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Hydrodynamic characteristics of X-Twisted rudder for large container carriers

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ABSTRACT: *This paper shows the numerical and experimental results about the hydrodynamic characteristics of X-Twisted rudders having continuous twist of the leading edge along the span. All the results were compared with those of the semi-balanced rudder. Calculation through the Reynolds-Averaged Navier-Stokes Equation (RANSE) code with propeller sliding meshes shows large inflow angle and fast inflow velocity in the vicinity of ±0.7 R from the shaft center, so it may cause cavitation. Also, X-Twisted rudder has relatively small inflow angles along the rudder span compared with semi-balanced rudder. For the performance validation, rudders for two large container carriers were designed and tested. Cavitation tests at the medium sized cavitation tunnel with respect to the rudder types and twisted angles showed the effectiveness of twist on cavitation and the tendency according to the twist. And the resistance, self-propulsion and manoeuvring tests were also carried out at the towing tank. As a result, in the case of X-Twisted rudder, ship speed was improved with good manoeuvring performance. Especially, it was found out that manoeuvring performance between port and starboard was well balanced compared with semi-balanced rudders.*

KEY WORDS: X-Twisted rudder; Large container carrier; Cavitation; Inflow angle; Reynolds-Averaged Navier-Stokes Equation (RANSE) code; Cavitation test; Resistance and self-propulsion test; Manoeuvring test.

INTRODUCTION

The purpose of a rudder is to generate sufficient side force to maintain the ship on a straight course, and to control the course of the ship. Because a stern rudder is more effective than a bow rudder in course change in motion ahead, the rudder is placed at the stern. To enhance the effectiveness of the rudder, it is placed behind the propeller stream, where the flow is accelerated. However, this accelerated inflow often leads to an increased danger of cavitation on the propeller and rudder. The cavitation leads to possible surface erosion, and disturbs the flow along the surface, changes the effective profile properties, and reduces lift force if the cavitation causes a complete separation of flow from the suction side. And since rudder shape is not symmetrical with respect to the propeller slip-stream, non-symmetric hydrodynamic characteristics occur and the try to keep the neutral rudder angle to maintain a straight course as small as even possible is needed.

Nowadays, as national trading volumes continue to increase, a major trend for ship design is to seek bigger, faster and more economical vessels. According to this trend, ship size and the required engine power are increasing. However, while increasing engine power, ship owners, having regard to the cost and the overall efficiency, prefer a single screw vessel to a twin screw vessel. Thus, propeller loading increases, and new hydrodynamic problems such as cavitation of propeller and rudder have resulted.

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Since the 1950s, most large vessels have adopted the semi-balanced rudder having a horn structure for structural support to bear the spanwise bending moment (Mandel, 1953). For this semi-balanced rudder, cavitation problems are inevitable due to the gap between horn and rudder. There have been many attempts to resolve this problem. Nishiyama (1975) showed the empirical formula of inflow angle and the effectiveness of reaction rudder (twisted rudder) as the preventive measure on rudder cavitation. At the 24th ITTC in 2005, several methods to reduce rudder cavitation were introduced. The first is changing the rudder section to reduce cavitation. The NACA 64 series or HSVA-MP profile were generally considered. These enable flat pressure distribution over the leading edge of the suction side (Abbott and Doenhoff, 1959; Brix, 1993). However, this causes a backward movement of the pressure center, so the balance of the rudder must be carefully chosen (Lee, Ahn and Chang, 2007). The second method is application of a strip to reduce the flow exchanges through the gap or sacrificial strip at the edge of the horn or rudder. The third method is a stainless steel overlay or a plastic coating on particular parts. Seo, Lee, Kim and Oh (2010) introduced flow injection in combination with blocking bars to reduce gap flow. Notwithstanding many efforts, cavitation problems due to discontinuity of gap and fast inner flow continue to be reported (Kim, et al., 2006; Paik, et al., 2008, Pak and Lee, 2010).

Shen, Jiang and Remmers (1997) reported through experiments in a Large Cavitation Tunnel that the twist of a full spade rudder can reduce the cavitation of the rudder. However, there had been reluctance to applying the full spade rudder to large merchant vessels, because only one pintle bears all forces and moments on the rudder. Thus, use of this rudder was restricted to small special vessels, such as warships.

In 2003, an innovative attempt was made: the application of a twisted full spade rudder, named the Becker Twisted Leading Edge King Support Rudder (TLKSR) for large container carriers. Its upper and lower sections are twisted in opposite directions oriented toward the inflow. This rudder was proved not only to overcome the drawback of erosion around the gap of the semi-balanced rudder, but also to improve propulsion efficiency (Mewis and Klug, 2004). However, at 24th ITTC in 2005 it was pointed out that the discontinuity of the blade located coaxially with the propeller shaft center may aggravate hub vortex cavitation and resultant erosion.

For all of the advantages, development of the new full spade rudder was limited, because the KSR arrangement for support of a large full spade rudder was the patent of Becker Marine Systems, until it expired on June 2007. Since then, a lot of twisted rudders that have taken into consideration the inflow characteristics have been developed based on that support system. Nowadays, in the case of large container carriers, the use of semi-balanced rudder is gradually reducing, and the use of the full spade rudder has become the mainstream. Kim, et al. (2009) introduced a method for design of a full-spade twisted rudder section, by using a genetic algorithm based on the Vortex Lattice Method. Choi, Kim, Lee and Park (2010) reported the superiority of a twisted rudder to a full spade rudder with the respect to the speed and the cavitation performance by using numerical and experimental research.

