Parametric Studies of Hydrodynamic Performance of the Control Fins on SWATH Ships

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Abstract

In order to facilitate the offshore wind farm constructions and future maintenance, developments and operations of the support vessels for personnel transfer become one of the important issues. Considering seaworthiness and safe operations, the SWATH (Small Water Area Twin Hull) ship is one of the selections since it has the advantages of small tonnage and excellent seakeeping performance. In this paper, parametric studies of hydrodynamic performance of the control fins on SWATH ships will be carried out, and these control fins are used as providing hydrodynamics forces of the ride control system. The resistance of a SWATH ship in calm water is first computed by both potential flow and viscous flow RANS methods, and compare to the experimental data. Good agreements between the numerical results and experimental data are obtained. The ship motions of this SWATH ship with and without control fins are then computed by both potential flow methods and viscous RANS method to verify the accuracy of computations. Once the accuracy of these computations are verified, the parametric studies are carried out. A perturbation potential based, unsteady flow boundary element method to solve the control fin motion problem in time domain is developed. In this method, the ship motions of the SWATH ship are first computed, and then transferred into the inflows of the control fins, and an unsteady flow problem is solved by time marching scheme. The effectiveness of control fin geometries thus can be investigated by parametric studies. After parametric studies, several control fin geometries are selected for the viscous flow computations for verification purpose. The presented parametric study procedure is an efficient way to design the control fin geometries considering hydrodynamics, and the control scheme can also be included for investigating the effectiveness of control algorithms.

Keywords: SWATH, control fin, resistance, seakeeping, RANS, BEM

1. Introduction

In order to facilitate the offshore wind farm constructions and future maintenance, developments and operations of the support vessels for personnel transfer become one of the important issues. Considering seaworthiness and safe operations, the SWATH (Small Water Area Twin Hull) ship is one of the selections since it has the advantages of small tonnage and excellent seakeeping performance. In developing SWATH, seakeeping problem caused by wave exciting forces is always an issue that can't be avoided. At present, the mechanism for motion control includes control fins, anti-rolling tanks, gyroscope stabilizers and rudders, etc. Among these, control fins are the most widely used devices for reducing the wave induced motions. In recent development, the control fins can reduce vertical acceleration of the vessel by 50% to 60%. The research and development of the motion control of the high-speed SWATH includes many issues. This paper applies the potential flow and viscous flow methods to calculate the forces and balance of the ship's motion and control fins. First, potential and viscous flow methods are used to compute the ship resistance and motion, and the results are verified with the experimental data. Secondly, the flow field of viscous flow simulations is converted into control fin's inflow and solve it through the unsteady boundary element method based on perturbation potential. Finally, the geometries of control fins are changed under a fixed projected area. The above-mentioned unsteady boundary element method is applied to evaluate the efficiency of control fins, and the viscous flow is used to verify the evaluation result.

Compared to mono-hull ships of the same tonnage, twin-hull vessels have larger space and the slender hull makes the resistance relatively small. However, when the sea is rough, the pitch and roll motion of the hull may easily cause discomfort to the passengers, which limits the advantage that the catamaran can have high stability only in calm sea. In 1938, Creed proposed the concept of a platform for aircraft operations, but it was not adopted by the US Navy. In 1968, the US Navy proposed the first small water-plane area twin-hull ship project which was generated by Lang (1989). It exactly defines SWATH as a small water-plane area twin-hull. SWATH consists of two submerged lower hulls, the upper deck and two stream-lined struts, which connect between lower hulls and upper deck, and two pairs of control fins, one pair is at bow and the other is at stern. In 1973, the world's first SWATH---SSP KAIMALINO launched. It consists of torpedo-liked submerged hull, providing the base of streamlined struts which support the cross structure. The location near the bow is equipped with two controllable canards to assist the motion control and stabilization of the fins. Full-span stabilizer fins located near the stern has two control flaps to resist the Munk Moment and provide dynamic pitch stability. Several model tests during the design phase and full-scale investigation have verified its excellent seakeeping performance and laid the foundation for the development of SWATH. The test results also have proved that the instability of SWATH during pitch motion. Hence, stabilizing fins are in needs to provide the stability under high-speed condition. This instability is caused by the smaller pitch period of SWATH in the waves. Lee et al. (1974) proposed a method for determining the size of stabilizer fins to maintain the stability of pitch motion under high-speed navigation. The design of stabilizer fins is based on the stability of coupled pitch and heave motion. In addition to demonstrating that the stabilizing fins does improve the sailing performance of SWATH, and it has also been found that the ship equipped with forward and backward fins is more stable than the backward fins only. Kihara (2008) developed fin control design system makes effective use of the negative restoring moment for better pitch stability.

