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A Method of a Trimaran Vertical Movements Reduction Control and Hardware Realization

BOWEN ZENG[1], YANG SONG[2], AND LINHE ZHENG[1]

[1]College of Automation, Harbin Engineering University, Harbin 150001, China

[2]Engineering Training Center, Harbin Engineering University, Harbin 150001, China

Corresponding author: Bowen Zeng (zengbowen@hrbeu.edu.cn)

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ABSTRACT The vertical movements of a trimaran, which can produce a vertical acceleration, always make people feel seasickness and cause equipment damage on the board. This paper presents a method of a trimaran vertical stabilization control. First, the trimaran mathematical equation is obtained by the numerical simulation and verified by the trimaran experiment in the water tank. Then, the vertical stabilization appendages, including T-foil and flap, are designed and installed at the bottom of the trimaran. Second, an active controller of the appendages is designed and a decoupling method is applied to decouple T-foil and flap, the attack angles of T-foil and flap are obtained in real-time, and the mathematical simulation verified the effect of the decoupling method. Finally, every hardware parts are selected and composed, then, the hardware of the control system is realized and installed on the trimaran, in water tank experiment, the controller was verified in water tank experiment and the experiment results show that it has a good vertical stabilization effect for the trimaran.

INDEX TERMS Trimaran stabilization control, decouple, T-foil and flap, hardware system.

I. INTRODUCTION

With the development of the naval technology, the traditional mono-hulls have been unable to meet people's requirement in some cases, and then the multi-hulls emerging. The trimaran studied in this paper is a kind of multi-hull, it has a wide deck, high speed and excellent seakeeping [1]. However, due to the wave force and moment, the trimaran can produce vertical movements which include heave and pitch motions, and the vertical acceleration caused by heave and pitch motions may lead the crew feel sickness and damage to the equipment on board [2]. For the ship vertical stabilization control, the appendages are often installed on the ship, [3]–[6] investigate a ship installed T-foil and flap with different active control algorithm, and the results show that the effect of appendages with active control are very useful. The authors of [7] developed a trimaran model installed T-foil, the results show that in the condition of fixed T-foil installation, the passive T-foil and active controlled T-foil can reduce the vertical movements by about 20% and 40%. In [8], active fins are used for a ship heave and pitch reduction, and verified the effect by numerical simulation and experiment.

Compared with the passive appendages, the active controlled appendages are more and more popular, and many control algorithms are used for ship stabilization control. In the university of Madrid, Spain, S. Esteban, J.M. Giron-Sierra and other scholars designed the conventional PID controller for high-speed ships. With the controller and actuator, the seasickness rate decreased from 47.67% to 12.86% in the sea condition SSN5 and 40 knots, which achieved a good stabilization effect, but the saturation rate of attack angle of the T-foil was not considered [9]. [10] designed the predictive controller and compared the control result with PID controller. Compared with PID controller, the worst acceleration (WVA) was only increased by 1.47%, but the mechanical vibration of the actuator decreased by 73.66%. Multivariable classic control was used to decrease the MSI (Motion Seasickness Index) of a high speed ferry [11]. A robust controller is designed for high speed, this is the first time in a high speed ship robust controller is used to reduce the pitch, in SSN4, 40 knots,

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FIGURE 1. The trimaran sailing in calm water and the trimaran geometry model.

relative to the PD controller, MSI was reduced by 0.4%, in SSN5, 40 knots, relative to the PD controller, MSI has increased by 19.8%, obviously robust controller effect is not good [12]. In [13], a fuzzy PD control is designed and carried out a real ship experiment. This was the first time that fuzzy controller used for vertical stabilization on a high-speed ship. At the speed of SSN5 and 40 knots, compared with no controller, WVA decreased by 41.09% to 5.832%. MSI dropped 56.14% to 12.0813%, verified the effectiveness of the advanced algorithm and could be used in a real marine environment. Sliding mode control [14] and model predictive control [15] are also used in the research of ship motion stabilization. Reference [16] used a linear quadratic regulator for wave piercing catamarans motion control, and reference [17] developed an intelligent control based on PSO (Particle swarm optimization) for a ship roll motion. The authors of [18] presented an adaptive robust fin controller based on a feedforward neural network. These advanced methods have excellent results in simulation, however, these algorithms perform poorly in actual engineering. The decoupling PD control presented in [4] was successfully applied to solve actual engineering problem.

The paper is organized as follows. Section 2 presents the trimaran mathematical model, including the trimaran heave and pitch motions. Section 3 gives the appendages and the installation position. In section 4, the details of the appendages decoupling and controller design are presented. In section 5, the trimaran hardware realization and experimental are presented and reported. Finally, section 6 concludes the present work.

