Journal of System Simulation

Volume 31 | Issue 11 Article 9

12-13-2019

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Recommended Citation

Li Xiaochen, Yin Yong. Fast Simulation of Yacht in Calm Water Based on Improved Savitsky Method[J]. Journal of System Simulation, 2019, 31(11): 2264-2274.

第 31 卷第 11 期
2019 年 11 月

系统仿真学报©
Journal of System Simulation

Vol. 31 No. 11
Nov., 2019

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基于改进 Savitsky 方法的静水游艇快速仿真

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摘要：提出了一种改进的 Savitsky 方法以提升游艇模拟器中运动数学模型的精度。建立三自由度游艇运动数学模型，对游艇排水状态下运动进行仿真。*将游艇几何模型做棱柱形假设，采用改进 Savitsky 方法进行阻力计算*，并进行船舶预滑行和滑行运动仿真试验。试验结果与模型试验结果进行对比，阻力计算结果与快速性试验结果精确度较高，船舶操纵性试验结果与传统方法基本一致。改进方法加入游艇模拟器后运行良好，结果准确。改进后的 Savitsky 方法可以有效提升游艇快速仿真精度，对游艇模拟器的研究具有一定意义。

关键词：改进 Savitsky 方法；游艇模型简化；阻力计算；快速仿真；游艇模拟器

中图分类号：U674.91　　文献标识码：A　　文章编号：1004-731X (2019) 11-2264-11

OI: 10.16182/j.issn1004731x.joss.19-FZ0303E

Introduction

The rise of the yacht has driven the development of related industries. Yacht simulator is one of them, which is mainly used to train yachtsmen. For better training effects, the simulator needs precise mathematical model of ship motion. Accurate forces and moments are key factors in mathematical models. Yacht is a kind of High Speed Craft (HSC). There are two types of pressure acting on a hull: hydrostatic

Received: 2019-05-17　　Revised: 2019-07-11;
Supported: Central Universities(3132019011), Open fund of polar Ship Navigation Safety Research Center (3132019306);
Biographies: Li Xiaochen (1990-), male, Luoyang, Henan, PhD student, Research direction: ship motion modeling, navigation simulator.

pressure and hydrodynamic pressure. Hydrostatic pressure mainly acts on low speed domain and hydrodynamic pressure plays a major role on higher speed domain, which is quite different with displacement vessels. In general, the volumetric Froude number Fn_∇ is the criterion for distinguishing yacht's movement. $Fn_\nabla < 1.0$ is called displacement regime, $Fn_\nabla > 3.0$ is called planing regime, and the transitional area $1.0 > Fn_\nabla > 3.0$ is called semi- displacement or pre-planing regime.

Plenty of scholars have done a lot of work in the field of HSC. Early research focused on Experimental Fluid Dynamics (EFD)[1-3]. The EFD reveals the effects of different hull forms and ship speed. Regression formulas and empirical formulas have good results and they can be used for fast simulation. However, EFD consumes a lot of manpower and resources. These formulas are only accurate for experiment hull forms. The theory does not apply when the hull form changes. Along with the promotion of theory and computing power, Computational Fluid Dynamics (CFD)[4-5] is gradually becoming a popular method for studying on ships. The development of CFD has experienced from two-dimensional theory to three-dimensional theory, from potential method to viscous method[6-7]. CFD can model a specific hull form according to the ship data. The numerical results agree pretty well with the experimental test. But CFD always takes a long time to compute, which is a big problem in yacht simulator. Suitable for different hull forms and fast simulations are key factors of mathematic models in this research. EFD and CFD methods can not satisfy two requirements at the same time. This paper presents an improved Savitsky method, which is a semi-empirical method, to simulate the motion of yacht. Hull form of yachts is simplified into prismatic hull. Deadrise angle and beam are assumed to be constant. The theory for displacement vessels is used in displacement regime. And the Savitsky method is used in planning regime. An improved theory is used to model yacht motion in pre-planing regime. The agreement between calculated and experimental results is satisfactory. The calculation efficiency can meet the requirements of yacht simulator.

