An Experimental Study on Effects of Stern Duct on Manoeuvrability

by

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Abstract

Effects of stern duct located in front of a propeller to improve propulsion performance on manoeuvrability is studied here. The authors conducted turning circle tests and zigzag tests using the free-running model ship of a bulk carrier as a case study to investigate the effects. Manoeuvring characteristics of the model ship are compared between following four kinds of stern-appendages condition; (1) with a stern duct, (2) with the stern duct and a small skeg, (3) with the stern duct and a large skeg, and (4) with no stern-appendages. Weather Adopted Duct (WAD) developed by National Maritime Institute, Japan was employed as the stern duct. The comparison shows that the stern duct, WAD, improves course stability and reduces turning ability, qualitatively the same effects of the skegs on manoeuvrability. In addition, the authors have compared the effects of a stern duct with those of the skegs quantitatively by introducing a parameter, rudder-stern-appendage area ratio, which is relating to the lateral projected area of stern-appendages. As the result, it is clarified that the increase of the lateral projected area of a stern duct has almost equivalent effects to that of a skeg on manoeuvrability quantitatively.

＊　流体性能評価系，＊＊ 流体設計系

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Nomenclature

A_{LD} : Lateral projected area of stern duct [m^2]
A_{LS} : Lateral projected area of skeg [m^2]
A_R : Lateral projected area of rudder movable part [m^2]
d : Draft in full load condition [m]
D_P : Propeller diameter [m]
GM : Lateral metacentric height [m]
H_R : Rudder height [m]
k_{YY} : Pitch gyration radius [m]
K' : Turning ability index [-]
L : Length between perpendiculars [m]
r : Yaw rate [deg./s]
r' : Non-dimensional value of yaw rate [-]
R^2 : Coefficient of determination [-]
S_3 : Portion of lateral projected stern-area in the rectangular which is composed of base line, A.P., S.S.0.5, and shaft center line of the propeller [m^2]
S_4 : Sum of S_3 and lateral projected area of a duct above propeller shaft[m^2]
T' : Course stability index [-]
V : Ship speed [m/s]
ψ : Yaw angle [deg.]
θ_{OA} : Overshoot angle [deg.]
δr : Helm angle for straight run [deg.]

1. Introduction

It is required for ships to save energy consumption by compulsory regulation of Energy Efficiency Design Index (EEDI)[1]. A stern duct located in front of a propeller is one of effective devices for saving energy consumption. Effect of a stern duct on propulsion performance have been researched well[2][3][4], and some types[3] are in practical use. However, effect of a stern duct on manoeuvrability have not yet clarified sufficiently.

Researches on a skeg for improving manoeuvrability should be of some help. Lee and Yum[5] have investigated hydrodynamic coefficients in Abkowitz model[6] for a container carrier equipped with a skeg by Planar Motion Mechanism (PMM) test. Their numerical simulation of turning and zig-zag manoeuvres using the hydrodynamic coefficients has revealed that a skeg worsens turning abiltiy and improves course stability. Yamada[7] has revealed using trial data at sea that lateral projected areas of a skeg and a rudder affect course stability. These former researches on a skeg imply that a stern duct has some effects on manoeuvrability since it also increase the lateral projected stern-area.

Researches on a ducted propeller are also helpful to estimate effect of a stern duct on manoeuvrability. However, the results are not directly applicable to a stern duct, since there is a difference of locations of the ducts between a ducted propeller and a stern duct though duct configurations are similar to each other. The duct of a ducted propeller is located around the propeller and its diameter is larger than that of the propeller while the diameter of a stern duct is usually smaller. Followings are past researches on effects of a ducted propeller on manoeuvrability comparing with a conventional propeller. Okamoto *et. al.*[8] have studied effect of a ducted propeller using a large model of a tanker for free-running tests and have found that a ducted propeller decreases directional stability. Tatano *et. al.*[9] have reported data of free-running model tests indicating that a ducted propeller make a tanker who is directionally stable unstable. On the contrary, Gunsteren and Gunsteren[10] have reported theoretical consideration that a ducted propeller improves directional stability and reduce turning ability on the basis of full-scale measurement of tugs. These confusing findings imply analogy of effects of a stern duct by those of a skeg mentioned above might not be straightforward.

