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HIGH-SPEED CATAMARAN'S LONGITUDINAL MOTION ATTENUATION WITH ACTIVE HYDROFOILS

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ABSTRACT

This paper mainly studies the longitudinal motion prediction method and control technology of high-speed catamaran using the active hydrofoils. To establish the longitudinal motion equations of the ship basing on the 2.5D theory. Using the CFD software to obtain the hydrodynamic data of the hydrofoil. Bring the hydrodynamic expression of hydrofoils into the longitudinal motion equations of the ship. Predicting the longitudinal motion of High-speed catamaran before and after added the hydrofoils. A specific catamaran has been predicted with this approach, the result indicates this approach is workable and this prediction approach provides the theoretical basis for assessing the stabilization ability of appendages and possess the engineering practical value.

Keywords: High-speed catamaran; Longitudinal motion attenuation; 2.5D theory; Hydrofoil

INTRODUCTION

As an important member of high-performance ships, high-speed catamaran attracted widespread attention and research in the industry, high-speed catamaran have advantages of good stability, large open deck and high speed, so this kind of ship has a broad application prospect in the field of military and civilian [1–5]. The high-speed catamaran will bring sharp longitudinal oscillation motion (heaving and pitching) when sailing in the sea with high speed. This is a big problem which the rapid development of the high-speed catamaran will facing. It will bring the worse performance of motion and safety for high-speed catamaran. Adding stabilizer appendage can effectively improve the intense longitudinal oscillation of the high-speed catamaran. This paper study the method to predict longitudinal motion of high-speed catamaran with active hydrofoils.

This paper set up the longitudinal motion equation for high-speed catamaran based on the 2.5D theory [6–9]. Establish hydrofoil hydrodynamic model and adding hydrodynamic force of hydrofoil to the longitudinal motion equations of catamaran. Solving and programming these equations in regular waves and irregular waves, the stabilization capability of hydrofoils are assessed.

LONGITUDINAL MOTION EQUATIONS

Ships are partially submerged objects with six degrees of freedom for their motion (with constraints related to its interaction with water). Three of the referenced motions are rotational: pitch, roll and yaw. The other three are translational: heave, surge and sway. Each motion can be described with a differential equation, with terms induced by the other motions (there are couplings between motions due for instance to gyroscopic effects). For the sake of simplicity, let us disregard deformations of the ship, due for example to flexible modes. Supposing the ship is divided into symmetric parts by the X-Z vertical plane, the six differential equations can be grouped into two decoupled sets: one is related to longitudinal motions (surge, heave and pitch), the other is related to lateral motions (sway, roll and yaw). The interest in this paper is centered on longitudinal motions.

Analysis of experimental data shows that heave and pitch motions are the most relevant for the purpose of the research, while surge motion has negligible effects. The signs of heave and pitch are as follows: Pitch angle is positive when the bow goes down the horizontal. Heave position is positive from the origin upwards along axis Z.

From the point of view of physics, the longitudinal motion equations are [10]:

$$(a_{33}+m)\ddot{z}+b_{33}\dot{z}+c_{33}z+a_{35}\ddot{\theta}+b_{35}\dot{\theta}+c_{35}\theta=F_3(t) \quad (1)$$

$$(a_{55}+I_y)\ddot{\theta}+b_{55}\dot{\theta}+c_{55}\theta+a_{53}\ddot{z}+b_{53}\dot{z}+c_{53}z=F_5(t) \quad (2)$$

The left-hand side of the equations constitutes a model of the ship's dynamics (the semi submerged body). In this paper, this part will be denoted as the forces-to-motions model. The right-hand side of the equations will be denoted as the waves-to-forces model, giving the forces due to waves. In Eq. (1) and Eq. (2):

m — the mass of the ship (tonne);
θ — pitch angle (deg);
z — heave translation (m);
I_y — pitch moment of inertia (tonnem^2);
a_{33}, a_{55} — the added mass (a_{33} tonne, a_{55} tonnem^2);
b_{33}, b_{55} — the damping coefficient (b_{33} kN s/m, b_{55} kN ms/rad);
c_{33}, c_{55} — the restoring coefficient (c_{33} KN/m, c_{55} KNm/rad);
F_3, F_5 — waves forces (F_3: heave kN/m, F_5: pitch kN).

All of the above hydrodynamic coefficients and wave force are obtained by the 2.5D theory [9], through the two-dimensional time domain source distribution method.

