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Research on roll stabilization for ships at anchor

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Abstract: With the increasing importance of ocean exploitation, providing anti-rolling stability for ships at anchor has become more and more important. The lift-generation theory of traditional fin stabilizers is based on incoming flow velocity, which is not suitable for explaining lift generated at anchor. We analyzed non-steady flows, with forces on fin stabilizers generated by non-incoming flow velocity conditions, and gave a new lift-generation model. The correctness of the model was proven by comparing experimental results of fin stabilizer motion under non-incoming velocity conditions from the fluid computation software with that from the emulator of the lift-generation model. Finally, the model was used in an anti-rolling system on a ship and the reduction of roll was much better than what could be achieved by passive anti-rolling tanks.

Keywords: at anchor; anti-rolling; lift-generation model; fluent simulation
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1 Introduction

With the development of ocean engineering in these years, the number of ships which work at anchor becomes larger and larger. So, the anti-rolling problem of ship at anchor is much more important. The theory of lift-generation on the traditional fin stabilizer is similar to the fixed-airfoil plane, the lift only generates when the flow of water passes the fins. There is no lift generated when the ship is adrift because the pressures between the up-surface and down-surface are the same.

Some research institutions began to study this problem in 1998, Quantum Controls of the Netherlands and Quantum marine Engineering in Florida developed the fin stabilizer system at anchor in 2002. The result showed that the anti-rolling capacity of the system was great when it worked in the flow without incoming flow velocity[1]. The domestic research and international research on the problem are both at the beginning because the lift model hasn't been built. The lift model and its characteristic under non-incoming flow condition are studied in the light of hydrodynamics theory in this paper, and simulation is done at last.

2 Lift-generation model on fin stabilizer at anchor

The incoming flow velocity is needed for the forces generated on traditional fin stabilizer. The difference of pressure between up-surface and down-surface is zero under the non-incoming flow velocity condition so that the lift can not be generated. So the mode of motion different from traditional fin stabilizer should be applied to fin stabilizer to generate enough lift to reduce ship roll at anchor. Modeling the lift generated by motion of fin stabilizer at anchor is the key to the problem[2-8].

The shape and mode of motion of fin stabilizer at anchor is shown in Fig.1. The fin stabilizers are installed zygomorphicly in ships generally. The fin shaft is extended inside the ship. The periodic lift generated depending on oscillation of the fin is used to reduce ship roll. The fin stabilizer is in steady flow when the ship is sailing. But it is in non-steady flow when the ship is at anchor so that the analysis on lift becomes more complex. Thus, the oversea research on it is mainly based on experiment, and the integral theory model hasn't been built up to now. The analytic method is used to study the lift model and the

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characteristic of fin stabilizer at anchor in this paper. The fin stabilizer is considered as a plane fin to be analyzed for simplifying the problem. Finally, the result is corrected according to tank experiment.

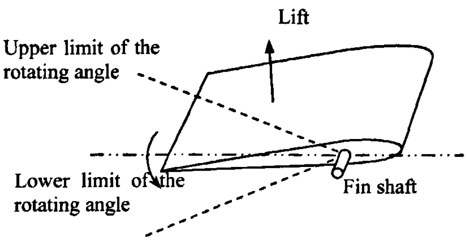

Fig.1 Motion mode of the fin stabilizer system at anchor

The water around fin stabilizer is compelled to move when the fin stabilizer pitches. The expelled water will produce the lift which is normal to the surface of fin stabilizer and is in direct proportion to tonnage per unit time. The lift rests with rotate speed of the fin, i.e. drag. The fin stabilizer is considered as a plane for analyzing this problem easily. The fin shaft is treated as origin and the body fixed system is built as Fig.2 shown.