This paper demonstrates the characteristics of the X-Twisted rudder, which was developed in Hyundai Heavy Industries to overcome the cavitation problems of large container carriers in the way of the leading edge also considering manufacturing productivity (Chang, Choi, Son and Ahn, 2012). Because this rudder is continuously twisted along the span, it is free from cavitation due to discontinuity in the vicinity of the propeller shaft center. To validate the performance of the X-Twisted rudder, the rudders for 8,000 *TEU* and 13,000 *TEU* container carriers were designed and tested in the research facilities of Hyundai Maritime Research Institute (HMRI). Through various model tests such as resistance, self-propulsion, cavitation and manoeuvring tests, the superiority of the X-Twisted rudder was proven.

THE NEWLY DEVELOPED X-TWISTED RUDDER

Geometric characteristics of the X-Twisted rudder

The features of the X-Twisted rudder are shown in the following Fig. 1. A symmetry section is used at the shaft center position of X-Twisted rudder. Above and below the shaft center, for a right turning propeller, ±5 *degrees* of rudder nose at a radius of propeller (1.0 *r/R*) to port and starboard side are applied respectively. The difference from other twisted rudders is that all the leading edges of the horizontal section are on a line, thereby reducing the angle between inflow and leading

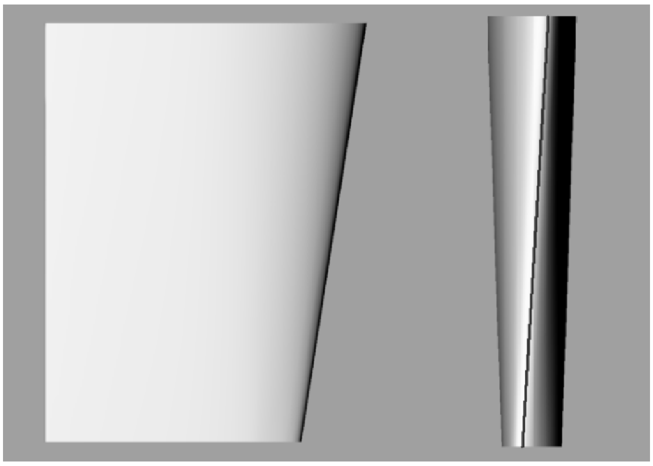

Fig. 1 Drawing of the X-Twisted rudder.

edge at critical areas of ±0.7 *r/R* vulnerable to cavitation. This feature is to improve not only the cavitation performance but also manufacturing productivity. The mean twist angle of the rudder is optimized to 5±1.5 *degrees* according to the ship types. The maximum thickness of rudder is located at the A.P. position to easily insert the rudder stock.

The influence on stern profile

Most area of the full spade rudder is put into the accelerated propeller stream, in order to enhance its effectiveness. This leads to a small aspect ratio. However, because the balance of the rudder is limited, the length from AP to stern end becomes longer. Fig. 2 shows the geometric characteristics of the full spade rudder compared with the semi-balanced rudder.

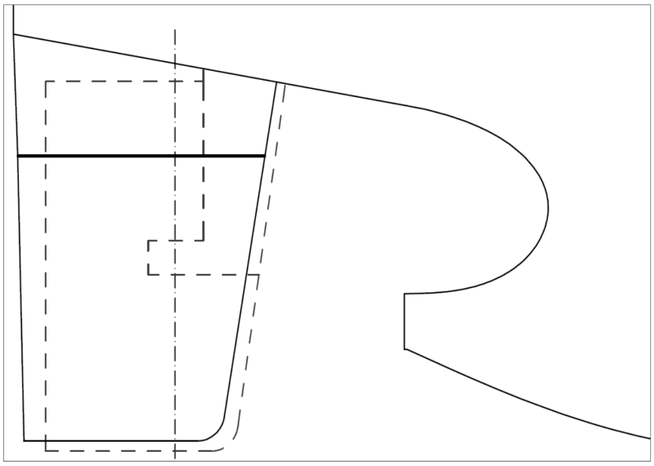

Fig. 2 Geometric characteristics of the full spade rudder compared with the semi-balanced rudder.

In order to reduce rudder torque, an adequate balanced portion must be secured. The full spade rudder has a smaller forepart compared with the semi-balanced rudder, because of the absence of horn, in spite of a high balance ratio. As a result, the boss end should be moved backward to improve the speed performance because it is well-known that speed performance improves as the distance between propeller and rudder decreases. Or this space can be used for other energy saving devices.

In order to locate the major part of the rudder within the propeller downstream, the rudder dangles far below the stern frame, thus a large skeg structure above the rudder is necessary. This has a positive influence on rudder force, but potentially has a bad impact on the speed performance of the ship.

