Experimental Study on Rolling Motion Model of a Quad-Hull-USV

Zhiwei Cao, Songling Yang, Bao jiang Wang, Chenyi Zhuang

***Abstract*— At present, the ship type of USV is relatively single. When the USV encounters harsh sea conditions, it is relatively difficult to carry out the task, which affects the safety of the USV and the degree of the task execution. This paper studied a roll attenuation test of a new type of small waterplane area quad-hull-USV in six working conditions. We changed the composition of restoring torque and damping to established four different mathematical models of roll damping. Based on the theory of system identification and intelligent optimization algorithms, we adapted a piece of self-programming software for system identification including genetic algorithm and particle swarm optimization algorithm developed in C# language in our research. The rolling test data under six working conditions were identified and analyzed. The optimal rolling motion mathematical models under different working conditions were obtained, and the variation trend of moment coefficients under different draft water was analyzed. By comparing the relative error values, the reliability of the self-programming software for system identification was proved. It provides a good basis for further research on the advantages of quad-hull-USV.**

***Index Terms*— small waterplane area quad-hull-USV, roll damping tests, system identification, roll motion mode**

I. INTRODUCTION

In recent years, with the improvement of intelligent level, there is no boat got rapid development. while the existing unmanned boat hull form is relatively single, give priority to with monomer glider and ordinary catamaran, when the mission area is relatively poor, because the ship wave resistance is poor, no one boat and cannot achieve the best performance, in order to reduce the impact of weather conditions for task execution, adapt unmanned craft to the higher sea condition, the need to improve the ship type of unmanned craft, so looking for a kind of ship form to adapt to bad weather is necessary.

Small waterplane multi-body ship has the advantages of good sea-keeping, large deck area, and the ability to arrange more equipment. It can also reduce the impact on the mission in adverse environment.

Over the years, a large number of scholars have done a lot of research on small waterplane multi-body ship.

In 2017, sun xiaoshuai et al [1] conducted numerical and experimental studies on the attenuation of hydrostatic free roll of small waterplane catamaran with stable fins, and found that nonlinear damping exists in the attenuation motion of hull free roll.

In 2018, zhang mingxia et al [2] used the star-ccm + platform to study the law of resistance change of small waterplane trimaran with different lateral body positions.

Based on the above research, this paper designs a small waterplane four-hull ship with diamond arrangement. Its rolling motion mode [3-5] is different from that of simple single ship, and its motion is very complex. This article through to a lozenge arrangement of small waterplane four segments static water rolling test model, and then through the two optimization based on particle swarm and genetic algorithm, based on the rolling system identification software, and the test data processing, get the related coefficient of rolling motion patterns, preliminary discussed the change law of each parameters relevant to the movement of experimental model is also given the approximate equation of rolling motion.

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II. HYDROSTATIC ROLL TEST

A . Test model

In this roll test, a model of a small waterline four-body unmanned boat with a floating diamond arrangement was selected. The main dimensions are as follows:

Table 1.1 Main Hull Parameters of Optimized Small Waterplane Area Quad-Hull-USV

Main scale	symbol	Numerical value	Unit
Length	L	1.14	m
Moulded Breadth	B	0.72	m
Molded depth	D	0.42	m
Design draft	T	0.19	m
Design discharge	Δ	30	kg
Design speed	V	4	kn
Demihull space	C_0	0.16	m
Submerged body length	L_h	0.5	m
Submerged body diameter	D_1	0.14	m
Pillar length	L_s	0.42	m
Pillar max length	t_s	0.08	m

Fig 1.1 Three views of the ship model

B . Test equipment and software

The MTi-G is a miniature inertial measurement system with integrated GPS signals. It can output three-axis acceleration, three-axis angular velocity, and three-axis attitude angle (pitch angle / roll angle / heading angle). Built-in high-precision anti-vibration gyroscope chip (10°/h), it can output three-axis attitude angle with high precision in vibration environment and non-uniform magnetic field environment.