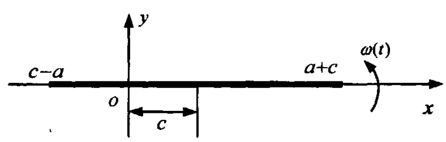

Fig.2 The fin stabilizer at the reference frame along with the fins

According to the hydrokinetics theory, when the plane moves in water, the instantaneous drag at some point on the plane can be fixed on the formula below.

$$\mathrm{d}F_1(t)=\frac{1}{2}C_d\rho v^2(t)e\mathrm{d}x, \tag{1}$$

where C_d is the coefficient of drag, and it is a nondimensional constant, which is generally measured by experiment. ρ is water density, $v(t)$ is the velocity at this point, and e is the width of the plane. Assumingly, the length of the plane is $2a$, the distance between the midpoint of the plane and the shaft is c, the angle-velocity of pitching is $\omega(t)$. The composition of forces exerting on the plane can be ensured as Eq.(2) because the directions of the forces exerting on both sides of the plane are contrary.

$$F_1(t)=\int_0^{a+c}\frac{1}{2}C_d\rho x^2\omega^2(t)e\mathrm{d}x-\int_{c-a}^{0}\frac{1}{2}C_d\rho x^2\omega^2(t)e\mathrm{d}x=$$
$$\frac{1}{3}C_d e\rho\left(3a^2c+c^3\right)\omega^2(t). \tag{2}$$

i.e. the drag is in direct proportion to the square of the instantaneous angle-velocity when the fin stabilizer pitches.

The kinetic energy of the water around the fin stabilizer can be changed continually when fin stabilizer accelerates or decelerates in the water. The counterforce exerting on the fin generated by accelerated or decelerated water is the added mass force.

It is assumed that the added mass force functions at a point where the distance is d between the fin shaft and trailing edge. So $F(t)$ can be expressed as follows.

$$F_2(t)=\frac{J}{d}\ddot{\alpha}(t)=\frac{J}{d}\dot{\omega}(t), \tag{3}$$

i.e. the added mass force is in direct proportion to the angle-acceleration when the fin stabilizer pitches.

J is the added moment of inertia of the fin stabilizer. Integrating relevant theories of hydrodynamics and dynamics, the following formula can be got:

$$J=\pi\rho\, a^2c^2+\frac{\pi}{8}\rho(a^2-b^2)^2. \tag{4}$$

According to Eqs. (2) and (3), and considering the problem about the direction of the force, the effective lift generated on fin stabilizer at anchor can be written as follows.

$$L=F_1(t)+F_2(t)=\left(k_1\omega|\omega|+k_2\dot{\omega}\right)\cos\alpha, \tag{5}$$

where k_1 , k_2 are constants, ω is pitching angle-velocity of the fin stabilizer surrounding the fin shaft, and α is the angle formed by the fin stabilizer and horizontal position.

From Eq.(5), when the angle of the fin stabilizer reaches 90° , the lift is zero, and the force on the fin completely represents thrust, so it loses the anti-rolling function. Therefore, the angle of the fin stabilizer must be restricted to some extent when the fin stabilizer works, i.e. $\alpha\le\alpha_{\max}$.

3 Simulation of lift-generation model

To validate the lift-generation model, the model will be simulated by Fluent software. The parameters used in simulation are given as follows.

Adopting NACA0015 shape of the fin, it is 1.6 m× 2.8 m, the mode of motion is represented as

$$\theta = a\sin(\frac{\pi}{4}t + \frac{\pi}{2}),$$

so the instantaneous angle-velocity can be attained as

$$\dot{\theta} = \frac{a\pi}{4}\cos(\frac{\pi}{4}t + \frac{\pi}{2}),$$

the instantaneous angle-acceleration is represented as

$$\ddot{\theta} = -\frac{a\pi^2}{16}\sin(\frac{\pi}{4}t + \frac{\pi}{2}),$$

where a represents the maximum angle that the fin can reach, i.e. the maximum open angle of the fin. $a=\frac{\pi}{9}$ and $a=\frac{\pi}{6}$ are respectively applied in simulation, corresponding to the maximum open angles of 20° and 30°, respectively.

The lift on fin simulated under two modes of motion is respectively shown as Figs.3 and 4. At the beginning of the fin motion, the rule of the lift generated on the fin is unstable. After some time, the rule of the change about the lift tends to stability. The situation after stable lift generating is shown as the following figures.

The same mode of motion is substituted in Eq.(5), the figures simulated in Matlab are shown as Figs.5 and 6.

