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A PROPOSAL ON STANDARD RUDDER DEVICE DESIGN PROCEDURE BY INVESTIGATION OF RUDDER DESIGN PROCESS AT MAJOR KOREAN SHIPYARDS

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Key words: rudder concept design, rudder initial design, rudder detailed design, ship maneuvering performance, Korean major shipyard.

ABSTRACT

Recently, a very large vessel's maneuvering performance, rudder performance and rudder design's importance are considered to be an important subject. However, there have been few studies on the design process of rudder device before. The aim of this paper is to investigate a design process of rudder device and to propose a generalized design process of rudder device. Firstly, we investigated the rudder device design process of Korean major shipyards. And the differences of a torque calculation method, rudder section design, maneuvering performance examination method, etc. were analyzed theoretically. Secondly, the design process of rudder device was divided into concept design, initial design and detail design, rudder profile and design method have been selected through rudder form determination process. And principal dimension and steering gear capacity were determined. Maneuvering performance was also examined by simulation tool. In detail design, design criteria which had been considered in rudder initial design was investigated thoroughly. Also a rudder torque, rudder cavitation performance and rudder structure analysis were estimated. And maneuvering performance was also examined by model test. Finally, based on the results of investigation, the design process of rudder device was generalized and proposed.

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I. INTRODUCTION

Recently, great attention has been paid to a very large vessel's maneuvering performance because of the seriousness of sea pollution problems from stranding and collision accidents. In this perspective, excellent rudders have been studied in many domestic and international research institutions, universities and enterprises until now. Although experimental studies have been extensively made on the subject, no systemized or generalized rudder design process has been known until now. At this point, this paper suggests the standard rudder device design process which was compared with and generalized from the various processes of Korean major shipyards. For this, rudder design process of Korean major shipyards was firstly examined. And then, based on the results of investigation and analysis, the design process of rudder device was generalized and proposed.

II. COMPARISON AND ANALYSIS OF THE RUDDER DEVICE DESIGN PROCESS OF KOREAN MAJOR SHIPYARDS

1. General Considerable Factors for Rudder Device Design

General factors considering rudder design process of Korean major shipyards are things such as ship's maneuvering performance, possibility of installing and removing propellers, steering gear capacity for rudder' control and avoidance of erosion by cavitation. In addition, shipyard 'A' takes account of ship owners' requirement and balance ratio of classification guidance and design regulations, as well as the selection of a shaft diameter considered with rudder stock's stiffness. And shipyard 'B' considers lightweight of rudder device, high lift capacity compared with same kinds of steering gear and constancy of initial design form.

1) General Considerable Factors for Rudder Device Design

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A. Principal considerations for classification regarding rudder device design

Strength bearing torque and rudder force which carries thickness and quality of rudder stock was the principal consideration for classification regarding rudder design at Korean major shipyards. In detail, pintle, bearing bush and sleeve are all considered for rudder stock. Forging, quality of casting material and welding part are also considered important. For quality of casting material, strength of rudder horn casting, stern boss casting and rudder upper and lower casting are specially taken into consideration.

B. Computational standards of steering gear capacity

Computational standards of steering gear capacity have great influence on balance ratio. In shipyard 'A', torque estimated from both classification standard and data selected from vessels should be satisfied and it is varied according to maker options and arrangement space. Shipyard 'B' experientially selects approximate figures from maximum torque estimated with Jossel-Beaufoy method and DnV rule. And maximum torque was reckoned to 1000ton-m. shipyard 'C' is apt to make economical selections because steering gear capacity goes in proportion as price.

C. Distance between rudder and propeller

Gap between the movable and the fixed of rudder device is 50 mm in common. Some vessels which aim at minimizing gap cavitation adopt 35 mm. Distance between rudder and propeller should be designed for the cavitation not to influence on the distance, which is adjusted to install and remove the propeller.

2) Comparison of Rudder Device Design Process in Korean Major Shipyard

Major shipyards have something in common with designing rudder device although there are differences in detail in the four processes of rudder design like in Fig. 1. Here is the order of rudder torque calculation, process of rudder type, method of maneuvering performance investigation and considerable factors for concept design.

A. Order of rudder torque calculation

Each shipyard has a difference in the order of calculating rudder torque. Shipyard 'A' calculates torque after designing rudder form while shipyard 'B' makes comparisons among vessels and then approximates torque at the last stage of designing. This shipyard confers torque to deciding steering gear capacity.

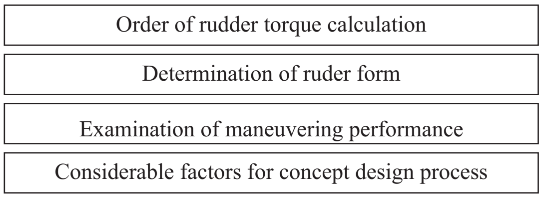

Fig. 1. Difference of shipyard design process.

