For the co-rotating system, the relative torque fluctuation coefficient achieves its maximum value when the incoming flow angle is about 80° and its minimum value when the incoming flow angle is around 0°. If the incoming flow angle remains constant, the relative torque fluctuation coefficient increases, with some fluctuations, as the relative distance increases until it reaches its maximum value when the relative distance is around 2.75. After that, the relative torque fluctuation coefficient decreases slowly, with some fluctuations, as the relative distance increases. Similar to the discussion of the relative efficiency in Part I, one may note that the relative distance and incoming flow angles that correspond to the maximum or minimum relative torque fluctuation coefficients depend on turbine's configurations as well as on the TSR.

3.1. Sensitivity analysis

After confirming that the relative torque fluctuation coefficient is quasi-symmetric to the plane when the incoming flow angle is around 0°, we conducted a sensitivity analysis with respect to the TSR using a finer grid, as was done in the sensitivity investigation in Part I. Specifically, we investigated the relative torque fluctuation coefficients of the systems when the TSR is equal to 4.25 and 5.25 while the rest of the parameters remain the same (Fig. 3). In general, the results, when obtained using a finer grid, are expected to allow a more precise interpretation. The relative torque fluctuation coefficients are all greater than one, thus the hydrodynamic interactions between the two turbines in all scenarios are positive. Comparing the relative torque fluctuation coefficient in the counter-rotating system at the same incoming flow angle and the same relative distance when the TSR is equal to 4.75, the relative torque fluctuation coefficients when the TSR is 4.25 and 5.25 are both lower. In the co-rotating system, comparing the relative torque fluctuation coefficient when the TSR is equal to 4.75, at the same incoming flow angle and the same relative distance, the relative torque fluctuation coefficients when the TSR is 4.25 and 5.25 are both higher. Note that at the same TSR, (1) the relative torque fluctuation coefficient of a co-rotating twin-turbine system changes less than that of a counter-rotating system in the computational domain, and (2) the maximum values of the relative torque fluctuation coefficient of a counter-rotating system are higher than those of a co-rotating system in the computational domain. Thus, the relative torque fluctuation coefficient of the co-rotating system is greater than that of the counter-rotating system.

Of course, one cannot just decide to let the system operate at a certain TSR based on above analysis because those results do not mean that the torque fluctuates the least when the relative torque fluctuation coefficient is the highest. One also should check the coefficient that directly indicates the torque fluctuation, i.e., the torque fluctuation coefficient of the system before designing a twin-turbine system, since this value depends on the TSR (Table 3). One can note, among the systems with all three TSRs., i.e., 4.25, 4.75, and 5.25, that the maximum torque fluctuation coefficient can be obtained when the system is a co-rotating system, the relative distance is 2.5, and the incoming flow angle is 50°. The minimum torque fluctuation coefficient can be obtained when the system is a counter-rotating system, the relative distance is 1.5, and the incoming flow angle is 0°.

4. Comparison between the hydrodynamic interactions impact on the torque fluctuation and the power output

We evaluate the relative torque fluctuation coefficient in the same domain, i.e., the relative distance is less than five and the incoming flow angle is between 0° and 90°, as we did for power output in Part I. The main purpose of this study is to understand the relationship of the system configuration and the impact of hydrodynamic interactions between turbines on the important characteristics such as power output and torque fluctuation. The general analysis is provided in Part I and in Section 3 of this paper. Here, we discuss the difference between the impacts of the hydrodynamics interaction on power output and on torque fluctuation. It is noted that the maximum power output and maximum relative torque fluctuation coefficient of counter-rotating systems both can be obtained with the relative distance of 1.5 and the incoming flow angle of 90°. This is because the wake vortices shed from side-by-side counter-rotating systems destroy part of themselves. Consequently, a side-by-side configuration can have improved power output and torque fluctuation. As to the co-rotating system, it is understood that the design philosophy is to augment the local velocity or to shed more negative vortices so as to increase the power output or reduce the torque fluctuation. Thus, the incoming flow angle is very critical here. However, the power output is a time-averaged value, while torque fluctuation is a time-dependent value. Therefore, the optimal incoming flow angles for them may be different. The main reason is that the shedding of wake vortices from the turbine is a periodic phenomenon. Thus, it affects the measure of torque fluctuation more as the torque