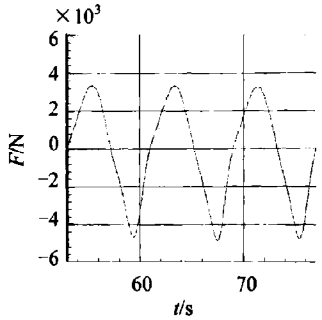

Fig.3 $\theta = \frac{\pi}{9}\sin(\frac{\pi}{4}t + \frac{\pi}{2})$

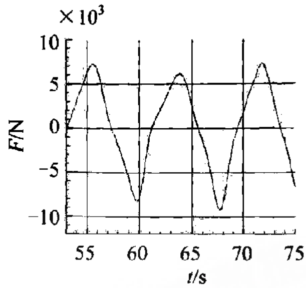

Fig.4 $\theta = \frac{\pi}{6}\sin(\frac{\pi}{4}t + \frac{\pi}{2})$

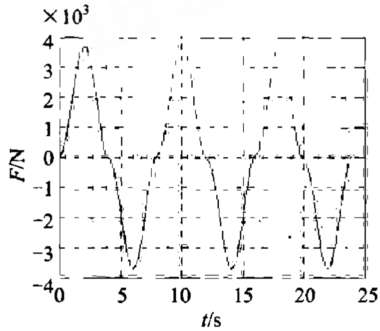

Fig.5 $\theta = \frac{\pi}{9}\sin(\frac{\pi}{4}t + \frac{\pi}{2})$

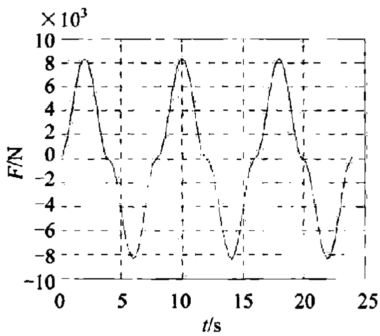

Fig.6 $\theta = \frac{\pi}{6}\sin(\frac{\pi}{4}t + \frac{\pi}{2})$

Comparing the two figures, it can be seen that the curves of the lift simulated by Fluent and calculated according to the lift model have approximate changing rule and amplitude. Therefore, it can be considered that the lift on the fin is reflected approximately by Eq.(5).

4 The simulation of ship anti-rolling at anchor

4.1 The simulation of the long crested wave

The long crested wave is simulated by ITTC double parameters stochastic wave spectrum in this paper. The ITTC double parameters wave spectrum is[9]

$$S_\zeta(\omega)=\frac{173h_{1/3}}{T_1^4\omega^5}\exp(-\frac{691}{T_1^4\omega^4}), \tag{6}$$

where $h_{1/3}$ is the wave height, T_1 is the average period of the wave.

Considering the height of one point on the wave, and neglecting the high order harmonic wave, the long crested wave can be described as

$$\zeta(t)=\sum_{i=1}^{n}\zeta_{ai}\cos(\omega_i t+\varepsilon_i). \tag{7}$$

It can be known from the wave theory that ζ_{ai} is the amplitude of the harmonic wave, initial phase ε_i is a random variable, equably distributing among $0\sim 2\pi$. As stated above, determine the frequency range for the simulation and discrete it, then calculate the spectrum $S_\zeta(\omega_1)$,..., $S_\zeta(\omega_n)$ corresponding with the discrete frequency. The relationship between the wave amplitude ζ_{ai} and spectrum is

$$\zeta_{ai}=\sqrt{2S_\zeta(\omega_i)\Delta\omega}. \tag{8}$$

After determining the wave amplitude ζ_{ai} and the initial phase ε_i of every harmonic wave, the harmonic waves can be confirmed. The long crested wave can be acquired by adding up all the harmonic waves:

$$\zeta(t)=\sum_{i=1}^{n}\sqrt{2S_\zeta(\omega_i)\Delta\omega}\cos(\omega_i t+\varepsilon_i). \tag{9}$$