1 Mathematical modeling of the problem

1.1 Simplify yacht hull form

To get better performance of movement, the hull forms of yachts are always designed to be warped. Due to complicated mathematical expression, it is hard to calculate the hydrodynamics of the yacht fast. Simplifying the yacht into a prismatic hull can effectively reduce the difficulties of modeling and the quantities of calculation. Appropriate value of beam and deadrise angle are chosen as constant parameters for simplified hull. The principle of parameter selection is different for different yachts. Midship width, mean wetted width and maximum chine width are often considered to be beam simplified parameter. Similarly, midship deadrise angle, mean deadrise angle and maximum chine deadrise angle are considered to be deadrise angle simplified parameter. Fig. 1 is a comparison of a yacht before and after simplification. It's significant that the simplified hull is easy to study.

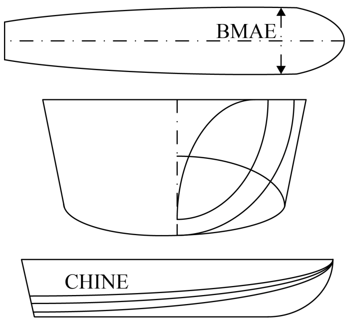
1.2 Coordinate Systems

There are two coordinate systems: earth-fixed coordinate system *xyz* and ship-fixed coordinate system *XYZ*. The *xy* plane is in the calm water surface. The *x*-axis is pointing east, the *y*-axis is pointing north, and the z-axis is pointing upwards. The ship is

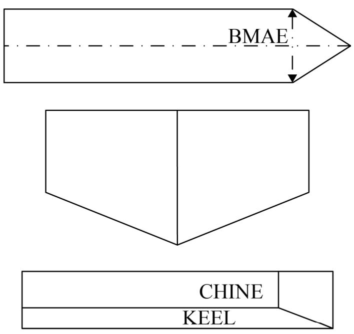
https://dc-china-simulation.researchcommons.org/journal/vol31/iss11/9
DOI: 10.16182/j.issn1004731x.joss.19-FZ0303E

第 31 卷第 11 期 系统仿真学报 Vol. 31 No. 11
2019 年 11 月 Journal of System Simulation Nov., 2019

moving along the negative x-direction. The origin of *XYZ* is fixed at the COG of the ship. The *X*-axis is pointing to the stern and the *Y*-axis towards the starboard. *Z*-axis is pointing upwards. The pitch angle τ is positive when the bow is going up.



(a) real yachts with mutative width and deadrise angle



(b) prismatic hull

Fig. 1 Simplified diagram of yacht hull form

1.3 Equation of motion

Base on manoeuvring theory, the ship-fixed system allows development of a suitable mathematical model to simulate its manoeuvring. The mathematical model can be described by the Eq. (1), using the coordinate system in Fig. 2

$$\begin{aligned} m(\dot{u} - rv) &= X \\ m(\dot{v} + ru) &= Y \\ I_{ZZ}\dot{r} &= N \end{aligned} \tag{1}$$

Where, m is ship's mass, the unknown variables are u, v and r, which mean surge velocity, lateral velocity at midship and yaw rate. Here, X, Y and N are forces and moments in different directions, subscript H, P and R mean hull, propeller and rudder.

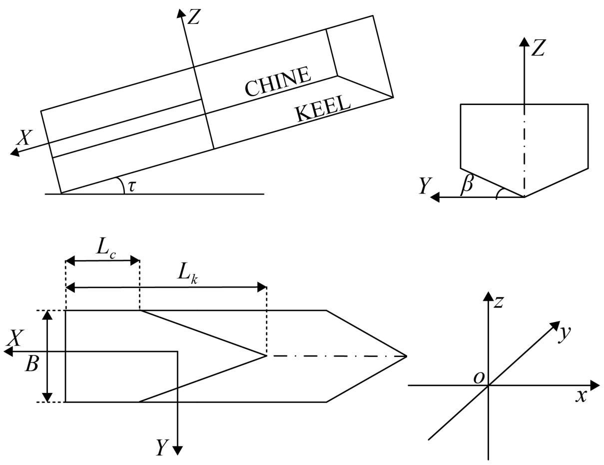


Fig. 2 Coordinate system

$$\begin{aligned} X &= X_H + X_P + X_R \\ Y &= Y_H + Y_P + Y_R \\ N &= N_H + N_P + N_R \end{aligned} \tag{2}$$

This is according to the concept given by the Mathematical Modelling Group (MMG) of Japan[8-9].

The auxiliary equation from the ship-fixed coordinate system to the space-fixed coordinate system is:

$$\begin{cases} x = u\cos\psi - v\sin\psi \\ y = v\cos\psi + u\cos\psi \\ \dot{\psi} = r \end{cases} \tag{3}$$

Where, x_1, y_1 is ship position, ψ is course.

