Research on Motion Reduction of a T-Foil on the Wave-Piercing Catamaran

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Abstract. When the wave-piercing catamaran (WPC) sails on the waves, if the wavelength is near to the length of WPC, the pitching amplitude will be large. After years of research, it is found that installing the appendage is a good method of reducing shaking. T-foil is a good choice. In order to study the anti-pitching effect of the T-foil, this paper establishes the motion model of the wave-piercing catamaran and solves the motion equations. The result shows that the amplitude of pitting and heaving can be reduced by 10%.

1. Introduction

In the 21st century, maritime traffic is more and more developed, and ships are sailing faster and faster at sea. Therefore, it is particularly important to improve the seakeeping performance of ships. Through the research in recent years, it is found that appendages are quite effective to improve the seakeeping performance [1]. Professor Ding [2] in Harbin Engineering University found that installing a fin stabilizer on the bow helps to reduce the vibration of the bow. The T-foil [3], which has a high lift-drag ratio, is a good anti-rolling method, it can produce large lift, damping forces and inertia force, which can reduce the amplitude of longitudinal motion. The stern flap [4]-[5] can improve the flow field of the stern and it can inhibit the waves of the stern, so it can reduce the wave resistance and improve the speed and the seakeeping of the ship. Based on this idea, the anti-pitching effect of T-foil is studied in this paper.

2. Mathematical Model

2.1. Theoretical study on seakeeping performance

Fig.1 shows the model of wave piercing catamaran and T-foil. Based on the assumption of micro wave amplitudes and Newton second law, the coupled equations of ship’s motion in longitudinal direction can be obtained [6]:

\[
\begin{align*}
\left( M_{33} + A_{33} \right) \ddot{\xi}_3 + B_{33} \dot{\xi}_3 + C_{33} \xi_3 + A_{35} \dot{\xi}_5 + B_{35} \dot{\xi}_5 + C_{35} \xi_5 &= F_{31}^{(e)} e^{-i\omega t} + F_e \\
\left( I_T + A_{33} \right) \ddot{\xi}_5 + B_{35} \dot{\xi}_5 + C_{35} \xi_5 + A_{33} \dot{\xi}_3 + B_{33} \dot{\xi}_3 + C_{33} \xi_3 &= F_3^{(o)} e^{-i\omega t} + M_T
\end{align*}
\]
In the equations, subscripts 3 and 5 represent the pitching and heaving of a ship, respectively. \( \xi_3, \xi_5, \ddot{\xi}_5 \) are displacement, velocity and acceleration of a ship, respectively. \( M_\mu \) is the mass matrix, \( A_\mu \) is added mass coefficient, \( B_\mu \) is the hydrodynamic damping coefficient, \( C_\mu \) is the restoring force coefficient, \( F_\mu^{(e)} \) is complex amplitude value for wave disturbance power. \( F_T \) and \( M_T \) are the force and torque which T-foil produces.

![Wave piercing catamaran and T-foil](image)

**Fig. 1.** Wave piercing catamaran and T-foil

### 2.2. Hydrodynamic calculation formula of ship

Ship motion is a linear simple harmonic motion, assuming that water is a kind of non-rotating, non-stick, ideal fluid. Boundary condition for fluids around a ship can be obtained by potential flow theory:

\[
\begin{align*}
[L] \nabla^2 \Phi(x, y, z, t) &= 0, \text{In the entire flow field} \\
[F](\frac{\partial}{\partial t} - U \frac{\partial}{\partial x})^2 \Phi(x, y, z, t) + g \frac{\partial}{\partial z} \Phi &= 0, \text{When } z = 0 \\
[S] \vec{n} \cdot \nabla \Phi(x, y, z, t) &= V_S \vec{n}, \text{ On the surface } S \\
[B] \lim_{t \to \infty} \Phi(x, y, z, t) &= 0 \\
[R] \text{Infinite radiation conditions}
\end{align*}
\]