In this paper, in order to clarify fundamental effects of a stern duct on manoeuvrability, the authors carried out turning circle tests and zigzag tests using a free-running model ship of a bulk carrier as a case study. Manoeuvring characteristics of the model ship are compared between following four kinds of stern-appendages condition; (1) with a stern duct, (2) with the stern duct and a small skeg, (3) with the stern duct and a large skeg, and (4) with no stern-appendages. Weather Adopted Duct (WAD)[2] developed by National Maritime Research Institute, Japan (NMRI) was employed as the stern duct. Moreover, the authors have compared the effects of the stern duct with those of the skegs quantitatively by introducing a parameter, rudder-stern-appendage area ratio, which is relating to the lateral projected area of stern-appendages. The comparison shows effects of a stern duct are equivalent to those of a skeg quantitatively.

2. Manoeuvring tests

2.1 Method of manoeuvring tests

Manoeuvring tests were carried out at the Marin Dynamics Basin (length 60m, width 26m, depth 3.2m) in National Research Institute of Fisheries Engineering (NRIFE). The tests consisted of ±10/10deg. and ±20/20deg. zigzag tests, and ±35deg. turning circle tests in calm and deep water. Let + represents starboard and – represents port, respectively.

The model propeller and the steering gear were driven by a DC motor and a stepping motor, respectively. Surge, sway and heave acceleration, and roll, pitch and yaw angles and their rates were measured by a fiber optical gyro. The trajectory of a model ship, and surge and sway velocities at the center of gravity were measured by an optical positioning system. The control signals and the measured data were transmitted by Bluetooth.

The model ship was accelerated by a kind of catapult consisting of guide frames and drop weights to push a model ship, so that it could achieve a target value of initial speed with short distance. The steering and the measurement were started simultaneously after the model ship attained the designated speed.

2.2 Model ship

The model ship was a bulk carrier in full load condition, which is shown in Fig.1. Its principal dimensions are listed in Table1. Tests were carried out in four kinds of stern-appendages condition as shown in Fig.2 and listed in Table2. $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$ in Table2, which are detailed in section 3, are indices regarding lateral projected areas of a rudder, A_R, and stern-appendages based on Yamada's proposal[7]. Stern ducts shown in (b), (c), and (d) in Fig.2 are WAD[2] of identical dimensions.

Steering speed of the rudder model was 26.0deg./s corresponding to full-scale 65deg./28s defined by SOLAS.

Rotational speed of the propeller was kept constant at which the design speed of the model ship, 0.699m/s, could be achieved in calm water. Speed tests which determine rotational speed of a propeller during manoeuvring tests have shown negligible difference of the rotational speed for the ship speed among four kinds of stern-appendages condition Thus, the rotational speed of the model ship was set 1205RPM for all kinds of stern-appendages condition.

Table1 Principal dimensions of a subject ship

	Unit	Full	Model
Scale	-	1	1/125
Length between perpendiculars (L)	m	294.5	2.356
Breadth	m	50.0	0.400
Draft in full load condition (d)	m	16.5	0.132
Longitudinal length to the center of buoyancy from midship (Aft:+)	m	-7.33	-0.059
Design speed	m/s	7.82	0.699
Lateral metacentric height (GM)	m	7.4	0.059
Ratio of pitch gyration radius to L (k_{YY}/L)	-	0.250	0.250
Ratio of lateral projected area of a rudder, movable part to Ld (A_R/Ld)	-	0.010	0.010
Rudder Height (H_R)	m	12.9	0.103
Propeller diameter (D_P)	m	8.9	0.071

Table2 Conditions of stern-appendages

No.	Stern duct	Skeg	$(A_R+2S_3)/(Ld)$	$(A_R+2S_4)/(Ld)$
a	w/o	w/o	2.42 %	2.42 %
b	with	w/o	2.53 %	2.76 %
c	with	with(small)	2.71 %	2.94 %
d	with	with(large)	3.13 %	3.36 %