Fig 1.2 MTi-G Micro AHRS Inertial Measurement System

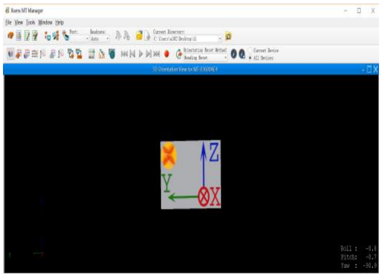

Fig 1.3 Operating Software Interface

C . Roll test procedure

Due to the limitations of the test conditions, this test mainly tests the variation of the roll angle attenuation of the unmanned boat model during the free-water free decay process, and determines the roll attenuation law of the boat model through the obtained results. The roll attenuation test in water, the site of this test is the tow pool of XX University of Science and Technology, the specific test steps [6] are as follows:

(1) Considering the impact of the pool boundary on the test results, this test will place the ship model in the center of the pool, adjust the floating state of the ship model by adjusting the ballast, and make the draft at the design waterline;

(2) Pass the raft The code is adjusted so that the center of gravity is approximated at the center of gravity of the design, and the MTi-G inertial gauge is placed horizontally at the center of gravity of the ship model, and the data line is used to connect the MTi to the computer on the shore;

(3) When the boat is in the positive float State, read the real-time roll angle of the boat model through the on-shore operating software, adjust the small weight position through a small range, and make the initial roll angle displayed on the software, the initial roll angle is between ±0.5°;

(4) By applying a force perpendicular to the base plane to the ship model to obtain the desired roll angle, click on the recorded data and release the ship model, wait for the ship model to return to the positive float state, stop the data acquisition, and save the test data;

(5) Repeat (4) -(5) process, the initial roll angle of the total of four groups, including: 4 °, 6 °, 8 °;

(6) By adding weights to make the ship model draught at 1.1 times the design water line, re-run the still water roll Test, repeat (4)-(6) process, Inspection process is as follows:

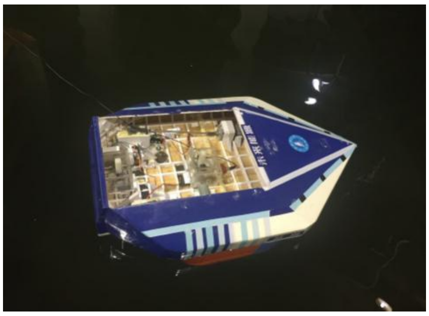

Fig 1.4 Rolling Attenuation Test of Small Waterplane Area Quad-Hull-USV in Still Water

III. SYSTEM IDENTIFICATION

A. Identification algorithm selection

The identification procedure used in this paper adopts particle swarm optimization algorithm [13] and genetic algorithm respectively. Therefore, the following two identification schemes are adopted for different algorithms: Scheme 1: Rolling identification program using genetic algorithm, basic parameter setting: The population size is 200, the crossover probability is 0.8, the mutation probability is 0.15; the number of calculations is 2000 generations, the genetic factor is 0.05, and the evolution weights are 0.3, 0.5, and 0.7 respectively. Scheme 2: The roll identification procedure using particle swarm optimization algorithm, basic parameter setting: population size 200, variable weight, the maximum speed limit of particle flight is 0.11, 0.13, 0.15, and the algebra is 2000 generation.

B. Rolling identification mathematical model

In this paper, through the combination of linear, nonlinear and sinusoidal values[14], the recovery moment term and the damping moment term are combined to form four different identification formulas, from which the roll motion of the four-body unmanned boat with the best matching small waterline surface is found. equation.

Identification Equation 1 When the ship is tilted to a small angle, the damping torque and the restoring moment are both linear:

$$\ddot{\varphi}+2\frac{N}{I_{xx}}\dot{\varphi}+\frac{Dh}{I_{xx}}\sin\varphi=0 \qquad (1)$$

The design variables are: I_{xx}, N, h, as a preference, the range of values is:

$I_{xx}\in[0,1], N\in[0,0.0001], h\in[0,1]$

Identification formula 2 is when the damping torque is nonlinear and the restoring torque is linear:

$$\ddot{\varphi}+2\frac{N}{I_{xx}}\dot{\varphi}+\frac{W}{I_{xx}}\left|\dot{\varphi}\right|\dot{\varphi}+\frac{x}{I_{xx}}\dot{\varphi}^{3}+\frac{Dh}{I_{xx}}\sin\varphi=0$$

