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Research on wave and tidal current law prediction and coupling mechanism applied to ocean energy utilization

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Abstract. The energy efficiency of integrated wave and current turbine is closely related to the velocity and direction of wave force and tidal current force.To study the blade motion of the wave-tidal current integrated variable-pitch turbine, raise the capacity efficiency of the turbine, take Fishing grounds of Changjiang estuary Port as an example,based on the tidal current and wave features data in recent two years,time series prediction model was established to predict the changes of wave and tidal current in the next 24 hours respectively, and the prediction accuracy is up to 93%. The wave theory applicable to Fishing grounds of Changjiang estuary Port was confirmed as the second-order strokes wave theory, the wave-tidal current coupling equivalent velocity vector was deduced, which is related to the tidal current velocity, flow direction, average wave direction, average wave period and significant wave height. The predicted wave-current coupling velocity vector is obtained after the predicted 24 hours wave-current data was substituted into it, which can provide a method and basis for the design of marine energy turbine's variable angle law in the future, and can be applied to the development of new energy and the prediction of Marine environment.

1. Introduction

Among the many clean new energy sources, wave energy and tidal energy are more promising renewable energy sources in terms of energy density and technical feasibility, and they are the current research hotspots [1].Since the frequency and phase of wave and tidal energy are different in different seas, they are researched and utilized separately at home and abroad, but there are problems such as low total conversion efficiency and poor reliability. In the development and utilization of marine renewable energy, wave and tidal current are inseparable and have the role of mutual integration. Integrating wave energy and tidal current energy into the same operating system can enhance the multi-energy interconnection and promote the complementary advantages of multiple energy sources,improve the power generation capacity per unit volume of sea and output more stable performance, which can reduce the use of backup power generation equipment in previous renewable energy generation [2].The development of wave-tidal current integrated technology in China is relatively late[3,4].In 2011, the integrated power generation scheme of wave energy and tidal energy was first proposed by Shanghai Ocean University[5].However, the complete theoretical system of integration mechanism of wave and tidal energy integration has not been established yet, it is far from large-scale promotion and application[6].

The variable-pitch turbine can adapt to the change of tidal current velocity and direction by adjusting the blade declination, so as to improve the self-starting performance and energy acquisition efficiency of the turbine [7].However, most of the variable-pitch turbines do not consider the role of wave integration, while the actual sea state is not a single tidal effect. In order to further improve the energy capture efficiency of variable-pitch turbine, the posture change law of the turbine should be designed according to the coupling law of wave and tidal current.For the determined sea area, the tide and wave have certain rules [8], and the data are strongly correlated with each other. Long Short-Term Memory model(LSTM) as a powerful recursive neural network can be imported to maintain internal input memory and can effectively solve the problem of interrelated data with the concept of temporal and directional circulation being introduced [9].

Fishing grounds of Changjiang estuary sea area has abundant tidal and wave energy resources, less extreme sea conditions, and more complete public data, so this paper selects Fishing grounds of Changjiang estuary sea area as the data source object, analyzes the public tidal and wave data from 2019 to 2020, and uses LSTM neural network model to predict waves (average wave direction, average wave period, effective wave height) and tidal data (current velocity and direction). The accuracy of the model is verified by using real data. On this basis, the wave-current coupling mathematical mechanism is deduced, and the wave-tidal current data is converted into the equivalent tidal current velocity vector, the combined vector superimpose onto the tidal current velocity is calculated, thus providing a design basis for the blade motion of the variable-pitch turbine.

2. LSTM prediction model of tidal current and wave in Fishing grounds of Changjiang estuary

2.1. LSTM neural network

Long Short-Term Memory model(LSTM) is a variant of a recursive neural network that consists of two states and three gates. At time t, the LSTM network has three inputs, which are the input value x_t at the current time, the output value h_{t-1} at the previous time and the state c_{t-1} of the unit. Input gate i_t, forget gate f_t and output gate o_t receive the same input $[h_{t-1}, x_t]$ and are used to control the update process of the unit state c_t through activation function σ. The schematic diagram of the LSTM network is shown in Fig. 1:

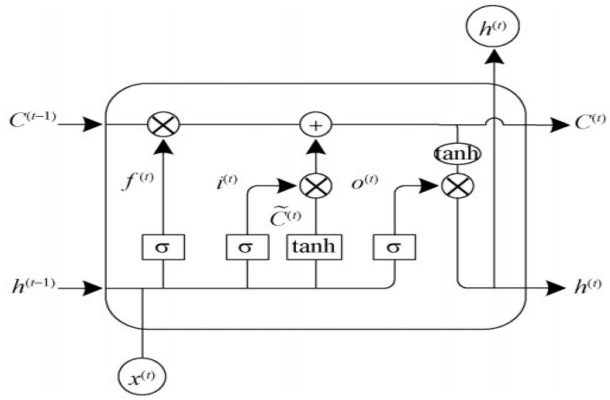

Figure 1. The schematic diagram of the LSTM network.

2.2. Design and simulation of prediction algorithm

2.2.1. Structure of training sets. Since the tidal current velocity, tidal current direction, average wave direction, average wave period and significant wave height are five parameters that are highly correlated with the acquisition of seawater power, these five parameters are selected for analysis. The above five parameters are all periodic and independent of each other, so LSTM models based on these five columns time series data are established respectively to predict the tidal current and wave changes in the next 24 hours. The input and output of the training model are constructed by the sliding window recursive structure. Compared with the training sets of the traditional structure, the recursive structure training sets adopt the data training at multiple moments, which ensures the time coupling of the input and output. Let X^i be the vector that constitutes the input and the vector Y^i be the vector that constitutes the output, the number of vectors are both i, the length of the input window is j(j<t), the window length is the number of input steps ,and the number of output steps is 24. The training sample structure of recursive structure as in equation (1).

$$\left\{ \begin{bmatrix} t \\ t+1 \\ \vdots \\ t+j-1 \end{bmatrix} \begin{bmatrix} t+1 \\ t+2 \\ \vdots \\ t+j \end{bmatrix} \cdots \begin{bmatrix} t+n-j-23 \\ t+n-j-22 \\ \vdots \\ t+n-24 \end{bmatrix} \right\} \tag{1}$$

Where,n is the number of samples.

2.2.2. Simulation of LSTM training. The tidal current (velocity,flow direction) and wave (wave period, wave height, wave direction) data of Fishing grounds of Changjiang estuary Port from 2019 to 2020 are obtained from National Marine Information Center Net and ERA5 respectively. The LSTM algorithm was written by Matlab to predict the tidal current and wave changes at next 24 moments. The stacked LSTM network composed of three hidden layers is used to train the single column data, the dropout algorithm is used to improve the generalization ability and robustness of the model. The The model structure of LSTM network is shown in Fig. 2. In the multi-step prediction process, LSTM is expanded into a feed-forward neural network, and the input vector and output vector are acquired from the first moment in a circular way, thus forming the input vector set X_{in} and the output vector set Y_{out} .

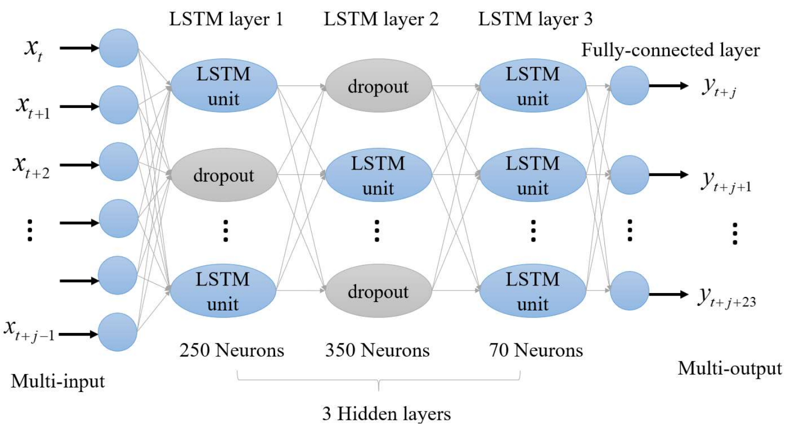

Figure 2. The model structure of LSTM network.