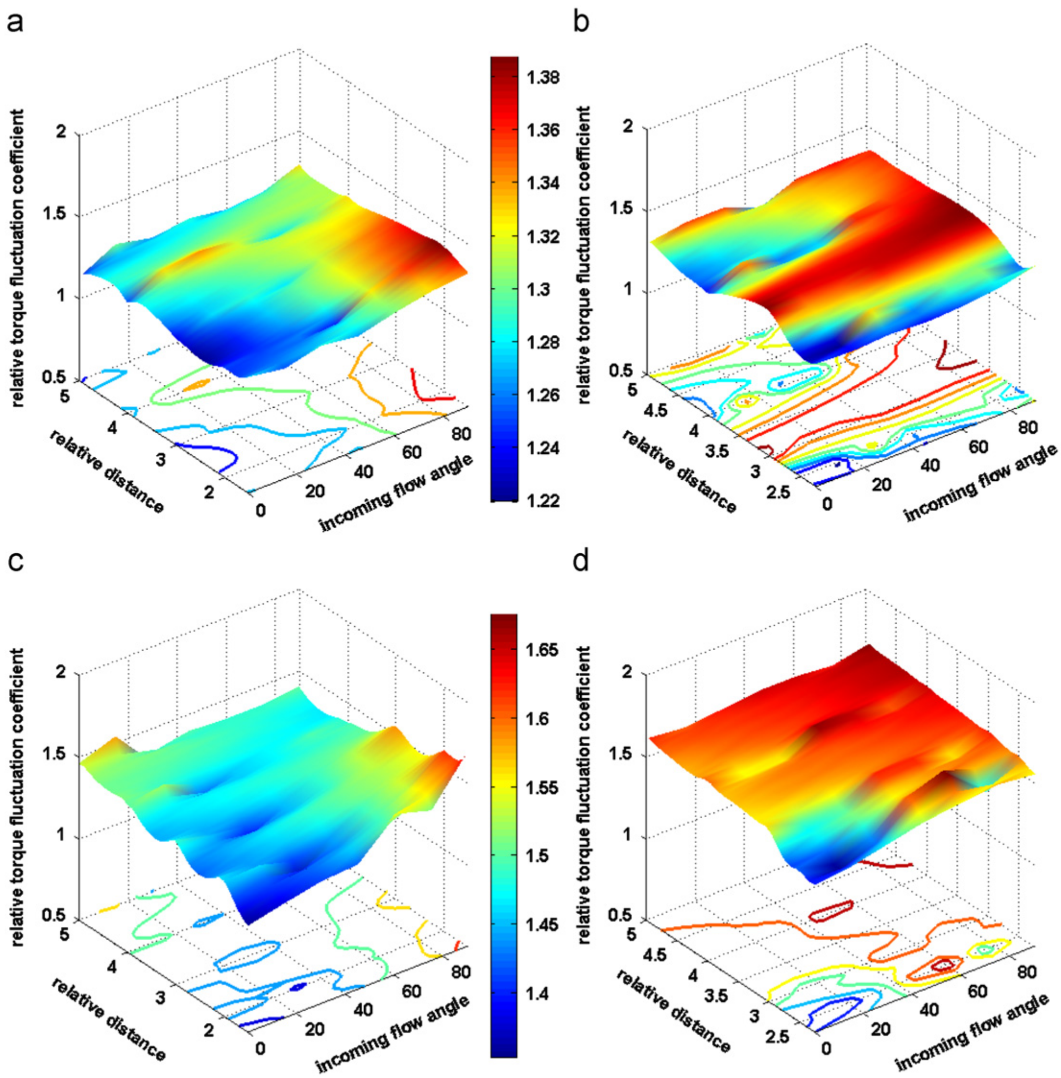

Fig. 3. Relative torque fluctuation coefficient of twin-turbine systems (a) TSR=5.25 counter-rotating; (b) TSR=5.25 co-rotating, (c) TSR=4.25 counter-rotating and (d) TSR=4.25 co-rotating.

Table 3
Summary of maximum and minimum torque fluctuation coefficient and relative torque fluctuation coefficient.