In order to pursue better seaworthiness, many scholars have invested in the method of predicting the dynamic characteristics of SWATH at the design stage. Lee (1977) proposed a method for predicting motions, vertical stability, and wave loading in waves. Under the potential flow assumptions, the utilizations of strip theory, empirical methods, and slender-body theory are presented to the motion equation for motion prediction in waves. With the advancement of technology, numerical simulations have been used for the hydrodynamic computation of SWATH. Krishna et al. (2014) have computed the resistance and dynamics of SWATH by CFD tool, SHIPFLOW, and evaluated the motion characteristics of SWATH through the analysis software SEDOS based on the strip theory. Begovic, Bertorello and Mancini (2015) have used the CFD commercial software StarCCM+ to perform the resistance, self-propulsion, and motion simulations of SWATH in calm water under with and without pitch and heave conditions. This research confirms the feasibility of CFD as an evaluation tool during the preliminary design phase, as well as the correction of pitch and control of the stabilizer fin at high speed.

2. Resistance computation and verification

Table 1 The particular dimensions and the computational conditions of SWATH6A models

Main Features	Model scale (1:22.5)
Displacement(m^3)	0.246
L_{WL} (m)	2.33
L_{OA} (m)	3.250
Draft(m)	0.359
Beam of Each Hull at the Waterline(m)	1.018
Transverse Strut Separation (m)	1.020
Max Diameter of Main Hull(m)	0.204
Transverse GM(m)	0.129
Longitudinal GM(m)	0.302
Radius of Gyration for Pitch(m)	0.75
Radius of Gyration for Roll(m)	0.45
V_m (m/s)	2.168
Fn	0.384

Table 2 The particular dimensions of SWATH6A Fins

Fin Section NACA 64-015				
	Chord (m)	Span (m)	Max. Thickness (m)	1/4 Chord Pivot (m)
Forward Fin	0.115	0.138	0.017	0.034
Afterward Fin	0.199	0.238	0.030	0.123

In this paper, we select SWATH 6A ship type as our main research and analysis object for resistance verification. SWATH 6A is an open ship type, there are more experimental data to compare. Table 1 and Table 2 present the particular dimensions of SWATH6A model and Fins. Fig.1 shows that (a) abbreviated lines of SWATH 6A model (b) bare hull of SWATH 6A model (c) SWATH 6A model with control fins.

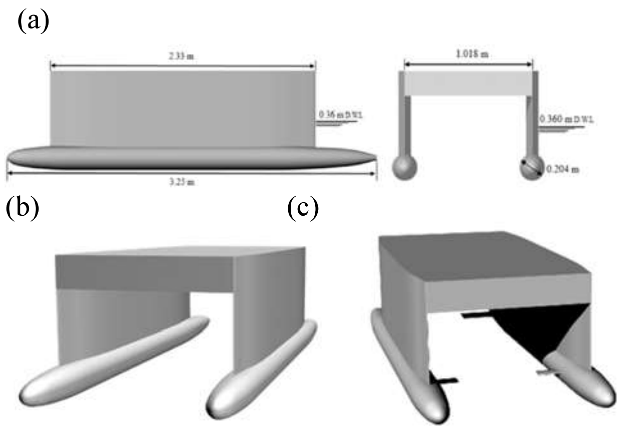

Fig. 1 (a) Abbreviated lines of SWATH 6A model (b) bare hull of SWATH 6A model (c) SWATH 6A model with control fins

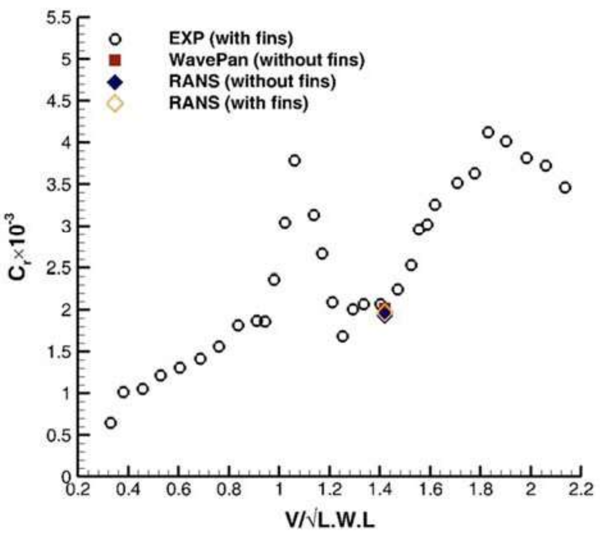

Fig. 2 Comparison of residuary resistance coefficients among potential flow method, viscous flow method and experiment for SWATH 6A