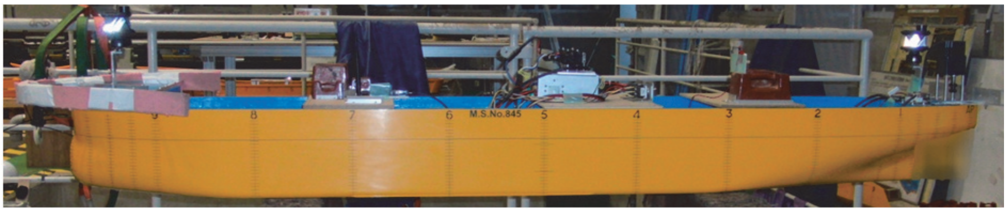
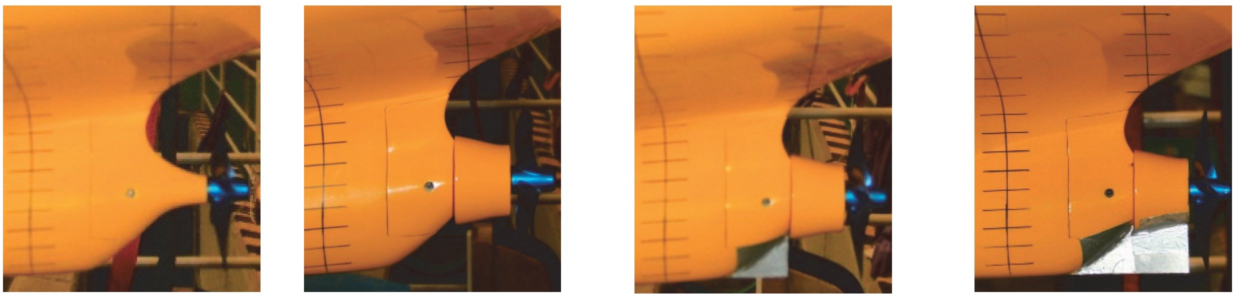


Fig.1 A model ship



(a) w/o stern duct, skeg (b) with stern duct w/o skeg (c) with stern duct, small skeg (d) with stern duct, large skeg

Fig.2 Conditions of stern-appendages

2.3 Test result

Measurement in each condition was repeated twice or more. Two of measured data whose initial deviation of yaw angle, ψ, and the rate, r, were sufficiently small are adopted for analysis in order to reduce dispersion of the measurement. Thus, overshoot angles (OAs) and turning characteristics (TCs), advance (Adv.), tactical diameter (T.D.) and transfer (Trans.), shown hereafter are averages of the twice.

2.3.1 Zigzag tests

1st and 2nd OAs in ±10/10deg. and ±20/20deg. zigzag tests are shown in Fig.3. From Fig.3 it is found that OAs of three conditions with the duct, (b) to (d), tend to decrease by attaching a skeg as Lee and Yum[5] have reported. In addition, they also decrease as lateral projected area of a skeg, A_{LS}, that is, area surrounded by green lines in Fig.4 as an example of the condition (d), increases, though exceptions are 1st OAs in ±10/10deg. zigzag tests. It is found from test result of two no skeg conditions, (a) and (b) in Fig.3, that the stern duct tends to make OAs smaller, though exceptions are 1st OA in +10/10deg. zigzag test and 2nd OA in -10/10deg. test. These exceptions are caused by the fact that variation in turning motion of a ship in ±10/10deg. zigzag manoeuvres is small and, thus, sensitive to the initial conditions[11] while initial deviation of ψ and r should be responsible. Therefore, it is considered that OA decreases in general as A_{LD} and A_{LS} increase and it means that a stern duct and a skeg have similar effect on OA.