B. Determination of rudder form

Determination of rudder form, which means determining section form and movable part area, has the second difference in rudder design process. Every major shipyard has difference in process. Rudder area, distance between rudder and propeller and distance between stern and rudder are to be considered sooner or later than the determination of rudder form.

C. Examination of maneuvering performance

The third difference is in the methods to examine the maneuvering performance. They are divided into three, one by previous ship data, another by model test, and the third by simulating maneuvering math model, of which the second and the third one show differences. Difference in model test method may lie in various towing tank environments, and that in simulation method can be explained by the fact that each shipyard uses its own way concerning maneuvering performance.

D. Considerable factors for concept design process

The other difference is in the considerable factors for concept design. Most of all, ship owners' requirement should be reflected on concept design. Korean major shipyards use great amount of data base for shipbuilding. Accordingly, it is important to get information of similar kinds of vessels, and be prepared to meet the ship owners' requirement and classification standards. Therefore, each shipyard considers factors differently.

3) Rudder Design Process Outline

Just above, we analyzed and compared the design process of some Korean major shipyards. Let us begin with the proposal of the rudder device design process. Fig. 2 shows rudder design process outline. As the diagram indicates, the rudder design process is compared of concept design, initial design and detail design.

III. RUDDER CONCEPT DESIGN PROCESS

One of the most important points of the rudder concept design process is that the draft should meet ship owners' requirement. Fig. 3 summarizes the process of rudder concept design. Firstly, specifications of similar ships should be

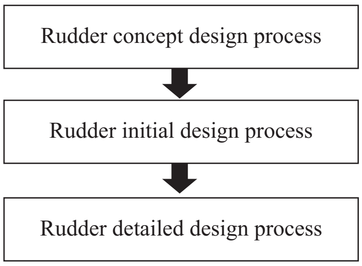

Fig. 2. Rudder design process outline.

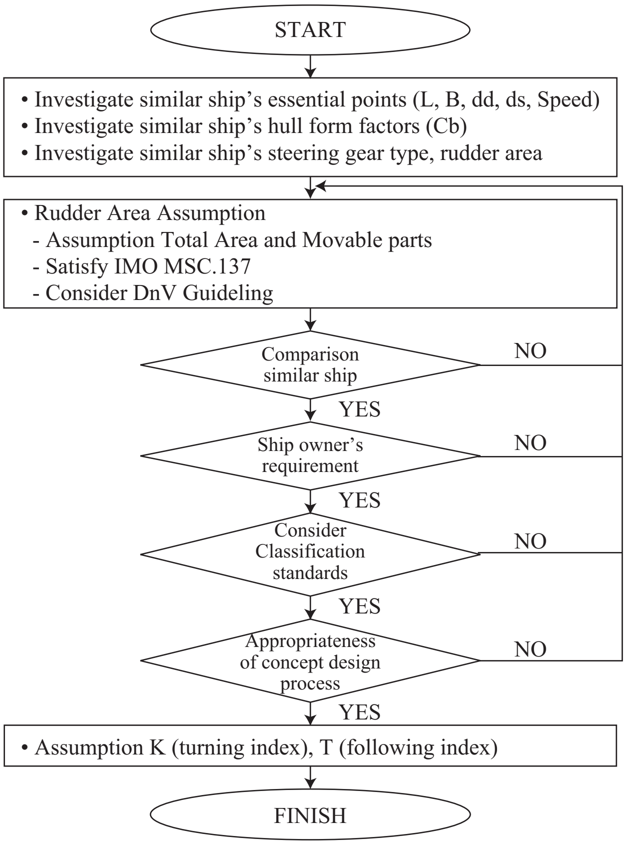

Fig. 3. Rudder concept design flow chart.

investigated such as hull form factors, steering gear type, rudder area and maneuvering performance. Secondly, spec should be concluded, and rudder area be estimated. Thirdly, the estimated rudder' area should be compared with that of similar ships and then, ship owner's requirement and classification' standard are to be examined. Finally, estimation of K (turning index) and T (following index) leads to finishing concept design process.

1. Investigation of Similar Ship's Specifications

Rudder area is estimated with regard to specifications of similar ships. This trend is reflected on the decision of hull form optimizing ship owners' requirement. It is convenient to decide optimized rudder design through iteration.

Table 1. Comparison of bit error rates for the simulation.