1.4 Forces and moment acting on hull

The forces and moments acting on the hull can be expressed by the following Eq. (4):

$$\begin{aligned} X_H &= (X_{\dot{u}} - m)\dot{u} + (X_{vr} + m)vr + \\ &\quad X_{vv}v^2 + X_{rr}r^2 - Resistance \\ Y_H &= Y_0 + (Y_{\dot{v}} - m)\dot{v} + Y_{\dot{r}}\dot{r} + Y_v v + (Y_r - m)r + \\ &\quad Y_{vvv}v^3 + Y_{vvr}v^2 r + Y_{vrr}vr^2 + Y_{rrr}r^3 \\ N_H &= N_0 + N_{\dot{v}}\dot{v} + (N_{\dot{r}} - I_{ZZ})\dot{r} + N_v v + N_r r + \\ &\quad N_{vvv}v^3 + N_{vvr}vr^2 + N_{rrr}r^3 \end{aligned} \tag{4}$$

Where, $X_{\dot{u}}$, X_{vr}, X_{vv}, X_{rr}, $Y_{\dot{v}}$, $Y_{\dot{r}}$, Y_v, Y_r, Y_{vvv}, Y_{vvr}, Y_{vrr}, Y_{rrr}, $N_{\dot{v}}$, $N_{\dot{r}}$, N_v, N_r, N_{vvv}, N_{vvr} and N_{rrr} are called the hydrodynamic derivatives for force and moment acting on hull on maneuvering.

The resistance characteristics of the yachts has significant difference with displacement vessels. In displacement regime, the resistances of both yachts and displacement vessels are low. And the resistance increases rapidly as the speed grows up. In pre-planing regime, the resistance of yachts is higher than that of displacement vessels. In planning regime, as the composition of the resistance has changed, the resistance has hardly increased. But the resistance of the displacement vessels still increases. Therefore, the resistance calculation method of yachts is obvious different from that of displacement vessels.

The resistance in displacement regime can be expressed as follows:

$$Resistance_{displacement} = \frac{1}{2}\rho C_t u^2 S \tag{5}$$

Where, ρ is water density, C_t is total resistance coefficient, S is wetted surface area.

S in simulator is calculated by two empirical equations. Eq. (6) is for single propeller and Eq. (7) is for twin propellers.

$$S=\nabla^{\frac{2}{3}}\left(3.432+0.305\frac{L}{B}+0.443\frac{B}{D}+0.643C_b\right) \tag{6}$$

$$S=\left(1.54D+0.45B+0.904BC_b+0.026C_b\frac{B}{D}\right)L \tag{7}$$

Where, ∇ is the displacement volume of ship, L is ship length, B is ship width, D is ship's draft, C_b is block coefficient.

C_t is separated into three parts.

$$C_t = C_f + \Delta C_f + C_r \tag{8}$$

Where, C_f is frictional resistance, C_r is residual resistance, ΔC_f is roughness subsidy coefficient.

C_f can be calculated by ITTC-57 formula.

$$C_f = 0.075\big/\left(\lg R_n - 2\right)^2 \tag{9}$$

Where, $R_n = (VL)/\nu$ is Reynolds number.

ΔC_f is a parameter of ship length, which is obtained by experimental test. There are many ways to calculate C_r, such as Todd method and Lap-Keller method. After years of development by marine simulator, the methods above can be used in combination to get better results. Zhang did a lot of related research.

The composition of the resistance in planing regime is different from that in displacement regime. When the yacht is moving at planing regime, the buoyancy of the yacht is neglected, and the gravity is provided by lift force. The force of the yacht is as shown in Eq.(10)

$$Resistance_{planing} = \Delta \tan\tau + R_f / \cos\tau \tag{10}$$

Where, Δ is ship weight, R_f is friction force.

The key factors in calculating the resistance of yachts are τ and R_f. The Savitsky method[10-14] is developed based on a large amount of experimental data, which can effectively calculate τ. As shown in Eq. (11), C_{L0}, λ_W and Fn_B must be calculated in advance.

$$C_{L0} = \tau_{\deg}^{1.1}(0.012\lambda_W^{0.5} + 0.005\,5\lambda_W^{0.5} / Fn_B^2) \tag{11}$$

Where, C_{L0} is lift coefficient for zero deadrise angle, λ_W is mean wetted length to beam ratio, Fn_B is breadth Froude number.

