Design optimization and numerical verification of adaptive composite blades for hydro-turbine

Liang Fang¹,², Xiaogang Xu¹,³, Qiang Li³ and Zhenbo Wang¹*

¹College of New Energy, China University of Petroleum, Qingdao, Shandong, 266580, PR China
²Department of Marine Engineering, Weihai Ocean Vocational College, Weihai, Shandong, 264300, PR China
³College of Petrochemical Technology, Lanzhou University of Technology, Lanzhou, Gansu, 730000, PR China
*Corresponding author’s e-mail: wangzhb@upc.edu.cn

Abstract. In this paper, an adaptive composite blade is designed based on the composite mechanics and bending torsion coupling theory, and the blade structure is optimized by a multi-parameter and multi-objective optimization method. Furthermore, the dynamic interaction between the flow and structure domain during the bend-twist coupling process was also studied by the two-way fluid-structure coupling method to verify the hydrodynamic performance and structural performance of the optimized blade. The results show that the multi-parameter and multi-objective optimization method is suitable for the design of composite blades. The optimized blade has better hydrodynamic performance and structural performance, manifesting a higher energy utilization and less concentrated stress.

1. Introduction
Tidal current energy has the characteristics of high exploitability, renewable, clean, and environmental protection, which attracts people's attention and becomes the focus of research and development all over the world. Hydro-turbine is the core device of tidal current energy utilization technology. Its main function is to convert the kinetic energy of tidal current into available electric energy. Among them, the horizontal axis hydro-turbine has the characteristics of high-power generation efficiency, good self-starting performance, and stable output power.

For composite blades, both bending and torsion deformations occur simultaneously. This phenomenon, known as the bend-twist coupling effect, is the focus of current blade design research. In recent years, many researchers have studied the bending-torsion coupling characteristics of composite materials, mainly focusing on the research of bending-torsion coupling theory, the design of wind turbine bending-torsion coupling blades[1], the vibration problem of wind turbine bending-torsion coupling blades[2], and the structural performance analysis of wind turbine blades based on structural finite element method.

At present, there are few studies on Tidal Turbine blades. And the previous studies all used structural the finite element analysis method based on one-way fluid-structure coupling, which cannot simulate the instantaneous change of blade torsion angle during the process of bend-twist coupling. Based on the theory of composite mechanics and bend-twist coupling, the composite blades of horizontal axis tidal current turbine with bending-torsion coupling effect are optimized in this paper.
Moreover, the two-way fluid-structure coupling method is used to capture the dynamic interaction process between the fluid domain and the structure domain when the blade bending-torsion coupling occurs, and the self-adaptation of the blade and its influence on the hydrodynamic performance and structural performance of the turbine are studied.

2. Modelling method

2.1. Blade model setup

2.1.1. Model section. In order to facilitate the verification of the results, the blade model is referred to reference [3]. The rotor adopts NACA638XX airfoil and three-blade rotor structure. The hub diameter is 0.1 times of the impeller diameter. The front and back ends of the hub are hemispherical and smooth. The rotor is shown in the following figure 1.

![Figure 1. Experimental and computational models.](image)

2.1.2. Model section. The blade adopts D-shaped structure, consisting of a main spar running along the length of the blade, enclosed by a skin to give the blade its hydrodynamic shape [4]. The thickness and laying method in different parts of blade are different. The specific blade structure is divided into three parts: web, beam cap and blade skin. Among them, the beam cap is the core structure to realize bend-twist coupling. The blade can achieve directional torsion by setting suitable laying materials and laying angles.