First, we compute the residuary resistance with potential flow wave-making resistance program WavPan and RANS software Star CCM+, and then compare the results with experimental values. The experimental data are compiled by Yeh and Neal (1977), as shown in Fig. 2, where the horizontal axis is $V/\sqrt{L.W.L}$, here, V is the ship speed, $L.W.L$ is the length on waterline, and the vertical axis is the residuary resistance coefficient ($C_R \times 10^{-3}$). In order to understand the influence of the control fins on the resistance in calm water, we calculated the conditions with and without the control fins. Under the condition without the control fins, since the experimental data only has the resistance value with the control fins, we use WavPan and RANS to verify each other, and the error is 4.268%. Under the condition with the control fins, the comparison between RANS and the experimental data is made, and the error is 7.129%. From Fig. 2, it can be seen that the residuary resistance with the control fins under RANS is slightly higher than that without the control fins, because the control fins only accounts for a small proportion of the total volume. Therefore, whether the condition with or without control fins has little effect on the residuary resistance. We then directly use the experimental data as an error analysis for WavPan and RANS without control fins. The error of WavPan is 4.9%, and the error of RANS error is 8.9%. Both the errors are less than 10%. Hence, although the calculations of WavPan and RANS are different, they still have credibility

3. Motion computation and verification

We still use the SWATH 6A ship for the simulations and verifications of the motions. The potential flow method and the viscous flow method are used for the motion calculation in the regular wave, and verifications. Finally, we will observe the flow field from the viscous flow calculations.

3.1 Computation of potential flow method

SWA-SMP is a potential flow program, modified from the strip theory of mono-hull, and is specially used to calculate the motion of a SWATH in waves. In order to verify the accuracy and reliability of the SWA-SMP, verification was performed using SWATH 6A, where the calculated ship speed was 2.168 m/s , the wave steepness was $1/60$, and the inflow angle was 180 degrees. The results are compared with the experimental data (Kallio 1977). Fig.3 and Fig.4 are the comparison results of SWA-SMP and the experimental data of the heave and pitch response amplitude operator (RAO) with control fins. Where the horizontal axis is λ / L_{pp} , λ is the wavelength, L_{pp} is the length of the ship, and the vertical axis is the Heave RAO and Pitch RAO, respectively. The definitions are as follows:

$$\text{Heave RAO} = \frac{\text{Amplitude of Heave Motion}}{\text{Amplitude of Incoming Wave}} \tag{1}$$

$$\text{Pitch RAO} = \frac{\text{Amplitude of Pitch Motion}}{\text{Wave Number} \times \text{Amplitude of Incoming Wave}} \tag{2}$$

From Fig.3 and Fig.4, we can see that when λ / L_{pp} is between 3 and 7, the SWA-SMP calculation results are similar to the experimental data. Response amplitude operator will gradually increase as λ / L_{pp} increases, and will produce a maximum when λ / L_{pp}

is between 4 and 6. Table 3 and Table 4 show the computational error of SWA-SMP with control fins. In order to compare the error with the experimental values, the numerical values in Table 3 and Table 4 are interpolated from the SWA-SMP calculations in Fig.3 and Fig.4, and the errors are define the error as Eq.3. The dynamics range we select is the values between 0 and the largest experimental values.

$$Error(\%) = \frac{|\text{Exp.Value-Com.Value}|}{\text{Dynamic Range}} \times 100(\%) \qquad (3)$$

where Exp. Value is experimental value and Com. Value is computational value. Dynamic Range is the difference between the maximum in the experimental data and 0. This definition can avoid the situation where the data is too small, leading to an error amplification. As can be seen from Table 3 and Table 4, the maximum errors of heave and pitch motion are 15.88% and 12.86% respectively. It can be seen that SWA-SMP gives reasonable predictions.

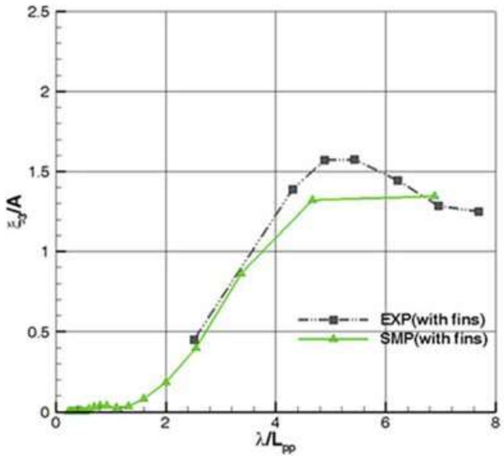

Fig. 3 Heave RAO comparison between SWA-SMP results and experimental data.

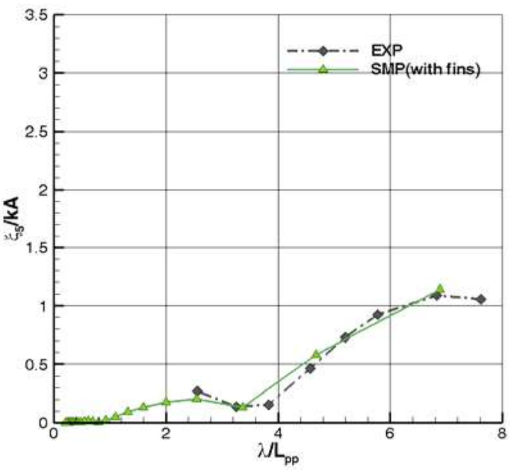

Fig. 4 Pitch RAO comparison between SWA-SMP results and experimental data.