\( V_S \) is the ship’s speed, \( \vec{n} \) is inner surface normal vector, \( S \) is wet surface area of a ship, \( \Phi(x, y, z, t) \) is speed potential, it can be divided into two parts: constant speed potential and unsteady speed potential:

\[
\Phi(x, y, z, t) = [-(U_x + \Phi_s(x, y, z))] + \Phi_\delta(x, y, z, t) \tag{3}
\]

\[
\Phi_\delta(x, y, z, t) = \Phi_\delta(x, y, z)e^{-i\omega t} = (\phi_1 + \phi_\delta + \phi_R)e^{-i\omega t} \tag{4}
\]

\( \Phi_s(x, y, z) \) is steady wave disturbance potential during ship navigation, \( \Phi_\delta(x, y, z, t) \) is unsteady speed potential, it can be divided into incident potential \( \phi_1 \), diffraction potential \( \phi_\delta \) and radiation potential \( \phi_R \).

Boundary conditions must be satisfied on the surface \( S \):

\[
\frac{\partial}{\partial \vec{n}} (\phi_1 + \phi_\delta) = 0 \tag{5}
\]

\( \phi_R \) is radiation potential, it can be expressed as:
\[ \phi_n = \sum_{j=1}^{\infty} \xi_j \phi_j \quad (6) \]

\( \phi_j \) is speed potential of the motion modal unit amplitude, \( \xi_j \) is oscillation amplitude.

Basic assumptions and conditions are given as below:

1. The fluid is assumed to idea fluid: irrotational, potential, inviscid and incompressible flow.
2. The wave is assumed to a small amplitude wave, so the motion of the catamaran is a slight swing.
3. The ship is assumed to a thin-tall body, the transverse dimension of the wave-piercing catamaran is smaller than the longitudinal dimension.
4. Boundary conditions are assumed to linear constraints, high-order items are ignored.
5. Constant items are ignored.

According to the above assumptions, the three-dimensional boundary conditions of the wave-piercing catamaran can be simplified into two-dimensional boundary conditions, so added mass and damping can be obtained conveniently.

\[ \begin{align*}
[L] & \frac{\partial^2 \phi_j}{\partial y^2} + \frac{\partial^2 \phi_j}{\partial z^2} = 0, \text{In the entire flow field} \\
[F] & \frac{\partial^2 \phi_j}{\partial z} - k \phi_j = 0, \text{When } z=0 \\
[S] & \frac{\partial \phi_j}{\partial n} = -i \omega \xi_j, \text{On the surface } S \\
[B] & \lim_{y \to -\infty} \nabla \phi_j = 0, \text{At the bottom of water} \\
[R] & \lim_{y \to \infty} \left[ \frac{\partial \phi_j}{\partial y} \mp i \kappa \phi_j \right] = 0, \text{At infinity}
\end{align*} \quad (7) \]

### 2.3. Hydrodynamic calculation formula of T-foil

The total vertical force caused by the T-foil can be divided into 3 parts:

\[ F_i^f = I(t) + D(t) + L(t) \quad (8) \]

\[ F_i^f = F_i^f 1 \quad (9) \]

Where \( I(t) \) is inertial force of hydrofoil, it can be calculated by:

\[ I(t) = \left( m^{(I)} + a^{(I)} \right) \left( \dddot{\xi}_3 - \dddot{\xi}_5 \right) \quad (10) \]

While \( D(t) \) is horizontal viscous drag, it can be calculated by:

\[ D(t) = \frac{D_i}{2} A^{(I)} C^{(I)} \left( \dddot{\xi}_3 - \dddot{\xi}_5 - \dddot{\xi}_v \right) \left( \dddot{\xi}_3 - \dddot{\xi}_5 - \dddot{\xi}_v \right) \quad (11) \]