HYDRODYNAMIC OF HYDROFOIL

HYDROFOIL SELECTION

Hydrofoils mounted below the bow position of catamaran, when the high-speed catamaran sailing on the waves, the water will be at a certain angle of attack relative to the flow of the hydrofoil surface, and generates movement in the opposite direction of the ship's force, effective inhibited the longitudinal motion of the vessel.

The selected hydrofoil is NACA0021, shown in Figure 1. The mounted position is shown in Figure 2.

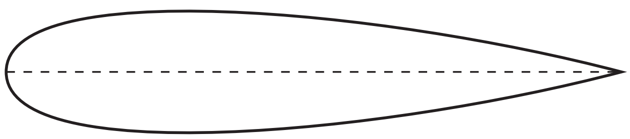

Fig. 1. NACA0021 airfoil

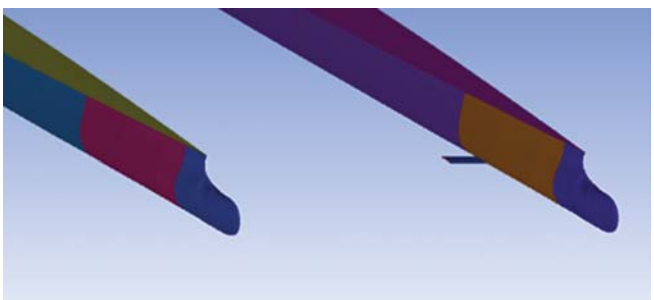

Fig. 2. Mounted position of hydrofoil

HYDRODYNAMIC FORCE OF HYDROFOIL

Based on the hydrodynamic theory, the lift force of hydrofoil is

$$F_F=\frac{1}{2}\rho U^2 A C_L \quad (3)$$

where ρ (kg/m^3) is fluid density, U (m/s) is ship speed, A (m^2) is projected area of hydrofoil and C_L is the lift coefficient of hydrofoil.

C_L is related with the attack angle of hydrofoil, in a wide range of attack angles (less than angle of stall), lift coefficient and angle of attack is linear relationship, it can be expressed as:

$$C_L=\frac{dC_L}{d\alpha}\cdot\alpha \quad (4)$$

where α is effective angle of attack, $\frac{dC_L}{d\alpha}$ is the slope of hydrofoil lift coefficient curve, which is obtained by the fitting curve based on the computational fluid dynamics calculation. The fitting curve of hydrofoil lift coefficient is shown in Figure 3.

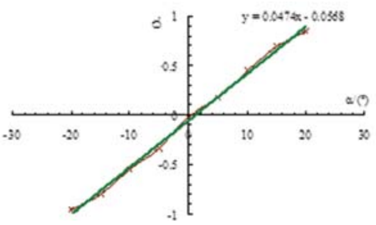

Fig. 3. Fitting curve of hydrofoil lift coefficient

The lift force formula of hydrofoil is:

$$F_F=\frac{1}{2}\rho U^2 A\frac{dC_L}{d\alpha}\cdot\alpha \quad (5)$$

so the lift moment formula of hydrofoil is:

$$M_F=(-l_F)\frac{1}{2}\rho U^2 A\frac{dC_L}{d\alpha}\cdot\alpha \quad (6)$$

where l_F(m) is the horizontal distance between the lift point of hydrofoil and center of gravity of the ship.

The actual movement of hydrofoil is unsteady. But generally speaking, the impact of unsteady movement of hydrofoils is small, so we can calculate the hydrofoil lift assume the hydrofoil movement is steady. When we calculate the real attack angle of hydrofoil, we need consider the extra angle caused by the heave, pitch of ship body. For active hydrofoil, the actual effective attack angle of hydrofoil including 3 parts: the swinging angle of the hydrofoil φ, the pitching angle θ of hydrofoil together with the ship body, an additional angle θ_F course by the movement of ship body. So the formula for the real attack angle of hydrofoil is

$$\alpha=\varphi-\theta+\theta_F \quad (7)$$

According to the research of Esteban S. [11], considering the combined action of the instantaneous heave speed of ship $\dot{z}$, vertical velocity of wave on hydrofoil $\dot{\zeta}$, angular velocity of pitch $\dot{\theta}$ and ship speed v, θ_F can be written as follow:

$$\theta_F = \arctan\frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U} \tag{8}$$

θ_F is a small value, so it can be simplified to

$$\theta_F = \frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U} \tag{9}$$