Table 3 Computational errors of the heave RAO with control fins.

λ / L_{PP}	2.51	4.31	4.89	5.20	6.22	6.96
EXP	0.450	1.387	1.573	1.574	1.445	1.286
Strip Theory	0.384	1.194	1.323	1.326	1.337	1.345
Error(%)	**4.19**	**12.26**	**15.88**	**15.76**	**6.86**	**3.75**

Table 4 Computational error of the pitch RAO with control fins.

λ / L_{PP}	2.56	3.26	3.83	4.56	5.20	5.77	6.96
EXP	0.268	0.138	0.152	0.463	0.730	0.924	1.089
Strip Theory	0.202	0.142	0.292	0.545	0.717	0.860	1.148
Error(%)	**6.06**	**-0.37**	**-12.86**	**-7.53**	**1.19**	**5.88**	**-5.42**

3.2 Computations of motions in regular waves

We have validated the computational results of SWA-SMP in last section. In this section, RANS and SWA-SMP are used to estimate heave and pitch motions with or without control fins. Fig.5 and Fig.6 show the calculated results without the control fins, and Fig.7 and Fig.8 show the calculated results with the control fins. The wave steepness of the regular wave was 1/60, and the inflow angle was 180 degrees. The wave steepness is defined as $2A/\lambda$, where A is the amplitude, and λ is the wavelength.

Fig.5 is a comparison of numerical simulations of the heave RAO without control fins. Fig.6 is a comparison of numerical simulations of the pitch RAO without control fins. The horizontal axis is λ / L_{pp}, and the vertical axis is the heave RAO and pitch RAO. From Fig.5 and Fig.6, it can be observed that the heave and pitch motions of the two methods are similar. For λ / L_{pp} between 4 and 6, the heave and pitch RAO have a maximum value. Fig.7 and Fig.8 are the comparison results of the numerical simulations of the heave and pitch RAO with control fins. Table 5and Table 6 show the computational errors of RANS computations of the heave and pitch RAO with control fins. In order to compare the error with RANS, the values calculated from the SWA-SMP in Fig.7 and Fig.8 are also interpolated and listed in Table 5 and Table 6, and the errors are also obtained by using the Dynamic Range method.

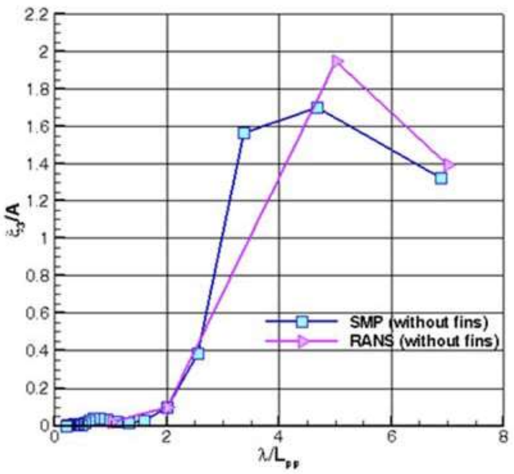

Fig. 5 Comparison of the Heave RAO without control fins from strip theory and RANS method

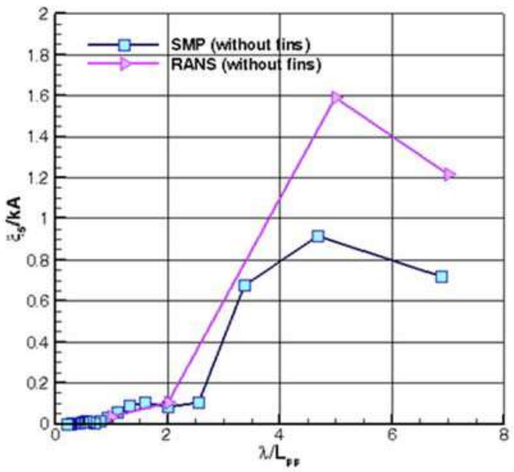

Fig. 6 Comparison of the Pitch RAO without control fins from strip theory and RANS method