$\frac{A}{Ld}$	High-speed Liner	1.2~1.7%
	Large Cargo Ship	1.4 × (1/70)~1.4 × (1/50)%
	Small Cargo ship	1.7~2.3%
	Waterside Vessel	2.0~2.3%

2. Assumption of Rudder Area

The rudder area has a great influence on ship's turning ability. There are various methods of deciding rudder area. But DnV method and A/Ld method will be described here. Firstly, DnV method appears as follows.

$$\frac{A_R}{L \cdot d} = 0.01 + 0.5 \cdot \left(\frac{C_B}{L/B}\right)^2 \tag{1}$$

where A_R = rudder area

Secondly, assumption by A/Ld is as follow.

$$A(m^2) = \left(\frac{1}{70} \sim \frac{1}{60}\right) \times (Ld) \tag{2}$$

Also Table 1 summarizes the value of A/Ld of diverse ships.

3. Judging Fitness of Concept Design Process

Estimated rudder area is compared with that of similar ship; ship owners' requirement is examined with consideration of price and rudder size proper for ship; concept design is scrutinized through classification standards.

4. Assumption of K (turning index), T (following index)

K (turning index) and T (following index) are assumed to evaluate the turning ability of the ship as the last course of concept design. K shows tendency of turning velocity, T displays tendency of turning angle velocity. When a ship makes a turn using angle 10°(δ1), 20°(δ2) and 30°(δ3), and the angle speed is 0.4°/sec, 0.6°/sec and 0.8°/sec each, angle speed is a multiple of rudder angle.

$$\begin{aligned} 0.4°/\sec &= K_1\delta_1 = K_1 \times 10°,\ K_1 = 0.04/\sec \\ 0.6°/\sec &= K_2\delta_2 = K_2 \times 10°,\ K_2 = 0.03/\sec \\ 0.8°/\sec &= K_3\delta_3 = K_3 \times 10°,\ K_3 = 0.027/\sec \end{aligned} \tag{3}$$

As Eq. (3) shows, K (turning index) is the turning angle speed, multiple of the rudder angle. K is varied with the size of rudder angle and loaded state even of the same ship. K can be just assumed from the size of ship and rudder angle in use. And the bigger rudder angle causes more turning resistance. Moreover, ship turning seems to take some time, not immediately after getting rudder angle. This delay is due to human

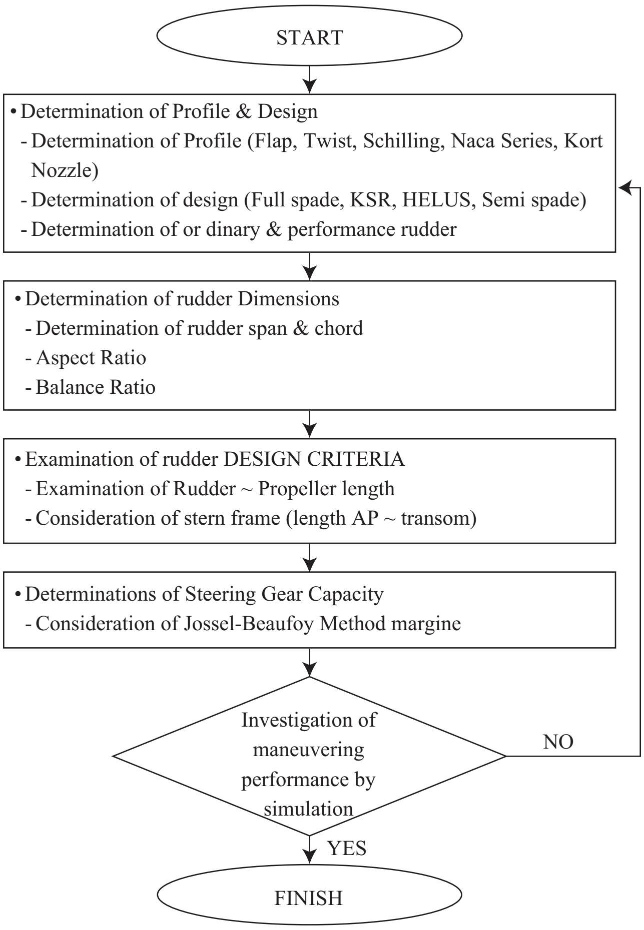

Fig. 4. Rudder initial design flow chart.

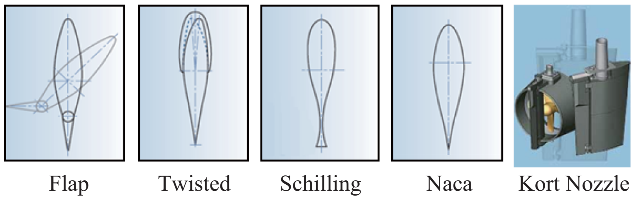

Fig. 5. Classification of rudder profile.