(2)

The design variables are I_{xx}, N, W, x, as a preference, the range of values is:

$I_{xx}\in[0,1], N\in[0,0.0001]$,
$W\in[0,0.01], x\in[0,15], h\in[0,1]$

The identification formula 3 is that when both the damping torque and the restoring moment are nonlinear, the model equation is:

$$\ddot{\phi}+2\frac{N}{I_{xx}}\dot{\phi}+\frac{W}{I_{xx}}\left|\dot{\phi}\right|\dot{\phi}+\frac{x}{I_{xx}}\dot{\phi}^{3}+\frac{C_1}{I_{xx}}\phi^3+\frac{C_2}{I_{xx}}\phi^2+\frac{C_3}{I_{xx}}\phi=0$$

(3)

The design variable is: $I_{xx}, N, W, x, C_1, C_2, C_3$, as a preferred, the range of values is:

$I_{xx}\in[0,1], N\in[0,0.0001], W\in[0,0.01]$
$, x\in[0,15], C_1\in[0,10], C_2\in[0,10], C_3\in[0,5]$

The identification formula 4 is that the damping torque is nonlinear, and the restoring moment is a linear plus square of the sine value plus three times:

$$\ddot{\phi}+2\frac{N}{I_{xx}}\dot{\phi}+\frac{W}{I_{xx}}\left|\dot{\phi}\right|\dot{\phi}+\frac{x}{I_{xx}}\dot{\phi}^{3}+\frac{C_1}{I_{xx}}(\sin\phi)^3+\frac{C_2}{I_{xx}}(\sin\phi)^2+\frac{C_3}{I_{xx}}(\sin\phi)=0 \qquad (4)$$

Design variables: I_{xx}, N, W, x, C_1, C_2 C_3, as a preferred, range of values is:

$I_{xx}\in[0,1], N\in[0,0.0001], W\in[0,0.01]$
$, x\in[0,15], C_1\in[0,10], C_2\in[0,10], C_3\in[0,5]$

Among the above four identification formulas, φ, $\dot{\varphi}$, $\ddot{\varphi}$, are the roll angle, roll angular velocity, and roll angular acceleration; I_{xx} the total moment of inertia of the hull roll; N the roll linear damping coefficient; W, x the roll nonlinear damping coefficient; C_1, C_2 The moment of recovery torque C_3 is a linear recovery moment coefficient, h is high initial stability and D is the displacement of the ship model;

The above four identification models, by measuring the angle of k moment the test, predict the roll angular velocity at the k+1 moment (taking model one as an example):

$$\dot{\varphi}'_{k+1}=(-2\frac{N\,t}{I_X}+1)\dot{\varphi}_{k+1}-(\frac{Dh}{I_X}\sin\varphi)t \qquad (5)$$

The error estimation criteria at the k+1 moment are as follows:

$$\varepsilon_{k+1}=\dot{\varphi}'_{k+1}-\dot{\varphi}_{k+1} \qquad (6)$$

Where: $\dot{\phi}_{K+1}$ is the measured value of the angular velocity of the moment; $\dot{\phi}'_{K+1}$ the value obtained by the identification result.

Then, the objective function is selected as shown in the formula, and the smaller the objective function value is, the better the formula fitting effect is.

$$F(x)=\left(\sqrt{1/N\sum_{k=1}^{N}(\dot{\varphi}'_{k+1}-\dot{\varphi}_{k+1})^2}\right)^{-1} \qquad (7)$$

IV. ANALYSIS OF TEST RESULTS

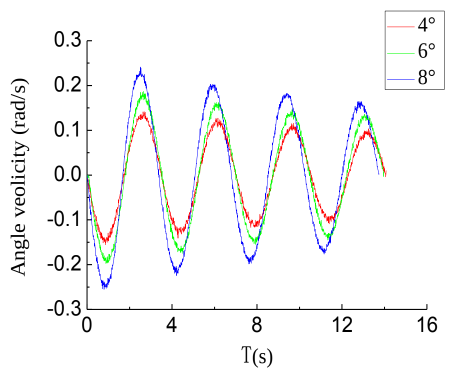

Fig 3.1 Design of Angular Velocity Attenuation Curves for Different Initial Roll Angles under Drawing Water