The final expression for the effective angle of attack:

$$\alpha = \varphi - \theta + \frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U} \tag{10}$$

Substitute Eq. (10) into Eq. (5), we can get

$$F_F = \frac{1}{2}\rho U^2 A \frac{dC_L}{d\alpha}(\varphi - \theta + \frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U}) \tag{11}$$

When the model of hydrofoil has chosen, $\rho U^2 A \frac{dC_L}{d\alpha}$ is a constant value under a certain ship speed U, suppose this constant value is K_F, because the catamaran has two hydrofoils, the total control force acting by hydrofoil can be expressed as

$$F_F = K_F(\varphi - \theta + \frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U}) \tag{12}$$

the total control moment is

$$M_F = (-l_F)\ K_F(\varphi - \theta + \frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U}) \tag{13}$$

THE STABILIZATION PRINCIPLE OF HYDROFOILS

The stabilization principle is the control force and moment which produce by hydrofoils can counteract the wave exciting force and moment [12], adding the control force and moment to the longitudinal equations of ship motion, we can get:

$$\begin{aligned}
&(m + a_{33})\ddot{z} + b_{33}\dot{z} + c_{33}z + a_{35}\ddot{\theta} + b_{35}\dot{\theta} + c_{35}\theta \\
&\quad = F_3 + K_F(\phi - \theta + \frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U}) \\
&(I_y + a_{55})\ddot{\theta} + b_{55}\dot{\theta} + c_{55}\theta + a_{53}\ddot{z} + b_{53}\dot{z} + c_{53}z \\
&\quad = F_5 - K_F l_F(\phi - \theta + \frac{l_F\dot{\theta} - \dot{z} + \dot{\zeta}}{U})
\end{aligned} \tag{14}$$

LONGITUDINAL MOTION PREDICTING METHOD OF HIGH-SPEED CATAMARAN WITH HYDROFOILS

Solving the steady-state solution of the longitudinal motion equations of catamaran with hydrofoils in frequency domain. Firstly, use heave equations of catamaran with hydrofoils as an example, the simplification equation is:

$$\begin{aligned}
&(m + a_{33})\ddot{z} + (b_{33} + \frac{K_F}{U})\dot{z} + c_{33}z + a_{35}\ddot{\theta} \\
&+(b_{35} - K_F\frac{l_F}{U})\dot{\theta} + (c_{35} + K_F)\theta = F_3 + K_F\phi + \frac{K_F}{U}\dot{\zeta}
\end{aligned} \tag{15}$$

The key problem is to determine the swinging angle φ of the hydrofoil, using PID control method, the size of the swing angle φ is determined by the value of ship movements [13–15], that is

$$\varphi = -K_{P\theta T}\ddot{\theta} - K_{I\theta T}\theta - K_{D\theta T}\ddot{\theta} - K_{PzT}\dot{z} - K_{IzT}z - K_{DzT}\ddot{z} \tag{16}$$

This is the ideal form of PID control method, $K_{P\theta T}$, $K_{I\theta T}$, $K_{D\theta T}$ are controller's control parameters of hydrofoil corresponding to the pitch angular velocity $\dot{\theta}$ of ship body, K_{PzT}, K_{IzT}, K_{DzT} are controller's control parameters of hydrofoil corresponding to the heave velocity $\dot{z}$ of ship body. Select certain value of PID control parameters which have good anti-pitching effecting, use fixed PID parameters, this allows us moved the control force and control moment which generated by the swing angle φ of hydrofoil to the left side of Eq.(15), Eq.(15) become:

$$\begin{aligned}
&(a_{33} + K_{Tf}K_{DzT})\ddot{z} + (b_{33} + K_{Tf}K_{PzT} + \frac{K_{Tf}}{U})\dot{z} \\
&+(c_{33} + K_{Tf}K_{IzT})z + (a_{35} + K_{Tf}K_{D\theta T})\ddot{\theta} \\
&+(b_{35} + K_{Tf}K_{P\theta T} - \frac{K_{Tf}l_F}{U})\dot{\theta} \\
&+(c_{35} + K_{Tf}K_{I\theta T} + K_{Tf})\theta = F_3 + \frac{K_{Tf}\dot{\zeta}}{U}
\end{aligned} \tag{17}$$

In the right side of Eq. (17), the heave velocity of wave on hydrofoil surface $\dot{\zeta}(t) = \omega_0 \cdot \zeta_a \cdot e^{kz} \cdot e^{i(\omega t - kx)}$, where ω_0 is wave circular frequency, ξ_a is amplitude of wave and k is wave number.