2.1.3. Theoretical basis for bend-twist coupling. According to the laminate theory, the constitutive equation of composite blades based on the symmetrical and anti-symmetrical laying methods is expressed as equation (1) and equation (2) respectively. Compared with the two formulas, when symmetrical lamination is adopted, the coupling effect in the laminate is significantly less than that in the anti-symmetrical lamination, which makes it easier to control the coupling relationship. Furthermore, the coupling effect will become more complex when the laying of laminates is random, neither symmetrical nor asymmetrical. For blades, the symmetrical laying method should thus be selected to make use of the bending-torsion coupling to achieve the adaptability of blades.
2.1.4. **Ply materials.** Hydro-turbine works in harsh underwater environment, which requires higher rigidity, fatigue resistance and corrosion resistance of materials. Considering the above requirements, the carbon fibre and glass fibre are the current preferred materials for blades [5]. Therefore, the blade paving materials are carbon fibre, glass fibre, light wood, PVC and other hybrid composite blades. Among them, carbon fibre and glass fibre are reinforcing materials for the blade, which play a decisive role in the performance of the blade, while light wood and PVC are internal filling materials, which play a smaller role. The emphasis of this paper is on the impact of bend-twist coupling to the blade adaptability, so the filling material is neglected. The mechanical properties of the two materials are shown in table 1 below. \( \sigma_x, \sigma_y, \sigma_z, \sigma_{xy}, \sigma_{yz}, \) and \( \sigma_{xz} \) represent the material stiffness at six degrees of freedom, respectively. \( \nu_{xy}, \nu_{yz} \) and \( \nu_{xz} \) represent the material Poisson's ratio. The Young's modulus of the material is not considered because the tensile deformation of the blade can be neglected when the turbine is working. The table shows that, the carbon fibre has greater flexural stiffness and smaller density than the glass fibre.

\[
\begin{bmatrix}
N_x \\
N_{xy} \\
M_x \\
M_{xy}
\end{bmatrix} =
\begin{bmatrix}
A_{11} & 0 & 0 & \tilde{B}_{16} \\
0 & A_{66} & \tilde{B}_{61} & 0 \\
0 & \tilde{B}_{16} & D_{11} & 0 \\
\tilde{B}_{61} & 0 & 0 & D_{66}
\end{bmatrix}
\begin{bmatrix}
\xi_x \\
\eta_{xy} \\
\kappa_x \\
\kappa_{xy}
\end{bmatrix}
\tag{2}
\]

| Table 1. Material properties. |
|-------------------------------|
|                               | Carbon fibre | Glass fibre |
| \( \rho(\text{kg/m}^3) \)     | 1490         | 1850        |
| \( \sigma_x(\text{GPa}) \)   | 121          | 35          |
| \( \sigma_y(\text{GPa}) \)   | 8.6          | 9           |
| \( \sigma_z(\text{GPa}) \)   | 8.6          | 9           |
| \( \nu_{xy} \)               | 0.27         | 0.28        |
| \( \nu_{yz} \)               | 0.27         | 0.28        |
| \( \nu_{xz} \)               | 0.4          | 0.4         |
| \( \sigma_{xy}(\text{GPa}) \)| 4.7          | 4.7         |
| \( \sigma_{yz}(\text{GPa}) \)| 4.7          | 4.7         |
| \( \sigma_{xz}(\text{GPa}) \)| 3.1          | 3.5         |

2.1.5. **Ply scheme.** In this paper, the leaves are divided into six regions. In each region, different materials are laid in a certain order and angle by using the axial warp knitted structure. The specific ply scheme is shown in table 2.

| Table 2. Material properties. |
|-------------------------------|
|                               | Length ratio (%) | Ply method |
| Root                          | 10–20            | \( [\pm45°/\pm45°/\pm45°/0°/\pm45°/\pm45°]/s \) |
|                               | 20–40            | \( [\pm45°/0°/\pm45°/0°/\pm45°/\pm45°]/s \) |
| Beam cap on pressure surface  | 40–60            | \( [\pm45°/\pm45°/\pm45°/20°/\pm45°/\pm45°]/s \) |
|                               | 60–80            | \( [\pm45°/\pm45°/\pm45°/20°/\pm45°/\pm45°]/s \) |
|                               | 80–100           | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
|                               | 20–40            | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
| Beam cap on suction surface   | 40–60            | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
|                               | 60–80            | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
|                               | 80–100           | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
|                               | 20–80            | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
| Inlet edge                    | 20–80            | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
| Outlet edge                   | 80–100           | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
|                               | 20–40            | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
| Web                           | 10–84            | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
| Tip                           | 100              | \( [\pm45°/\pm45°/\pm45°/\pm45°/\pm45°/\pm45°]/s \) |
2.2. Numerical model setup

Compared with the traditional theoretical analysis and experimental verification methods, the numerical simulation method can give relatively intuitive flow field simulation and numerical solution, and save manpower and material expenditure.