In the process of the roll test, each test condition is repeated three times, and the test data is compared with multiple test data, and the best set of test data is selected as the effective data for data processing, and the human factor band is minimized. The impact of coming. Figure 3.1 is a comparison of the angular velocity of the standard 4°, 6°, and 8° under water. It is found by comparison that the larger the initial roll angle, the larger the peak value of the roll angular velocity, indicating the same underwater, roll angle. The larger, the greater the recovery torque, in line with the rolling law, indicating that the data is available. As the roll angle increases, the roll period becomes smaller, indicating that during the increase of the roll angle, a nonlinear component appears in the restoring moment. In addition, as can be seen from the figure, the small water line surface in this paper The rolling decay period of the four-hull ship is relatively long, which may be caused by two reasons: First, because it is a small waterplane catamaran, it is coupled with the pitching motion of the ship model during the rolling process. The effect, because the roll cycle is similar to the pitch cycle, may form a "twist"; the second is because the equipment is arranged, because the equipment is mostly placed on the deck, it may lead to the ship's center of gravity is high, and the ship model is enlarged. The roll cycle needs to be improved.

The identification formula 3 is selected, and the objective function identified by the identification program of different algorithms is calculated by comparing the scheme 1 and scheme 2. The results are shown in Tables 3.1 and 3.2:

Table3.1 Case1: Identification Scheme-Objective Function Value

genetic algorithm				
Evolution weight		0.3	0.5	0.7
Design draft	Roll angle 4°	0.006223805	0.00622378	0.006223733
	Roll angle 6°	0.006524897	0.006524949	0.006524097
	Roll angle 8°	0.006329831	0.006329748	0.006329453
1.1 Design draft	Roll angle 4°	0.006874702	0.00687457	0.006877705
	Roll angle 6°	0.006468432	0.00646757	0.006467663
	Roll angle 8°	0.006650371	0.00665047	0.006650315

Table3.2 Case2: Identification Scheme-Objective Function Value

Particle swarm optimization				
Maximum Limit Percentage of Particle Flight Velocity		0.13	0.15	0.17
Design draft	Roll angle 4°	0.006229801	0.006225325	0.006226084
	Roll angle 6°	0 .006525657	0.006550773	0.006534387
	Roll angle 8°	0.006335822	0.006333615	0.006348594
1.1 Design draft	Roll angle 4°	0.006904338	0.006905715	0.006905367
	Roll angle 6°	0.006477969	0.006474437	0.00647633
	Roll angle 8°	0.006659219	0.006651776	0.006652629

By comparing the objective function values of each roll angle in Table 3.1 and Table 3.2, it is found that the objective function value calculated in the first scheme is smaller than the objective function value calculated in the second scheme, that is to say, the scheme 1 uses the genetic algorithm to identify the program. The effect is better. In the first scheme, when the evolution weight is 0.7, the identification results at different angles are relatively good. Therefore, the scheme of the following is selected.

The standard draught and 1.1 times draught conditions were selected, and the target function sizes under different identification formulas were compared, as shown in Figure 3.2.