When theoretical calculation of regular waves, wave exciting force, heave, pitch angle can express as $F_3 = F_0e^{iwt}$, $z(t) = z_0e^{iwt}$, $\theta(t) = \theta e^{iwt}$. Substitute these expression to the heave equation, eliminate time items e^{iwt},use complex expression and separate real part and imaginary part, we can get two equations:

$$\begin{aligned}
&[-\omega^2(a_{33} + K_{Tf}K_{DzT}) + (c_{33} + K_{Tf}K_{IzT})]z_{0r} \\
&-\omega(b_{33} + K_{Tf}K_{PzT} + \frac{K_{Tf}}{U})z_{0i} + [-\omega^2(a_{35} + K_{Tf}K_{D\theta T}) \\
&+(c_{35} + K_{Tf}K_{I\theta T} + K_{Tf})]\theta_{0r} - \omega(b_{35} + K_{Tf}K_{P\theta T} - \\
&\frac{K_{Tf}l_F}{U})\theta_{0i} = F_0 + \frac{K_{Tf}\omega_0\zeta_a e^{kz_0}}{U}\cos kx_0
\end{aligned} \tag{18}$$

$$\begin{aligned}
&[-\omega^2(a_{33} + K_{Tf}K_{DzT}) + (c_{33} + K_{Tf}K_{IzT})]z_{0i} \\
&+\omega(b_{33} + K_{Tf}K_{PzT} + \frac{K_{Tf}}{U})z_{0r} + [-\omega^2(a_{35} + K_{Tf}K_{P\theta T}) \\
&+(c_{35} + K_{Tf}K_{I\theta T} + K_{Tf})]\theta_{0i} + \omega(b_{35} + K_{Tf}K_{P\theta T} - \frac{K_{Tf}l_F}{U})\theta_{0r} \\
&= F_0 - \frac{K_{Tf}\omega_0\zeta_a e^{kz_0}}{U}\sin kx_0
\end{aligned} \tag{19}$$

Similarly we can obtain two equations using the same method to the pitch equation, solve these four equations we can get heave amplitude z_{0F} and pitch amplitude θ_{0F}, the wave and heave displacement phase difference ε_{zF}, the wave and pitch phase difference $\varepsilon_{\theta F}$.

EXAMPLES

CATAMARAN AND HYDROFOIL MODEL

Now predict the longitudinal motion of a specific catamaran, the principal dimension of selected hydrofoil and catamaran are shown in Table 1. and Table 2.

Tab. 1. Principal dimension of hydrofoil

Stabilization appendage	Items	Unit	Quantitative value
hydrofoil	wing chord	m	1.414
	wing span	m	2.828
	max thickness	m	0.297

Tab. 2. Principal dimension of catamaran

Items	Unit	Quantitative value
Lpp	m	97.177
BWL (side hull)	m	5.24
B_{WL}	m	28.115
Draft	m	3.62
Z_G	m	8.733
X_G	m	–5.258
∇	m^3	2398.8
Inertia radius of pitching	m	26.0125

Select ITTC two parameters wave spectrum:

$$S_\zeta(\omega)=\frac{173H_{1/3}^2}{T_1^4\omega^5}\exp\left[-\frac{691}{T_1^4\omega^4}\right]\quad (m^2\cdot s) \qquad \textbf{(20)}$$

where $H_{1/3}$ (m) is significant wave height, T_1 (s) is characteristic period, $\omega(s^{-1})$ is circular frequency.
The ship forward speed is 30 kn.

RESULTS

The following figures are frequency response prediction of longitudinal movement of high speed catamaran with and without hydrofoils. In these figures, β is the angle of wave direction, Z is the frequency response of heave of catamaran without hydrofoils, Z_{gf} is the frequency response of heave of catamaran with fix hydrofoils, Z_{gf} is the frequency response of heave of catamaran with active hydrofoils, θ is the frequency response of pitch of catamaran without hydrofoils, θ_{gf} is the frequency response of pitch of catamaran with fix hydrofoils, θ_{gf} is the frequency response of pitch of catamaran with active hydrofoils

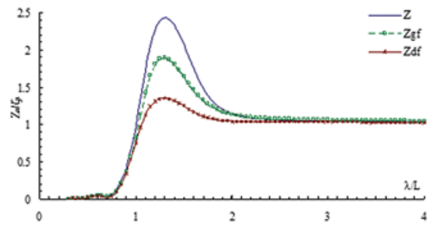

Fig. 4. Frequency response of heave (β=180°)