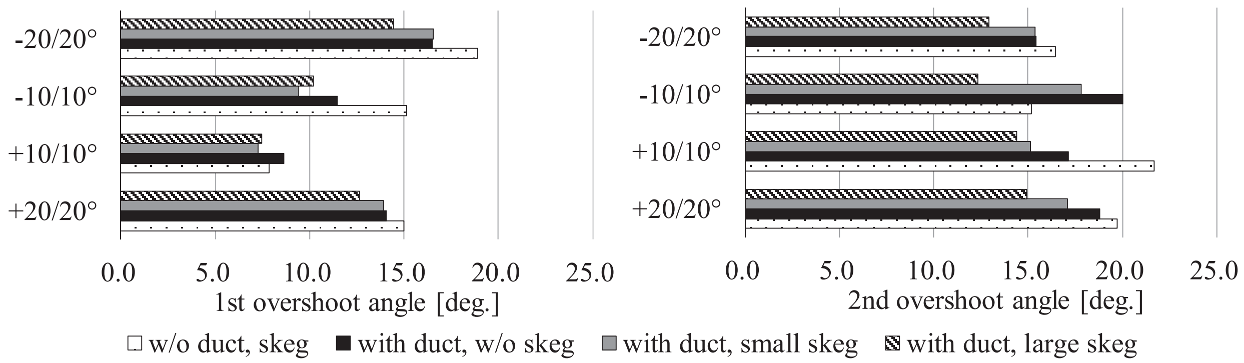


Fig.3 1st and 2nd overshoot angles in zigzag tests

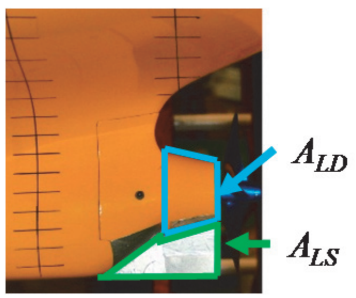


Fig.4 Definitions on Lateral projected areas of a stern duct, A_{LD}, and a skeg, A_{LS}

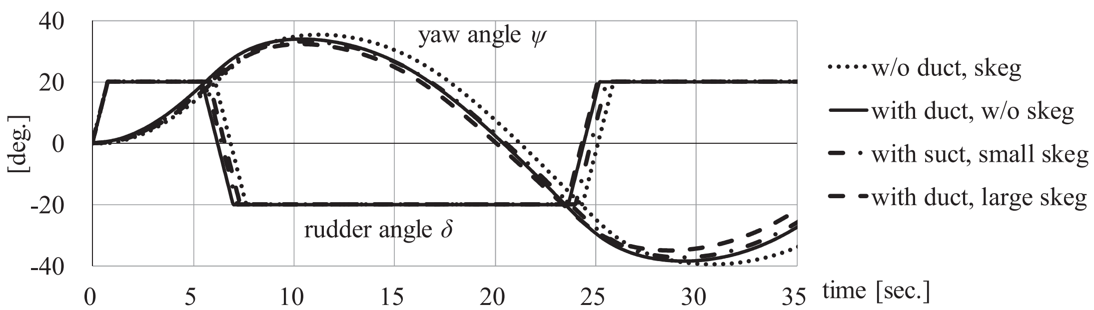


Fig.5 Time histories of ψ and δ in +20/20deg. zigzag test

Time histories of ψ and rudder angle, δ, in +20/20deg. zigzag test are shown in Fig.5 as an example. Fig.5 elaborates how the OAs in the four conditions are different from each other.

Turning ability index K' and course stability index T' are defined in Nomoto's first-order equation[12], Eq.(2.1).

$$T'\frac{dr'}{dt}+r'=K'\delta \tag{2.1}$$

where r' (=$r(L/V)$) is non-dimensional value of yaw rate and V is ship speed. T' and K' are obtained from the least-squares method using Eq.(2.2), that is, integration of Eq.(2.1) on time.

$$T'\left(r'_i - r'_s\right)+\left(\psi_i-\psi_s\right)=K'\int_{t'_s}^{t'_i}\delta_i dt+(t'_i-t'_s)K'\delta_r \tag{2.2}$$

where δr is helm angle for straight run, subscript i and s represent values at i-th time step and initial values, respectively. The interval of integration on time is set from steering start to the time when ψ achieves 2nd OA. T' and K' in Fig.6 are the means of ±10/10deg. or ±20/20deg. zigzag tests, respectively. They clearly show that T' and K' decrease as A_{LS} and the lateral projected areas of the stern duct, A_{LD}, that is, area surrounded by blue lines in Fig.4, increase.

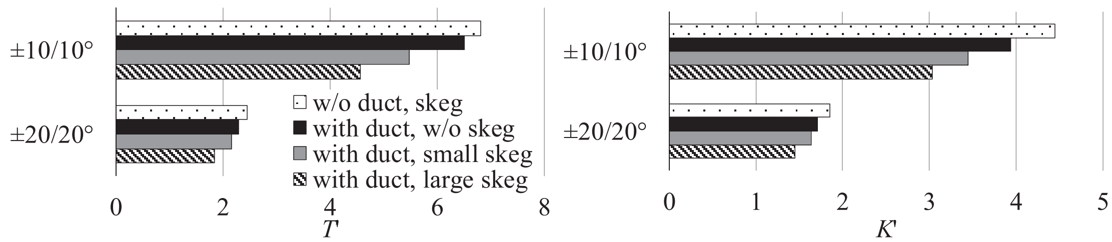


Fig.6 Course stability index T' and turning ability index K'