The model accuracy(*acc*)and root mean square error (RMSE) were used to evaluate the model. The *acc* calculation formula is as follows:

$$acc = \left(1 - \frac{\sum_{i=1}^{n} |e_i|}{\sum_{i=1}^{n} y_i} \right) \times 100\% \tag{2}$$

Where, $e_i = \hat{y}_i - y_i$ is the calculation error, $\hat{y}_i$ is the predicted value, and y_i is the actual value.

The calculation formula of RMSE is:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\hat{y}_i - y_i \right)^2} \tag{3}$$

In order to accelerate the convergence speed of neural network training and improve the computational efficiency, the data need to be normalized, and the expression is

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{4}$$

Where, $x_{\max}$ and $x_{\min}$ are the maximum and minimum values of sample data.

2.3. Model training results and analysis.

In order to test the validity and feasibility of the prediction algorithm, the last 144 data of each column dataset were used to forecast the data in the next 24 hours (i.e., 2021.1.1) respectively, and compared with the real value, as shown in Fig. 3.

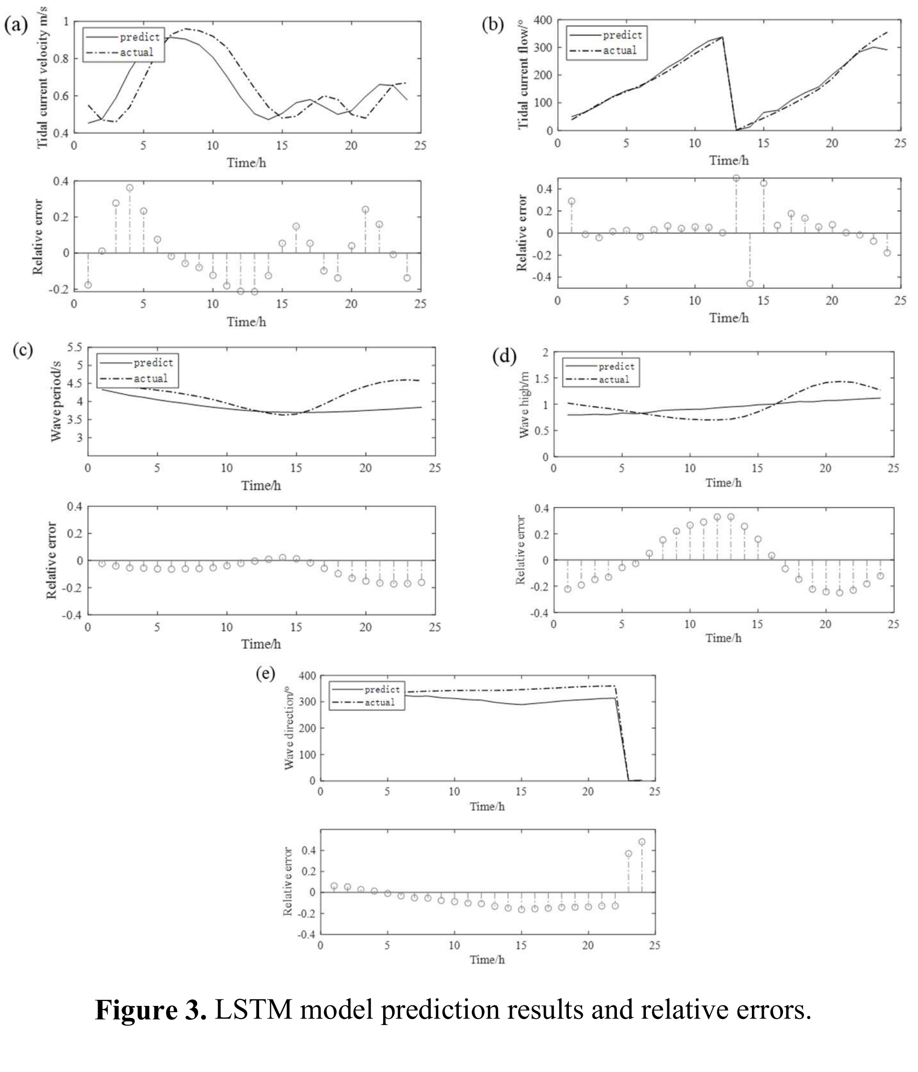

Figure 3. LSTM model prediction results and relative errors.

