ATTITUDE CONTROL OF FOIL-CATAMARAN

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Abstracts In this paper the attitude control system is developed for longitudinal motion of Foil-Catamaran in regular waves with all-movable foils which attached to fore and after part of the ship and verified the system by theoretical calculation and model-tests. The linearized equations of motion of the ship is employed to apply the linear control theories, the PID control and the LQR. The strip method was used to calculate hydrodynamic coefficients and wave exciting forces of the demi hull, and unsteady hydrodynamic forces of foils are considered by using the result of Wu(1972). About 40~60% of motions is reduced in experiments. The control system described in this paper is able to extended to 6-DOF motions or control in irregular wave with trivial modification. And it is applicable to hull shape development for better seakeeping performance and to determine the size and the position of hydrofoils for the attitude control.

Keywords Foil-Catamaran, Attitude Control, Motion Damping System

1. INTRODUCTION

During the last years there has been a continuing interest on the use of the attitude control system on the high speed ships.

The design concept of high speed Foil-Catamaran is to reduce the resistances by lifting the ship using foils. In general, about 60~90% of ship's weight is supported by the lift of foils.

The longitudinal motions, that is heave and pitch, of Catamaran are too large due to the lack of longitudinal stability. It comes to cause severe slamming on the cross structure and uncomfortable ride. So it is necessary to develope the control system of longitudinal motion of the ship.

It is possible for Foil-Catamaran to design an attitude control system, or motion damping system, using equipped foils or flaps. In this paper the attitude control system for the longitudinal motions of a Foil-Catamaran in regular waves, is developed. Two all-movable foils, attached to fore and after part of the ship, are used to control. The control system is verified by frequency domain analysis in theoretical calculation and by experiments in real time.

In the first place, the well-posed equations of motion are to be established including the unsteady hydrodynamic forces of foils. The foils, used for control in Foil-Catamaran, are subject to unsteady hydrodynamic forces due to water waves, ship motions, control outputs and so on. The theoretical modeling by Wu[4] for 2-D unsteady lifting problem, which is verified by experiments of Watanabe & Ishida[3], is used to facilitate to formulate the unsteady problem of the foils in this paper. The linear state space model is constructed from the equations of the motion and PID control and LQR are used to obtain control gains.

2. THE EQUATIONS OF LONGITUDINAL MOTION OF FOIL-CATAMARAN

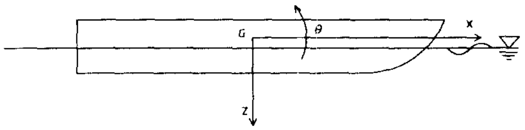

Fig.1 The coordinate system

The inertial coordinate system is described in Fig.1. The coordinate system of which origin is located at the center of gravity (G) of the ship is employed.

Supposing that the rotational motion of the ship is centering around G and the linear superposition is admissible, the equations of the motion of Foil-Catamaran is obtaied by incorporating hydrodynamic forces due to foils as follows.

$$\begin{aligned}(m &+a_{33})\dot{w}+b_{33}w+c_{33}z+a_{35}\ddot{\theta}+b_{35}\dot{\theta}+c_{35}\theta=F_F+F_H,\\ (I_{55} &+a_{55})\ddot{\theta}+b_{55}\dot{\theta}+c_{55}\theta+a_{53}\dot{w}+b_{53}w+c_{53}z=M_F+M_H,\end{aligned}\qquad(1)$$

where,

m : mass of the ship,
I_{55} : longitudinal Mass moment of inertia,
a : added mass or added mass moment of inertia,
b : damping coefficients,

c : restoring coefficients,
F_F : the forces due to foils,
M_F : the moments due to foils,
F_H : the wave exiting forces,
M_H : the wave exiting moments.

Subscripts 3 and 5 denote mode of heave and pitch respectively. Hydrodynamic coefficients a, b, and wave exiting forces and moments F_H, M_H can be obtained by solving the boundary value problems in ship hydrodynamics.

Under the assumption that drag components of the foils is negligible, the forces and moments due to the foils can be expressed considering only lift components of the foils as follows.

$$\begin{aligned} F_F &= f_a + f_f, \\ M_F &= -x_a f_a - x_f f_f, \end{aligned} \tag{2}$$

where,

f_f : lift of the after foil,
f_f : lift of the fore foil,
x_a : moment arm of the after foil,
x_f : moment arm of the fore foil.