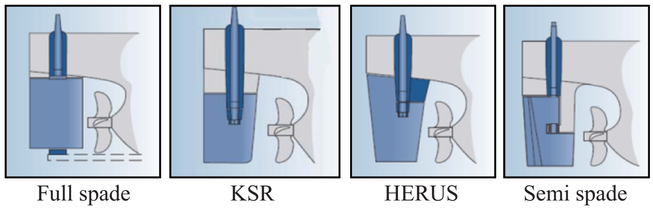

Fig. 6. Classification of rudder design.

feeling. At the beginning of turning, subtle angle speed makes it difficult to feel turning. As time passes on, accumulated angle speed makes it possible to recognize turning by sight. This time-elapse is called T (following index) [7].

IV. RUDDER INITIAL DESIGN PROCESS

Rudder initial design process is embodiment of results from the concept design. So, this process consists of courses able to be examined and compared with in the points of economy or basic layout functions like rudder form or dimension. Fig. 4 shows the rudder initial design flow chart. This diagram tells us that the rudder initial design is classified by decision of rudder profile, design, dimension, criteria and assumption of steering gear capacity.

1. Determination of a Rudder Type

NACA lines are generally used when rudder type determined with no specific requirement of ship owners' or maneuvering test results. NACA lines are suitable in thin section for resistance, and in thick one for strength. Rudder types are divided on the basis of the profile and design on the one hand, and into ordinary and performance on the other hand.

1) Decision of Rudder Profile

There are five kinds of rudder profile (Becker rudder standards): Twist, Flap, Schilling, NACA series and Kort Nozzle as appear in Fig. 5.

Let us focus on the twist rudder for the moment. The twist rudder can be specified by the section form, which has twist section at the leading edge. The feature can reduce the erosion of movable part and clearance. The flap rudder is used much lately. As additional flap angles are given to conventional rudder angles, this type brings about high lift. And it enhances its maneuvering ability and turning ability at low speed, compared with conventional rudders.

The shilling rudder is designed for high lift by rudder section form. The section profile has a rounded leading edge and a fishtail trailing edge. Firstly, a rounded leading edge promotes good flow properties at all rudder angles. Secondly, a fishtail trailing edge accelerates the flow and recovers lift over the aft section of the rudder. The NACA series is a type generally used for economical reasons. The rudder section is wider than that of an air-plane, and the shape of edge is varied according to ship's series. It makes the rudder increase the strength and decrease the stall. Let us move onto the Kort Nozzle.

The Kort Nozzle is the trailing edge of rudder plate fitted with propeller. When the angle of attack is changed, the turning ability is increased by the thrust of small propeller, and turning is easily gotten during the stoppage. It makes shipbuilding possible without tugging because the angle of attack can be changed into 90° or more.

2) Rudder Design Decision

There are four kinds of rudder design (Becker rudder standards can be consulted when rudder design decision is made): Full spade, KSR (King support rudder), Herus support, Semi-spade. Let us examine the full spade rudder in Fig. 6 for the first.

	Profile Type	Kc	
		Ahead Condition	Astern Condition
1	Single plate	10	10
2	Naca series	11	0.80
3	Flat side	11	0.90
4	Mixel	1.21	0.90
5	Hollow	1.35	0.90

Fig. 7. Coefficient Kc for ordinary rudder.

	Profile Type	Kc	
		Ahead Condition	Astern Condition
1	Fish tail = Schilling rudder	1.4	0.8
2	Flap rudder	1.7	1.3
3	Steering Nozzle	1.9	1.5

Fig. 8. Coefficient Kc for performance rudder.

The full spade rudder consists wholly of movable part and it doesn't have a horn. In this type, the weight loaded on rudder as well as the rudder weight is supported by one shaft. Recently, the full spade rudder type is used for very large vessels because it can avoid gap cavitation [2]. The KSR(King Support Rudder) is supported by the large shaft because it reduces a fatigue and bending moment. The Herus is designed for relatively slow and large vessels (e.x. bulk carriers and tankers). The type increases hydrodynamic efficiency by installing the Herus support. Finally, take a close look at the semi-spade rudder. It is composed of the rudder horn, pintle and semi-spade blade. As vessels are getting bigger and horsepower needed is increasing, there is growing necessity of rudder fit in size and shape bearing fluid weight [4]. Accordingly, the semi-spade rudder, which is in need of small torque, is increasingly used.

3) Decision of Ordinary and Performance Rudder

Section can be decided from coefficient Kc varied according to the shape of section. Ordinary rudder has kinds of types such as Single plate, NACA series, Flat side, Mixed and Hollow. Fig. 7 shows coefficient Kc for ordinary rudder. And performance rudder fit for vessels can be selected from Fish tail (Schilling) and Flap rudder as shown in Fig. 8.