The lift force is considered to be equal to yacht's gravity in planing regime. The lift coefficient of prismatic hull with non-zero deadrise angle is calculated by Eq. (12).

$$C_{L\beta} = \frac{F_{L\beta}}{0.5\rho V^2 B^2} = \frac{\nabla}{0.5\rho V^2 B^2} \tag{12}$$

Where, $C_{L\beta}$ is lift coefficient, $F_{L\beta}$ is lift force, V is ship's velocity.

The relationship between $C_{L\beta}$ and C_{L0} is:

$$C_{L\beta} = C_{L0} - 0.006\,5\beta C_{L0}^{0.60} \tag{13}$$

Where, β is deadrise angle.

λ_W is a variable influenced by the yacht's

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DOI: 10.16182/j.issn1004731x.joss.19-FZ0303E

第 31 卷第 11 期 系统仿真学报 Vol. 31 No. 11
2019 年 11 月 Journal of System Simulation Nov., 2019

speed. Due to special movement posture, λ_W is hard to measure. Savitsky method assumes

$$\lambda_W = (L_K + L_C)/2B \tag{14}$$

Where, L_c is chine wetted length, L_K is keel wetted length.

And he also found a connection among λ_W, longitudinal position centre of gravity from stern (LCG), B and Fn_B:

$$\frac{LCG}{\lambda_W B} = 0.75 - \frac{1}{5.21 Fn_B^2 / \lambda_W^2 + 2.39} \tag{15}$$

Newton method is used to solve Eq. (11) and Eq. (15). Then the first part of resistance in Eq.(10) can be obtained.

The second part of resistance R_f is calculated in a similar way to displacement vessels.

$$R_f = \frac{1}{2}\rho C_f u^2 S \tag{16}$$

The C_f is also obtained by ITTC-57 formula. However, the wetted surface area S is different from that in displacement regime. The S in planing regime is divided in two parts. The first part S_1 begins from the bow $(x = x_{bow})$ up to where chine wetting starts $(x = x_s)$

$$S_1 = 2\int_{x_{bow}}^{x_s} \frac{d(x)}{\sin\beta} dx = \frac{2}{\sin\beta}\int_{x_{bow}}^{x_s}\left(1+\frac{z_{\max}}{Vt}\right) x\tau dx =$$

$$\frac{\tan^2\beta}{\sin\beta}\left(1+\frac{z_{\max}}{Vt}\right) x_S^2 \tag{17}$$

Where, $z_{\max}$ is z-coordinate of maximum pressure.

The flow separation at the chine will start at x_s, which satisfies

$$\frac{B}{2} = \left(1+\frac{z_{\max}}{Vt}\right)\frac{Vt}{\tan\beta} = \left(1+\frac{z_{\max}}{Vt}\right)\frac{x_S\tau}{\tan\beta} \tag{18}$$

Therefore, S_1 can be reduced to

$$S_1 = \frac{\tan^2\beta}{\sin\beta}\left(\frac{B^2}{4(1+z_{\max}/Vt)\tau}\right) \tag{19}$$

The wetted area from $x = x_s$ to the transom is simply

$$S_2 = \frac{B}{\cos\beta} L_C \tag{20}$$

The total wetted area of yacht in planing regime is

$$S = S_1 + S_2 =$$

$$\frac{\tan^2\beta}{\sin\beta}\left(\frac{B^2}{4(1+z_{\max}/Vt)\tau}\right) + \frac{B}{\cos\beta} L_C \tag{21}$$

The total longitudinal drag force is then calculated.

As for the transition area, an improved theory is proposed to calculate resistance. Appropriate Fn_∇ interval of pre-plaing regime is selected for different ships. The τ and S are calculated by Savitsky method at the maximum value of the interval and by displacement vessels' method at minimum value of the interval. The two parameters are supposed to be linearly changed in this region. The resistance is a combination of the two methods mentioned above.

$$Resistance_{total} =$$

$$aResistance_{displacement} + bResistance_{Savitisky} \tag{22}$$

The weight factors a and b are determined by ship hydrodynamics performance. Every ship is different. The factors are obtained by simulation test. The improved method finds a balance between efficiency and precision, which is pretty suitable for simulator.