NUMERICAL RESULTS

The characteristics of inflow angle in the propeller stream have been reported by many researchers (Nishiyama, 1975; Shen, Jiang and Remmers, 1997; Molland and Turnock, 2007; Greitsch, 2008). Although Nishiyama (1975) suggested the empirical formula of inflow angle to rudder, it was necessary to confirm the interaction effects between propeller and rudder according to the rudder types. For this purpose, numerical calculations by using ANSYS Fluent (version 13) were carried out to obtain the inflow angles and velocities into the rudder for a large container carrier. Analysis with both the semi-balanced rudder and X-Twisted rudder were performed at model scale.

Reynolds stress model was used for turbulence modeling. The spatial discretization was performed by a least square cell based finite volume method. A second order upwind scheme was selected for momentum equation. The pressure and the velocities are coupled by means of SIMPLE algorithm. For more accurate consideration of the interaction between propeller and rudder, a sliding mesh scheme was used for the propeller region.

Fig. 3 represents the boundary conditions. Double body, Neumann condition, symmetric condition and the wall function were used for the free surface (ABED), outlet (DEF), outer domain (ABED and ACBEFD) and body surface, respectively. The computational domain was $0.0 \le x/L_{PP} \le 1.15$, $0.0 \le \sqrt{y^2+z^2}/L_{PP} \le 1.0$, $-90^\circ \le \tan^{-1}(z/y) \le 0^\circ$.

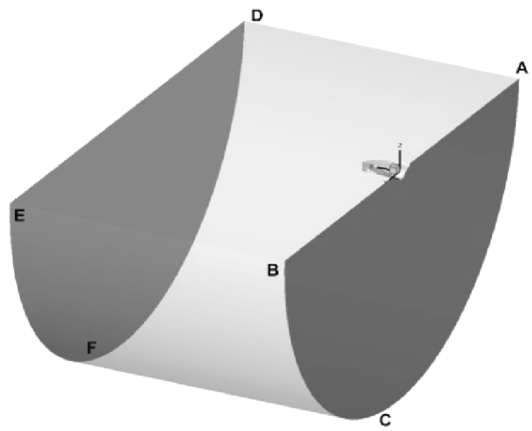

Fig. 3 Calculation domain and boundary conditions.

The surface grid of hull, propeller and rudder is shown in Table 1 and Fig. 4. All cells were composed of tetrahedron and hexahedron.

Table 1 Number of surface grid and total cell.

Hull and Rudder		Propeller	
Rudder	Total cell	Propeller	Total cell
27,382	1,725,815	25,465	826,576

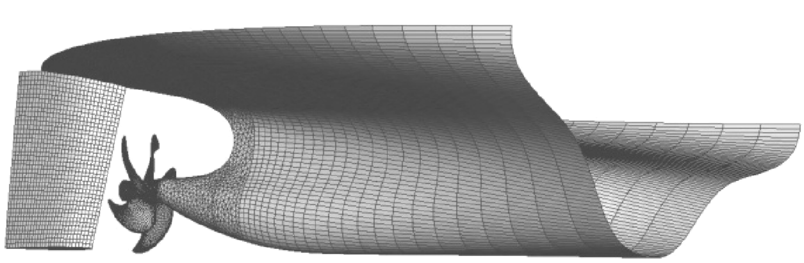

Fig. 4 Surface grids for numerical calculation.

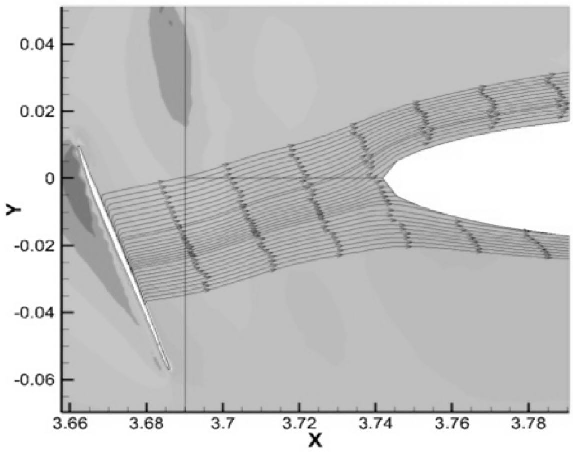

Fig. 5 Streamline into the rudder behind the propeller.

Fig. 5 demonstrates the example of the calculated flow direction into the rudder blade. Fig. 6 and 7 shows the calculated inflow angles into the rudder and the velocity distributions in axial, transverse and vertical components along a vertical transverse from the propeller shaft centerline at rudder angle. The inflow angle is the absolute value, not considering the twist of rudder leading edge.

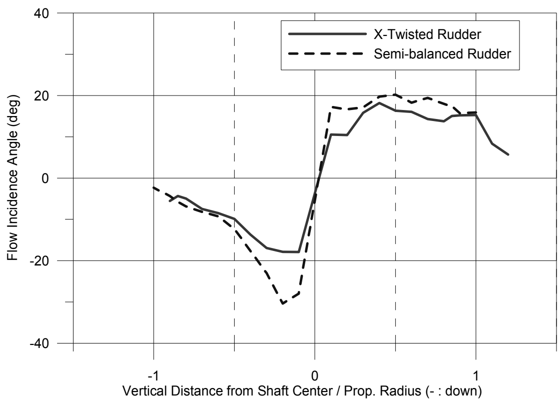

Fig. 6 Inflow angle along the rudder span.

