Modeling the Energy Output from an In-Stream Tidal Turbine Farm

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***Abstract*—This paper is based on a recent paper presented in the 2007 IEEE SMC conference by the same authors [1], discussing an approach to predicting energy output from an in-stream tidal turbine farm. An in-stream tidal turbine is a device for harnessing energy from tidal currents in channels, and functions in a manner similar to a wind turbine. A group of such turbines distributed in a site is called an in-stream tidal turbine farm which is similar to a wind farm. Approaches to estimating energy output from wind farms cannot be fully transferred to study tidal farms, however, because of the complexities involved in modeling turbines underwater. In this paper, we intend to develop an approach for predicting energy output of an in-stream tidal turbine farm.**

The mathematical formulation and basic procedure for predicting power output of a stand-alone turbine[1] is presented, which includes several highly nonlinear terms. In order to facilitate the computation and utilize the formulation for predicting power output from a turbine farm, a simplified relationship between turbine distribution and turbine farm energy output is derived. A case study is then conducted by applying the numerical procedure to predict the energy output of the farms. Various scenarios are implemented according to the environmental conditions in Seymour Narrows, British Columbia, Canada. Additionally, energy cost results are presented as an extension.

***Index Terms*—renewable energy, in-stream turbine, tidal current, tidal power, vertical axis turbine, farm system modeling, in-stream tidal turbine farm**

[1] A stand-alone turbine refers to a turbine around which there is no other turbine that might potentially affect the performance of this turbine.

NOMENCLATURE

Symbol	Description	Unit
ρ	Water density	kg/m^3
Γ	Vortex strength	m^2/s
Γ_B	Bounded vortex strength	m^2/s
Γ_S	Shedding vortex strength	m^2/s
ω	Angular velocity	$1/s$
τ	Time	s
θ	Azimuth angle	—
π	The ratio of a circle's circumference to its diameter	—
η	Power efficiency	—
η_m	Total mechanical power efficiency from the farm	—
$\bar{\eta}_m$	Average mechanical power efficiency from the farm	—
c	Hydrofoil chord length	m
C_D	Drag coefficient	—
C_L	Lift coefficient	—
d	Distance	m
f	General Coefficient	—
l	General length	m
L	Lift	$kg \cdot m/s^2$
r	Turbine radius	m
U	General velocity	m/s
U_r	Relative velocity	m/s
U_∞	Free stream incoming flow	m/s
V_P	General induced velocity	m/s
x_i	The x value of turbine number i tandem position	m

I. INTRODUCTION

Tidal power has received great attention because of its high energy density, high predictability and low environmental impacts. World-widely, the estimated tidal energy potential reaches 500~1000 TWh/yr [2]. However, this energy largely remains untapped. Early tidal power technology was based on barrages which extract potential energy from tides functioning like a traditional hydro dam (i.e., harness energy by utilizing the elevation difference between high tides and low tides), and this technology has been abandoned since 1980's due to its significant ecological footprint[3]. The subsequent development of tidal power had been slow in the 1980's, and has been reinvigorated in the past decade as tidal current turbines are experimentally employed to extract kinetic energy from tidal currents [5-8]. Due to the accessibility and geographical limitations, recent tidal current turbines are quite often projected to be constructed in a confine channel, which are called in-stream tidal current turbines. The working principle of an in-stream tidal turbine is similar to that of a typical wind turbine. An in-stream tidal turbine farm (i.e., a group of tidal turbines located at one site) is similar to an offshore or on-land wind farm. However, those experiences from wind study cannot be readily transferred to tidal energy output estimation for the reasons that (1) although offshore wind farms have been commercialized for a while, the related research primarily focuses on the operation and maintenance of the farms [9-11]; (2) wind farms are often located in open areas where geological conditions do not restrict design options, while in-stream tidal turbine farms are generally restricted by the geological conditions; and (3) the physical characteristics of tidal turbines, such as the Reynolds Number is different from that of wind turbines.