II. PROBLEM STATEMENT

For more convenience to studied the trimaran in this paper, the trimaran is transformed to a trimaran geometry model and is shown in FIGURE.1 and the trimaran parameters are listed in Table 1.

Affected by wind, wave and current, the trimaran will produce vertical movements when sailing in marine. The vertical movements of a trimaran cause deck damage, passenger seasickness and damage to equipment on board. Therefore, it is necessary to restrain the vertical movements of a trimaran. To suppress the vertical movements of a trimaran, the common method is installing appendages. In order to study the

TABLE 1. Trimaran Parameters.

Name	Main hull	Side hulls
Length overall (m)	6.800	2.354
Beam (m)	1.351	0.131
Draught (m)	0.249	0.087
Depth (m)	0.517	0.362
Mass (kg)	509.608	------

problem of vertical stabilization, the mathematical model of the trimaran is established as follows [7]:

$$\begin{aligned}(m+a_{33})\ddot{x}_3+b_{33}\dot{x}_3+c_{33}x_3+a_{35}\ddot{x}_5+b_{35}\dot{x}_5+c_{35}x_5=F_3\\(I_{yy}+a_{55})\ddot{x}_5+b_{55}\dot{x}_5+c_{55}x_5+a_{53}\ddot{x}_3+b_{53}\dot{x}_3+c_{53}x_3=M_5\end{aligned} \tag{1}$$

where m is the trimaran mass, I is the longitudinal inertia of trimaran, x_3 is the trimaran heave, x_5 is the pitch, a_{ij} is the added mass, b_{ij} is the damping coefficients, c_{ij} is the restoring force and moment coefficients. F_3 is the wave force, M_5 is the wave moment.

Deforming Eq. (1) to state space equation like the following formula:

$$\begin{bmatrix}1 & 0 & 0 & 0\\0 & m+a_{33} & 0 & a_{35}\\0 & 0 & 1 & 0\\0 & a_{53} & 0 & I+a_{55}\end{bmatrix}\begin{bmatrix}\dot{x}_3\\\ddot{x}_3\\\dot{x}_5\\\ddot{x}_5\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\-c_{33} & -b_{33} & -c_{35} & -b_{35}\\0 & 0 & 0 & 1\\-c_{53} & -b_{53} & -c_{55} & -b_{55}\end{bmatrix}\begin{bmatrix}x_3\\\dot{x}_3\\x_5\\\dot{x}_5\end{bmatrix} + \begin{bmatrix}0 & 0\\1 & 0\\0 & 0\\0 & 1\end{bmatrix}\begin{bmatrix}F\\M\end{bmatrix} \tag{2}$$

Define:

$$T=\begin{bmatrix}1 & 0 & 0 & 0\\0 & m+a_{33} & 0 & a_{35}\\0 & 0 & 1 & 0\\0 & a_{53} & 0 & I+a_{55}\end{bmatrix}$$

$$A_1=\begin{bmatrix}0 & 1 & 0 & 0\\-c_{33} & -b_{33} & -c_{35} & -b_{35}\\0 & 0 & 0 & 1\\-c_{53} & -b_{53} & -c_{55} & -b_{55}\end{bmatrix}$$

$$B_1=\begin{bmatrix}0 & 1 & 0 & 0\\0 & 0 & 0 & 1\end{bmatrix}^T A=T^{-1}A_1,$$

$$B=T^{-1}B_1 C=\begin{bmatrix}1 & 0 & 0 & 0\\0 & 0 & 1 & 0\end{bmatrix}$$

Then, the trimaran motion equation is as follows:

$$\begin{cases}\dot{x}=Ax+Bu\\y=Cx\end{cases} \tag{3}$$

TABLE 2. **The Hydrodynamic Coefficients of 18 Knots and 40 Knots of the Trimaran.**

Parameters	Value(40kn)	Value(18kn)
a_{33}	421.7149	850.5934
a_{35}	-89764.44	-35566.82
a_{53}	379.6439	1106.628
a_{55}	-4335.054	-523.8116
b_{33}	3448.1	2702.697
b_{35}	5618.124	5436.334
b_{53}	171.9148	39.88711
b_{55}	13595.55	13579.53
c_{33}	34270.0256	34270.0256
c_{35}	4816.5574	4816.5574
c_{53}	4816.5574	4816.5574
c_{55}	100090.7347	100090.7347

Taken the condition of 40 knots speed as ab example, the added mass coefficients, damping coefficients and restoring force coefficients at the encounter frequency of 0.5rad/s is shown in the following Table 2.