1.5 Forces and moment induced propeller and rudder

The forces and moments induced by propeller and rudder can be modeled by the following equations

$$\begin{aligned} X_P &= (1-t_P)\rho K_T D_P^4 n^2 \\ Y_P &= 0 \\ N_P &= 0 \end{aligned} \tag{23}$$

Where, t_P is thrust deduction coefficient, K_T is propeller thrust open water characteristic, n is propeller revolution.

The terms on rudder force are assumed as follows

$$X_R = -\left(1-t_R\right)F_N \sin\delta$$
$$Y_R = -\left(1+a_H\right)F_N \cos\delta \qquad (24)$$
$$N_R = -\left(x_R + a_H x_H\right)F_N \cos\delta$$

Where, t_R is steering resistance deduction factor, δ is rudder angle, a_H is rudder force increase factor, x_H is longitudinal coordinate of acting point of the additional lateral force, x_R is longitudinal coordinate of rudder position, F_N is rudder force.

$$F_N = \frac{1}{2}\rho A_R f_\alpha U_R^2 \sin\alpha_R$$

Where, A_R is the profile area of movable part of mariner rudder, f_α is rudder lift gradient coefficient, U_R is resultant inflow velocity to rudder, α_R is effective inflow angle to rudder.

2 Numerical results and discussions

Based on the methodology outlined in the preceding section, a computer code is developed in MATLAB and C++. For the given ships, appropriate value of beam and deadrise angle are selected to build simplified hull form. The frictional coefficient, total resistance and manoeuvring ability are discussed. Several different types of hull forms are chosen to verify the theory above.

2.1 Resistance test

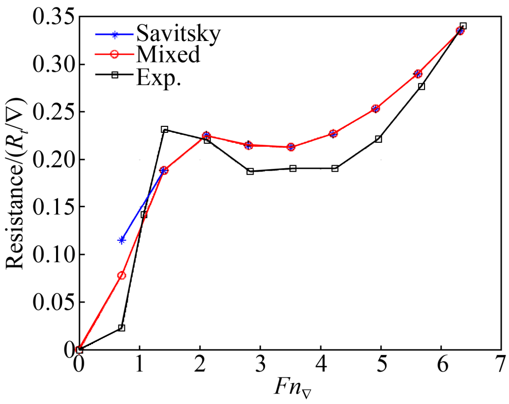
Three Deep-V planing hulls with hard-chine are selected as the first group to simulate. Kim[15] makes a series of model tests on this group of hull. Main characteristics of hull forms are shown in Tab. 1.

The first group of models are designed with the variations L_{OA}, L_{WL}, beam, weight, deadrise angle, section shape and higher speed. The simulation test mainly discusses the applicability of the improved method to different warped hull forms. In this group, the β_{mid} is regarded as constant value of beam to simplify the hull form. Then, the original models turn to be prismatic hull. $0.8 < Fn_\nabla < 1.2$ is a suitable interval of pre-planing regime. The resistances calculated by multiple methods in different Fn_∇ are compared to experimental results in Fig. 3.

Two modified planing hull models are chosen as the second group of models, which are designed with the variations beam, LCG, section shape and lower speed. This group of models is tested in the towing tank by Sun. The experimental results can be used to validate numerical algorithms. The simulation test mainly verifies the applicability of improved method to different loading conditions. The B_m is selected as the constant value of beam for simplified hull. Main characteristics of hull forms are shown in Tab. 2.

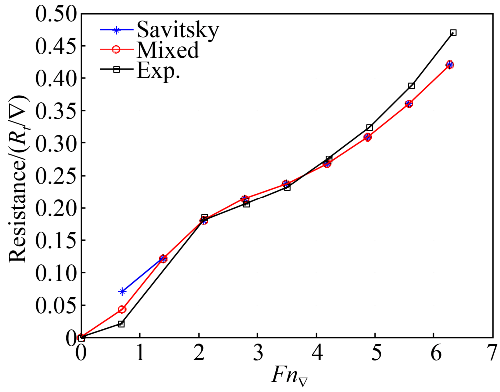
Tab. 1 Main dimensions of the first group of models

Dimension	Model 1	Model 2	Model 3
L_{OA}/m	0.927	1.092	1.123
L_{WL}/m	0.796	1.026	1.072
B/m	0.308	0.308	0.292
D/m	0.080	0.087	0.072
M/kg	9.103	9.467	9.467
L/B	2.586	3.334	3.872
$\beta_{A.P.}$/deg	20	17	20
$\beta_{mid.}$/deg	23	30	22
$B_{F.P.}$/deg	32	80	75