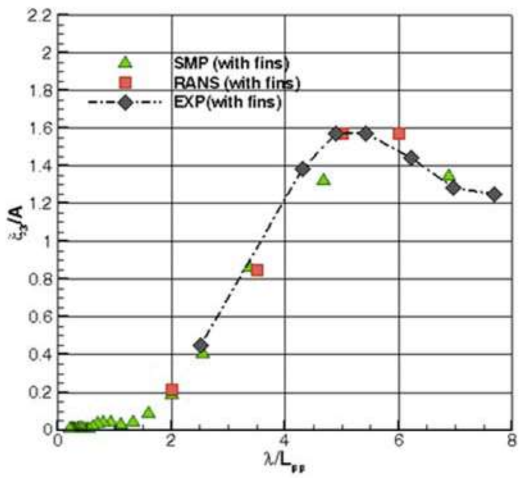

Fig. 7 Comparison of the Heave RAO with control fins from strip theory, RANS results and experimental data

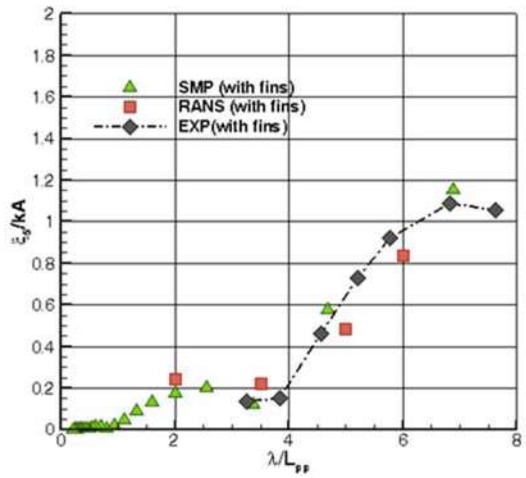

Fig. 8 Comparison of the Pitch RAO with control fins from strip theory, RANS results and experimental data

Table 5 Errors of the numerical simulations of the heave RAO with control fins. The table is obtained by interpolating values from Fig.7.

λ / L_{PP}	2.00	3.50	5.00	6.00
EXP	0.188	0.966	1.573	1.480
Strip Theory	0.186	0.907	-	-
Error(%)	**0.13**	**3.75**		
RANS	0.213	0.849	1.573	1.571
Error(%)	**-1.59**	**7.44**	**0.00**	**-5.79**

Table 6 Errors of the numerical simulations of the pitch RAO with control fins. The table is obtained by interpolating values from Fig.7.

λ / L_{PP}	2.00	3.50	5.00	6.00
EXP	0.372	0.144	0.645	0.961
Strip Theory	0.175	0.177	-	-
Error(%)	**17.91**	**-3.00**		
RANS	0.245	0.221	0.485	0.837
Error(%)	**11.55**	**-7.00**	**14.55**	**11.27**

From the above computational results, we can find that both numerical methods have better predictions for heave motion. By comparing the results from witt and without fins, we find that the maximum value is when λ / L_{pp} is between 4.0 and 7.0, so it can be inferred that resonance occurs in this range. In addition, the heave and pitch RAO with control fins are smaller than that without control fins in this interval. We believe that the control fins effectively reduces the motion of SWATH in the resonance zone and has higher stability during navigation.

4. Control fins performance evaluation and verification

The use of stabilizer fins can reduce motions of a SWATH in rough sea. The after-ward fins provide major vertical stability, and the larger area is, the greater the stability provided. However, when the area exceeds a certain value, the stability of the heave decreases, and the difference between the pitch and heave motions during the natural period also increases. For better performance, the forward fin was added to increase the damping of the heave motion. The combination of the forward and after-ward fins further optimizes the sailing performance of the SWATH hull in the wind and waves, but it also generates a pitching moment so that the stability of the pitch decreases as the speed increases. In order to effectively estimate the motion characteristics of a SWATH equipped with stabilizer fins. We first verify the consistency between the potential flow and the viscous flow method. We then try to find control fin shapes that have higher stability by parametric studies. An unsteady boundary element method is used for simulating control fins for parametric studies, and the inflow of fins is obtained from RANS computations.

This section mainly evaluates the fin performance of different shapes under the same area. Fig. 9 shows the original control fin geometry, where the left picture is a three-dimensional schematic diagram and the right diagram is a top view diagram. The control fins in the figure is bounded by the x-axis, connecting the hull and defining the bow in the -x direction. In the subsequent evaluation, the foil at the joint between the control fins and the hull was fixed, and change the control fins shape under the fixed area. We made the following parametric studies:

- First, we changed the rake so that the original rectangle's projected area shows a parallelogram with different degrees of steepness. By using the leading edge and the trailing edge of the top view as a base line, the rake is changed so that the control fins sweeps forward and backward. Fig10 is a top view of the control fins with different rakes. The rake of the top three charts is positive and the bottom is negative. From left to right, they are 0.5, 1, and 1.5, respectively.

- Under the constraints of equal area, change the upper line and height of the trapezoid. Fig.11 shows a plan view of the different trapezoidal control fins. The length of the upper line is gradually reduced from left to right and named A, B, and C. Then, the trapezoid of Fig.11 shows shapes of Fig. 10 symmetrical about the y axis, as shown in Fig.12. From left to right, the corresponding -A, -B, and -C are named.