Kawano *et. al.*[13] have reported that a relation between T', K' and OA, θ_{OA}, is approximated by Eq.(2.3).

$$\theta_{OA}=0.443K'\delta\cdot(0.693T') \tag{2.3}$$

Eq.(2.3) is obtained from Eq.(2.1) with the assumption that a rudder is steered instantaneously after ψ becomes steady. Thus, OA estimated by this equation can only show qualitative dependency of OA on T' and K'. By applying T' and K' in Fig.6 to Eq.(2.3), it is confirmed that OAs decrease as A_{LS} and A_{LD} increase. This tendency corresponds with that of the model tests shown in Fig.3, which validates the test results.

2.3.2 Turning circle tests

TCs in ±35deg. turning circle tests are shown in Fig.7. Non-dimensional trajectories in -35deg. turning circle test are shown in Fig.8 as an example. From Fig.7 it is confirmed that TCs increase by attaching a skeg and a stern duct. In addition, it is clarified that they also decrease as A_{LS} and A_{LD} increase.

3. Relation between effects of a stern duct on manoeuvrability and lateral projected area

Relation between the effects of stern appendages on manoeuvrability, and A_{LS} and A_{LD} is quantitatively investigated in this section, since the authors assume increase of A_{LD} affects manoeuvrability as like a skeg.

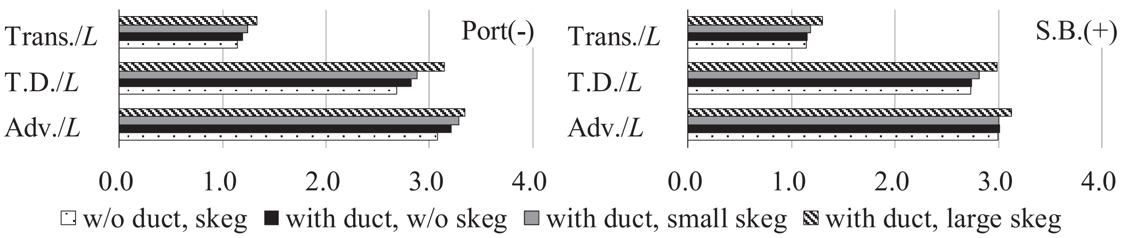


Fig.7 Turning characteristics in ±35deg. turning circle tests

d

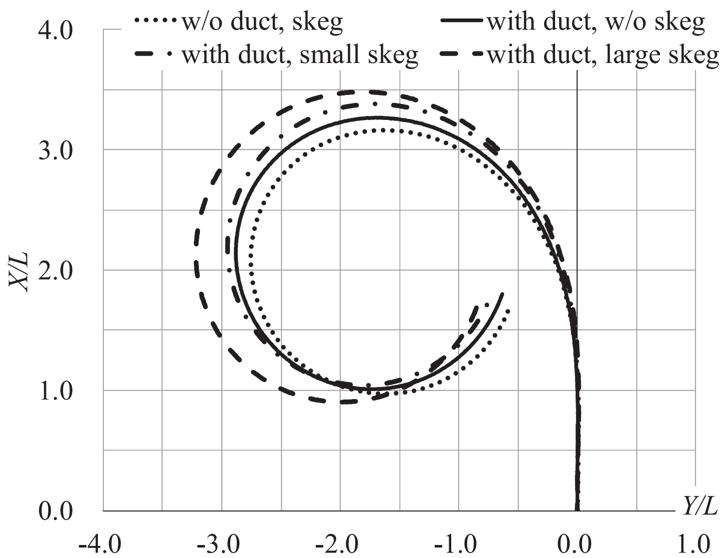


Fig.8 Trajectories in -35deg. turning circle tests

3.1 Rudder-stern-appendage area ratio

Yamada[7] has proposed a parameter, rudder-skeg area ratio $(A_R+2S_3)/(Ld)$, to evaluate influence of A_R and A_{LS} on spiral loop width. S_3 is defined as a portion of lateral projected stern-area in the rectangular which is composed of the base line, A.P., S.S.0.5, and shaft center line of the propeller as shown in Fig.9. Since loop width is interrelated to OA[7], this parameter can evaluate the effects of a skeg and a stern duct on maneuverability mentioned in section 2.