According to the above parameters, the trimaran equation at 40 knots can be obtained as follows:

$$
\begin{aligned}
Fh2H(s) &= \frac{0.0011s^2+0.0028s+0.0323}{s^4+5.2766s^3+74.2763s^2+166.5089s+1099} \\
Mp2H(s) &= \frac{-0.00001714s^2-0.0018s-0.0016}{s^4+5.2766s^3+74.2763s^2+166.5089s+1099} \\
Fh2P(s) &= \frac{0.0001255s^2+0.000094073s+0.0323}{s^4+5.2766s^3+74.2763s^2+166.5089s+1099} \\
Mp2P(s) &= \frac{0.00029415s^2+0.00077085s-0.0111}{s^4+5.2766s^3+74.2763s^2+166.5089s+1099}
\end{aligned}
\tag{4}
$$

III. ACTUATOR

The actuator selected in this paper is T-foil and flap, and the lift force and moment generated by T-foil and flap are used to inhibit the wave force and moment. The design size of T-foil and flap are shown in FIGURE. 2.

For the installation of T-foil, generally speaking, the flap is installed at the stern and the T-foil is installed at the bow of the trimaran. However, in order to ensure the T-foil does not out of the water when the trimaran sail, it is important to choose an appropriate installation position.

Taken all considerations into account, it can be concluded that the installation position of T-foil is 420 mm from the center line of pillar to the bow (20 stations), and 61mm from the horizontal wing section string line to the trimaran baseline. The installation position is shown in FIGURE. 3.

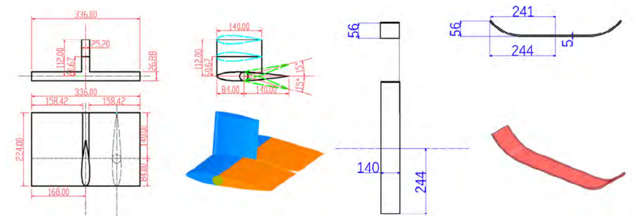

FIGURE 2. **The size of T-foil and flap.**

FIGURE 3. **The installation of T-foil and flap on the trimaran.**

TABLE 3. **T-foil and flap force under different attack angle.**

T-foil attack angle(deg)	T-foil lift force(N)	Flap attack angle(deg)	Flap lift force(N)
-15°	-772.05	-7.5°	-492.559
-10°	-460.65	-5°	-374.779
-5°	-211.28	-2.5°	-201.945
5°	267.65	2.5°	202.450
10°	532.11	5°	454.187
15°	847.06	7.5°	679.189

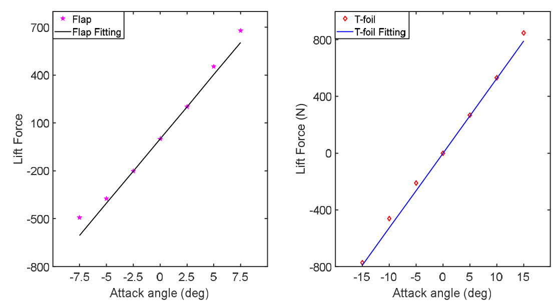

FIGURE 4. **The force of T-foil and flap, and the polynomial fitting.**

In order to design the controller for the actuator, first, the lift force of the T-foil and flap provided must be obtained. Taken the speed of 40 knots as an example, and calculating the lift force of the T-foil and flap at different attack angles, Table 3 shows the calculation results.

By fitting the above points at different attack angles, the slope of T-foil and Flap at 40 knots can be obtained. The fitting curve is shown in FIGURE .4.

The slope of T-foil and flap at 40 knots are 53.8 and 80.6 respectively by fitting above.

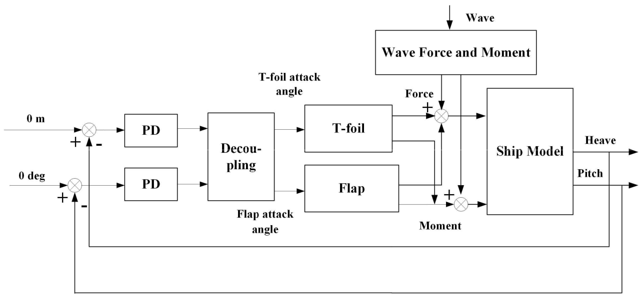

FIGURE 5. The control system of the trimaran.

IV. CONTROL SYSTEM

A. DECOUPLING ANSLYSIS

The vertical movements include heave and pitch motions, the direction of the heave is upward or downward, and the pitch motions are divided into two parts, one is the bow of the trimaran upward with the stern of the trimaran downward and the other is opposite. For heave motions, when the trimaran upward, the T-foil and flap are provided the downward force together, however, for pitch motions, the force direction provided by T-foil and flap are opposite. Therefore, using the T-foil and flap for the trimaran vertical stabilization, the attack angle of T-foil and flap must be decoupling. The trimaran control system with decoupling is expressed in FIGURE.5.