- Finally, it's the fish-liked type, based on tuna fins (Fig.13), the foil at the joint between the control fins and the hull was also fixed, and according to Fig.15, 2nd dorsal fins is selected as the design, as shown below in Fig.14, and was named fish-liked AA type.

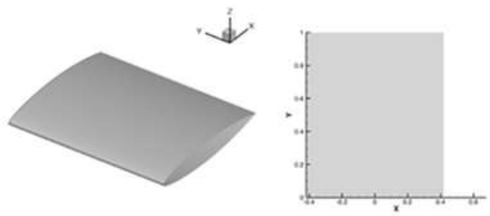

Fig. 9 The original control fin, the left one is a three-dimensional schematic diagram, and the right one is its top view.

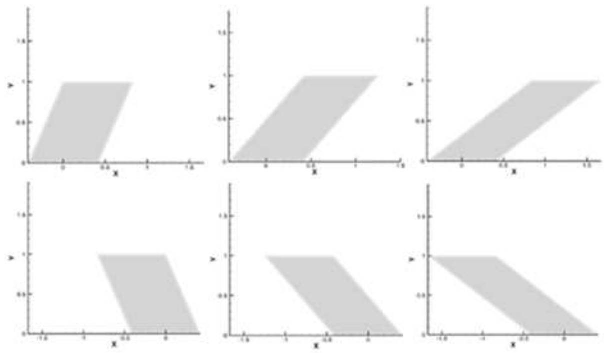

Fig. 10 Top view of the control fins with different rakes, and the slopes from top left to bottom right are 0.5, 1, 1.5, -0.5, -1 and -1.5

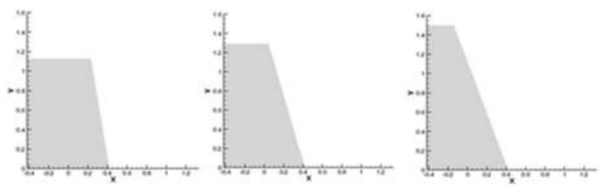

Fig. 11 Top view of trapezoid type control fins, from left to right were named as A, B, and C

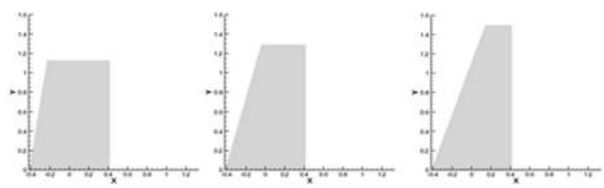

Fig. 12 Top view of trapezoid type control fins, from left to right were named as –A, -B, and -C

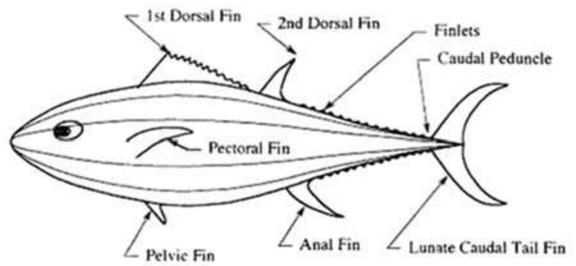

Fig. 13 Tuna diagram (Barrett 1994)

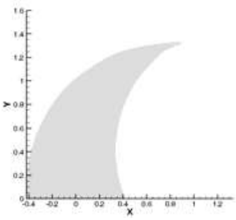

Fig. 14 Top view of the fish-liked type control fins, named as AA

According to the SWATH 6 series experimental report by James A. and Kallio (1976), it is necessary to use moving ballast water to give a pitch moment and flap angle of attack before making a regular wave motion experiment. The hull in calm water thus can maintain the running trim at zero, otherwise the hull will tend to trim by bow. We used unsteady boundary element method to calculate forces of different design fins at different angles of attack. The goal is to reduce the pitching moment caused by the forward and afterward fins and use it as an assessment benchmark.

The following figures show the results of forces in z-direction of different shapes, which are the forces at angles of attack 0, -2.5 and -5 degrees in one cycle. Figs.15~17 are the forces in the z-direction of the afterward fins of the rake, trapezoid and fish-liked type during one cycle. It can be clearly seen that the force magnitude varies with the angle of attack, and the greater the negative angle of attack, the greater the negative lift. In order to reduce the tendency of trim by bow, we consider the fins that will provide a larger negative lift as an effective design. Therefore, we further average the negative lift of the entire cycle. Fig. 18 shows the average force in the z direction at different angles of attack. From the figure, it can be found that the rake type has the smallest negative lift, and the trapezoid and the fish-liked type are relatively larger. Among them, the negative lift provided by the trapezoid –C type, trapezoid C type, and fish-liked AA type with the angle of attack of -5 degrees are three largest ones. In addition, at the zero angle of attack, it can be found that the average force of the z-directions of each model is almost the same due to equal area.