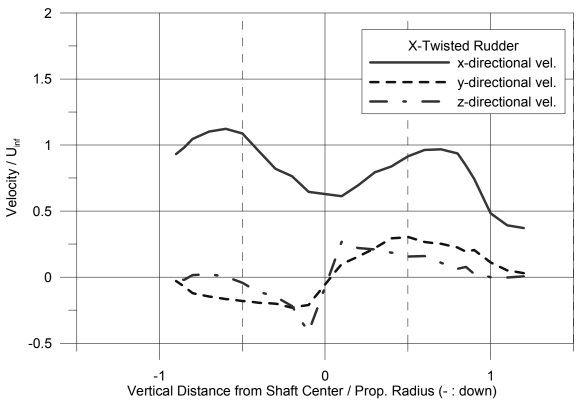

Fig. 7 Velocity distribution of X-Twisted rudder.

As the X-Twisted rudder has a smaller inflow angle along all vertical positions than the semi-balanced rudder due to the interaction, therefore the twist of the rudder section is expected to result in a favorable effect on cavitation because the leading edge of rudder blade is also headed to the inflow. Also, as a result of velocity distribution, speeds at the positions of ±0.7 *radius* of propeller are higher than at any other positions, so it is expected that those are the most important positions from the point of view of cavitation. The inflow speed at the rudder sole is still high, but cavitation can be avoided by means of a smoothly rounded lower face. At the vicinity of the propeller shaft center, the inflow angle is very high but axial speed is low, so it is expected that cavitation of rudder itself is not a concern. Especially, in the case of the X-Twisted rudder, because the rudder blade is continuous along the span, it is free from the worry about the aggravation of hub vortex cavitation and resultant erosion. But because the inflow angle of numerical results looks like somewhat exaggerated when compared with other researches previously mentioned, further experimental researches such as PIV for validation of these numerical results will be needed.

CAVITATION CHARACTERISTICS WITH RESPECT TO THE TWISTED ANGLES

From the results of the numerical analysis, it is expected that the twist of rudder gives favorable effect on the cavitation. But, because too high twist is not appropriate from the viewpoint of the productivity of rudder and the twist of trailing edge is not good for the rudder installation, optimized twist angle at the leading edge is determined to 5±1.5 *degrees* according to the ship types and the trailing edge isn't twisted.

To validate the effect of twisted angles at the leading edge, cavitation tests were carried out for X-Twisted rudders having different twist angles of 0, 3.5, 5.0 and 6.0 *degrees*. These rudders have the same profile, thickness ratio of root and tip, and aspect ratio. The results are shown in Fig. 8~11. Because rudder cavitation wasn't observed at small rudder angles, the test ranges of the rudder angle were extended up to 18° in order to examine the characteristics of cavitation inception.

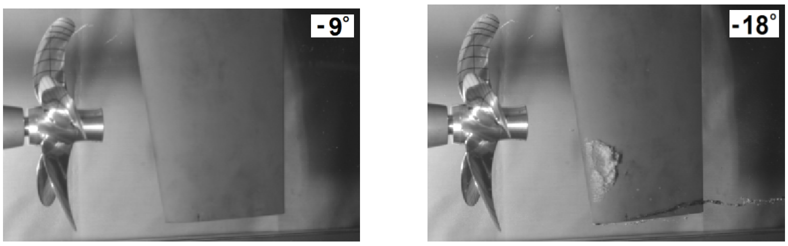

Fig. 8 Cavitation test results of twist angle 0°.

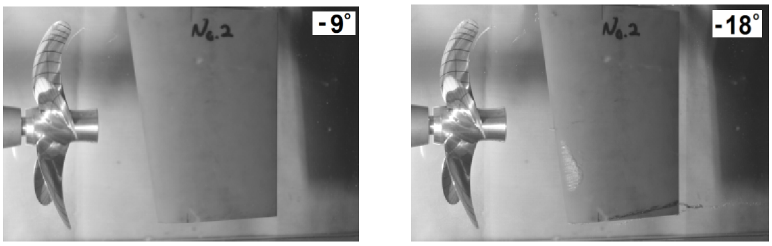

Fig. 9 Cavitation test results of twist angle 3.5°.

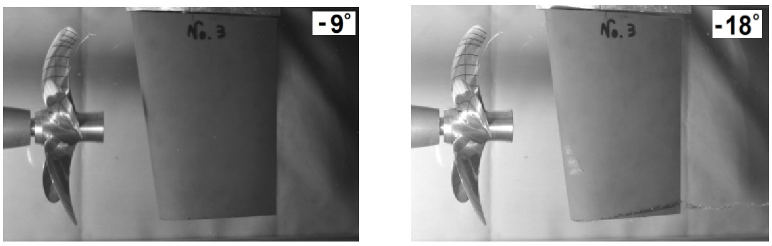

Fig. 10 Cavitation test results of twist angle 5.0°.

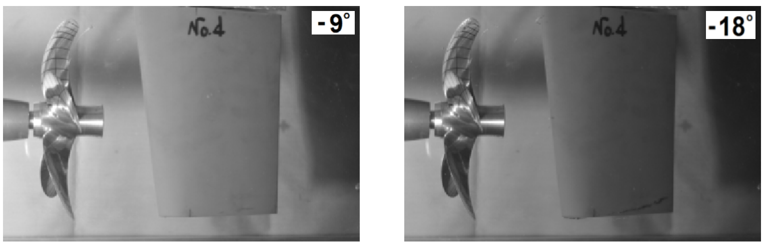

Fig. 11 Cavitation test results of twist angle 6.5°.