Table 2. Balance ratio and area ratio of general cargo ship.

	General Cargo Ship
Rudder Area Ratio (A_r/L·a)	1.4~1.7%
Rudder Balance Ratio (A_f/A_r)	22~24%

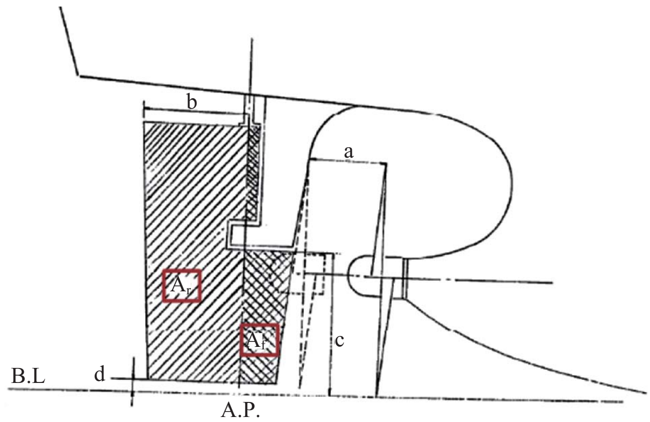

Fig. 9. Decision of rudder dimensions.

2. Decision of Rudder Dimensions

The aspect ratio and balance ratio offer the key to understanding decision of rudder dimension. Fig. 9 shows necessary components of deciding rudder dimension.

'a' refers to minimum tip clearance. Classification rules shows Eq. (4) as below.

$$Minimum\ Tip\ Clearance\ (DNV) = a \geq 0.2\ R(m) \qquad (4)$$

where a = distance of 0.7 R; R = radius of propeller.

'b' must be designed not to exceed end bulk-head. When it comes to propeller removal, 'c' need to maintain adequate dimension to avoid damage. When a ship docked, the distance 'd' with B.L (Bottom Line) and rudder needs to be fixed adequately.

$$General\ distance = 400(mm) \qquad (5)$$

As early as 1996, Sohn studied the effect of rudder area with reference to changes in span distance on course stability of a ship. It is widely known that the lift coefficient increases as the aspect ratio goes up. On the contrary, increasing aspect ratio is also likely to impede the stability course [5]. Therefore, aspect ratio 2.0 (1.6 in general) is used in Korean major shipyards. Balance ratio is important to determine the steering gear capacity, and it usually ranges from 23 to 28%. The area ratio and balance ratio in general cargo ship appear in Table 2.

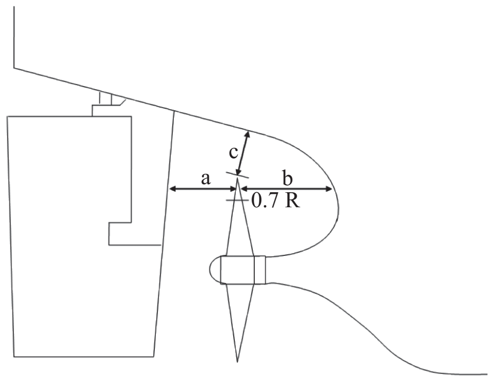

Fig. 10. Rudder design criteria.