3. STATE SPACE MODEL AND CONTROLLER DESIGN

3.1 State Space Model

The state vector and input vector are defined as follows.

$$\begin{aligned} \underline{x} &= [x_1\ x_2\ x_3\ x_4\ ]', \\ \underline{u} &= [\,u_1\ u_2\ ]', \end{aligned}$$

where,

$$\begin{aligned} &x_1 = w = \dot{z},\ x_2 = \dot{\theta},\ x_3 = z,\ x_4 = \theta, \\ &u_1 = \alpha_{ia},\ u_2 = \alpha_{\mathrm{if}}\,. \end{aligned}$$

And the system is reduced as follows.

$$M\dot{\underline{x}} = A^{\dagger}\ \underline{x} + B^{\dagger}\ \underline{u} + \Gamma^{\dagger}\ , \tag{3}$$

where,

$$M = \begin{bmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad A^{\dagger} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

$$B^{\dagger} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \qquad \Gamma^{\dagger} = \begin{bmatrix} c_{11} \\ c_{21} \\ 0 \\ 0 \end{bmatrix}.$$

$\Gamma^{\dagger}$, which is the wave exited forces, is modeled as disturbances in the state space model.

Let $A = M^{-1}A^{\dagger}$, $B = M^{-1}B^{\dagger}$, and $\Gamma = M^{-1}\Gamma^{\dagger}$, equation (3) is then rewritten as

$$\dot{\underline{x}} = A\underline{x} + B\underline{u} + \Gamma. \tag{4}$$

The output of the system is the same to the state, and the state feedback control system will be considered hereafter.

3.2 Controller Design

PID control and LQR were used to obtain control gains. When using PID control, coupled terms in equation(1) are dropped out and heave and pitch modes are decoupled.

A process, represented by the system equation, whatever its nature, is subject to an environmental change, ignorance of exact values of the process parameters, and other natural factors that affect a control system. So it is necessary to take care when the control system in theory is applied to the real system. It is appropriate that PID control, which accomplishes gain tuning easily in experiments, is adopted before the calculated gain by LQR is used.

The aim of the attitude control system in this case is not to track the desirable attitude or courses but to reduce the motion amplitude of the ship. So integral term in PID is not considered and PD controller is constructed. Proportional gain is set to make possible to reduce the displacement to the some degree, and derivative gain is to reduce the system into critical damping in theoretical calculations. Because lift of the foil is proportional to the square of induced velocity, the gain scheduled inversely proportional to the square of the ship speed in PID control.

An infinite horizon performance index of LQR can be described as follows for steady state feedback control.

$$J = \frac{1}{2}\int_0^{\infty} (\ \underline{x}^T Q \underline{x} + \ \underline{u}^T R \underline{u}) dt. \tag{5}$$

The control gain in this case can be obtained by solving ARE. Weighting matrix Q and R is designed in the control system to provide suitable performance.

4. MODEL TESTS

Experiments are indispensable to verify effects of the control system. The exactness of the system modelling can be verified and effects of the control system can be confirmed by virtue of model tests.

4.1 Test Devices and Conditions

The signal flow of the attitude control is illustrated in Fig.2.

Principal particulars of the model ship and the foil are shown in Table 1 and Table 2 respectively. Model ship is constructed by two separated bodies which are obtained by cutting a typical monohull ship in longitudinal direction. Body plan of the model ship is illustrated in Fig. 3.