The cavitation inception was observed at 15° of rudder angle in the cases of twisted angle 0°. That occurs at 18° in the cases of twisted angle 3.5° and 5.0°. In the cases of 6.5°, cavitation wasn't observed even at 18°. Even a non-twisted rudder doesn't cause a serious cavitation problem at rudder angles up to large rudder angles, but the higher twist angle can delay the cavitation inception. Moreover, considering that the cavitation can be delayed in model scale due to the scale effect, the twist of rudder section is adjudged to be appropriate measure in order to reduce the cavitation phenomena.

MODEL TESTS FOR PERFORMANCE VALIDATION

Target ships

Model tests for performance validation of the X-Twisted rudder were carried out. The target ships were 8,000 *TEU* and 13,000 *TEU* class container carriers. Model lengths are of 7.58 *m* and 8.60 *m*, respectively. Tests with the semi-balanced rudders were also carried out for direct comparison. Principal particulars of hull, propeller and rudder are listed in Table 2. Rudder profiles are shown in Fig. 12 and 13.

Table 2 Principal particulars of hull, propeller and rudders.

	8,000 *TEU* C/C		13,000 *TEU* C/C	
Hull	Design	Scantling	Design	Scantling
L/B	7.45	7.45	7.26	7.26
B/T	3.29	2.95	3.32	3.11
Propeller				
Pitch at 0.7 *R* [-]	1.09		1.04	
Rudder	X-Twisted	Semi-balanced	X-Twisted	Semi-balanced
A_R/LT_2	1.47	1.67	1.52	1.54
Aspect ratio	1.37	1.54	1.22	1.64

T_2 : scantling draft

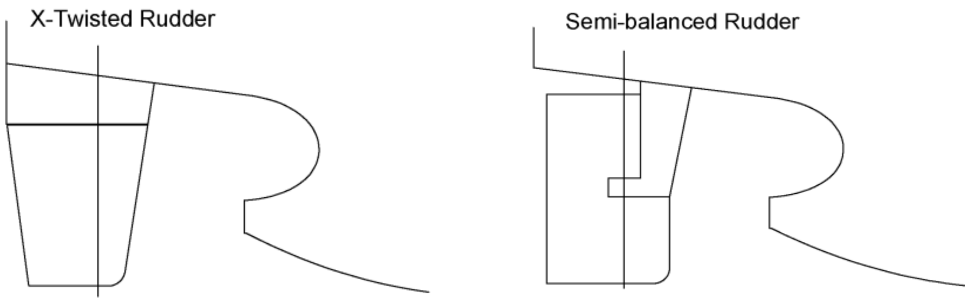

Fig. 12 Rudders of the 8,000 *TEU* class container carrier.

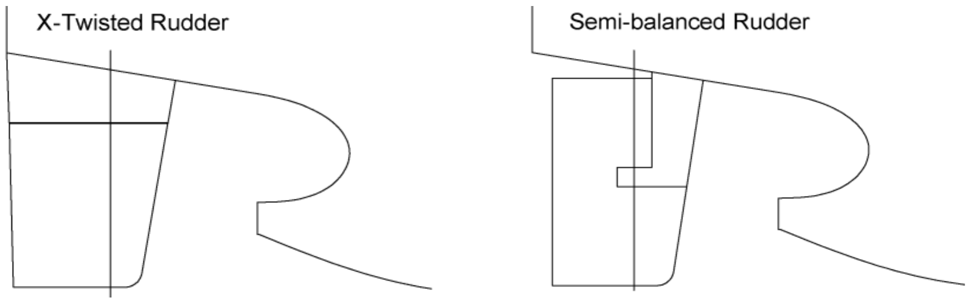

Fig. 13 Rudders of the 13,000 *TEU* class container carrier.

Resistance and self-propulsion test

Resistance and self-propulsion tests at design draft condition were carried out in the towing tank of HMRI. The dimensions of the towing tank are 210 *m* × 14 *m* × 6 *m*. The analysis of powering performance was performed by the ITTC 78 method published in 15th ITTC (1978). The results from the model test are listed in Table 3.

Table 3 Speed performance of X-Twisted rudder.

	8,000 *TEU*	13,000 *TEU*
Service speed [%]	▲0.23	▲0.12
RPM [%]	▲0.54	▲0.30

The ship speed was improved by 0.23 and 0.12 %, respectively, without big rpm changes. Significant improvement was not observed, but the favorable effects on speed performance were validated.

Rudder cavitation test

To look into the effect of twist angle on rudder cavitation, cavitation tests were carried out at design draft condition in the medium sized cavitation tunnel of HMRI. The cavitation phenomena was observed on port and starboard side of rudders within ±12° with 3° intervals. Fig. 14 and 15 show cavitation patterns on 9° starboard side for two container carriers.