The development of in-stream tidal current turbine farm model is still in the infancy stage. Studies have been conducted to estimate energy potentials in a number of oceanic countries, such as Brazil [12], Canada [13] and [14], India[15], Spain [4], the United Kingdom [16], and the United States [17]. These studies have been used by governmental agencies to determine whether and how to build in-stream turbine farms. In estimating energy, all of these studies assume that the efficiency of each turbine in a farm is equal to the maximum efficiency of a stand-alone turbine. Thus, the predicted energy outputs from these studies are inaccurate. The inaccuracy in energy output estimation is regarded as a significant barrier to the industrialization of tidal power since the results are not convincing to investors [18] and [19]. In order to develop an accurate and responsive approach to estimate energy output from an in-stream turbine farm, one should derive a relationship between the power output of an individual turbine and the farm.

In this paper, a systematic modeling approach for planning in-stream tidal turbine farms is developed in terms of predicting energy output. In Sections II and III, the procedure for predicting energy output from a farm is presented; the farm system model and the individual turbine model are presented respectively. In Sections IV to V, the implementation of the approach is discussed with a case study in Vancouver area. Finally, the conclusion is given in Section VI.

II FARM SYSTEM MODEL

The measure of power plant is usually developed based on cost-effectiveness analysis which can be also applied in the in-stream turbine farm It defined as the ratio of the total cost (sum of operational and maintenance cost and capital cost) to the total energy output, given as follows,

$$\text{energy cost} = \frac{omc + cap}{Energy} \tag{1}$$

where omc denotes levelized operation and maintenance cost, cap denotes levelized capital cost, and $Energy$ denotes lifetime energy output of the entire farm.

The objective of a cost-effectiveness analysis is to minimize the energy cost by minimizing the total cost and maximizing the energy output. The total cost incurring in producing tidal energy can be minimized by carefully selecting the operation and maintenance strategies, which is detailed in [20]. In this paper, we focus on the energy output.

A Energy Output

The energy output here refers to the amount of energy in the load center which is ready to be delivered to the existing electricity grid, which can be calculated as follows,

$$Energy = \int_0^T P_{out} dt \tag{2}$$

where P_{out} denotes the electrical power output from the in-stream tidal turbine farm, which is ready to be delivered to the electricity grid, and t and T denote the time increment and the lifetime of the in-stream tidal turbine farm, respectively.

The tidal current flow is highly predictable and its velocity is almost constant during one turbine revolution. Because the tidal energy output is an integral of the power output with respect to time, we can use the power output to represent the total energy output when calculating the energy cost. The process of the power output has two elements: 1) the electrical power system; and 2) the mechanical system.

B Electrical Power

For a given in-stream tidal turbine farm, the electrical power can be expressed as follows,

$$P_e = f\left(P_m\right) \approx f_e P_m \tag{3}$$

$$P_{out} = f\left(P_e\right) \approx f_t P_e \tag{4}$$

where P_e, P_m, f_e, and f_t denote the electrical power, the mechanical power, the electrical efficiency coefficient, and the transmission efficiency coefficient of the farm, respectively.

By combining (3) and (4), we can rewrite the electric power output as follows,

$$P_{out} \approx f_t f_e P_m \tag{5}$$

Farm configurations have very little influence on f_e and f_t; therefore, the focus of electric power output can be maintained by focusing on mechanical power output $-P_m$.

C Mechanical Power

The ideal mechanical power from a continuous flow can be written as follows,

$$P_{ideal-m} = \frac{1}{2}\rho A U_\infty^3 \quad (6)$$

where ρ, A, and U_∞ denote the density of sea water, turbine frontal area, and the incoming flow velocity.

The ideal mechanical power is a function of turbine frontal area and incoming flow velocity. The real mechanical power from the ocean flow is much less than the ideal power due to hydrodynamic energy losses. The ratio of the real power to the ideal mechanical power is defined as the mechanical power efficiency, given as follows,

$$\eta_m = \frac{P_m}{P_{ideal-m}} = \frac{P_m}{\frac{1}{2}\rho A U^3} \quad (7)$$

The mechanical efficiency can be predicted precisely using Reynolds Averaged Navier-Stokes methods and potential methods [21], the vortex method of which is briefly reviewed in Section III.