The prediction accuracy of the five time series datasets were 0.87, 0.93, 0.93, 0.82, 0.84, and RMSE values were 0.008, 1.93, 0.29, 0.05, 0.65, respectively. Due to wave and tidal current in the direction of the range of 0 ° ~ 360 °, the absolute error is larger compared with wave period and wave height and flow velocity. Therefore, RMSE values of 24 predicted values cannot fully evaluate the quality of the prediction model. The relative error and prediction accuracy in Fig.3. should be combined to make judgment. As can be seen from Fig.3. (b) and (d), the curve trend of predicted value and true value is similar, the relative error of tidal current direction and wave direction are small, so the prediction results are good, the other three prediction accuracy of time series dataset are greater than 85%, the highest accuracy reach 93%, and all the RMSE value are small. Therefore, this prediction model can accurately predict the changes of tide and wave data in the next 24 hours.

Compared with the fixed blade declination turbine, adjusting the blade declination angle according to the changing regular of tidal current and wave can make the turbine more efficient. The energy harvesting efficiency of the wave-tidal current generation turbine can be effectively improved by predicting the variation law of tidal current and wave in advance and designing the variation angle law of turbine blade in advance according to the variation law, and controlling the corresponding angle of blade deflection at the predicted time point with the corresponding control algorithm. According to the predicted data, the blade motion regular can be designed to make the maximum efficiency of the turbine per hour of a day for 82% probability.

3. Numerical analysis of coupling mechanism based on wave-current prediction data

Laboratory existing S airfoil bidirectional direct-drive power turbine structure as shown in Fig.4, the turbine can capture energy from both directions, the energy of wave and tidal current joint action on the turbine is always perpendicular to the turbine rotating plane. In the process of turbine posture law design, it is more convenient to calculate the equivalent vector of the coupling energy of wave and tidal current.

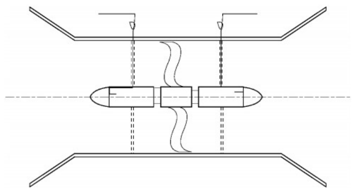

Figure 4. Schematic diagram of bidirectional direct-drive power turbine.

3.1. Calculation of wave energy

The parameters involved in the calculation of wave energy are: wave height H (m), gravitational acceleration g (m/s2), water height (m), wave period T (s), wave length L (m), wave number k, wave velocity c (m/s) and angular frequency w (rad/s).

The wave theory applicable to the Fishing grounds of Changjiang estuary Port should be determined according to the value of H/gT^2 and d/gT^2 [10]. The water depth of Fishing grounds of Changjiang estuary Port (31.05N124E) is about 23.5m. The significant wave height, mean wave period and mean wave direction corresponding to this position are obtained through ERA5 reanalysis data, and the time resolution is hour. Put the average significant wave height and wave period of 2019~2020 into H/gT^2 and d/gT^2, the values are respectively 0.0045 and 0.1268, which is in line with the applicable scope of the strokes second order wave. Therefore, the second order strokes are taken as the theoretical waveform of Fishing grounds of Changjiang estuary Port to solve the wave energy.

The dispersion relation of the second-order Stroks nonlinear wave is:

$$L = \frac{gT^2}{2\pi} \tanh dk \tag{5}$$

The velocity potential function is:

$$\Phi=\frac{\pi H}{kT}\frac{\cosh k(z+d)}{\sinh kd}\sin(kx-wt)+\frac{3\pi H^2}{16T}\frac{\cosh 2k(z+d)}{\sinh^4 kd}\sin 2(kx-wt) \tag{6}$$

The wave surface equation is:

$$\eta=\frac{H}{2}\cos(kx-wt)+\frac{\pi H}{8}\left(\frac{H}{L}\right)\frac{\cosh kd(2+\cosh 2kd)}{\sinh^3 kd}\cos 2(kx-wt) \tag{7}$$

The water particle movement velocity is:

$$u_x=\frac{\partial\Phi}{\partial x}=\frac{\pi H}{T}\frac{\cosh k(z+d)}{\sinh kd}\cos\Theta+\frac{3}{4}\frac{\pi H}{T}\frac{\pi H}{L}\frac{\cosh 2k(z+d)}{\sinh^4 kd}\cos 2\Theta \tag{8}$$

$$u_z=\frac{\partial\Phi}{\partial z}==\frac{\pi H}{T}\frac{\sinh k(z+d)}{\sinh kd}\sin\Theta+\frac{3}{4}\frac{\pi H}{T}\frac{\pi H}{L}\frac{\sinh 2k(z+d)}{\sinh^4 kd}\sin 2\Theta \tag{9}$$

Where, $\Theta = kx - wt$.