Considering the angle β between the direction of wave and the ship heading:

$$\zeta(t)=(\sum_{i=1}^{n}\sqrt{2S_\zeta(\omega_i)\Delta\omega}\cos(\omega_i t+\varepsilon_i))\sin\beta. \tag{10}$$

The wave spectrum $S_\zeta(\omega)$ is replaced by $S_{\alpha\omega}(\omega)$ in the simulation of transforming the wave to the wave slope angle.

$$S_{\alpha\omega}(\omega)=\frac{\omega^4}{g^2}S_\zeta(\omega). \tag{11}$$

$S_\zeta(\omega)$ is substituted by $S_{\alpha\omega}(\omega)$ in Eq.(10).

$$\alpha_z(t)=(\sum_{i=1}^{n}\sqrt{2\frac{\omega^4}{g^2}S_\zeta(\omega_i)\Delta\omega}\cos(\omega_i t+\varepsilon_i))\sin\beta. \tag{12}$$

The simulation has been done as the above descriptions, the parameters in the simulation: wave height $h_{1/3}=2$ m, wave average period $T_1=8$ s, angle between ship and wave heading angle $\beta=90^\circ$, the simulation curves are shown in Fig.7.

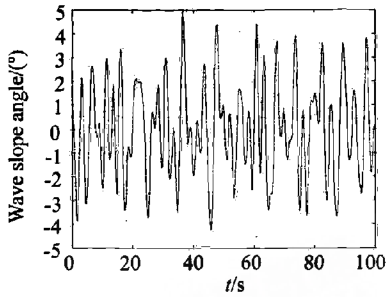

Fig.7 $h_{1/3}=2$ m $T_1=8$ s $\beta=90^\circ$

4.2 The simulation and analysis of the fin stabilizer system at anchor

The lift-model is used to simulate the ship roll at anchor by adding it to the ship roll model.

The attack angle is controlled to adjust the lift on the fin in the traditional fin stabilizer system, so the system is a typical position servo system. There is no incoming flow when the ship is at anchor. The lift on the fins is generated by the velocity and acceleration of fin oscillation. So, the system can be considered as a velocity system. The output of the controller is used to adjust the rotate speed of the fins to achieve suitable rotate speed and acceleration to produce enough force moment according to the ship roll[10].

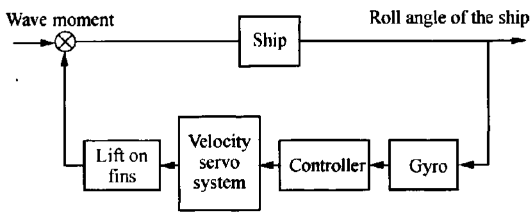

Fig.8 The block diagram of fin stabilizer system at anchor

Fig.8 shows the block diagram of the fin stabilizer system at anchor. The linear ship model in the simulation adopts the Conolly second order roll equation:

$$G_\varphi(s)=\frac{1}{T_\varphi^2 s^2+2T_\varphi n_u s+1}, \tag{13}$$

where T_φ is the natural roll period of the ship; n_u is the nondimensional roll damp of the ship.

Gyro is the measure component in the fin stabilizer system. It transforms the roll velocity to voltage signal.

$$G_a(s) = \frac{K_a s}{T_t^2 s^2 + sT_t n_t s + 1}. \quad (14)$$

The controller of the fin stabilizer system is used to adjust the rotate speed of the fin. The classical PID controller is suitable. The mathematic model is described as

$$G_c(s) = B\frac{1}{s} + D + Cs. \quad (15)$$

The velocity servo system drives the fins to rotate at the needed speed according to the output of the controller to produce the corresponding lift to antagonize the wave moment. The mathematic model of the system is approximately a one-order inertia tache.

$$G_s(s) = \frac{K_m}{T_m s + 1}. \quad (16)$$

The simulation parameters are described as follows: the wave height $h_{1/3} = 0.5$ m, 1 m, 2 m, the average wave period $T_1 = 8\,\mathrm{s}$, wave heading angle $\beta = 90^\circ$; the ship used in the simulation model: tonnage D=1100 t, ship natural roll period $T_\varphi = 8\,\mathrm{s}$, ship nondimensional roll damp coefficient $n_u = 0.145$, transverse metacentre height h=1.012 m, ship length L=69.38 m, ship width W=9.60 m, sea gauge d=3.15 m; a pair of 3.8 m^2 fins is adopted.