Both the T-foil and the Flap can generate force and moment, an unreasonable control strategy will not only reduce the vertical movements, but may lead to the intensified vertical movements of the trimaran. Therefore, in order to design a reasonable control strategy, it is necessary to decouple the T-foil and flap. The decoupling process is described as follows:

Lift force and moment generated by T-foil and flap can be expressed as follows [19]:

$$\begin{aligned} F_{T-foil} &= \frac{1}{2}\rho A U^2 C_L(\theta_1)\theta_1 = k_1\theta_1 \\ M_{T-foil} &= F_{T-foil}x_1 = k_1 x_1 \theta_1 \end{aligned} \tag{5}$$

$$\begin{aligned} F_{flap} &= k_2\theta_2 \\ M_{flap} &= F_{flap}x_2 = k_2 x_2 \theta_2 \end{aligned} \tag{6}$$

where k_1, k_2 are the relationship between the lift force and the attack angle of the T-foil and flap,x_1, x_2 are the distance of T-foil and flap to the center of gravity.

For the trimaran mathematical model, the force to heave transfer function is G_{FH}, the moment to heave transfer function is G_{MH},.the force to pitch transfer function is G_{FP} and the moment to pitch transfer function is G_{MP}. Then the heave and pitch generated by the attack angle of the T-foil are given by:

$$\begin{aligned} H_1 &= k_1 G_{FH}\theta_1 + k_1 x_1 G_{MH}\theta_1 = (k_1 G_{FH} + k_1 x_1 G_{MH})\,\theta_1 \\ P_1 &= k_1 G_{FP}\theta_1 + k_1 x_1 G_{MP}\theta_1 = (k_1 G_{FP} + k_1 x_1 G_{MP})\,\theta_1 \end{aligned} \tag{7}$$

The heave and pitch generated by the attack angle of the flap are given by:

$$\begin{aligned} H_2 &= k_2 G_{FH}\theta_2 + k_2 x_2 G_{MH}\theta_2 = (k_2 G_{FH} + k_2 x_2 G_{MH})\,\theta_2 \\ P_2 &= k_2 G_{FP}\theta_2 + k_2 x_2 G_{MP}\theta_2 = (k_2 G_{FP} + k_2 x_2 G_{MP})\,\theta_2 \end{aligned} \tag{8}$$

Therefore, the total heave and pitch can be superimposed by the heave generated by the T-foil and flap, as shown:

$$\begin{aligned} H &= H_1 + H_2 \\ P &= P_1 + P_2 \end{aligned} \tag{9}$$

Transferring Eq. (9) into matrix and combine it with Eq. (7) and (8), and Eq. (10) is obtained:

$$\begin{pmatrix} k_2 G_{FH} + k_2 x_2 G_{MH} & k_1 G_{FH} + k_1 x_1 G_{MH} \\ k_2 G_{FP} + k_2 x_2 G_{MP} & k_1 G_{FP} + k_1 x_1 G_{MP} \end{pmatrix} \begin{pmatrix} \theta_2 \\ \theta_1 \end{pmatrix} = \begin{pmatrix} H \\ P \end{pmatrix} \tag{10}$$

When we design the attack angle of the T-foil by pitch motion, the effect of the pitch generated by flap should be eliminated through the decoupling process, Similarly, when the attack angle of the flap is designed by heave, the effect of the T-foil should be eliminated. Defining the output of the pitch controller named u_1 to control the T-foil, and the output of the heave controller named u_2 to control the flap. The form of the decoupling filter is [4]:

$$W = \begin{pmatrix} 1 & w_2 \\ w_3 & 1 \end{pmatrix} \tag{11}$$

And the relationship of output attack angle and the controller output is shown in Eq. (12)

$$\begin{pmatrix} 1 & w_2 \\ w_3 & 1 \end{pmatrix} \begin{pmatrix} u_2 \\ u_1 \end{pmatrix} = \begin{pmatrix} u_2 + w_2 u_1 \\ u_1 + w_3 u_2 \end{pmatrix} = \begin{pmatrix} \theta_2 \\ \theta_1 \end{pmatrix} \tag{12}$$