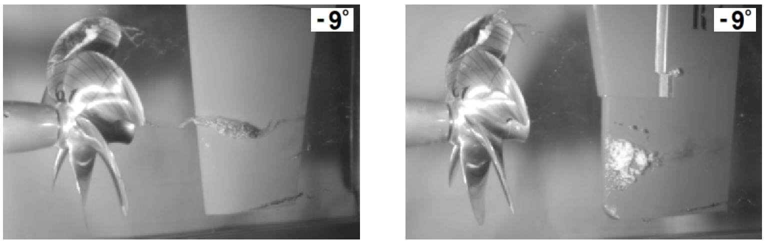

Fig. 14 Cavitation patterns of the X-Twisted rudder and semi-balanced rudder of the 8,000 *TEU* class container carrier.

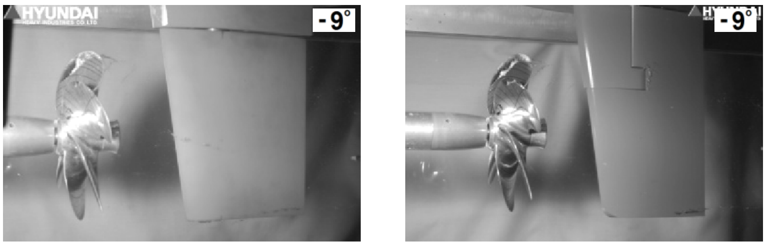

Fig. 15 Cavitation patterns of the X-Twisted rudder and semi-balanced rudder of the 13,000 *TEU* class container carrier.

As shown in the above figures, in the case of the semi-balanced rudder, cavitation occurred near the gap of the lower pintle and the sole of the rudder, but rudder cavitation does not appeared on the X-Twisted rudder below ±9 *degrees*. Because the rudder is rarely put to over 10 *degrees* (Greitsch, 2008), it is expected that the X-Twisted rudder doesn't cause a severe cavitation problem.

Manoeuvring model test

Manoeuvring model tests were carried out by using the Horizontal Planar Motion Mechanism (HPMM) at the towing tank. Tests were performed at the ship's self-propulsion point for accurate prediction of the ship's manoeuvrability, and an Abkowitz-type model with 3rd order nonlinear coupling terms was used as the mathematical model for the manoeuvring simulation (Strom-Tejsen and Chislett, 1966; Sung, Ahn, Lee and Rhee, 2009).

Simulation results are listed in Tables 4 and 5. In order to investigate the effects of twist, results of reaction rudders having discontinuous twist of upper and lower part of the leading edge were also compared.

Table 4 Manoeuvrability of 8,000 *TEU* class container carrier.

Type of Manoeuvre		X-Twisted rudder		Semi-balanced rudder		Reaction rudder	
		PORT	STBD	PORT	STBD	PORT	STBD
Initial turning	Track Reach [Lpp]	1.63	1.78	1.82	1.77	1.60	1.91
Turning test	Advance [Lpp]	3.13	3.22	3.25	3.16	3.40	3.59
	Transfer [Lpp]	1.48	1.50	1.63	1.53	1.60	1.69
	Tact. Dia. [Lpp]	3.44	3.50	3.72	3.67	3.68	3.86
10°/10° zigzag test	1st O. A. [deg]	17.4	13.6	14.8	16.9	28.9	11.5
	2nd O. A. [deg]	27.6	31.3	27.9	24.2	24.9	43.2
20°/20° zigzag test	1st O. A. [deg]	20.4	18.9	16.9	17.3	23.7	18.3

Table 5 Manoeuvrability of 13,000 *TEU* class container carrier.

Type of Manoeuvre		X-Twisted rudder		Semi-balanced rudder		Reaction rudder	
		PORT	STBD	PORT	STBD	PORT	STBD
Initial turning	Track Reach [Lpp]	1.66	1.72	1.67	1.65	1.52	1.77
Turning Test	Advance [Lpp]	3.12	3.15	3.25	3.23	2.99	3.10
	Transfer [Lpp]	1.41	1.40	1.56	1.53	1.45	1.50
	Tact. Dia. [Lpp]	3.40	3.38	3.67	3.60	3.44	3.54
10°/10° zigzag test	1st O. A. [deg]	14.2	12.8	15.3	17.5	18.4	10.5
	2nd O. A. [deg]	31.0	30.8	33.8	29.5	23.5	34.2
20°/20° zigzag test	1st O. A. [deg]	19.6	19.1	19.6	20.2	19.2	16.1

It can be seen that the X-Twisted rudder can improve overall manoeuvrability when compared with the rudder areas. This is due to the increased area located in the propeller stream and large skeg area which fills the vertical gap between hull and rudder. Also, the imbalance between port and starboard is improved compared with the other rudders. However, this imbalance can be easily improved by altering the initial rudder setting corresponding to the neutral rudder angle.

Fig. 16 and 17 show the rudder normal force and yawing moment of the ship. A positive yawing moment makes a ship turn right. A positive rudder normal force means a starboard directional force that is normal to the chord of the rudder.