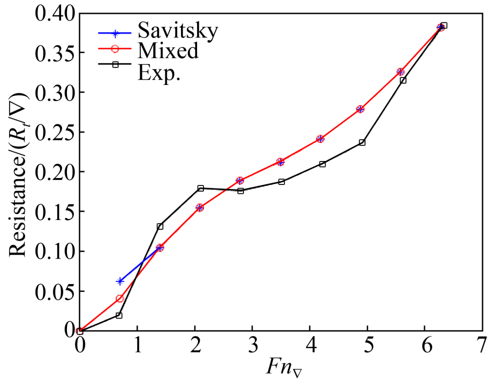


(a) Model 1

第 31 卷第 11 期　　系统仿真学报　　Vol. 31 No. 11
2019 年 11 月　　Journal of System Simulation　　Nov., 2019



(b) Model 2



(c) Model 3

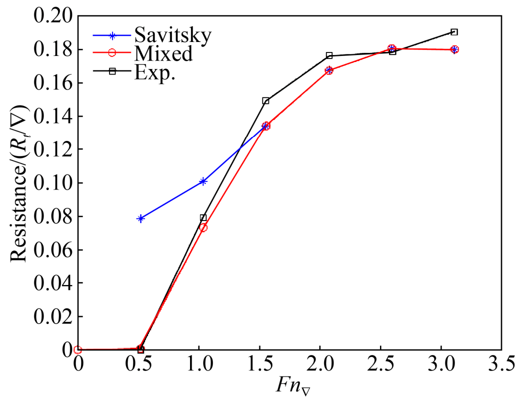
Fig. 3　Comparison of resistances calculated in different methods for the first group of models

Tab. 2　Main dimensions of the second group of models

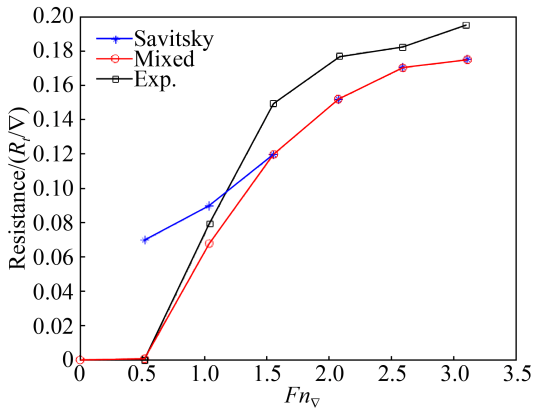
Dimension	Model 4	Model 5
L_{OA}/m	2.2	2.2
B/m	0.73	0.73
B_m/m	0.43	0.43
D/m	0.125	0.125
m/kg	55.8	55.8
LCG/%	75	79
β/deg	13.6	13.6

$0.5 < Fn_∇ < 1.5$ is a suitable interval of pre-planing regime. The same numerical test is made for the second group of models. The results are shown in Fig. 4.

There are large differences of hull forms among all test models. And it is obvious from Fig. 3 and Fig. 4 that Savitsky method has good results for all simplified models in planing regime. However, it cannot be applied to displacement regime, which can be proved by both equations and simulation results. As for pre-planing regime, Savitsky method is just suitable for some special models such as model 2 and model 3. The error of model 4 and model 5 is quite large. The improved method solves the problem in the Savitsky method. The resistance curve is in good agreement with the experimental curve in all speed domain. This method also has satisfactory results for different hull forms.



(a) Model 4



(b) Model 5

Fig. 4　Comparison of resistances calculated in different methods for the second group of models

Generally, $0.8 > Fn_∇ > 2.0$ is an appropriate interval for most ships. The range of $Fn_∇$ can be adjusted by simulation to achieve the best results. The weighted factors are determined by hydrodynamic characteristics of ships. All simulation results show that the improved method has high accuracy resistance calculation to all ship models.

2.2 Manoeuvring test

The maneuverability of yacht is the most important indicator of yacht simulator. It shouldn't be affected while changing the calculation method of the resistance. A real ship is selected to discuss the impact of improved method on maneuverability. Both real ship experiment and model test were studied by Muhammad[16].

The main characteristics of hull shapes are shown in Tab. 3.