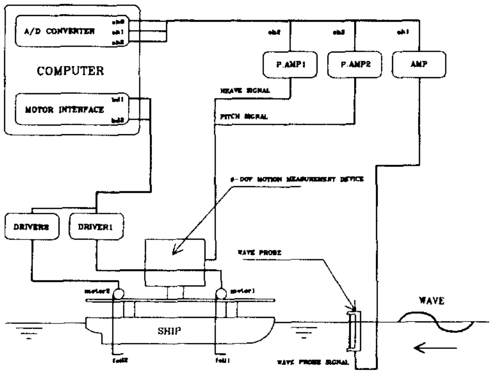

Fig.2 The setting of experimental devices

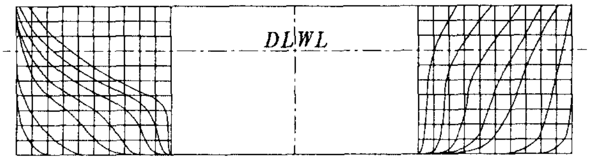

Fig.3 The body plan of the model ship

Table 1 Principal particulars of the model ship

Description	Particular
L. B. P.	1.00m
Breadth	0.10m
Depth	0.10m
Draft	0.07m
∇	0.009583m^3
LCB	-0.02m

Table 2 Principal particulars of foils and struts

Foil	Sect.	NACA0015
	Plan.	Rect.
	Chord	0.03m
	Span	0.15m
Strut	Plan.	Rect.
	Bread.	0.02m
	Thick	0.005m

Table 3 Test conditions for constant wave (λ/Lpp = 2)

Vel.(m/s)	1	1.5	1.8
Fn	0.319	0.479	0.638
$\omega_e(ND)$	2.775	3.276	3.579

Table 4 Test conditions for constant velocity (velocity = 1.8 m/s)

λ/Lpp	2	4	6
$\omega_e(ND)$	3.579	4.310	4.885

$$* \ \omega_e(ND) = \frac{\omega_e}{\sqrt{g/L_{PP}}}$$

Test conditions are shown in Table 3 and Table 4. The model ship is towed with constant speeds in regular waves. As the goal of model tests is to validate the control system mainly, test conditions are dedicated in moderate range of speed and wave height.

4.2 Data Reconstruction

Careful examination is required of signal processing in model tests unlike prototype system, because disturbances or noises in model tests stands out conspicuously in comparison to motion data due to the small scales of the model size. A sufficiently high sampling frequency is desirable in sampled-data control system.

In this paper the zero-order holder is used for the data sampling. Low-pass filter is used to remove high frequency noises. Measured state variables are heave and pitch displacements. Derivatives of them are obtained by the Pseudo differential.

5. RESULTS AND DISCUSSION

In Fig.4~Fig.7 RAO by theoretical calculationjs are plotted in a frequency domain. Control gain, obtained by LQR, was used in this calculation. The effect of the controller has come out clear. The faster the ship advances, the more significant the effect of control shows, as the effect of the foil increases according as the induced velocity. As uncontrolled system also decreases the motion, so the effect of a passive fin are perceived. Waves in low frequencies have long wave length and high amplitude. It is impossible for the control system to control the ship motion in this waves. In high frequencies the ship motion is very small, so the control system is of no avail.

In Fig.8~Fig.15 experimental results are plotted for the case that the wave length is double of the the ship length and the ship velocity is 1.8m/s. About 40~60% of motions are reduced in experiments.

In Fig.16 the comparisons between theoretical calculation and experimental results are plotted. Experimental results are somewhat mismatched with the theoretical calculation. It would come from the assumption of wave steepness to be 1/100 in theoretical calculation or captivity of surge in experiments and so on.

6. CONCLUSION

In this paper the attitude control system for longitudinal motion of Foil-Catamaran is developed and verified by theoretical calculations and model tests. From the results, good performance of the control system is confirmed.

In model tests the control system could not give a full play to its ability. Because velocities of heave and pitch obtained by the Pseudo differential were not accurate owing to noises in displacement signals. But