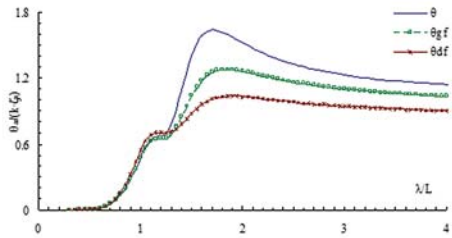

Fig. 5. Frequency response of pitch (β=180°)

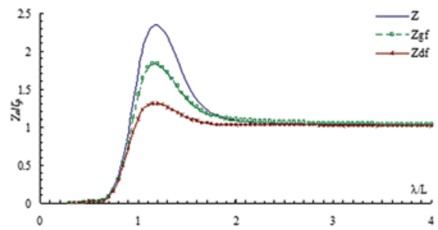

Fig. 6. Frequency response of heave (β=150°)

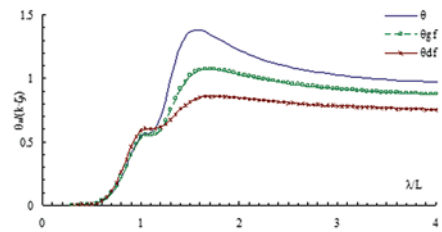

Fig. 7. Frequency response of pitch (β=150°)

Statistical values of longitudinal motion of catamaran in irregular wave and stabilization effectiveness are shown in Tab. 3. and Tab. 4.

CONCLUSION

In regular waves, the fixed hydrofoils have obvious stabilization effectiveness, active hydrofoils have better stabilization effectiveness than fixed hydrofoils. In short wave length region, the longitudinal motion response basically did not change with hydrofoils, in resonance region, the hydrofoils have good stabilization effectiveness, in long wave length region, the heave motion response basically did not change with hydrofoils but pitch motion response reduce a lot. In irregular waves, the stabilization effectiveness decreases with the sea state increase.

This paper provides a reference to research the automatic control model of stabilization for high speed catamaran longitudinal motion.

Tab. 3 Statistical values of heave of catamaran with and without hydrofoils and stabilization effectiveness

Working condition		Sea state		Statistical values of heave and effectiveness				
U (kn)	β (°)	$H_{1/3}$ (m)	T_1 (s)	Z_S (m)	Z_{S+GF} (m)	η_{GF} (%)	Z_{S+DF} (m)	η_{DF} (%)
30	180	1.25	6.13	0.670	0.543	18.90	0.417	37.69
		2.50	7.20	1.665	1.375	17.37	1.081	35.09
		4.00	8.21	2.760	2.342	15.13	1.905	30.97
		5.00	9.10	3.381	2.943	12.96	2.472	26.89
		6.00	10.51	3.794	3.421	9.84	2.999	20.96
	150	1.25	6.13	0.719	0.588	18.20	0.454	36.81
		2.50	7.20	1.671	1.399	16.24	1.115	33.25
		4.00	8.21	2.697	2.326	13.75	1.927	28.55
		5.00	9.10	3.274	2.898	11.49	2.481	24.22
		6.00	10.51	3.668	3.359	8.41	2.996	18.30

Tab. 4. Statistical values of pitch of catamaran with and without hydrofoils and stabilization

Working condition		Sea state		Statistical values of pitch and effectiveness				
U (kn)	β (°)	$H_{1/3}$ (m)	T_1 (s)	θ_S (°)	θ_{S+GF} (°)	η_{GF} (%)	θ_{S+DF} (°)	η_{DF} (%)
30	180	1.25	6.13	0.933	0.813	12.87	0.818	12.34
		2.50	7.20	2.549	2.132	16.38	2.004	21.37
		4.00	8.21	4.492	3.722	17.15	3.373	24.92
		5.00	9.10	5.627	4.666	17.08	4.152	26.20
		6.00	10.51	6.263	5.226	16.55	4.584	26.81
	150	1.25	6.13	0.975	0.840	13.87	0.833	14.54
		2.50	7.20	2.487	2.069	16.82	1.923	22.70
		4.00	8.21	4.212	3.480	17.38	3.125	25.80
		5.00	9.10	5.160	4.271	17.24	3.771	26.92
		6.00	10.51	5.626	4.687	16.69	4.082	27.45

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