2.2.1. Assumption. The research object of this paper is the hydrodynamic performance and structural performance of composite blades. In the calculation, we simplify the unsteady flow of the turbine flow field to the steady flow. In order to study the effect of bend-twist coupling effect on composite blades intuitively and ignore the influence of some factors, the following assumptions are made: (a) Steady flow; (b) Incompressible fluid; (c) Temperature was constant at 20°C; (d) Gravity in the flow field was neglected; (e) Cavitation effect of hydro-turbine was neglected; (f) Filling materials of blade were neglected.

2.2.2. Governing equations. The continuity equation and momentum equation are shown in equation (3) and equation (4) respectively.

\[ \rho \frac{\partial V}{\partial t} = \rho g - \nabla p + \mu \nabla^2 V \]

Where \( V \) is the velocity vector, \( \rho \) is the mixed density, \( g \) is the gravitational acceleration scalar, \( p \) is the pressure, \( \mu \) is the dynamic viscosity. For horizontal axis turbines, there is a relative rotating speed between the impeller and the external flow field. At this time, the \( V \) in the upper formula becomes the combined velocity \( V_c \) of the incoming flow speed and the impeller rotating speed. That is, \( V_c = V - V_\omega \), in which \( V_\omega \) is the rotation velocity vector. Besides, SST turbulence model is adopted, which can accurately predict the flow field on the smooth free surface, thus having more advantages in the case of turbine stall and blade flow.

2.2.3 Fluid-solid coupling equation. The transient effects of structures are solved by the time-domain method, and the structural-fluid system equations of motion are obtained by combining the structure and discretized fluid formulas. The staggered iteration method can be used to solve this equation, which can greatly improve the computational efficiency.

\[
\begin{bmatrix}
M & 0 & \hat{r} \\
\rho \hat{B} & \rho & \hat{p} \\
E & \hat{C} & \hat{p}
\end{bmatrix} \dot{r} + \begin{bmatrix}
\hat{C}_s & 0 & \hat{r} \\
0 & A & \hat{p}
\end{bmatrix} \dot{\hat{p}} + \begin{bmatrix}
K & -B^T & \hat{r} \\
0 & H & \hat{p}
\end{bmatrix} = \begin{bmatrix}
-f_0 \\
-q_0
\end{bmatrix}
\]

3. Results and discussion

3.1. Reliability verification

The main parameter to measure the hydrodynamic performance of a hydraulic turbine is the energy utilization rate \( Cp = T \omega \left( 0.5 \rho V_x^3 S \right)^{-1} \), and the blade tip speed ratio \( \lambda = \omega R V_x^{-1} \) is an important parameter to affect the energy utilization rate of a hydraulic turbine. Where \( \omega \) is turbine speed, \( V_x \) is water inflow velocity, \( T \) is turbine torque, \( S \) is impeller upstream area.

Figure 2 shows the \( Cp \) of hydro-turbine measured by numerical simulation method and test method to verify the reliability of the settlement results. Among them, the numerical simulation methods include one-way and two-way fluid-solid coupling methods. In the figure, the overall trend of the experimental curve is basically the same as that of the numerical simulation curve. With the increase of the velocity ratio, the energy utilization ratio increases first and then decreases. When \( \lambda > 7 \), the experimental value decreases obviously due to the occurrence of cavitation. The occurrence of cavitation is not considered in the calculation in this paper, so the numerical simulation results are higher. For the fluid-structure coupling method, when \( \lambda < 7 \), the results of two-way method are closer to the experimental values. Generally speaking, the two-way method can effectively simulate the
dynamic interaction between fluid domain and structure domain, and it is more suitable for solving hydro-elastic problems.

![Figure 2. Reliability verification diagram.](image)

3.2. **Blade optimization**

By using multi-parameter and multi-objective optimization method, considering the influence of multiple design variables on the optimization objectives, the optimal design variables are obtained.