TSR	Relative rotating direction	Max. C_{RTF} C_{TF} (D_r,ψ)	Min. $C_{RTF}C_{TF}$ (D_r,ψ)
4.25	Counter-rotating	1.58, 59 dBS (1.5, 90°)	1.05, 42 dBS (1.5, 0°)
4.25	Co-rotating	1.63, 65 dBS (4, 60°°)	1.11, 45 dBS (2.75, 10°)
4.75	Counter-rotating	1.69, 77 dBS (1.5, 90°)	1.1, 49 dBS (4, 0°)
4.75	Co-rotating	1.73, 79 dBS (2.5, 50°)	1.18, 53 dBS (4, 0°)
5.25	Counter-rotating	1.4,67 dBS (2.1, 90°)	1.02, 48 dBS (5, 0°)
5.25	Co-rotating	1.42 68 dBS (2, 15°)	1.08,50 dBS (4.5, 0°)

fluctuation is also a periodic phenomenon. Furthermore, because the period of one revolution is determined by the TSR, so is the torque fluctuation. Therefore, the optimal relative distance and incoming flow angle is not constant among different scenarios.

Additionally, the comparison also suggests that the impact of hydrodynamic interaction on the torque fluctuation is almost always constructive, while those on the power output are partially constructive and partially destructive. It is because the relative distance and incoming flow angle create a phase-offset, which can easily reduce the torque fluctuation. However, it can enhance the power output only when a quasi resonant phenomenon is developed. Nevertheless, this analysis does not mean the hydrodynamic interactions always make the torque of the system fluctuate less. An example of the hydrodynamic interactions that increase torque fluctuations is given in Section 5.1.

5. Discussion and conclusion

This paper extends the analysis work of a twin-turbine system with vertical axis tidal current turbines in a companion paper, Part I, by studying the torque fluctuation of the system. We follow the flow of analysis in Part I by discussing the relationship between the systems geometric configuration and the torque

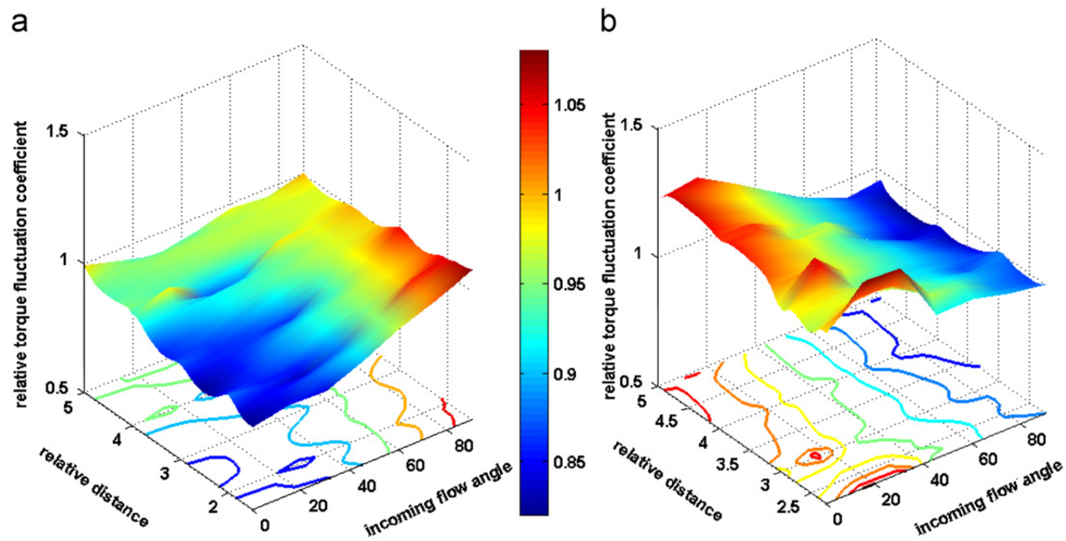

Fig. 4. Relative torque fluctuation coefficient of twin-turbine systems with the $63_{(4)}$-021 when (a) TSR=2.75 (a) counter-rotating and (b) co-rotating.

fluctuation. Specifically, we compare the impact of the hydrodynamics interaction on the torque fluctuation with that on the power output of the system. This section provides further insight, discussion, and conclusions of our findings.