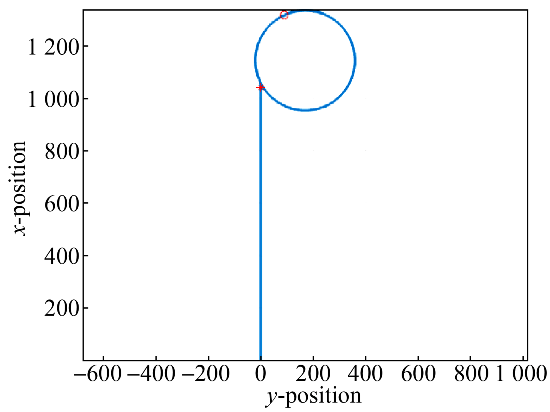
Tab. 3　Main dimensions of the real ship

Dimension	Ship
L_{OA}/m	22
B_m/m	4.906
D/m	1.243
m/kg	55.16
LCG/%	0.41
β/deg	22.9
C_b	0.435
Designed Speed/(m/s)	7.71

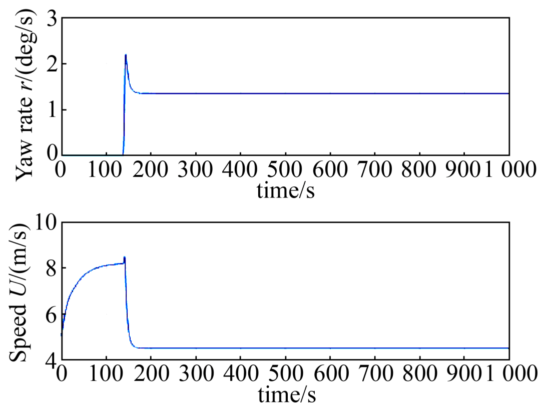
The hydrodynamic derivatives are measured by PMM test. The only difference between traditional method and improved method is the calculation way of resistance. All the derivatives and parameters of rudder and propeller can be found in Muhammad 's research.

The speed test, turning test and zigzag test were carried out using a time domain simulation. The simulation results are shown in Fig. 5~7. The summaries of the comparisons are shown in Tab. 4~6.

Fig. 5 shows the path and speed of the turning test. The results and comparisons are shown in Tab. 4. The improved method has better performance than traditional method in speed test. The simulation accuracy of speed is increased 3.8%. The tactical diameters of both methods are almost the same. Improved method only increases 0.1% in simulation accuracy.



(a) Path of 35° turning



(b) Speed of 35° turning

Fig. 5　Results of 35° turning manoeuvre simulated

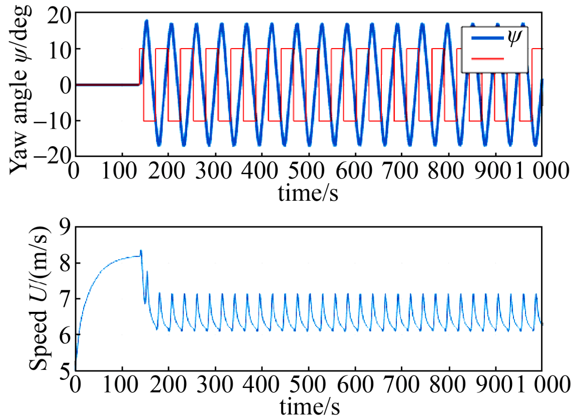
Tab. 4　Summary of 35° turning manoeuvre simulated

Parameter	Real Ship	Traditional method	Improved method
Speed/(m/s)	7.71	7.01	8.12
Error/%	0	9.1	5.3
Tactical diameter/m	342.5	341.12	341.34
Error/%	0	0.4	0.3

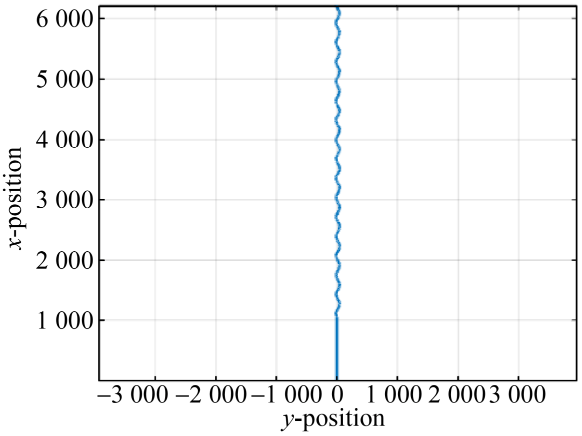
Fig. 6~7 are the results of zigzag test of different rudder angles. It is obvious from the table that both methods have large error. But the simulation results are very close. This is because maneuverability accuracy of yachts is mainly influenced by hydrodynamic derivatives. The resistance has little effect on the manoeuvre results. Actually, the improved methods improve the accuracy of speed and have no influence on yacht maneuverability.