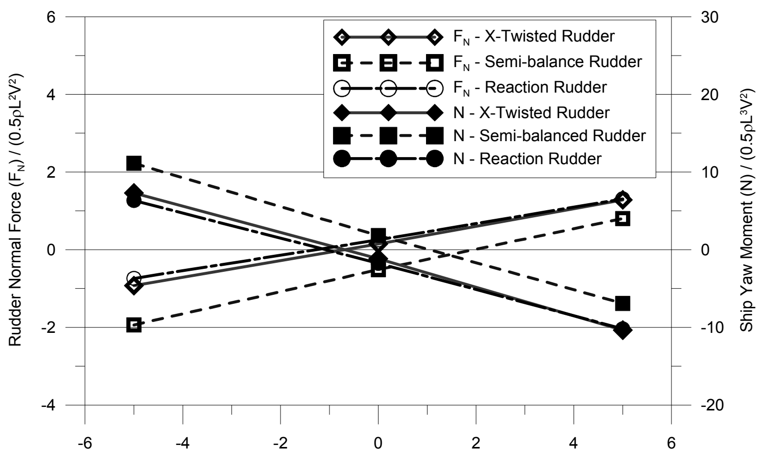

Fig. 16 Rudder normal force and yaw moment of 8,000 *TEU* class container carrier.

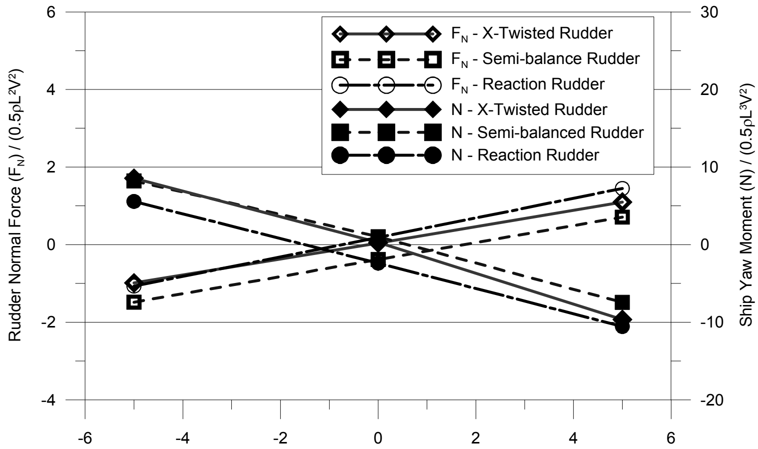

Fig. 17 Rudder normal force and yaw moment of 13,000 *TEU* class container carrier.

For a right rotating propeller working in the wake field of a ship, the center of thrust eccentricity is generally located at the right and upper part of the propeller. This acts as a moment turning the ship to port. Against this, the rudder plays a role as a compensating device for this unbalanced load distribution. As shown in above figures, when the rudder is kept to 0 *degrees*, the semi-balanced rudder tends to turn to starboard, but the X-Twisted rudder tends to turn slightly to port, while the reaction rudder clearly tends to turn to port.

Fig. 18 shows the rudder stock moment coefficients in the static rudder test of manoeuvring tests. The rudder stock moment is related to the steering gear capacity.

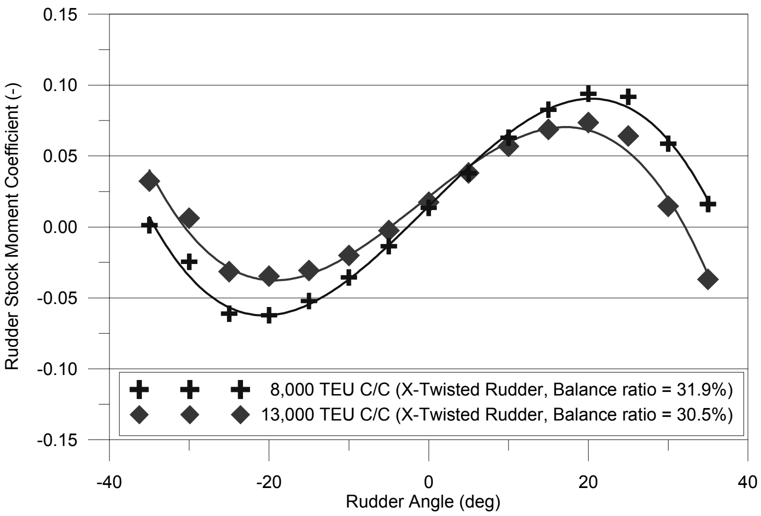

Fig. 18 Rudder stock moment coefficients with respect to the balance ratio.

The balance ratio of the X-Twisted rudder for the 8,000 *TEU* class was preliminary designed to be 31.9 *%*. However, it was shown that the maximum of the rudder stock moment coefficient didn't exist at the maximum rudder angle. This excessive balance ratio leads to an increase of steering gear capacity. Thus, the balance ratio of the X-Twisted rudder for the 13,000 *TEU* class container carrier was changed to be 30.5 *%* where the equilibrium was nearly achieved. And the excessive balance ratio must be avoided because the backward movement of the center of pressure with respect to rudder angle for the model is higher than that for a real ship (Brix, 1993) due to the difference of the Reynolds number.

Rudder open water tests were carried out at the circulation water channel to investigate the effects of aspect ratio and twist angle of rudder on rudder normal force. Rudder geometries were selected to cover the entire range of rudder profiles of real ships. Tests were performed at R_n=3.588×10^{-5} and with a ground board of gap =0.01 $\overline{c}$ (mean chord). Table 6 shows the effect of aspect ratio on the rudder normal force.