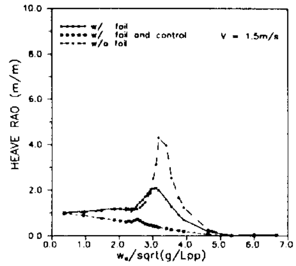

Fig.4 Heave RAO

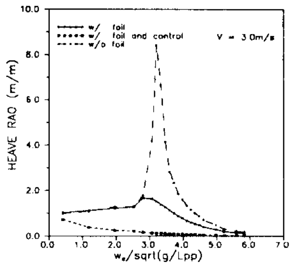

Fig.5 Heave RAO

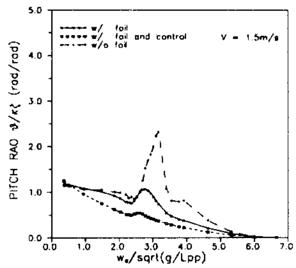

Fig.6 Pitch RAO

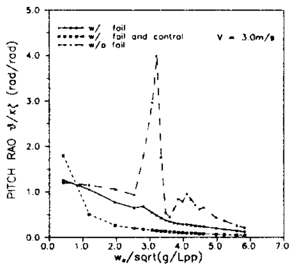

Fig.7 Pitch RAO

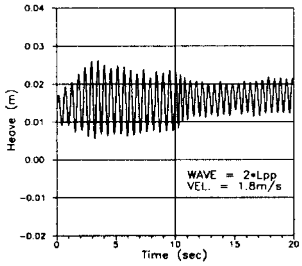

Fig.8 Heave motion with and without PID control.

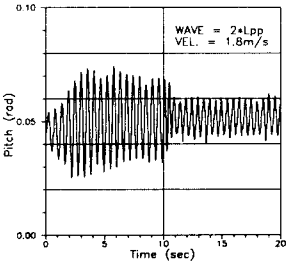

Fig.9 Pitch motion with and without PID control

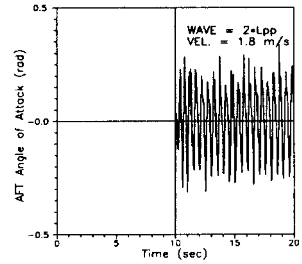

Fig.10 After foil control angle by PID control

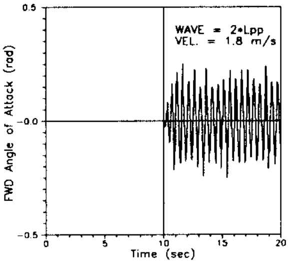

Fig.11 Fore foil control angle by PID control

because, in case of a prototype ship, the magnitude of motions are larger than them of the model, the influence of noises becomes little. In addition, the restriction owing to small time scale are relaxed in prototype ship. Therefore the control system, developed in this paper, will perform its duty excellently in prototype ship.

It will be extended to the more DOF system without difficulties if it is necessary. In future, variations of resistances of the ship due to the control system and the machinery system for the control system in a prototype ship should be investigated also.

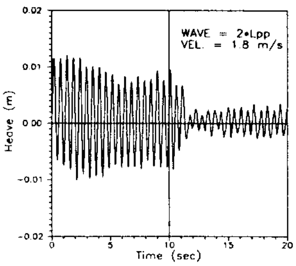

Fig.12 Heave motion with and without optimal control

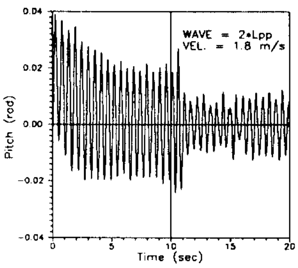

Fig.13 Pitch motion with and without optimal control

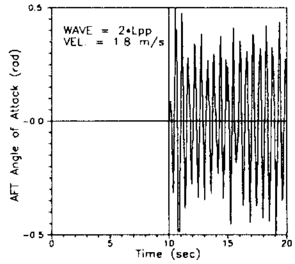

Fig.14 After foil control angle by optimal control

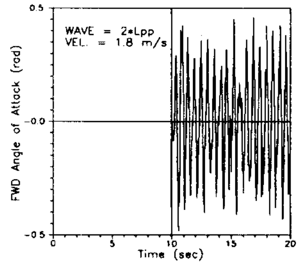

Fig.15 Fore foil control angle by optimal control

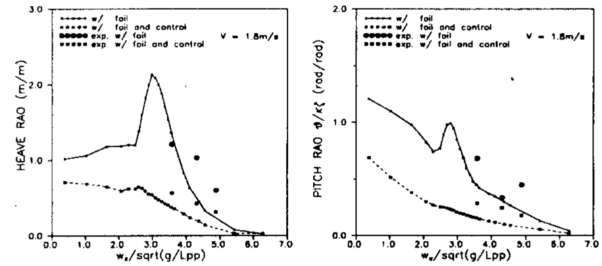

Fig. 16 Comparisons between Calculations and Experimental data

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