The anti-roll capacity of the fin stabilizer system is simulated at anchor. The results are shown in Table 1. The simulation curve under the sea condition of 1m wave height is represented at Fig.9 and Fig.10.

Table 1 Statistics of the anti-roll effect

Sea condition/m	Roll angle(without anti-roll)/ (°)	Roll angle(with anti-roll)/ (°)	Anti-roll effect/%
0.5	1.0720	0.1931	81.99
1	1.4944	0.3086	79.35
2	2.2234	0.9579	56.92

Because of the same period of the ship natural roll and the wave, the ship roll is serious even under the low sea condition. The attenuation of the ship roll is obvious after the usage of the fin stabilizer system, good anti-roll effect is achieved. The anti-roll effect can reach 80% under the sea condition of 0.5 m wave height. Along with increasing of the sea condition, the system can't afford enough energy to antagonize the wave moment because of the limitation of the system itself. Under the sea condition of 2 m sea height, the anti-roll effect decreases to 56%, but the system has a good performance under low sea condition.

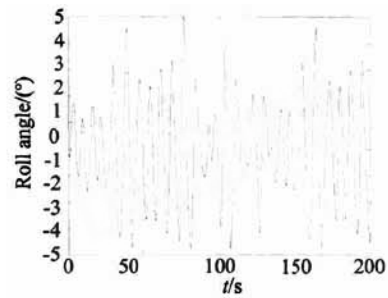

Fig.9 1m wave height, no anti-roll

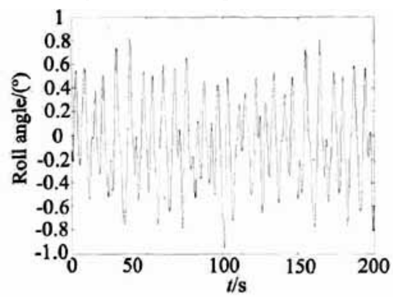

Fig.10 1 m wave height, anti-roll

5 The comparison between fin stabilizer system at anchor and passive anti-roll tank

Passive anti-roll tanks have been the only viable option to reduce the roll of an anchored ship for many years. Now, the anti-roll effects are compared between passive anti-roll tank and fin stabilizer system under the non-incoming flow velocity condition[11-12].

Figs.11~14 show the comparative results of anti-roll effects of passive anti-roll tank and fin stabilizer system under different sea conditions.

1) Passive anti-roll tank will enhance ship roll at specific frequency, it is decided by the character of passive anti-roll tank. The anti-roll result is best when the natural frequencies of anti-roll tank and ship roll equal the disturb frequency of wave. But the frequency of wave changes with the sea condition, the ship roll natural frequency will change as the loads change, yet the natural frequency of anti-roll tank is decided by its structure and will not be changed when

it is built. Thus the real frequency of anti-roll tank will not match the resonant frequency, then the anti-roll effectiveness of anti-roll tank becomes weak, even the phenomenon of increasing ship roll will come out. From Figs.11~13, it can be seen that the roll of ship with passive anti-roll tank increases when the frequency is bigger, that is bad for roll stabilization. The problem above will not appear in fin stabilizer system, the controller will control the pitch frequency of fin stabilizer when ship roll natural frequency and wave frequency change, so fin stabilizer system has the similar anti-roll result at its working frequency.

2) Fin stabilizer system requires energy to antagonize wave disturbing moment, the energy will become huge under high sea condition. When the sea condition is higher enough, the fin stabilizer system will not get enough energy to reduce ship roll, the anti-roll effectiveness will be lower than before. It can be seen from Table 1 and Figs.11~13 that fin stabilizer system has enough energy to encounter wave moment under 0.5 ~1 m sea condition, so the anti-roll result which reaches 75% is better; the fin stabilizer system has not enough energy to encounter wave moment under 2 m sea condition, so the anti-roll result decreases to 50% or so. As to passive anti-roll tank, it doesn't need energy assume, when ship is rolling, the water in anti-roll tank is also rolling to generate anti-roll moment to reduce ship roll. So the anti-roll effect of anti-roll tank is similar in a relative large-scale sea condition scope. When the anti-roll capacity of anti-roll tank doesn't exceed the designing capacity, the anti-roll effect will increase as the sea condition gets higher. The anti-roll effect comparison of fin stabilizer and passive anti-roll tank under different sea conditions is shown as Fig.14.