The energy of horizontal motion of wave particles acting on the turbine in unit wavelength is:

$$E_k=\int_0^L\int_{-d}^{\eta}\frac{1}{2}\rho(u_x^{\ 2}+u_z^{\ 2})dzdx \tag{10}$$

Substituting equations (5) ~ (10) into Equation (11) for integration, the wave energy in this sea area at a certain moment can be obtained as follows:

$$E_k=\frac{1}{16}\rho gH^2+\frac{7}{16}\rho\frac{\pi^2H^3}{T^2} \tag{11}$$

3.2. *Calculation of equivalent velocity of wave and tidal current*

The parameters involved in tidal current energy include seawater density ρ (kg/m^3)and flow area S(m^2).The tidal current energy calculation formula is as follows:

$$W=\frac{1}{2}\rho v^3 S \tag{12}$$

In order to couple the input energy of wave and tidal current acting on the turbine respectively, the wave energy is converted into tidal current energy under the same flow area, the equivalent velocity of tidal current energy corresponding to wave energy is calculated. The wave energy in unit wavelength is written in the form of tidal current energy:

$$\frac{1}{2}\rho v_w^{\ 3}S=\frac{1}{16}\rho gH^2+\frac{7}{16}\rho\frac{\pi^2H^3}{T^2} \tag{13}$$

The equivalent tidal current velocity v_w per unit wavelength of wave energy acting on the turbine is:

$$v_w=\left(\frac{1}{8S}\left(gH^2+\frac{7\pi^2H^3}{T^2}\right)\right)^{1/3} \tag{14}$$

The equivalent velocity is superimposed on the tidal current velocity v_t at this position to obtain the combined velocity v of wave-tidal current coupling. The vector form of tidal current velocity and equivalent wave velocity is:

$$\vec{v}_w=v_w\angle\vec{v}_w \tag{15}$$

$$\vec{v}_t=v_t\angle\vec{v}_t \tag{16}$$

Where, $\angle\vec{v}_w$ and $\angle\vec{v}_t$ represent wave direction angle and tidal current direction angle respectively.

Then the wave-current coupling velocity vector is:

$$\vec{v}=\vec{v}_w+\vec{v}_t=v\angle\vec{v} \tag{17}$$

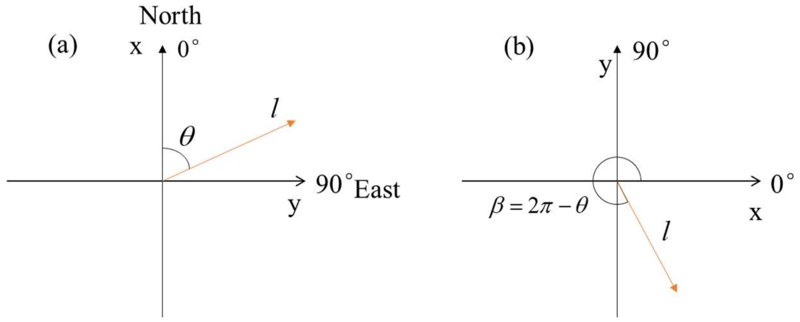

Figure 5. Schematic diagram of coordinate transformation.

Since the two-dimensional geographic coordinate system is different from the mathematical rectangular coordinate system **xoy**, so the coordinate system need to be transform. As shown in Fig. 5, (a) is the coordinate system of the combined velocity vector coupled by wave and tiadl current; (b) is the mathematical right-angle **xoy** coordinate system; in the coordinate system (a), due north (positive direction of the X-axis) is 0 degrees, and due east (positive direction of the Y-axis) is 90 degrees.