Then, expending Eq. (12), Eq. (13) can be obtained:

$$\begin{aligned} &\begin{pmatrix} k_2 G_{FH} + k_2 x_2 G_{MH} & k_1 G_{FH} + k_1 x_1 G_{MH} \\ k_2 G_{FP} + k_2 x_2 G_{MP} & k_1 G_{FP} + k_1 x_1 G_{MP} \end{pmatrix} \begin{pmatrix} \theta_2 \\ \theta_1 \end{pmatrix} \\ &= \begin{pmatrix} k_2 G_{FH} + k_2 x_2 G_{MH} & k_1 G_{FH} + k_1 x_1 G_{MH} \\ k_2 G_{FP} + k_2 x_2 G_{MP} & k_1 G_{FP} + k_1 x_1 G_{MP} \end{pmatrix} \\ &\times \begin{pmatrix} u_2 + w_2 u_1 \\ u_1 + w_3 u_2 \end{pmatrix} = \begin{pmatrix} H \\ P \end{pmatrix} \end{aligned} \tag{13}$$

where

$$\begin{aligned} G_{11} &= k_2 G_{FH} + k_2 x_2 G_{MH} \\ G_{12} &= k_1 G_{FH} + k_1 x_1 G_{MH} \\ G_{21} &= k_2 G_{FP} + k_2 x_2 G_{MP} \\ G_{21} &= k_2 G_{FP} + k_2 x_2 G_{MP} \end{aligned}$$

The heave motion is only related to the flap, the pitch motion is only related to the T-foil. Therefore, the heave H is only related with u_2, and the coefficient of u_1 is 0, the w_2 is shown as follows:

$$\begin{aligned} w_2 &= -(k_1 G_{FH} + k_1 x_1 G_{MH})/(k_2 G_{FH} + k_2 x_2 G_{MH}) \\ &= -G_{12}/G_{11} \end{aligned} \tag{14}$$

Similarly, w_3 is shown as follows:

$$\begin{aligned} w_3 &= -(k_2G_{FP} + k_2x_2G_{MP})/(k_1G_{FP} + k_1x_1G_{MP}) \\ &= -G_{21}/G_{22} \end{aligned} \tag{15}$$

The heave and pitch motions is given by:

$$\begin{aligned} H &= [(k_2G_{FH} + k_2x_2G_{MH}) - \frac{k_2G_{FP} + k_2x_2G_{MP}}{k_1G_{FP} + k_1x_1G_{MP}} \\ &\quad \times (k_1G_{FH} + k_1x_1G_{MH})]u_2 \\ P &= [(k_1G_{FP} + k_1x_1G_{MP}) - \frac{k_1G_{FH} + k_1x_1G_{MH}}{k_2G_{FH} + k_2x_2G_{MH}} \\ &\quad \times (k_2G_{FP} + k_2x_2G_{MP})]u_1 \end{aligned} \tag{16}$$

And the decoupling filter can be expressed as follows:

$$W = \begin{pmatrix} 1 & -\dfrac{k_1G_{FH}+k_1x_1G_{MH}}{k_2G_{FH}+k_2x_2G_{MH}} \\ -\dfrac{k_2G_{FP}+k_2x_2G_{MP}}{k_1G_{FP}+k_1x_1G_{MP}} & 1 \end{pmatrix} \tag{17}$$

For convenience, w_2, w_3 are expressed as:

$$\begin{aligned} w_2 &= (a_{m1}s^2 + a_{m2}s + a_{m3})/(b_{m1}s^2 + b_{m2}s + b_{m3}) \\ w_3 &= (a_{n1}s^2 + a_{n2}s + a_{n3})/(b_{n1}s^2 + b_{n2}s + b_{n3}) \end{aligned} \tag{18}$$

Assuming e_H is the loop deviation of heave, C_1, U_1 are the input and output before and after the decoupling link of heave loop, e_P is the deviation of pitch loop, C_2, U_2 are the input and output before and after the decoupling link of the pitch loop, then the controller is designed as follows:

$$\begin{aligned} U_1(k) &= K_{HP}e_H(k) + K_{HD}(e_H(k) - e_H(k-1)) \\ U_2(k) &= K_{PP}e_P(k) + K_{PD}(e_P(k) - e_P(k-1)) \end{aligned} \tag{19}$$

For w_2, it can be rewritten as:

$$\begin{aligned} w_2 &= (a_1s^2 + a_2s + a_3)/(b_1s^2 + b_2s + b_3) \\ &= (C_1 - U_1)/U_2 \end{aligned} \tag{20}$$