5.1. Discussion

One noticeable feature in the results, shown in Figs. 2 and 3, is that the relative torque fluctuation coefficient is greater than one in all scenarios. However, one cannot conclude, based on these results, that the torque of a twin-turbine system always fluctuates less than that of the corresponding stand-alone turbine. These are based on a system with NACA0015 blades. Theoretically, the torque and power results could be different, if the blade profiles are different. The following example is a case where the torque of the twin-turbine system fluctuates more than that of the corresponding stand-alone turbine, i.e., the relative torque fluctuation coefficient of the system is lower than one. This is twin-turbine system with the blade of $63_{(4)}$-021, solidity of 0.435, Reynolds number of 160,000, and the TSR at 2.25; the case we used for the validation in Part I (Fig. 4). For the counter-rotating system, the relative torque fluctuation coefficient is greater than one only when the incoming flow angle is close to 90°, i.e., the system is side-by-side. The maximum relative torque fluctuation coefficient can be obtained when the relative distance is 1.5 and the incoming flow angle is 90°, which is similar to the results in Figs. 2 and 3. For the co-rotating system, the relative torque fluctuation coefficient is greater than one when the incoming flow angle is less than 40° and, it depends on the relative distance. System 's maximum relative torque fluctuation coefficient occurs when the relative distance is around three and the incoming flow angle is around to 18°, which is different than the results shown in Figs. 2 and 3. This simple comparison suggests that the selection of the blade profile may affect the torque results for a co-rotating system more than for a counter-rotating system. It may be caused by the change of the vortex shedding characteristics (e.g., vortex shedding frequency and the strength of the wake vortices) induced by the profile of the blade. These characteristics in general are affected by the boundary layer separation at the blade, which is determined by the blade profile. Therefore, for the counter-rotating systems, other than the side-by-side system, where the wake vortices from each turbine destroy part of themselves, most of other scenarios may increase the torque fluctuation. The flow separation and blade profile optimization are beyond the scope of this paper and must be investigated in future reports.

Another feature worth noting is that the torque of the system, in which the TSR is 4.75, fluctuates much less than those of the systems where the TSR is 4.25 and 5.25. It is noted that the TSR value of 4.75 is the design TSR where the power fluctuates least in relation to the TSR. The power fluctuation is determined by the torque fluctuation since power is equivalent to the average torque in the time domain. Thus, one can state that the torque of the design TSR of a system will fluctuate less than the torque at other TSRs. This feature also can be applied when analyzing the impact of the incoming flow angle on the power output and on torque fluctuation.

Unlike the relative power coefficient that can be easily applied to multiple-turbine systems, such as an array (e.g., Li and Calisal, 2010e), there are some limitations using the relative torque fluctuation coefficient. For example, the relationship between the relative power coefficient of a multiple-turbine system and the power coefficients of all turbines in the system is linear, while the relationship between the relative torque fluctuation coefficient of the system and the torque fluctuation coefficients of turbines in the system are highly nonlinear. Thus, unless the power electronic components of all turbines in the array are linked together, it is unlikely to apply this relative torque fluctuation coefficient to the system because the torque of each turbine does not directly interact with each other.[4] Also, for a multiple-turbine system with more than three turbines, the way in which their shafts couple together will affect the torque fluctuation. Nevertheless, in the twin-turbine system, the relative torque fluctuation coefficient is a good index of the torque fluctuation because the mechanical coupling is straight forward.

5.2. Conclusions

Similar to what was presented in Part I, the discussions on the torque fluctuation only provide a generic guide for turbine system designers; the exact configuration parameters of a specific

[4] There is indirect interaction between the torque of each turbine through the wake interaction, but it cannot be evaluated using the method presented here. We may discuss this in a future paper.

twin-turbine system must be determined according to the detailed system design. Overall, from the above investigation, that results suggest

- The torques of most twin-turbine systems fluctuate less than those of the corresponding stand-alone turbines, i.e., the torque fluctuation coefficients of the twin-turbine systems are higher than those of the corresponding stand-alone turbines.
- The relative torque fluctuation coefficient of a counter-rotating system is lower than that of a co-rotating system under the same operational conditions.
- Comparing the torque fluctuation of twin-turbine systems with the power output of twin-turbine systems, it is noted that the impacts of the hydrodynamic interaction on the former are much more constructive.
- The numerical tool and the results presented in this paper are expected to help turbine system designers to predict the torque fluctuation of twin-turbine systems. We suggest that they design the system by considering the impacts of hydrodynamic interaction on power output and the torque fluctuation together. In general, the counter-rotating system with a relative distance of 1.5 and incoming flow angle of 90° has good performance in both torque fluctuation and power output.