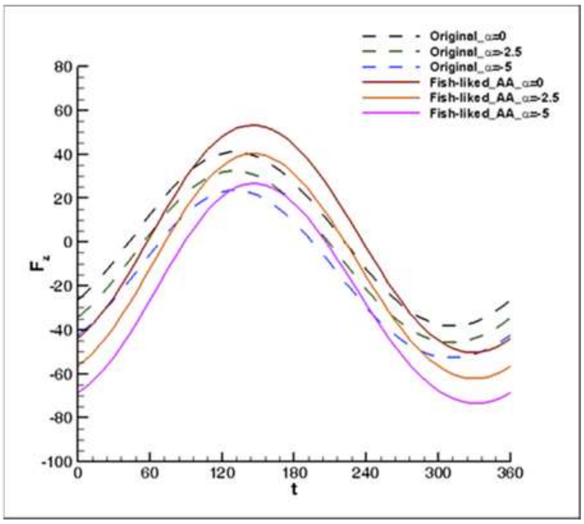

Fig. 15 Computational results of z-direction force of rake type control fins at different angles of attack

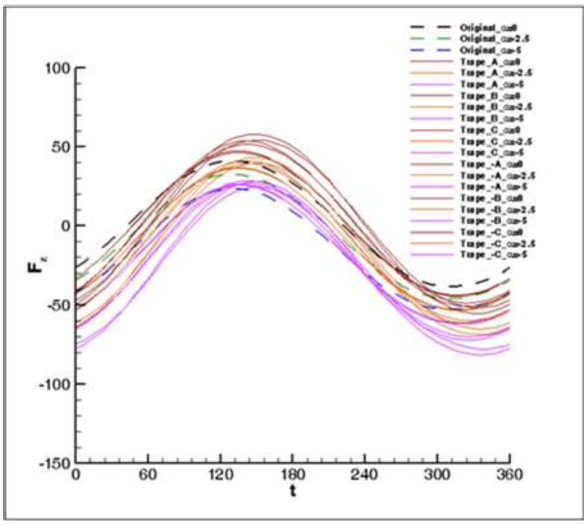

Fig. 16 Computational results of z-direction force of trapezoid type control fins at different angles of attack

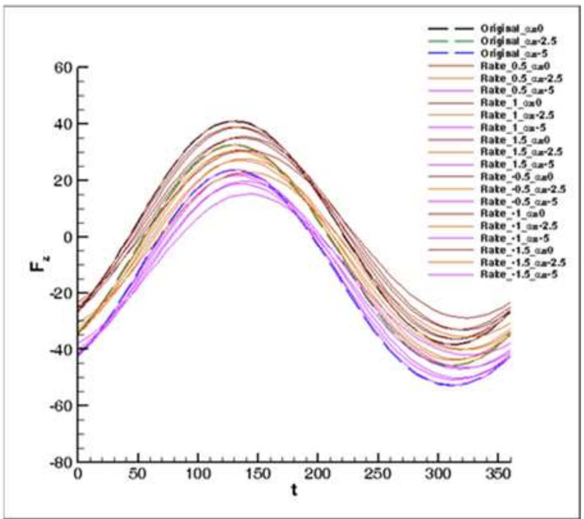

Fig. 17 Computational results of z-direction force of fish-liked type control fins at different angles of attack

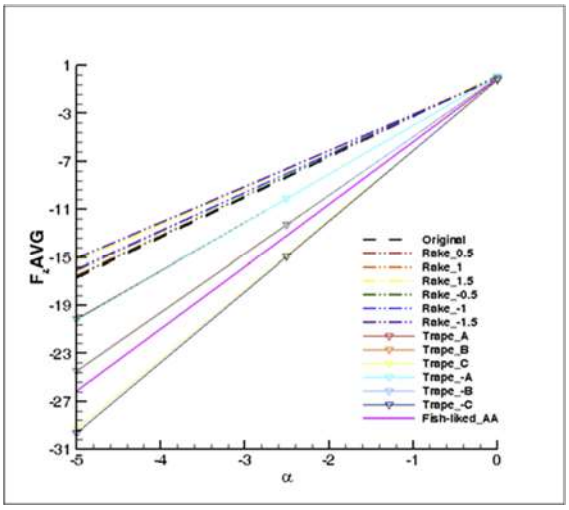

Fig. 18 Comparison of average z-direction force average for all types of control fins at different angles of attack.