### 3.2.1 Mathematical model.

The design variables, objective functions, and constraints are shown in turn below.

\[
\begin{align*}
    d &= [d_1, d_2, \ldots, d_i, \ldots, d_n] \\
    \beta &= [\beta_1, \beta_2, \ldots, \beta_i, \ldots, \beta_n] \\
    &\begin{bmatrix} 
        Cp \\
        Dt \\
        M 
    \end{bmatrix} \\
    &\begin{bmatrix} 
        Cp \geq [Cp] \\
        Dt \leq [Dt] \\
        M \leq [M] 
    \end{bmatrix}
\end{align*}
\]

### 3.2.2 Response surface analysis.

Sensitivity analysis can effectively evaluate the impact of variables on the objective function. It can be seen from the figure 3 that the change of installation angle has a great influence on the energy utilization rate and the maximum deformation of the blade, but has little effect on the total mass of the blade; the thickness of single-layer carbon fibre has a great influence on the maximum deformation of the blade and the total mass of the blade, and has little effect on the energy utilization rate of the blade.
3.2.3 Optimization results. Specific constraints:

\[
\begin{align*}
Cp & \geq 0.41 \\
Dt & \leq 0.2 \text{m} \\
M & \leq 2400 \text{Kg}
\end{align*}
\] (9)

Under the constraints, the three optimal design variable schemes are shown in table 3. The three schemes all meet the design requirements, and the difference between them is not large. Under the condition that the total mass of the blade is not different, the scheme with the highest energy utilization rate is selected first in this paper. The turbine is working 24 hours without interruption. It can keep working for a long time under the condition that the structure and performance of the turbine meet the requirements. Higher energy utilization rate can bring more benefits. Although the total blade mass will increase with it, compared with the constraint condition of nearly 2400kg, 15kg is only 0.625%, which has little effect on the total cost. Finally, the installation angle is 5.07 degrees and the thickness of single-layer carbon fibre is 0.005059m. The installation angle is approximately 5 degrees and the thickness of single-layer carbon fibre is 0.0075m.

| Installation angle (°) | Thickness of single-layer carbon fibre (m) | Cp | Dt (m) | M (kg) |
|------------------------|------------------------------------------|----|--------|--------|
| 5.07                   | 0.0075059                                | 0.41585 | 0.19709 | 2396.7 |
| 4.894                  | 0.0074317                                | 0.4135  | 0.19669 | 2381.6 |
| 4.766                  | 0.0074629                                | 0.41163 | 0.19328 | 2387.9 |

Table 4 verifies the reliability of the predicted results. The verification results show that the total deviation between the calculated results and the predicted values is less than 1%, and all of them satisfy the established constraints. The approximate installation angle and the thickness of single-layer carbon fibre meet the design requirements.

| Cp             | Dt (m) | M (kg) |
|----------------|--------|--------|
| Predicted value| 0.41585| 0.19709| 2396.7 |
| Validation value| 0.41495| 0.19799| 2395.1 |
| Deviation      | -0.22% | 0.46% -0.07% |

The final optimization results are shown in table 5.
Table 5. Final optimization results.

| Variable                  | Optimization target |
|---------------------------|---------------------|
| Installation angle        | 5°                  |
| Thickness of Single-Layer Carbon Fibre | 0.0075 m |
| Energy utilization rate   | 0.41495             |
| Maximum deformation       | 0.19795 m           |
| Mass                      | 2395.1 kg           |

3.3. Blade performance analysis

3.3.1 Analysis of hydrodynamics performance. Energy utilization rate is the main parameter to measure the hydrodynamic performance of hydraulic turbines. The calculation results of energy utilization are shown in figure 4. In the figure, the energy utilization ratio of composite bending-torsion coupled blade turbine is obviously higher than that of steel blade turbine, which proves that the hydrodynamic performance of the turbine can be effectively improved after the bending-torsion coupling effect of the blade occurs. Through the bending-torsion coupling effect, the energy utilization rate increases by 4.69% at the optimal speed ratio of 6. With the increase of speed ratio, the energy utilization rate increases. At the maximum speed ratio of 9, the energy utilization rate increases by 15.43%.