6. Future work

Here, we identify a few important issues to be studied based on this study. The two turbines in a twin-turbine system are expected to work together, which indicates that the system has only one torque output to electric generator. One may, however, still let the torque of each turbine be produced individually in some situations. In this situation, it was assumed that the designer would like make sure that the torque fluctuation coefficients of each individual turbine remain higher than that of the corresponding stand-alone turbine.

The optimization shown in Part I and this paper cover relative distance, incoming flow angle, and relative rotation direction. There is, however, another very important characteristic that we have not discussed, the relative phase angle. The relative phase angle describes the phase angle difference between the two turbines in a twin-turbine system. For example, in Fig. 1, the upstream turbine has one of its blades at the 12 o'clock position while the downstream turbine has one of the blades at the 6 o'clock position. In this case, the relative phase angle difference is 30°. The relative phase angle will affect the interaction between wake vortices and downstream turbines, and this investigation involved more statistical analysis. As the scope of this paper focused on the relationship between the configuration of the twin-turbine system and torque fluctuation, we decided not to present this in detail. Some preliminary discussion can be found in Li (2007), and we shall discuss this in a future paper of this topic.

Another target worth pursuing is to use the twin-turbine to study the noise emission and wake fluctuation. We have shown that noise emission and wake fluctuation are the two important characteristics in evaluating a tidal current turbine system (Li and Calisal, 2010b). The results shown in Part I and in this paper both suggest that an optimally configured twin-turbine system provides improved power and torque characteristics compared to the stand-alone turbine. The module to simulate the noise emission and wake fluctuation can be introduced into the twin-turbine model following the procedure given in Li and Calisal (2010b).

Lastly, as this study is developed based on DVM-UBC, a potential flow code where free surface effect, sea bottom effect and turbulence effect are not included, we shall also quantify these effects' impact on the turbine system's power output, torque fluctutations and other characteristics. These investigations need some fundamental improvements of the methods or hybrid with other methods.

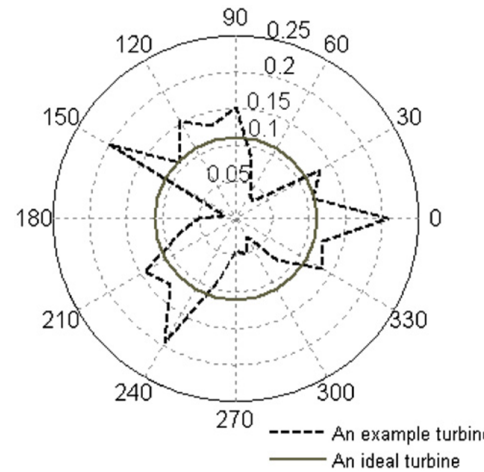

Fig. 5. Torque fluctuation in time domain.

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Appendix A

In Section 2, the relative torque fluctuation coefficient for a system of turbines was defined in Eq.(4) based on the torque fluctuation coefficient of a stand alone turbine. Here, we present the formulation of the torque fluctuation coefficient and use a stand-alone turbine as the example.[5] First, the dimensionless torque of an example three-bladed turbine is calculated. The blades of the turbine are NACA0015, the solidity is 0.375, the TSR is four, the height of the turbine is 1.5 times the turbine radius, and the Reynolds number is 160,000. Torque fluctuation during a revolution is presented in the time domain. Fig. 5 shows the fluctuation of the dimensionless torque of the turbine in the time domain with the dimensionless torque of the ideal turbine. The dimensionless torque of the ideal turbine is presented here for comparison purposes. The torque does not fluctuate; it is set to generate the same amount of power as the example turbine, except with a constant torque. It is understood that signals should be quantified in the frequency domain rather than in the time domain. Thus, we transform the dimensionless torque from the time domain to the frequency domain using the Welch method. This is a numerical method based on the Fast Fourier Transform for estimating spectral

[5] As the torque output of the twin-turbine system in this paper goes to one torque meter rather than two, the mechanical principle of the torque fluctuation of the twin-turbine system is the same as that of a stand-alone turbine. Thus, here we use a stand-alone turbine as the example to illustrate the formulation of the torque fluctuation coefficient.