https://dc-china-simulation.researchcommons.org/journal/vol31/iss11/9
DOI: 10.16182/j.issn1004731x.joss.19-FZ0303E

第 31 卷第 11 期 2019 年 11 月
系统仿真学报
Journal of System Simulation
Vol. 31 No. 11 Nov., 2019

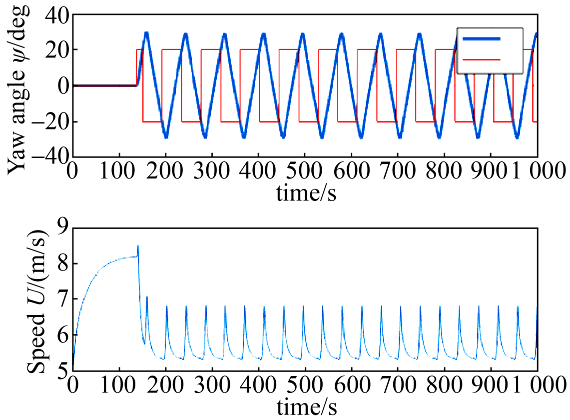


(a) Yaw angle and speed of 10°/10° zigzag

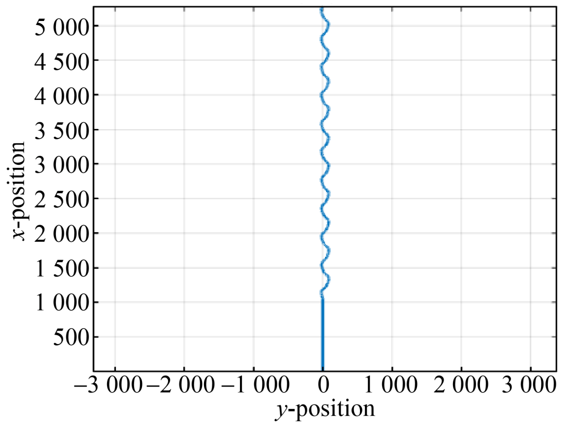


(b) Path of 10°/ 10° zigzag

Fig. 6 Results of 10°/10° zigzag manoeuvre simulated



(a) Yaw angle and speed of 20°/20° zigzag



(b) Path of 20°/20° zigzag

Fig. 7 Results of 20°/20° zigzag manoeuvre simulated

Tab. 5 Summary of 10°/10° of zigzag manoeuvre simulated /deg

First overshoot angle 10/10			Second overshoot angle 10/10		
Real ship	Traditional method	Improved method	Real ship	Traditional method	Improved method
4.7	7.6	7.9	6.7	7.3	7.1
Error/%	61.7	68.1	Error/%	9.0	6.0

Tab. 6 Summary of 20°/20° of zigzag manoeuvre simulated /deg

First overshoot angle 20/20			Second overshoot angle 20/20		
Real ship	Traditional method	Improved method	Real ship	Traditional method	Improved method
7.2	9.9	10.1	7.5	9.4	9.4
Error/%	37.5	40.3	Error /%	25.3	25.3

Fig. 8 are the yacht simulator systems. The same theory is reproduced in C++ program in yacht simulator systems to verify its practicability. Newton method and fourth order Runge-Kutta method are used to solve the functions. The time step of numerical method is 500ms in system. The actual computation time of one step in this research is less than 1ms, which means it can meet the requirement of fast simulation.

(a) Six degrees of freedom hydraulic platform

(b) Yacht simulator

Fig. 8 Yacht simulator systems

3 Conclusion

In view of the analysis and validation process undertaken in this research, the following conclusions can be drawn:

Prismatic hull simplified method is suitable for most of hull forms. The simulation accuracy is satisfactory as long as appropriate simplified parameters are chosen.

Different ships have different Fn_∇ interval of pre-planing regime. These parameters are determined by ship hydrodynamic performance. Some test need to be taken to find a suitable Fn_∇ range.

The improved method has better performance on speed simulation than the old method. And it has no influence on the maneuverability of yacht.

The computational efficiency of the improved method is sufficient to support fast simulation. This is extremely important for yacht simulator.

The new method improves the simulation accuracy of the yacht simulator.

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