In which \( L(t) \) is lift of the hydrofoil, it can be calculated by:

\[ L(t) = \frac{D_i}{2} V^2 A^{(I)} C_{\alpha} \alpha(t) \quad (12) \]
m is mass of hydrofoil. \(a_i = \frac{F_i}{g}\) refers to added mass, s is the length of span, c is the chord length of the hydrofoil. \(C_{D0}\) is hydrofoil’s cross flow resistance coefficient. \(A^i\) is area of the hydrofoil. \(c_{in}\) is slope of the lift coefficient curve of the hydrofoil. \(\alpha(t)\) is angle of attack for the hydrofoil pressure point:

\[
\alpha(t) = \tilde{\xi}_v(t) + (\tilde{\xi}_{\dot{v}}(t) - 1\tilde{\xi}_v(t) - \tilde{\xi}_v(1,0,-d,t))/V
\]

While \(\dot{\xi}_v\) is vertical induced velocity of incident wave, it can be calculated by:

\[
\dot{\xi}_v(x,y,z,t) = \frac{\partial \Phi_i}{\partial z} e^{-i\omega t} = -i\omega_0 A e^{i[k(z+i(x\cos\beta-y\sin\beta)]} e^{-i\omega t}
\]

Where \(\omega_e\) is encounter frequency, \(\omega_0\) is incident wave frequency, \(\beta\) is wave angle, \(k_0\) is wave number, \(A\) is amplitude of incident wave.

3. Numerical calculation and simulation

3.1. Simulation of hydrofoil lift coefficient

The plan view of the T-foil is shown in Fig. 2. It has double convex profile. Its fundamental parameters are as follows: aspect ratio is 2.63, relative thickness is 0.09, length of span is 5m. It has flap and the chord length of flap is 0.6m. Amplitude of the flap’s angle is 15°.

![Fig. 2. The plan view of the T-foil](image-url)

The lift coefficient of a three-dimensional hydrofoil is defined as:

\[
C_L = \frac{F}{\frac{1}{2}\rho V^2 c l}
\]

In which \(\rho\) is density of water, \(V\) is the velocity of water flow, \(c\) is the average chord length of the hydrofoil and \(l\) is the length of the span.

The hydrofoil type is NACA 16009. The 3D model of the T-foil was built in Solidworks 2016. The model is symmetrical, so only half of model was used. Simulation calculations were performed in ANSYS Fluent.
The calculation area and boundary conditions [7] are shown in Fig. 3. Reynolds number is \( Re = \frac{vL}{\nu} = 1.9 \times 10^7 \), where \( v \) is velocity of water flow and it is 10m/s, \( L \) is chord length, \( \nu \) is kinematic viscosity. The turbulence model of simulation is SST \( k-\omega \) model.

![Fig. 3. Computational domain and boundary conditions](image)

**Table 1.** Lift coefficient of hydrofoil at different angles of attack

| angle of attack | Lift coefficient | angle of attack | Lift coefficient |
|----------------|-----------------|----------------|-----------------|
| 0              | 0.003           | 8              | 0.4249          |
| 1              | 0.065           | 9              | 0.466           |
| 2              | 0.1221          | 10             | 0.488           |
| 3              | 0.175           | 11             | 0.5055          |
| 4              | 0.2289          | 12             | 0.511           |
| 5              | 0.28            | 13             | 0.505           |
| 6              | 0.3321          | 14             | 0.494           |
| 7              | 0.38            | 15             | 0.49            |

![Fig. 4. Lift coefficient curve with different angles of attack](image)
Table 1 shows the lift coefficient of hydrofoil at different angles of attack, Fig. 3 shows lift coefficient curve with different angles of attack. From Fig. 4 we can see that as the angle of attack increases, the lift coefficient of the hydrofoil will increase first, then it will reach the maximum value at $12^\circ$, after that it will decrease. Therefore, $12^\circ$ is the stall angle. When the angle of attack is less than $12^\circ$, the relationship between the lift coefficient and the angle of attack can be approximated shown by a straight line. Therefore, we can fit a linear function to find the slope of the lift coefficient curve as Fig. 5 shows. $C_{Lm}$ is slope and we can see $C_{Lm} = 0.047$. After knowing the slope of the lift coefficient, if we want to know the lift coefficient, we only need to know the angle of attack.