Substituting $k_1 = 53.8$, $k_2 = 80.6$, $x_1 = 3.63$ and $x_2 = 80.6$ into Eq. (20), the sampling time is $T = 0.08$, the above equation is rewritten as a difference equation:

$$\begin{aligned} C_1(k) &= \frac{a_{m1}/T^2 + a_{m2}/T + a_{m3}}{b_{m1}/T^2 + b_{m2}/T + b_{m3}}U_2(k) \\ &\quad - \frac{2a_{m1}/T^2 + a_{m2}/T}{b_{m1}/T^2 + b_{m2}/T + b_{m3}}U_2(k-1) \\ &\quad + \frac{a_{m1}/T^2}{b_{m1}/T^2 + b_{m2}/T + b_{m3}}U_2(k-2) + U_1(k) \\ &\quad - \frac{2b_{m1}/T^2 + b_{m2}/T}{b_{m1}/T^2 + b_{m2}/T + b_{m3}}U_1(k-1) \\ &\quad + \frac{b_{m1}/T^2}{b_{m1}/T^2 + b_{m2}/T + b_{m3}}U_1(k-2) \\ &\quad + \frac{2b_{m1}/T^2 + b_{m2}/T}{b_{m1}/T^2 + b_{m2}/T + b_{m3}}C_1(k-1) \\ &\quad - \frac{b_{m1}/T^2}{b_{m1}/T^2 + b_{m2}/T + b_{m3}}C_1(k-2) \end{aligned} \tag{21}$$

where

$$\begin{aligned} a_{m1} &= -0.0011k_1 + 0.00001714k_1x_1 \\ a_{m2} &= -0.0028k_1 + 0.0018k_1x_1 \\ a_{m3} &= -0.0323k_1 + 0.0016k_1x_1 \\ b_{m1} &= 0.0011k_2 - 0.00001714k_2x_2 \\ b_{m2} &= 0.0028k_2 - 0.0018k_2x_2 \\ b_{m3} &= 0.0323k_2 - 0.0016k_2x_2 \end{aligned}$$

For w_3, it can be rewritten as:

$$w_3 = \frac{a_1s^2 + a_2s + a_3}{b_1s^2 + b_2s + b_3} = \frac{C_2 - U_2}{U_1} \tag{22}$$

Take the sampling time $T = 0.08$, simplify the above equation and write it as a difference equation:

$$\begin{aligned} C_2(k) &= \frac{a_{n1}/T^2 + a_{n2}/T + a_{n3}}{b_{n1}/T^2 + b_{n2}/T + b_{n3}}U_1(k) \\ &\quad - \frac{2a_{n1}/T^2 + a_{n2}/T}{b_{n1}/T^2 + b_{n2}/T + b_{n3}}U_1(k-1) \\ &\quad + \frac{a_{n1}/T^2}{b_{n1}/T^2 + b_{n2}/T + b_{n3}}U_1(k-2) + U_2(k) \\ &\quad - \frac{2b_{n1}/T^2 + b_{n2}/T}{b_{n1}/T^2 + b_{n2}/T + b_{n3}}U_2(k-1) \\ &\quad + \frac{b_{n1}/T^2}{b_{n1}/T^2 + b_{n2}/T + b_{n3}}U_2(k-2) \\ &\quad + \frac{2b_{n1}/T^2 + b_{n2}/T}{b_{n1}/T^2 + b_{n2}/T + b_{n3}}C_2(k-1) \\ &\quad - \frac{b_{n1}/T^2}{b_{n1}/T^2 + b_{n2}/T + b_{n3}}C_2(k-2) \end{aligned} \tag{23}$$

where

$$\begin{aligned} a_{n1} &= -0.00001255k_2 - 0.00029415k_2x_2 \\ a_{n2} &= -0.000094073k_2 - 0.00077085k_2x_2 \\ a_{n3} &= -0.0323k_2 + 0.0111k_2x_2 \\ b_{n1} &= 0.00001255k_1 + 0.00029415k_1x_1 \\ b_{n2} &= 0.000094073k_1 + 0.00077085k_1x_1 \\ b_{n3} &= 0.0323k_1 - 0.0111k_1x_1 \end{aligned}$$

where K_P and K_D are the gains of proportional and derivative, respectively.

B. SIMULATION RESEARCH

The simulation condition is 40kn SSN 4, and the random spectrum is adopted by ITTC two-parameter spectrum. Simulink was used to build each module, as shown in the following FIGURE.6 and FIGURE.7.

Through simulation, the heave and pitch curves in the condition of 40 knots SSN 3 can be obtained as shown in the FIGURE.8 below:

The other condition is shown in Table 4.

Through simulation analysis, we verify the feasibility of the controller, and we will apply the above method in experiment.