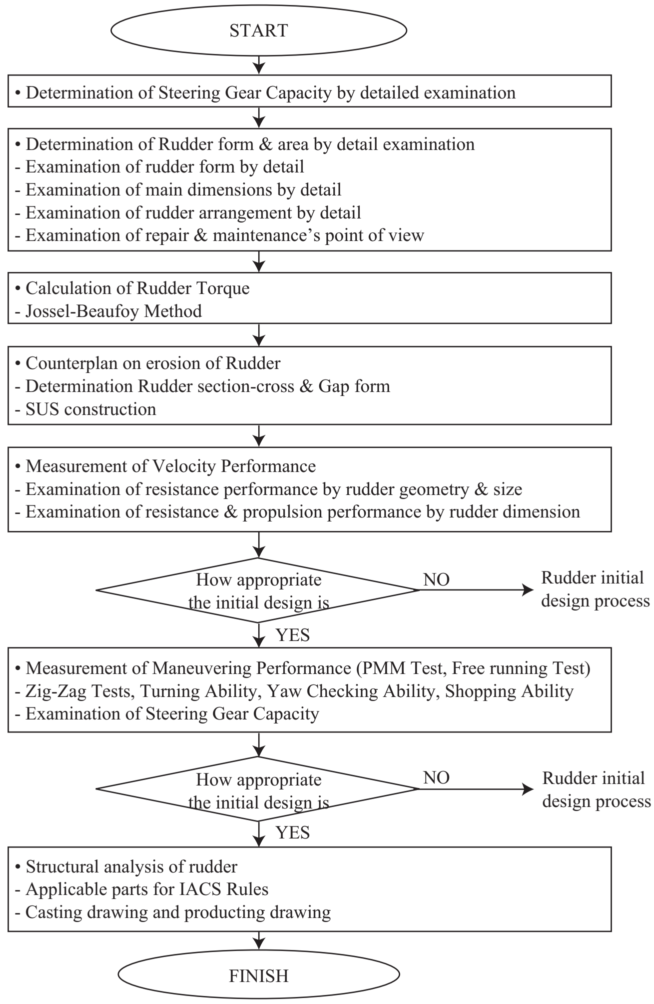

Fig. 11. Rudder detail design flow chart.

3. Investigation of Rudder Design Criteria

Distance between rudder and propeller, distance between hull bottom and rudder, and influence of stern frame are to be considered when rudder design criteria is investigated. First of all, distance between rudder and propeller is proper to be located near just behind the propeller. In Fig. 10, if the interval between 'a' and 'b' gets larger, the vibration becomes smaller, and the performance of propeller propulsion improves greatly.

$$a \geq 0.2\ R \tag{5}$$

$$b \geq (0.7\text{-}0.04Z)\ R \tag{6}$$

$$c \geq (0.48\text{-}0.02Z)\ R \tag{7}$$

where, R = propeller diameter/2
Z = number of propeller blade

4. Assumption of Steering Gear Capacity

The steering gear capacity is estimated by using Jossel-Beaufoy method. This method will be examined later again in Eq. (9) through (14) at 5.2.

5. Investigation of Maneuvering Performance by Simulation

Simulation method is practical to calculate ship's motion control for the optional steering motion. It is essential to make an accurate assumption of the maneuvering hydrodynamic forces which describe rationality of the maneuvering mathematical model and characteristics of fluid. KORDI (The Korean Ocean Research and Development Institute) and Korean major shipyards have made research and constructed maneuvering hydrodynamic coefficient data base (DB) on tanker hull form. And they have developed the M-view program which can estimate a maneuvering ability of the ship in initial design.

V. RUDDER DETAIL DESIGN PROCESS

Layout for the rudder structure, form and dimensions are determined during the process of rudder detail design. Also, if the information of rudder initial design has mistakes, the process of initial design has to be repeated.; therefore, the process of rudder detail design can have course of feedback. Fig. 11 summarizes the process of rudder detail design. To sum up, the process of rudder design is comprised of, making decision of rudder structure, steering gear capacity, rudder area and rudder form. And it is also followed by handling erosion of cavitation, and assessing velocity performance and maneuvering performance.

1. Decision of Rudder Dimension

Let us focus on decision of the rudder form. Rudder profile or rudder form design at the initial stage are considered first when rudder dimension is decided at the detail design process. Secondly, distance between the rudder center of gravity (CG) and the A.P. should be adjusted to be minimal. As Fig. 12 show, for example, 'h' should be minimal when 'd' and rudder center of gravity (CG) are fixed [3].

2. Calculation of Rudder Torque

Jossel-Beaufoy method is used for rudder torque calcula-

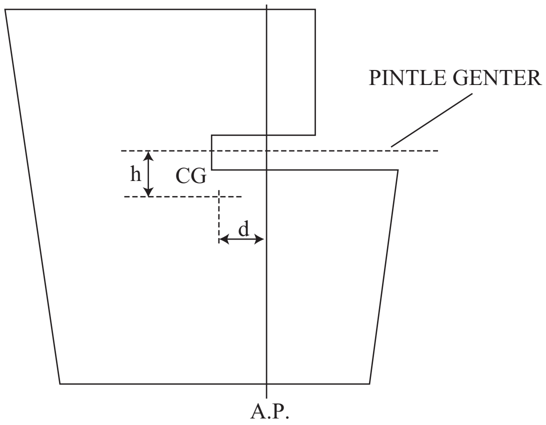

Fig. 12. Decision of rudder dimensions.