As can be seen from Fig. 5, the vertical axis of coordinate system (a) is the x-axis, and the horizontal axis is the y-axis. A vector of angle θ and length l in frame (a) corresponds to a vector of angle $2\pi-\theta$ and length l in frame (b), with the same sign projected on the x-axis and the opposite sign projected on the y-axis.Substitute the velocity vector, in the coordinate system (a), the projection of the velocity vector $\vec{v}_1$ in the x direction is $v_{x_1}=v_1\cos(2\pi-\angle\vec{v}_1)$, and the projection in the y direction is $v_{y_1}=-v_1\sin(2\pi-\angle\vec{v}_1)$; In frame (b), the projection of the velocity vector $\vec{v}_2$ in the x direction is $v_{x_2}=v_2\cos(\angle\vec{v}_2)=v_2\cos(2\pi-\angle\vec{v}_1)$, and the projection of the velocity vector in the y direction is $v_{y_2}=v_2\sin(\angle\vec{v}_2)=v_2\sin(2\pi-\angle\vec{v}_1)$, and $\angle\vec{v}_1+\angle\vec{v}_2=2\pi$, $v_1=v_2$.

According to the above transformation relation, the two velocity vectors of tidal current and wave are decomposed in coordinate system (b), and the combined vector $\vec{v}_2$ is obtained by superposition of the components, as shown in equation 18. The transformation relation is used to transform the combined vector into the coordinate system (a), and the coupling velocity vector in the real geographic coordinate system can be obtained, as shown in Equation 19.

$$\begin{cases} v_{x2}=v_{w2}\cos(\angle\vec{v}_{w2})+v_{t2}\cos(\angle\vec{v}_{t2}) \\ v_{y2}=v_{w2}\sin(\angle\vec{v}_{w2})+v_{t2}\sin(\angle\vec{v}_{t2}) \\ v_2=\sqrt{{v_{x2}}^2+{v_{y2}}^2} \\ \angle\vec{v}_2=\mathrm{atan}\dfrac{v_{y2}}{v_{x2}} \end{cases} \tag{18}$$

$$\begin{cases} v_1=v_2 \\ \angle\vec{v}_1=2\pi-\angle\vec{v}_2 \end{cases} \tag{19}$$

Substituting the predicted data of tidal current velocity, flow direction, mean wave period, mean wave direction and significant wave height in the next 24 hours in Chapter 2 into Equations (14) to (19), the predicted coupling velocity vector for the next 24 hours can be obtained, as shown in Table 1. The coupling velocity vector also varies periodically.

Table 1. Wave-tidal current coupling results based on predicted data.

Time/h	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Coupling velocity m/s	0.66	0.48	0.33	0.29	0.39	0.54	0.68	0.83	0.96	1.06	1.09	1.01
Coupling direction/°	8	25	50	271	312	346	17	50	82	291	316	339
Time/h	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Coupling velocity m/s	0.90	0.78	0.70	0.65	0.60	0.48	0.28	0.10	0.48	0.83	1.04	1.08
Coupling direction/°	356	10	22	37	55	78	284	59	297	319	339	358

The coupling of tidal current energy and wave energy simplifies the action of complex sea water motion on the turbine into an equivalent velocity vector varying with time. According to the change of predicted equivalent velocity size to design the turbine blade motion regular, and according to the predicted equivalent velocity direction to design the gesture change regular of the turbine, the turbine can achieve the maximum energy efficiency in most of the day under the drive of the corresponding automatic control system.

4. Conlusion

Take Fishing grounds of Changjiang estuary Port as an example, the LSTM models according to tidal current (velocity and flow direction) and wave (wave period, significant wave height, average mean wave direction) per hour data for the past two years were established, the future data within 24 hours were predicted, the wave-tidal current coupling mechanism was studied, the conclusion is as follows:

(1) LSTM prediction accuracy of tidal current and wave characteritics are 0.87, 0.93, 0.93, 0.82, 0.84, the accuracy is high, so the LSTM prediction model for wave and tidal current prediction is effective.

(2) Wave – tidal current coupled velocity vector acting on the turbine is a function of tidal current velocity, flow direction, wave period, wave direction and wave height.

(3) The coupling velocity vector in the next 24 hours can be predicted by combining the prediction data of five time series and the wave-tidal current coupling velocity vector function. The predicted data can be applied to the design of the blade motion regular and the rotation regular of the turbine fuselage,which can effectively improve the hourly energy efficiency of the turbine in the working process,and further applied to the development of new energy and the prediction of marine environment.

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