D Nondimensionlization

According to the discussion above, we can use power output to represent energy output and use power efficiency to represent power output; therefore, we can use efficiency to represent the energy output. Thus the objective here (i.e., to maximize the energy output) can be considered as to maximize the total mechanical efficiency of the turbine farm, i.e., the sum of the efficiency of the turbines in the entire tidal turbine farm. For a turbine farm, given the number of turbines of a specified size, the total mechanical power efficiency can be written as follows,

$$\eta = \sum_{i=1}^{N} \eta_{m,i} \quad (8)$$

where $\eta_{m,i}$ denotes the power efficiency from turbine number i, and N denotes the total number of turbines in the farm.

III TURBINE HYDRODYNAMIC MODEL

Section II shows how energy output can be estimated and why we simulate power output and mechanical efficiency of each individual turbine in a farm. In this section, we present the procedure for predicting the power output of a farm. According to the blade rotating direction, there are horizontal and vertical axis turbines as shown in Figure 1. In this paper, the vertical axis straight blade turbine is discussed.

Figure 1 Vertical Axis Tidal Turbine (on left hand side, courtesy of Bluenergy) and Horizontal axis tidal turbine (on right hand side, courtesy of MCT)

A Hydrodynamics of a Stand-alone Vertical Axis Tidal Turbine

The power output of a turbine can be obtained by calculating lift and drag based on the vortex theory as describe in Li and Calisal[22], which will be briefly reviewed before we present the analysis of farm hydrodynamics. According to the definition of the lift and drag coefficients, the lift (*L*) and drag (*D*) can be expressed as

$$L = \frac{1}{2}\rho C_L c U_r^2 \quad (9)$$

$$D = \frac{1}{2}\rho C_D c U_r^2 \quad (10)$$

where C_D, C_L, U_r and c denotes the drag coefficient, the lift coefficient, relative velocity, and the blade chord length, respectively.

The relative velocity can be obtained by using the Biot Savart Law to calculate the induced velocity induced by the wake vortices [23]. These wake vortices can be obtained by differentiating the blade bound vortices at each time step which is used to represent the turbine's blade element. The strength of these blade bound vortices can be obtained by using Kutta-Joukowski law as follows,

$$\Gamma_B = \frac{1}{2} C_L c U_r \quad (11)$$

During the turbine rotation, the relative velocity will be updated by calculating the bound vortices at each time step; one can calculate the lift and drag at each time step and thus to obtain the tangential force, F_t, with which, the mechanical power output of the turbine can be obtained as follows,

$$P_m = F_t r \bullet \frac{d\theta}{dt} \quad (12)$$

where θ, F_t, and r denote the turbine azimuth angle, the tangential force, and the turbine radius, respectively.

B Hydrodynamics of a Turbine Farm

The distribution of turbines in a farm can be expressed as two factors: the lateral distance and tandem distance as shown in Fig. 2. Between these two factors, the tandem distance plays the key role here because the main hydrodynamic interaction between turbines is the vortex shedding from the upstream turbine to the downstream one [24]. Thus, the relationship between the efficiency of the upstream turbine and the efficiency of the downstream turbine can be written as follows,

$$\eta_{m,i} = f\left(\eta_{m,i-1}, K_O, d\right) \quad (13)$$

where K_O denotes operation effect factor which is a function of blade number, turbine radius, and blade angle of attack.