Fig. 13. Decision of rudder dimensions.

tion. The Jossel-Beaufoy method is used to get the value of moment and rudder force. The Jossel-Beaufoy method is given as

$$\begin{aligned} F_N &= 58.8AU_r^{\,2}\sin\alpha \\ &= 15.6AU^2\sin\alpha \end{aligned} \tag{9}$$

$$(CP)_c = (0.195 + 0.305\sin\alpha)\times c \tag{10}$$

$$Q_H = AcV_t^2(4.36 - 11.8\frac{d}{c})10^{-3} \tag{11}$$

where α = angle of attack
Ur(m/s), U(knots) = influx speed
Vt(knots) = trial speed
A = rudder area
c = rudder chord length
d = rudder stock and rudder front length
Q_H = torque of rudder stock

The variables of formula stated above are rudder area, influx speed and angle of attack. The aspect ratio, balance ratio and sweepback angle, which are considered in calculating the lift for blade section, are not generally taken into consideration in these formula. The characteristics of rudder horn part are not considered, either. Rudder aspect ratio k_R, Rudder section form coefficient k_c, Coefficient of rudder position in propeller wake k_l are used in IACS formula to solve perpendicular force, point of application and torque affection rudder.

$$F_N = 0.312k_Rk_ck_lAV^2 \tag{12}$$

$$r = c(\partial - k) \tag{13}$$

$$Q_R = F_N r \tag{14}$$

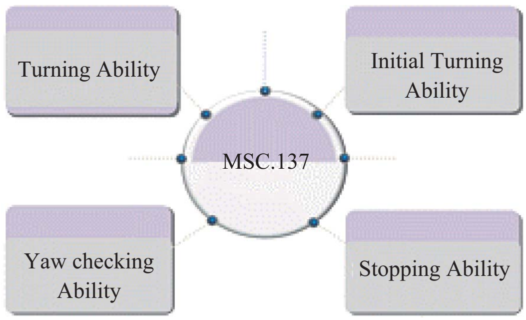

Fig. 14. Type of resolution MSC.137.

where F_N = rudder normal force
A = rudder area
V = ship speed
α = angle of attack
k = balance ratio of rudder
c = rudder chord length
Q_R = torque of rudder

The two formula above don't have factors for propeller and hull form, but they are used extensively in partial affairs [6].

3. Counterplan on Erosion of Rudder

Let us now examine a counterplan on erosion of rudder more closely. To begin with, the critical problem of erosion is cavitation. Cavitation is related to erosion damages on rudder. It generally occurs around leading edge of lower-face, behind gap of lower pintle and rudder shoe. Fig. 13 shows cavitation part and main part of erosion of 2,700 TEU container ship.

To put it more concretely, with the increase of ship size and speed, loading on the propeller is increasing, which in turn increases the rotational speed in the propeller slipstream. The rudder placed in the propeller slip stream is therefore subject to severe cavitation with the increased angle of attack due to the increased rotational induction speed of the propeller. Now, the methods to reduce rudder erosion will be examined. The

Table 3. Summary of maneuverability of MSC.137.

Item	Description	Criteria
Turning ability	Implementing left, right and turning test at the given test speed	Advance < 4.5 L Tactical diameter < 5 L
Initial Turning ability	Advance when applicating 10° bow angle and rudder angle to left or right	< 2.5 L
Yaw checking ability (Zig-zag test)	10°/10° Zig-zag (1st Overshoot Angle)	L/V < 10(/sec); 10° L/V > 30(/sec); 20° 10 < L/V < 30(/sec); < 5° + 0.5(L/V)
	10°/10° Zig-zag (2nd Overshoot Angle)	1st Overshoot Angle + 15° < 35° in general
	20°/20° Zig-zag (1st Overshoot Angle)	< 25 V°
Stopping ability	Track reach distance of Crash stop astern test	< 15 L

first thing is that improvement of the rudder cross-section, such as using twist cross-section in leading edge, can reduce rudder erosion. Secondly, improving the form around the gap is another method. In the case of a horn-type rudder, the rudder erosion is severe around the gap. Thirdly, using full spade type rudder without gap is another one to reduce erosion also. Additionally, special device in the inner part, SUS construction and special paints are examples of erosion reduction.

4. Measurement of Velocity Performance

Let us focus on the measurement of velocity performance. The ship owner emphasizes the ship's velocity performance always comes first in contracting decision. For example the ship owner demands the optimum main engine considering target ship speed and F.O.C (fuel of consumption). At this point, the shipyard determines the rudder geometry and size considering the ship's velocity performance.

The measurement of velocity performance considers the effect of hull and propeller by resistance occurrence. There are four kinds of method to measure velocity performance in general.: Model resistance measurement test, Model wake velocity measurement test, Propeller open water test, and Self-propulsion test. The test results of velocity performance are used to design the rudder [1].

5. Measurement of Maneuvering Performance

Maneuvering performance is measured by PMM test and Free running test. There are four kinds of standard for ship manoeuvrability: Turning ability, Initial turning ability, Yaw checking ability and Stopping ability. Fig. 14 shows the type of manoeuvrability.