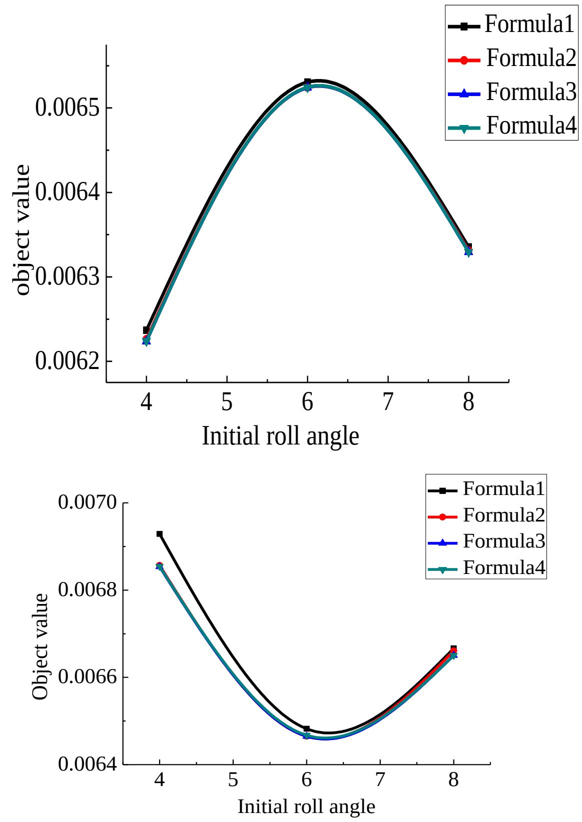

Fig 3.2 Object Functions of Four Identification Formulas with Different Drafts

It can be seen from Fig. 3.2(a) that under the standard eating water, the value of the objective function identified by Equation 1 is large, and the value of the objective function identified by Equation 3 is the smallest, indicating that under the standard eating water, the recovery torque is nonlinear, damping torque. Equation 3, which is nonlinear, is more realistic.

It can be seen from Fig. 3.2(b) that when 1.1 times draught, when the small angle is swayed, the objective functions of the identification formulas 2, 3, and 4 are basically the same, indicating the nonlinear recovery moment effect when the underwater angle is small. Very small, as the roll angle increases, the objective function of Equation 3 is the smallest when both the nonlinear damping moment and the restoring moment are present, indicating that the nonlinear restoring moment during the rolling process increases with the increase of the roll angle. The proportion is larger and larger, and formula 3 is more suitable. By comparing the objective function curves of formula 3 and formula 4 with (a) and (b), it can be seen that the sine value of the roll angle is used and the roll angle is directly used. The difference is basically not changed for the ship's roll motion equation.

Taking the design to eat underwater, the initial roll angle is 4° as an example, and using Equation 3 for identification processing, the obtained roll motion equation under this condition is:

$$\ddot{\phi}+0.000214\dot{\phi}+0.007997|\dot{\phi}|\dot{\phi}+46.21827\dot{\phi}^3$$
$$+39.48438\phi^3+6.675959\phi^2+3.131189\phi=0$$

In the identification result, a piece of data is randomly intercepted, as shown in Table 3.3: Table 3.3 Comparison of experimental angular velocity and fitting angular velocity error.

Table3.3 Comparison of experimental angular velocity and fitting angular velocity errors

T	Test angular velocity	Fitting angular velocity	Relative error %
2.83	0.12464617	0.12275348	1.51845
2.84	0.12803909	0.12307775	3.87486
2.85	0.12173671	0.12635112	3.79048
2.86	0.11943113	0.12014273	0.59582
2.87	0.11986223	0.11784175	1.68566
2.88	0.11728089	0.11822192	0.80237
2.89	0.12141208	0.11564924	4.74651
2.91	0.11058406	0.11653368	5.38018
2.92	0.11247425	0.10894689	3.13614
2.93	0.11289662	0.11076339	1.88954
2.94	0.10792767	0.11113684	2.97344
2.95	0.10928379	0.10621209	2.81075
2.96	0.11053170	0.10750535	2.73799
2.97	0.10793639	0.10869095	0.69908
2.98	0.10814234	0.10609798	1.89043

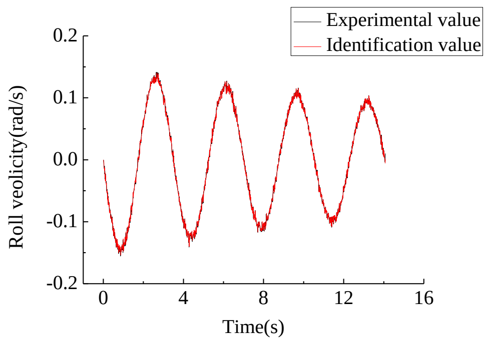

Figure3.3 Fitting Curve of Angular Velocity of Test and Identification

It can be seen from Table 3.3 that the identification operation using Equation 3 is performed, and the fitting error of the obtained angular velocity is basically within 5%. Figure 3.3 shows the experimental angular velocity of the design under water, the initial roll angle of 4° and the identified fitting angular velocity. Contrast, it can be found that the overall fitting effect is better, indicating that the genetic algorithm is good in the reliability of the program, and can meet the requirements of predicting the angular velocity of the next moment.