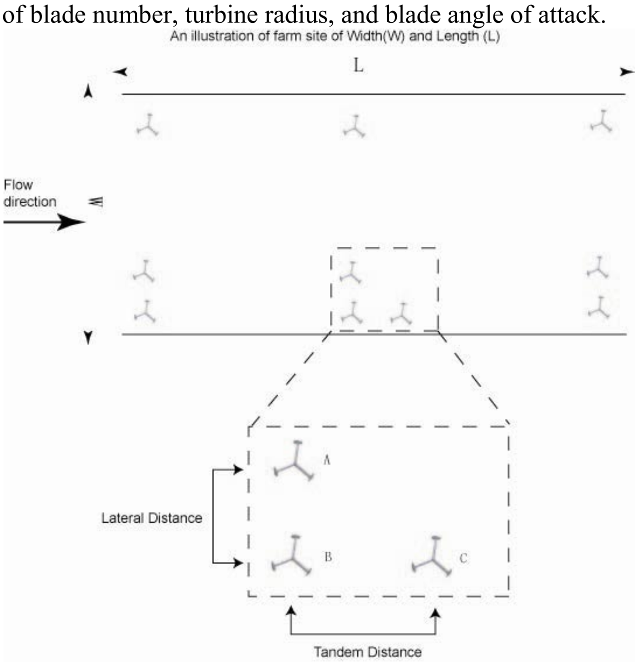

Figure 2 Illustration of an ideal turbine farm

We extend above analysis of a stand-alone turbine to farm study here. Because the vertical axis tidal turbine is a lift-driven turbine, the power output is quasi proportional to the lift. Equation (11) shows that the lift is proportional to the strength of bounded vortex on the blade. Thus, the power output and the mechanical efficiency are proportional to the strength of the vortex. Therefore, a quasi linear relationship can be built between vortex strength and the efficiency as follows,

$$\eta = C\sum \Gamma_B \qquad (14)$$

where C is a constant determined by turbine configuration and local environment such as blade arm angle and flow velocity. By differentiating Eq. (14), we get,

$$\Delta\eta = C\Delta\sum \Gamma_B \qquad (15)$$

Because the strength of wake vortices is equal to the difference of strength of bound vortices in time, Eq. (15) can be rewritten as follows,

$$\Delta\eta = C\sum \Gamma_S \qquad (16)$$

where Γ_S denotes the vortex shedding strength.

The term on the left hand side of Eq.(16) represents efficiency change, while term on the right hand side represents the vortex wake strength, which is a time dependent variable. The vortices decay when being convected in the wake. Mathematically, the vortex strength exponentially decay as suggested by Hansen [25], given as follows

$$\Gamma_j = \Gamma_0 e^{(-K_C\tau)} \qquad (17)$$

where Γ_j, Γ_0, τ, and K_C denote the vortex strength at the jth step, the initial vortex strength, the vortex decay time, and the decay factor, respectively.

The shedding vortices travel along with the local flow. The vortices traveling velocity can be written as

$$\vec{U} = \vec{U}_\infty + \vec{U}_P \qquad (18)$$

where U_P denotes the perturbation velocity.

The vortex traveling distance, d_v, can be obtained by integrating U with respect to t from 0 to τ (the life of the vortex):

$$d_v = \int_0^\tau U dt \qquad (19)$$

In the wake, we have

$$U_\infty \gg U_P \qquad (20)$$

During its life cycle, the tidal current speed can be considered as constant because a typical tidal cycle is much longer than the life cycle of a vortex. Then, by plugging Eq. (20) into Eq. (19), Eq. (19) can be written as

$$d \approx U\tau \qquad (21)$$

$$\Rightarrow d_{down} \propto \tau \qquad (22)$$

where d_{down} denotes the downstream relative distance between two turbines.

Turbine rotating speed can be maintained constant by controlling it with a motor, which indicates that the frequency of vortex convection in the wake area can be considered as a constant. Therefore, the sum of the wake vortices strength is a constant in given a period at certain distance. Thus, by plugging Eq.(22) into Eq. (13), Eq. (13) can be written as:

$$\eta_{m,i} = \eta_{m,i-1}\left(1 - e^{-k_O d}\right) \qquad (23)$$

IV CASE STUDIES

In this section, we apply the procedure developed in the previous section to estimate the energy output of an in-stream tidal farm at Seymour Narrow, a site in British Columbia, Canada, and then to predict the energy cost. Considering the environmental conditions at the Seymour Narrow in British Columbia, a 2000-meter long segment is selected where 14kn high-speed current is available. The employed turbine is a typical three blades turbine with a 10-meter diameter.

A Assumptiosns

The following premises and assumptions are made to implement the calculation,

- The tandem distances between any two adjacent rows are the same
- The channel is wide enough that the wall effect can be neglected, that is $W \gg 2r$ (see Figure 2)
- The incoming flow velocity is constant and large enough to operate the turbine. That is to say, there is no small island or marine structures in the site to perturb the flow.