Table 6 The effect of aspect ratio on the rudder normal force coefficient.

Λ_G	Sweep angle	Twist angle	f_α
1.153	2.802	0.0	2.426
1.298	2.490	0.0	2.529
1.452	2.227	0.0	2.636
1.600	2.025	0.0	2.708
1.750	1.848	0.0	2.780

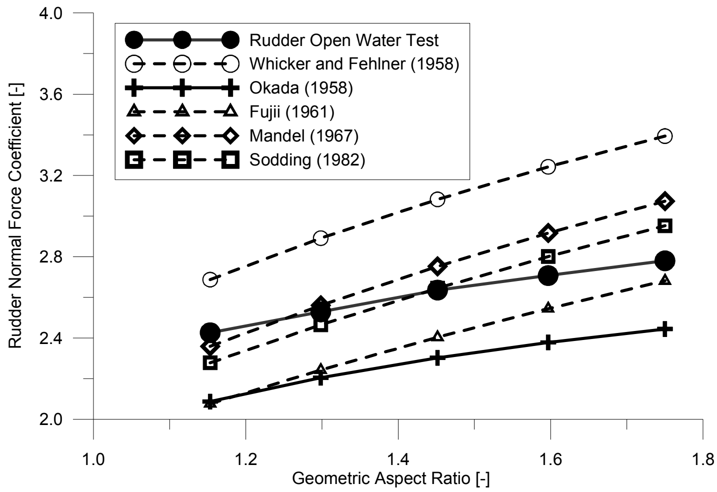

Fig. 19 Effect of aspect ratio on the rudder normal force.

Fig. 19 shows the results compared with other empirical formulae (Whicker and Fehlner, 1958; Okada, 1958; Fuji and Tuda, 1961; Mandel, 1967; Södding, 1982). As a result, the increasing tendency of the rudder normal force coefficient is evident as the aspect ratio increases. However, when compared with other empirical formulae, it is likely that this effect is limited.

The effect of twist angles is shown in Fig. 20. Besides open water tests, test results behind the hull and propeller in the manoeuvring test at the towing tank are also included.

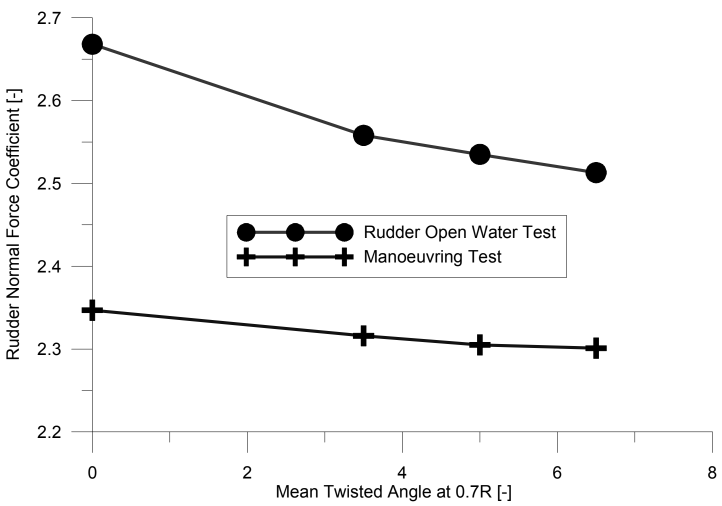

Fig. 20 The effect of twist angle.

The results show that as twist angle increases, the rudder normal force coefficient tends to decrease. These coefficients were obtained with data up to 15 *degrees* therefore these were possibly exaggerated because the some regions of twisted forms were located in the stall region because the stall occurs early in model test. However, this effect was alleviated in the manoeuvring tests, due to the rotational flow from the propeller. Differences in absolute quantities between both tests are due to differences of the wake field and width of the ground board.

CONCLUSIONS

This paper shows the hydrodynamic characteristics of the X-Twisted rudder that has been developed to reduce the cavitation damages and improve manufacturing productivity. Numerical analysis of the propeller stream shows, as is well-known, that for a right turning propeller the rudder nose should be above the propeller axis on the port side, below it on the starboard side, and the positions of the rudder at ±0.7 R of propeller are the critical positions from the point of view of cavitation. And the twist at the propeller shaft center line is unnecessary, because the speed at that position is relatively low. Furthermore, through the cavitation tests in the propeller stream with respect to twist angles, in the case of full spade rudders, at moderate rudder angles even the non-twisted rudder doesn't cause serious cavitation phenomena, but the higher twist angle can delay cavitation inception and reduce the cavitation area at the model scale.

Various model tests were carried out to validate the characteristics of the X-Twisted rudder. All results were compared with those for the semi-balanced rudder for direct comparison. From the cavitation tests, the reduction of cavitation area was confirmed. From the resistance and self-propulsion tests, in the case of X-Twisted rudder, as ship speed was improved, the favorable effect on ship speed was validated. From the manoeuvring tests, the X-Twisted rudder can improve overall maneuverabiltiy and especially the manoeuvrability between port and starboard was well balanced. From the rudder open water tests, the increasing tendency of the rudder normal force with respect to the aspect ratios was confirmed, but the twist may exert a deleterious influence on the rudder normal force.

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