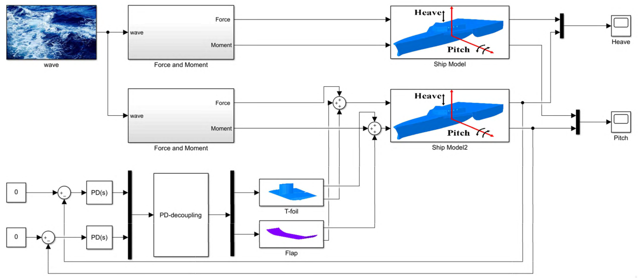

FIGURE 6. The simulation of the trimaran control system.

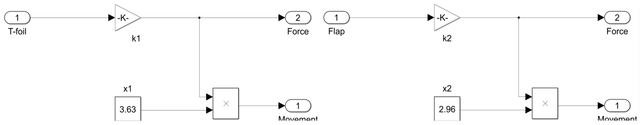

FIGURE 7. The subsystem of T-foil and flap.

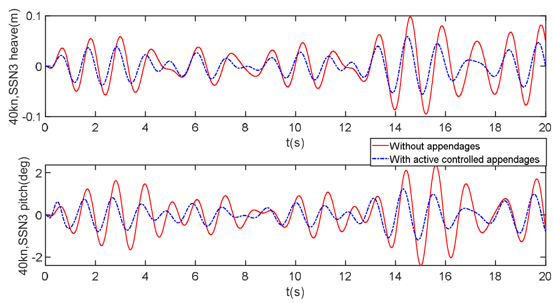

FIGURE 8. Comparison of the trimaran without appendages and with active controlled appendages (Simulation).

TABLE 4. The Effect of the stabilization controller through the simulation.

Speed/SSN	Heave	Pitch
18knots/SSN3	38.79%	51.24%
18knots/SSN4	31.27%	38.96%
40knots/SSN3	41.18%	56.83%
40knots/SSN4	34.75%	36.08%

V. HARDWARE IMPLEMENTATION AND EXPERIMENTAL ANALYSIS

The diagram of hardware structure system is shown in FIGURE.9.

A. INDUSTRIAL PC

The Industrial PC adopts the real-time operating system VXWOKS, which is mainly responsible for the acquisition of heave and pitch angle signals, the control of heave and pitch as well as their decoupling, the conversion of attack angle and displacement of T-foil and flap, and the output of 232 to the DSP at the bottom. The sampling control output cycle is 80ms.

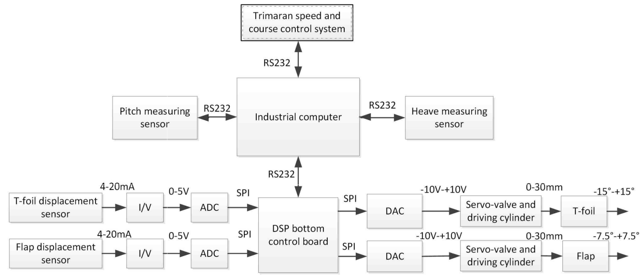

FIGURE 9. The hardware system of the trimaran.

B. ATTITUDE MEASUREMENT SENSORS

Pitch angle sensor measures pitch angle, 232 interfaces, the heave sensor measures the displacement, 232 interfaces.

C. DSP CONTROL PANEL

According to the position of the T-foil and the flap, the motion of the two appendages can be controlled respectively.

D. COURSE AND SPEED CONTROL SYSTEM

The trimaran sails at a fixed course speed to satisfy the speed requirements of the Flap and T-foil control. The trimaran's propulsion device is double water jet propulsion, driven by motor jet pump, battery power, vector nozzle control course. The above hardware parts are set up and the experimental analysis of the trimaran is carried out at the same time.

Generally, there are two kinds of driving devices for driving T-foil and flap, one is a motor drive and the other is a hydraulic drive. The advantage of using the motor drive is that it is easy to use and control. However, due to the large driving force required on the actual trimaran, it is often driven by hydraulic means. The trimaran designed in this paper is scaled by actual trimaran, and the whole control system is designed for the actual trimaran application. In this design, the hydraulic method is used to drive the T-foil and flap. In addition to the large driving force, the hydraulic drive has the characteristics of small size, excellent dynamic performance and high life.

This design uses a combination of hydraulic pump station, ATOS servo valve, hydraulic cylinder and displacement sensor to control the T-foil and flap. The hydraulic pump station selected here is the HKL compact pumping station. The pumping station has excellent performance, small volume, large surface area of cooling ribs and good heat dissipation. The main parameters are shown in Table 5.

Electro-hydraulic servo valve selects the electro-hydraulic proportional servo valve produced by ATOS, the type is DLHZO-TEB-040-L71. It is controlled by analog quantity, the input voltage is $\pm 10V$, which corresponds to the opening size of the internal spool, thus controlling the flow rate. The parameter table of the DLHZO-TEB-040-L71 electro-hydraulic servo valve is shown in Table 6.