3) Through the comparison among Figs.11~13, the phenomenon of increasing ship roll with passive anti-roll tank fixed in ship under low sea condition becomes more serious than that under high sea condition, which will deteriorate the anti-roll effect of passive anti-roll tank under low sea condition.

Under low sea condition (less than 2 m), fin stabilizer at anchor has good performance to antagonize wave moment, and it has good anti-roll effect at different frequencies; yet the anti-roll effect of anti-roll tank is bad, even increasing the roll in high frequency range. The anti-roll effect of fin stabilizer at anchor becomes worse, because fin stabilizer system can not get enough energy to antagonize wave moment under high sea condition (more than 2 m); yet the anti-roll effect of anti-roll tank becomes better than that under low sea condition, because the anti-roll capacity of passive anti-roll tank increases with ship roll.

In a word, as to the roll stabilization problem without incoming flow, fin stabilizer system at anchor is more suitable to reduce ship roll than passive anti-roll tank under low sea condition and in offing sea area.

Where 1) is the ship roll angle without any anti-roll experiments, 2) is the ship roll angle with passive anti-roll tank in ship, 3) is the ship roll angle with fin stabilizer system in ship.

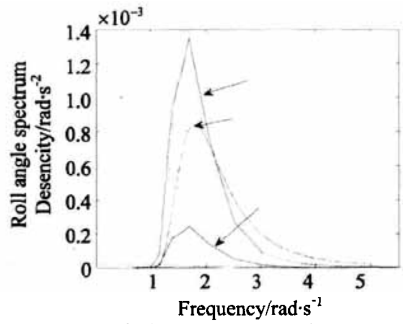

Fig.11 0.5 m wave height

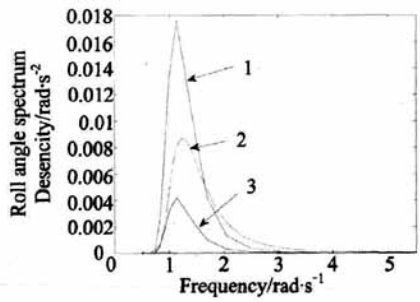

Fig.12 1 m wave height

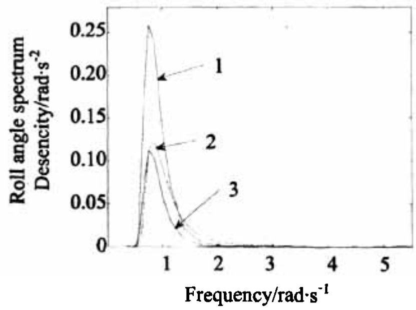

Fig.13 2 m wave height

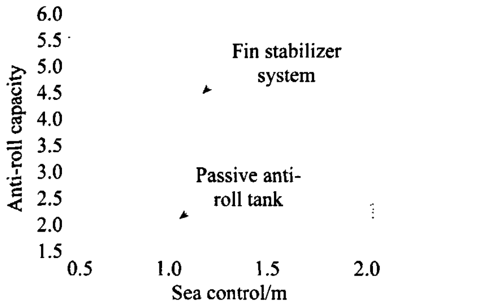

Fig.14 Comparison between fin stabilizer system at anchor and passive anti-roll tank under different sea conditions

6 Conclusions

The lift generation model is built without incoming flow to antagonize wave moment to attain ship roll stabilization at anchor. The lift model can be used to simulate lift through simulation analysis. The lift model is used to simulate ship roll under different sea conditions and good results are got. After comparing fin stabilizer at anchor with passive anti-roll tank, the fin stabilizer system at anchor is more suitable to reduce ship roll than passive anti-roll tank under low sea condition (less than 2m). And better anti-roll effect is achieved.

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