Furthermore, through the self-adaptation of blades, the energy utilization rate can reach more than 40% in a larger speed ratio range (5-9), which makes the turbine maintain a higher efficiency and effectively avoids the runaway of the lower turbine with a high speed ratio, thus ensuring that the turbine can maintain a relatively stable output under complicated underwater conditions.

![Figure 4. Comparison of the hydrodynamic performance.](image_url)

3.3.2 Analysis of Structural Performance. For the structural performance of the blade, the stress magnitude and distribution of the blade should be analyzed. Figure 5 shows the stress distribution of the skin and web of composite blades and structural steel blades, respectively. Comparing the two diagrams, it can be seen that the maximum equivalent stress of composite blade skin is smaller than that of structural steel blade skin. Because of the different thickness of the layers between different parts of the blade, there is a certain degree of stress concentration in the blade, but the stress distribution of the two kinds of blades is different. In the different layers of the blade, there are many stresses concentration points in the steel structure blade, while the composite material. There is only one blade, and the stress concentration is relatively low. The stress distribution of web of structural steel blades is mainly in the contact position between web and skin, while that of composite blades is relatively uniform, and there is almost no concentrated stress on web.
Fig. 12 shows that the maximum equivalent stress of composite blades is significantly less than that of structural steel blades at different speed ratios. With the increase of speed ratio, the maximum equivalent stress of structural steel blades continues to increase, while the maximum equivalent stress of composite blades tends to be stable. At the maximum speed ratio of 9, the maximum equivalent stress can be reduced by 23.35%. It can be seen that the stress concentration on the composite blade can be effectively reduced due to the adaptive bending-torsion coupling performance of the composite blade.

![Composite blade and Steel blade](image)

**Figure 5.** The stress distribution of the blade.

![Graph showing stress change](image)

**Figure 6.** The maximum equivalent stress of the blade due to the change of tip speed ratio.

### 4. Conclusion

1. The two-way fluid-structure coupling numerical simulation method can effectively capture the dynamic interaction process of fluid domain and structure domain in the bending-torsion coupling effect of composite blades, and accurately predict the hydrodynamic performance and structural performance of composite blade turbine with bending-torsion coupling.

2. The symmetrical lamination method in this paper can effectively realize the bending-torsion coupling effect of composite blades, and the bending-torsion coupling effect makes the blades adaptive.

3. The multi-parameter and multi-objective optimization method has high prediction accuracy and can be used to optimize composite blades of hydraulic turbines.

4. Adaptive blades with bending-torsion coupling characteristics can effectively improve the hydrodynamic performance of hydraulic turbines. The energy utilization ratio of the optimal speed ratio is increased by 4.69%, and in a larger speed ratio range (5-9), the turbine can maintain a higher energy utilization ratio, effectively avoiding the runaway of the high-speed ratio lower turbine, thus ensuring that the turbine can also maintain a relatively stable output under complex underwater conditions.

5. Adaptive blades with bending-torsion coupling characteristics can effectively improve the structural performance of turbine blades. The maximum equivalent stress of the blade decreases...
obviously, and the effect is more obvious at high speed than at working condition. The reduction of maximum equivalent stress can effectively ensure the stability of the structure of the turbine under complicated underwater working conditions.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (52176050, 51506225), the General Program of Natural Science Foundation of Shandong Province (ZR2020ME174).

References
[1] Liu W., Gong J., Liu X., Zhang X. (2011) The adaptive blade design of wind turbine based on beam flap-twist coupling theory. Acta Energiae Solaris Sinica, 32(7): 1014-1019.
[2] Yang J., Gao W. (2003) Research on the coupled blade-bending and shaft-torsion vibration of rotating machinery. Power Engineering, 23(4): 569-573.
[3] Bahaj A. S., Molland A. F., Chaplin J. R., Batten W. M. J. (2007) Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank. Renewable Energy, 32(3): 407-426.
[4] Harper P. W., Hallett S. R. (2015) Advanced numerical modelling techniques for the structural design of composite tidal turbine blades. Ocean Engineering, 96:272-283.
[5] Marsh G. (2004) Tidal turbines harness the power of the sea. Reinforced Plastics, 48(6):44-47.