Through the identification calculation, the roll motion equations of six sets of test conditions are obtained respectively. The formula with the highest identification accuracy is used to analyze the variation law of each moment coefficient with different initial roll angles, as shown in Figure 3.4-3.5. Show.

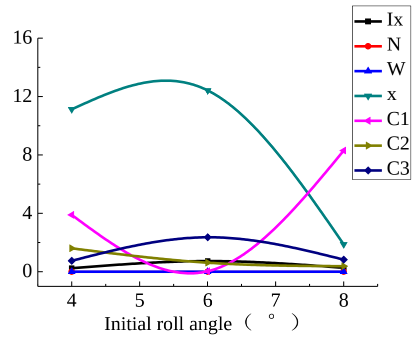

Fig 3.4 Design Curves of Moment Coefficients Varying with Initial Roll Angle Under Draft Water

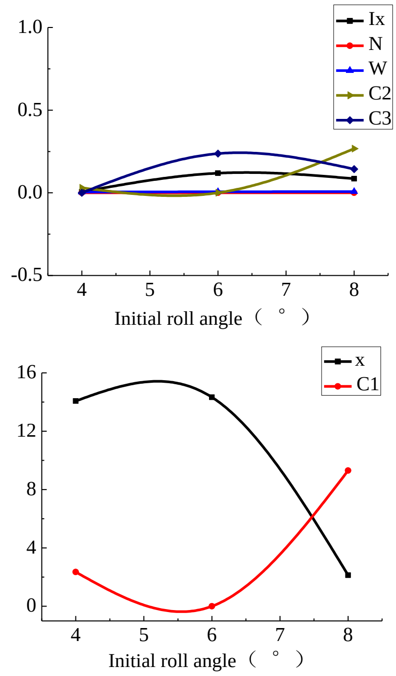

Fig 3.5 1.1-Fold Underwater Moment Coefficients Versus Initial Rolling Angle

Comparing the recovery torque coefficient in Figure 3.4-3.5, it can be seen that in the case of fixed draft, the torque coefficients change with the change of the roll angle, the total moment of inertia of the hull roll remains basically unchanged, and the coefficient of the recovery moment is cubic. The magnitude of the recovery moment coefficient varies greatly with the change of the roll angle. The coefficient of the linear recovery moment increases first and then decreases with the increase of the initial roll angle. Under the two kinds of eating water, the cube recovery torque coefficient is the initial. The increase of the roll angle decreases first and then increases. When designing the draft, the quadratic nonlinear recovery torque coefficient decreases with the increase of the roll angle. At 1.1 times the draft, the quadratic nonlinear recovery torque coefficient It increases with the increase of the roll angle; it shows that the composition of the restoring moment is mainly a nonlinear part during the rolling of the four-hull ship.

Comparing the damping torque coefficient in Figure 3.4-3.5, it can be seen that in the case of fixed draft, the coefficient of cubic non-linear damping torque in the coefficient of damping torque varies greatly with the variation of the rolling angle, linear damping moment coefficient and square damping. The torque coefficient changes little and stabilizes near the zero point, indicating that only the cubic nonlinear damping torque is active in the damping torque, and there is no linear damping torque and quadratic nonlinear damping torque. Under the two kinds of eating water, the coefficient of the third-order damping moment increases first and then decreases with the increase of the initial roll angle. By combining the change of the restored moment coefficient, it can be seen that the ratio of the restoring moment is mainly at the time of the large angle roll. The damping torque has a large effect, which is consistent with the characteristics of the small waterline ship.

V. CONCLUSION

In this paper, the model test and system identification method are used to study the hydrostatic roll attenuation motion mode of a diamond-shaped small waterplane four-body unmanned boat. The identification procedure based on genetic and particle swarm algorithm is adapted and identified. Under the six working conditions, it is most suitable for the hydrostatic rocking mathematical equation of the ship model in the text, which can accurately describe the roll motion process. Through comparison and analysis, the variation law of each moment coefficient of different eating underwater with initial roll angle is obtained, and the reliability of the system identification software is verified. The research shows that the system identification software can predict and analyze the roll state of the ship. It provides a good foundation for further study of the excellent performance of small waterplane four-hulled ships.

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