As the tandem distance is the most important factor in the approach, we neglect the lateral distance in the simulation so as to simplify and facilitate the calculation. Thus, the discussion here is focused on a column of turbines rather than an array of turbines. Additionally, in order to study the relationship between the efficiency of a turbine in the farm and mechanical efficiency of a stand-alone turbine, we define a total relative efficiency, the ratio of total efficiency of the farm to the efficiency of a stand-alone turbine to replace the total efficiency. It is given as follows,

$$\hat{\eta} = \frac{\eta}{\eta_S} \tag{24}$$

B Result Analysis

The data in Fig. 3 describe the relationship between different tandem distance and the total relative efficiency when the turbine operation factor is equal to 0.4. It shows that the maximum total relative mechanical efficiency is about 1300%. In this situation, there are about sixteen turbines in a column and the tandem distance is about twelve times turbine diameter. Therefore, the average relative mechanical efficiency can be calculated accordingly, which is about 82%. However, these results only show the solution of one possible operation factor (i.e., K_o=0.4) in Seymour Narrows. This might not be the best in other situations. A general result of the relationship between the relative total mechanical efficiency with different turbine tandem distances and different turbine design is investigated as shown in Fig. 4. It is obviously noted that with a higher operation factor, the turbines may be placed closer together when obtaining maximum efficiency. This might because the higher operation factor provides less negative impact on the downstream turbine from its upstream neighbor. In general, the optimal tandem distance is six to ten times turbine diameter, although this operation factor might not be achieved due to design reasons.

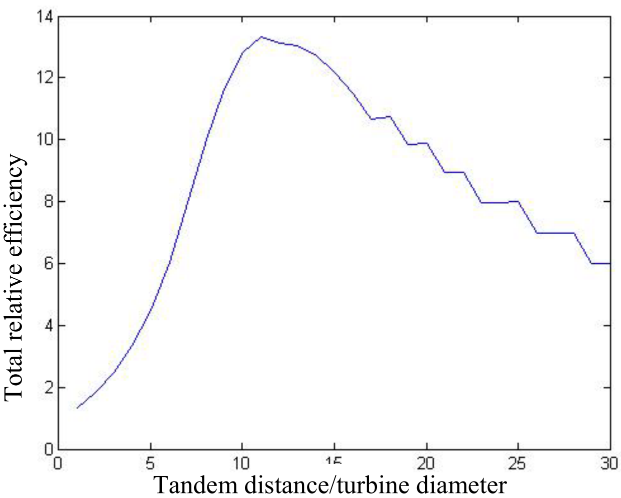

Figure 3 The performance vs. tandem distance

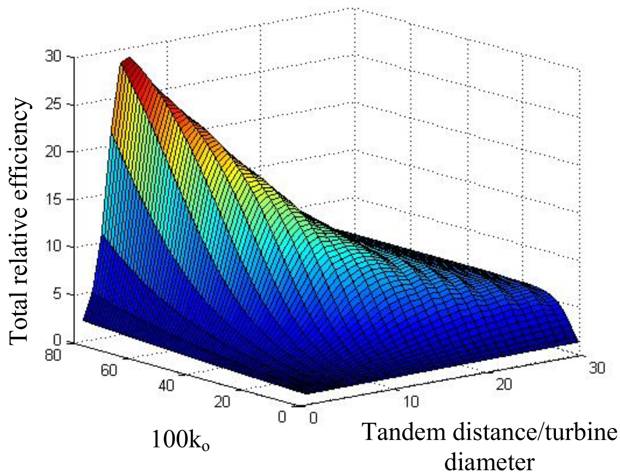

Figure 4 Total efficiency with different operation factors and relative tandem distance

Besides the total relative efficiency, the average mechanical efficiency is another important objective. The total mechanical efficiency can be increased by adding more turbines in the farm. However, the marginal energy cost will be extremely high when the total turbine number reaches a certain value. Therefore, a threshold value of turbine number should be decided for an optimal farm. This value can be given as follows,

$$\bar{\hat{\eta}} = \frac{1}{N}\sum_{i=1}^{N}\hat{\eta}_{m,i} \tag{25}$$

Figure 5 shows the relationship between the operation factor and relative tandem distance and the average relative efficiency. One can notice that as long as the tandem distance is bigger enough, the average relative efficiency is close to 100% because the interaction induced by the vortex shedding is avoided, i.e., $\hat{\eta}_{m,i} \rightarrow \eta_S, i = 1,2,3 \cdots N$.