What is important in the turning ability is the advance and tactical diameter. According to IMO regulations, the advance should not exceed 4.5 ship lengths, and tactical diameter should not exceed 5 ship lengths. Let us turn to initial turning ability. According to IMO, with the application of 10° rudder angle to port/starboard, the ship cannot travel more than 2.5 ship lengths by the time the heading has changed by 10° form the original heading. Also the track reach in the full astern stopping test should not exceed 15 ship lengths. However, this value may be modified by the administration where ships of large displacement make this criterion impracticable, but should in no case exceed 20 ship lengths. Table 3 shows that summation of maneuverabilty of resolution MSC.137.

Fig. 15 shows a comparison for 35 degree rudder turning ability with KVLCC2 ship.

Figs. 16 and 17 shows a comparison for 10/10° and 20/20° Zig-zag tests with KVLCC2 ship.

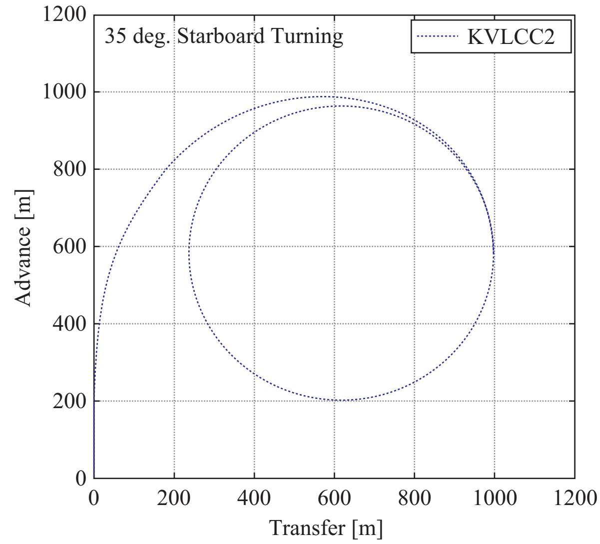

Fig. 15. Simulation of turning ability.

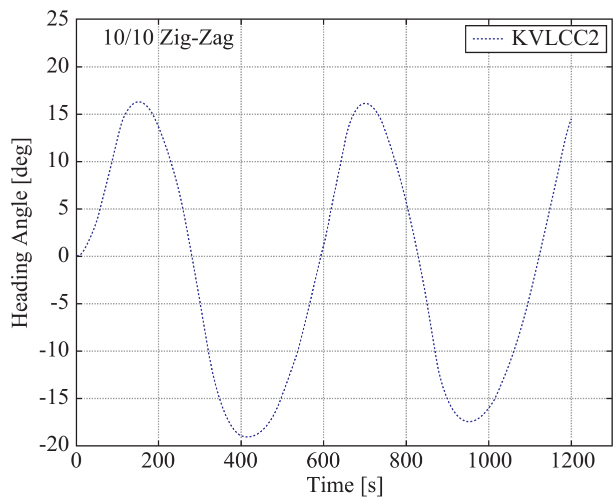

Fig. 16. 10/10 Zig-zag test.

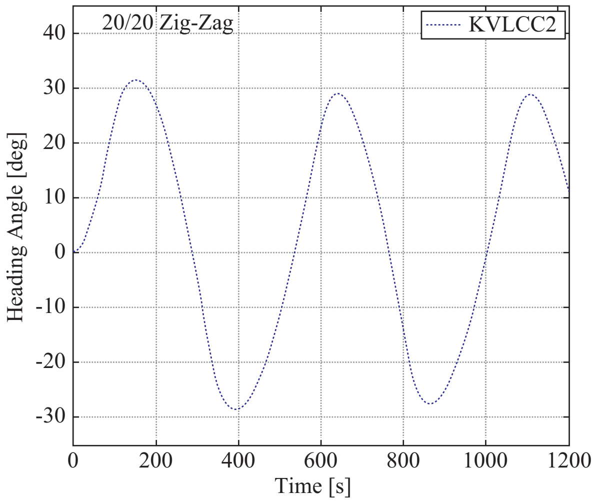

Fig. 17. 20/20 Zig-zag test.

6. Structural Analysis of Rudder

In short, structural analysis of rudder is a course for casting drawing, production drawing and applicable parts for IACS rules.

VI. CONCLUSIONS

This paper is intended to investigate the rudder design process of Korean major shipyards. Also it suggests a generalized design process of rudder device. There are three kinds of rudder design outline: Rudder concept design process, Rudder initial design process, Rudder detail design process. Here is the summary of the main points of various kinds of design process.

- Rudder concept design process: Decision of rudder area, K (turning index) and T (following index)
- Rudder initial design process: Decision of rudder form, dimension and criteria, Assumption of steering gear capacity, Investigation of maneuvering performance by simulation.
- Rudder detail design process: Reexamination of result of initial design, Decision of rudder torque, Measurement of maneuvering performance by model test.

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