TABLE 5. HKL Pumping Station Parameters.

Type	HKL
Maximum discharge (L/min)	22
Maximum working pressure	700bar
Rated frequency (HZ)	50
Mass (KG)	19.2kg
Length/width/height (mm)	368/196/251
Defense grade	IP54

TABLE 6. DLHZO-TEB-040-L71 Electro-Hydraulic Servo Valve Parameters.

Type	DLHZO-TEB-040-L71
Maximum discharge (L/min)	70
Power supply (V)	24
Input signal (V)	-10~10
Mass (KG)	2.3kg
Length/width/height (mm)	217/46/140

TABLE 7. KYDM-L/LE Displacement Sensor Parameters.

Type	KYDM-L/LE
Output current (mA)	4~20
Power supply (V)	12~24
Effective range (mm)	0~50
Maximum load resistance (Ω)	600
Maximum nonlinear error (%)	0.05

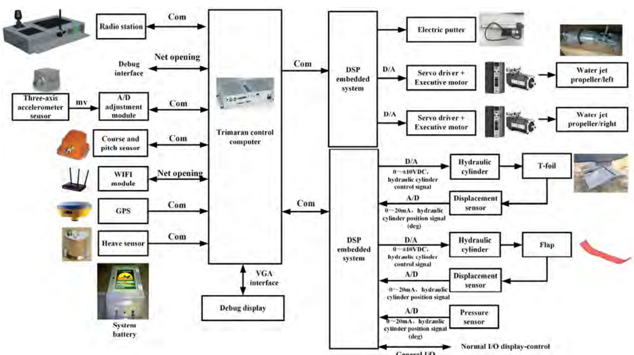

FIGURE 10. The trimaran hardware system.

The displacement sensor is installed on the upper part of the hydraulic cylinder. The displacement sensor selected in this design is KYDM-L/LE displacement sensor. The sensor is a three-wire current sensor with an output current of 4~20mA. The main advantage of using current sensor is that in a complex environment, the anti-interference ability is strong. The KYDM-L/LE displacement sensor parameter is shown in Table 7.

The hardware system is loaded on the trimaran, and the T-foil and flap are controlled by the upper control algorithm. FIGURE.10 shows the trimaran hardware system.

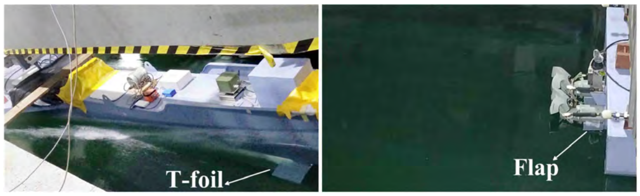

FIGURE 11. The trimaran sailing in water tank.

TABLE 8. The Effect of the Stabilization Controller.

Speed/SSN	Heave	Pitch
18knots/SSN3	35.13%	48.25%
18knots/SSN4	27.63%	36.41%
40knots/SSN3	32.47%	41.04%
40knots/SSN4	29.32%	38.65%

Then, the trimaran vertical stabilization experiment is performed. FIGURE 11 shows the trimaran with active T-foil and flap sailing in the water tank.

Through the water tank experiment, the effect of active stabilization appendages is shown in Fig, (the condition of 40 knots, SSN4), and Table 8 shows the effect of other conditions.

VI. CONCLUSION

In this paper, the vertical movements of a trimaran are restrained. According to Table 7, the effect of controller is obviously, which proves the design of stabilization is reasonable and the control algorithm is effective.

For better effect of stabilization control, the decouple method of T-foil and flap need to be improved. The decouple method is relies on the trimaran mathematical model, and the model has errors. And the controller parameters need to be optimized.

In future work, the stabilization control system will be applied in actual multihulls, for the mentioned points above, the improved decouple method and optimized controller parameters will be obtained with better results.

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BOWEN ZENG was born in Changde, China, in 1976. He received the B.A. degree in industry automation, the M.Sc. degree in control science and engineering, and the Ph.D. degree in control science and engineering from Harbin Engineering University, in 2001, 2006, and 2012, respectively, where he is currently a Lecturer with the College of Automation. His research interests include ship motion control and embedded system design and application.

YANG SONG was born in Daqing, China, in 1979. She received the B.A. degree in industry automation and the M.Sc. degree in control science from Harbin Engineering University, in 2004 and 2009, respectively, where she is currently a Teacher with the Engineering Training Center. Her research interest includes advanced industrial processes control.

LINHE ZHENG was born in Suihua, China, in 1993. He is currently pursuing the Ph.D. degree with the College of Automation, Harbin Engineering University, China. His research interest includes ship motion stabilization control.