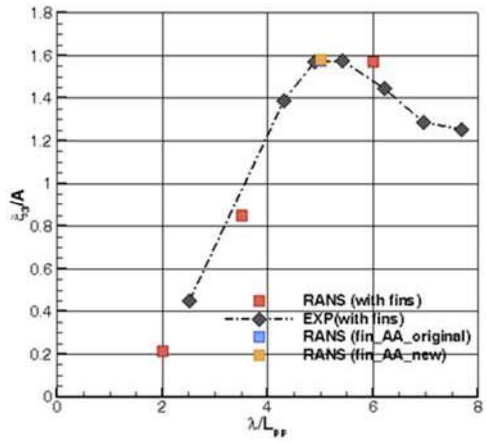

Fig. 19 Comparison of numerical simulations of heave RAO of original design, fish-liked AA and experiment under different feedback moments

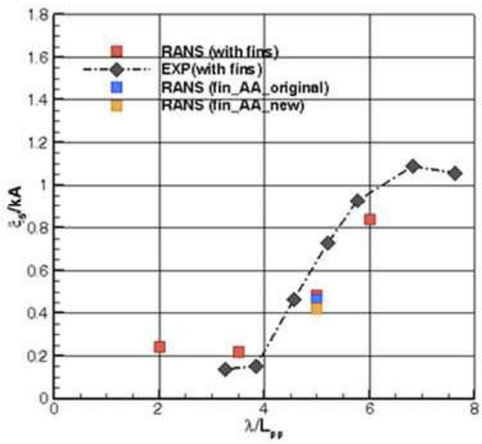

Fig. 20 Comparison of numerical simulations of Pitch RAO of original design, fish-liked AA and experiment under different feedback moments

As can be seen from the geometric parameters of SWATH 6A in Table 1, the control fin length can be installed between two hulls is limited. When varying the geometric parameters of the afterward fins, not only the span of the fins is only limited by the hull spacing, but also the mutual interference of the tip vortices generated by two afterward fins needed to be avoided. However, the extent to which this interference phenomenon may affect is unknown. Therefore, except improving the tendency to trim by bow, and to providing maximum negative lift, the criteria for selecting the optimal design also need to meet the constraints of the parameters of the span. To satisfy both goals, we evaluated the fish-liked AA type at an angle of attack of -5 degrees as the best design, because it can provide larger negative lift and the span is smaller and more conservative than the trapezoid C and -C types.

Finally, we verify whether the evaluation results can effectively improve the performance of SWATH in waves. We equipped SWATH models with the fish-liked type with an angle of attack of -5 degrees on the afterward fins. Using the viscous flow method to calculate it in the regular wave, where the wave steepness was 1/60, the inflow angle was 180 degrees, and λ / L_{PP} is 5. In the calculations, we respectively take the feedback moment of the original design used to maintain the zero pitch angle of the navigation, and the new feedback moment of the fish-liked AA type, and compared with the results of the original design of afterward fins. Fig.21 and Fig.22 show comparisons of numerical simulations of the heave and pitch RAO of the original design and the fish-liked AA type with different feedback moments. In heave motion, the use of the fish-liked AA type afterward fins did not have a significant effect, and the two feedback moment results were slightly higher than the original design. In pitch motion, regardless of the original or new feedback moment, the fish-liked AA type afterward fins are effective in reducing pitch motions.

5. Conclusion

In this paper, based on the computational results of the potential flow and viscous flow method, the resistances and motions of a SWATH ship are first investigated, and the parametric studies were carried out for studying the effectiveness of different control fin geometries. We have the following conclusions:

1. When there are control fins, the calculated results of the two methods are similar to the experimental values. The control fins have little

effect on the residuary resistance.

2. In heave and pitch motions, the trend of the calculated results of the two methods is similar to the experimental value. When λ / L_{PP} is between 4.0 and 7.0, the maximum response amplitude is generated due to the resonance of waves and SWATH.
3. Control fins can reduce resonance and help reduce the effect of waves on SWATH.
4. Both potential flow strip method and RANS method give reasonable prediction of pitch and heave motions.
5. From parametric studies of the control fin geometries, we found that:
   (1) The maximum negative lift of different shapes increases with the negative attack angle, in order of attack angle -5 degrees, -2.5 degrees, 0 degrees.
   (2) The negative lifts of all rake type control fins in any angle of attack are less than the original design
   (3) The negative lift of all trapezoid type control fins in any angle of attack are greater than the original design. Among them, the -C type has the largest negative lift.
   (4) The negative lift of the fish-liked type control fins in any angle of attack are greater than the original design.
   (5) Trapezoid and fish-liked type control fins are better than rake type.
6. It was verified from viscous flow calculations that the fish-liked AA type fins effectively reduced SWATH's pitch motion under regular waves. However, it slightly increased the heave RAO.

In this paper, we have established a potential flow method for evaluating the effectiveness of control fins, and results were verified by RANS method. In the future, we will conduct further analysis and verification of this method, and expect that this method can be applied to the analysis of different control fins during the design phase.

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