![Fig 5. Linear relationship between lift coefficient and angle of attack](image)

3.2. Numeral Calculations and analysis

The fundamental parameters of the wave-piercing catamaran are as follows: the total length is 93m and the length of demihull is 92.4m, the moulded breadth is 26.2m and the width of the demihull is 4.5m, the draught is 3.4m and the molded volume is $1450\text{m}^3$. According to strip theory, I program the equation of ship’s motion in Matlab when the ship is driving at a speed of 40 knots in the wave. Seakeeping performances of a wave-piercing catamaran with a T-foil and no T-foil are calculated, we can get the frequency response curves of pitching, heaving and gravitational acceleration as Fig. 6, Fig. 7 and Fig. 8 show. $\lambda$ is wavelength. $L$ is length of ship. $\theta_a$ is the angle of pitching and $\zeta_a$ is the amplitude of heaving, $\zeta_w$ is the amplitude of wave and $k$ is wavenumber, $a$ is acceleration at the ship’s center of gravity and $g$ is gravity acceleration. According to recommendations of ITTC, the result of the calculation is expressed by dimensionless parameters. $\theta_a / k\zeta_a$, $Z_a / \zeta_a$ and $aL / g\zeta_a$ are pitching response operator, heaving response operator and acceleration response operator, respectively. $L$ is length of ship.
In Fig. 6, Fig. 7 and Fig. 8, solid line represents the WPC with no T-foil and dotted line represents the WPC with a T-foil. Fig. 6 shows that when the wavelength increases, the pitching angle will increase first, when $\lambda / L \approx 2$, the pitching angle is the largest, then it will decrease slowly. Fig. 7 shows that when the wavelength increases, the amplitude of heaving will increase first, when
\( \lambda / L \approx 1.5 \), the amplitude of heaving reaches the maximum value, then it will decrease, when \( \lambda / L \geq 2.5 \), amplitude of heaving tend to steady. Fig. 8 shows that when the wavelength increases, the acceleration at the center of gravity will increase first, when \( \lambda / L \approx 1.5 \), the acceleration at the center of gravity reaches the maximum value, after that it will decrease drastically. We can see that T-foil has the effect of reducing ship’s motion from Fig. 6, Fig. 7 and Fig. 8. When \( \lambda / L \) is between 1 and 2, the movement of ship is very severe, which should be avoided.

|                | pitching | heaving | gravitational acceleration |
|----------------|----------|---------|---------------------------|
| With no T-foil | 0.849    | 0.963   | 23.21                     |
| With a T-foil  | 0.768    | 0.858   | 20.64                     |
| Decrease percentage | 9.6%   | 10.9%   | 11.1%                     |

Table 2 shows the comparison of amplitude reduction with a T-foil and with no T-foil. From table 2 we can see that the T-foil can reduce the pitching amplitude by 9.6%, the heaving amplitude by 10.9%, and acceleration at the center of gravity by 11.1% of the wave-piercing catamaran. It is proved that T-foil is a good appendage of motion reduction. However, the effect of motion reduction is not very good, it is only 10%.

4. Conclusion
Through the calculation of the lift coefficient of the hydrofoil and seakeeping performs of the ship, we can get that installing a T-foil in a wave catamaran is a good method of reducing longitudinal motion’s amplitude. This is because the T-foil can provide greater lift and damping torque in water, which can suppress the movement of the ship. I will try to find a better appendage in future research.

Acknowledgments
We acknowledge the financial support from the National Natural Science Foundation of China (Grant No. 51475179 and No.51679099), and the Fundamental Research Funds for the Central Universities, HUST.2016JCTD207.

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