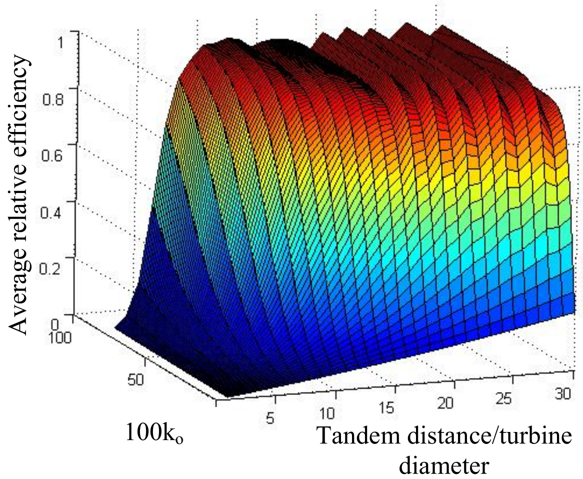

Figure 5 Average efficiency with different operation factors and relative tandem distance

V DISCUSSION

By using data from [16] and [26] with the energy output predicted from above analysis and the cost model developed in [20], the energy cost of the farm in Seymour Narrow can be obtained. Particularly, we presented three scenarios according to the size of the farm, small scale (10 turbines), medium scale (30 turbines) and large scale farm (100 turbines). The data in Fig. 6 show the levelized energy cost of a certain year, and this is why the cost increases when the year increases. The levelized capital cost is a constant though the turbine's life; the O&M cost significantly increases when turbine get old, the energy cost increases. The energy cost also reduces when the farm scale become larger as the O&M cost per turbine reduces. Comparing the local electricity price [27], it is noted that the energy cost of a large farm, the lowest among three farms, is about 2~3 cent/kWh higher than the small commercial price while 4~5 cent/kWh.

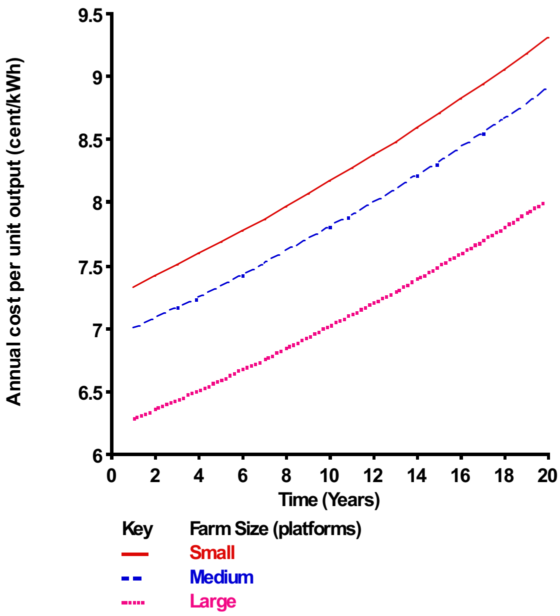

Figure 6 Tidal energy cost (in net present value) in Seymour, BC

VI CONCLUSION

Generation and distribution of the tidal power is a very complicated problem because of the lack of detail analysis of turbine working principle and the complexity of the ocean natural environment. Given the present knowledge of tides, principle of turbine and computational ability, this study developed a systematic framework of tidal farm modeling method. In general, some conclusions are drawn here,

- The approach can estimate the energy output based on given turbine design, turbine farm distribution, and local condition.
- The approach allow user to test the sensitivity of individual component, although complete sensitivity analysis is not conducted in this study. Characteristics of every component are given as inputs in the methodology.
- Seymour narrow does have a very good potential to install tidal turbine. British Columbia can develop the tidal power!!

VII FUTURE WORK

In this work, in order to simplify the calculation process and facilitate calculation speed, some nonlinear relationships are linearized. A fully nonlinear model could be developed to describe a more complicated situation. The interactions are mainly induced by turbine rotating phase difference, relative distance, turbine size, and arm blade angle. Therefore, the constraint function of the objective functions can be regarded as a function of turbine geometry, incoming flow velocity, turbine number and turbine relative distance, given as follows,

$$F\left(\eta_{m,i}, N, \text{Geometry}(n, r, c\cdots), U_{\infty}\cdots\right) = 0 \tag{26}$$

where n denotes the blade number of a turbine.

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