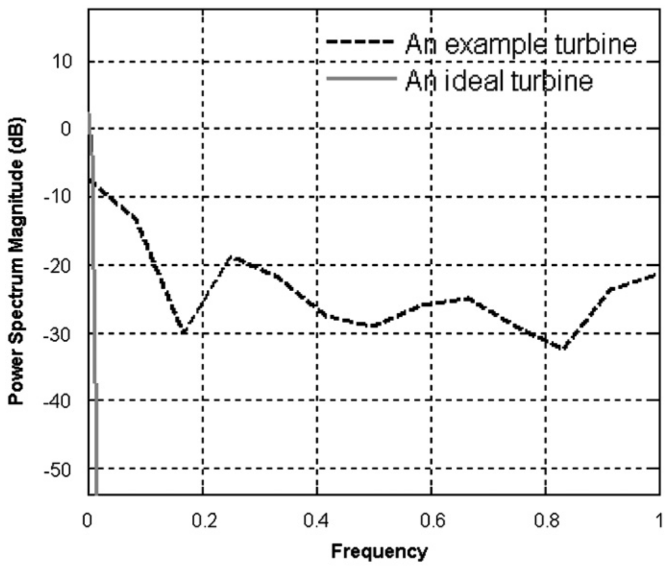

Fig. 6. Torque fluctuation in frequency domain.

density of a random signal (Welch, 1967). The Welch method has been widely used in engineering, applied physics, and sciences for analyzing signals (Oppenheim and Schafer, 1975; Proakis and Manolakis, 1996; and Alkan and Yilmaz, 2007). By using the Welch method, the transformed torque fluctuation in the time domain is shown in Fig. 5[6] and the torque fluctuation transformed into the frequency domain is shown in Fig. 6. One may note that the frequency is normalized with respect to the revolution period. For the ideal turbine, it is clear that only one signal exits, i.e., the DC component. For the example turbine, the first peak represents the power spectrum magnitude (PSM) of the main torque, while the remaining peaks represent those of the torque fluctuations. If the magnitude of the first peak is much greater than those of the second and the third peaks, the torque is more stable. However, in this case, the second peak is comparable with the first peak. Furthermore, even the third and fourth peaks are all almost as high as the second peak. To quantify the torque fluctuation, we define the torque fluctuation coefficient,C_{TF}, as the ratio of the difference of the first two peaks of torque PSM to the difference of the corresponding frequency as follows:

$$C_{TF} = \frac{(T_{peak,1} - T_{peak,2})}{(f_{peak,1} - f_{peak,2})} \tag{6}$$

where $T_{peak,1}$, $T_{peak,2}$, $f_{peak,1}$ and $f_{peak,2}$ denotes the first and second peaks of the torque PSM and the corresponding normalized frequencies, respectively. Thus, it is clear that the larger the C_{TF}, the less the torque fluctuates. By using Eq. (5), we get $C_{TF,example}=46$ dBS for our example turbine, and $C_{TF,ideal} \to \infty$ for the ideal turbine.

Appendix B

The twin-turbine model is briefly introduced in Section 2.1. Here, we present some discussions on this model and describe how it predicts the power output, as a review of Part I. Basically, the twin-turbine system model uses the stand-alone turbine model as a sub-module developed by Li and Calisal (2007), such that the two models share several similar principles. For example, if one turbine has three blades, the twin-turbine system is modeled by simulating the behavior of six blades in the twin-turbine model, while the stand-alone turbine is modeled by simulating the behavior of three blades on the stand-alone turbine model. Several assumptions are made to maintain the rigorous mathematical modeling of the physics: (1) there no auxiliary structures or other turbines around the studied twin-turbine systems and (2) in the wake, the velocity at a single point is assumed by superimposing all the induced velocities upon the undisturbed incoming flow velocity. Two sets of vortices are used to represent the two turbines and their wakes in the system. After initializating 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. In this study, we define the relative distance of a co-rotating twin-turbine system at 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 sub-module to simulate the behavior of each turbine. Then, the wake vortices generated by each turbine will interact with each other as well as with the turbines. This part of the simulation is controlled by the main program. In the meantime, a loop is formed to calculate the position, strength, and velocity of each vortex. This loop is the main process for calculating the hydrodynamic interaction between the two turbines, which ends when a convergence criterion is satisfied. When each step is converged, the sub-module calculates the blade force and wake of the system; the main program then calculates the power and the torque accordingly.

In Part I, we showed the validation of the twin-turbine model by comparing the performance of the twin-turbine system obtained with the numerical model with that obtained with the experimental test. The test was conducted in the towing tank 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. The comparison shows that the twin-turbine model can predict the performance of twin-turbine systems with acceptable accuracy.

[6] We use azimuth angle to represent the time domain which shows the position of the blade in a revolution.

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