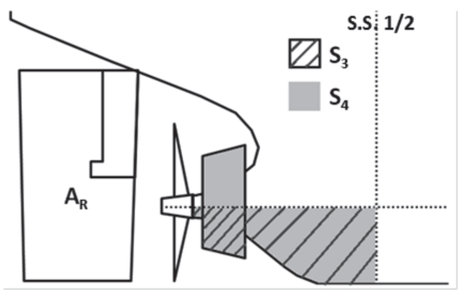


Fig.9 Definitions on A_R, S_3, and S_4

The part of A_{LD} below a propeller shaft is included in S_3. However, $(A_R+2S_3)/(Ld)$ neglects the part of A_{LD} above the propeller shaft. It is estimated that this part affects manoeuvrability as like S_3, since it also contribute increase of lateral projected area of stern. S_4 is introduced by adding A_{LD} above the propeller shaft to S_3 in order to investigate effects of this part on manoeuvrability and it is investigated which parameters are suitable to interrelate manoeuvrability with them quantitatively. $(A_R+2S_4)/(Ld)$, rudder-stern-appendage area ratio, and $(A_R+2S_3)/(Ld)$ are shown in Table 2. Since the stern duct wasn't used in the stern-appendage condition (a), $(A_R+2S_4)/(Ld)$ corresponds with $(A_R+2S_3)/(Ld)$, 2.42% as shown in table 2. Thus, data whose abscissas are 2.42 in Figs. 10 through 12 overlap each other.

3.2 Comparison of manoeuvring characteristics with lateral projected area of the stern duct and the skegs

Variation of 1st and 2nd OAs in zigzag tests depending on $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$ is shown in Fig.10. They are means of 10/10deg. and -10/10deg., 20/20deg. and -20/20deg. zigzag tests, respectively. Dashed lines are apploximated lines regarding $(A_R+2S_3)/(Ld)$ and Chain lines are those regarding $(A_R+2S_4)/(Ld)$. Coefficients of determination R^2 of each line are also listed in this figure. R^2 is calculated by Eq.(3.1) and $R^2 = 1$ means the residual of regression analysis is zero.

$$R^2 = 1 - \frac{\text{the sum of squares residual}}{\text{the sum of squares deviation}} \tag{3.1}$$

It is found from Fig.10 that OAs decreases almost linearly to both $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$, though R^2 of 1st OAs in ±10/10deg. zigzag tests are small relative to the others. Thus, increase of A_{LD} below a propeller shaft or whole A_{LD} has equivalent effect to those of A_{LS} on OA quantitatively. The small R^2 of 1st OAs in ±10/10deg. zigzag tests relative to the others should be caused by initial deviation of ψ and r as mentioned in section 2.

Variations of T' and K', and TCs depending on $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$ are shown in Fig.11 and Fig.12, respectively. They shows that both T' and K' decrease almost linearly and all TCs increase linearly as $(A_R+2S_3)/(Ld)$ or $(A_R+2S_4)/(Ld)$ increases. Therefore, it is estimated increase of A_{LD} below a propeller shaft or whole A_{LD} also has equivalent effects to those of A_{LS} on T', K' and TCs quantitatively.

Fitting lines of Figs. 10 through 12 enable to estimate the variation of manoeuvrability quantitatively using the lateral projected area of a stern. For example, judging from $(A_R+2S_4)/(Ld)$, it is predicted that 1st OA in 10/10 zigzag test decreases by 14%, 2st OA in 10/10 zigzag test decreases by 15%, and T' and K' in 10/10 zigzag test decreases by 18% along with 0.5% increase of $(A_R+2S_4)/(Ld)$. In case of TCs, advance increases by 3.4%, tactical diameter increases by 7.1% and transfer increase by 8.1% along with 0.5% increase of $(A_R+2S_4)/(Ld)$. These estimations are also possible using the variation of $(A_R+2S_3)/(Ld)$.

Figs. 10 through 12 show some R^2 are improved if S_3 is altered to S_4 but the others worsen. The means of R^2 in Figs. 10 through 12 based on $(A_R+2S_3)/(Ld)$ or $(A_R+2S_4)/(Ld)$ are 0.927 and 0.931, respectively. Therefore, both $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$ can correlate A_{LD} with A_{LS} in terms of manoeuvrability.

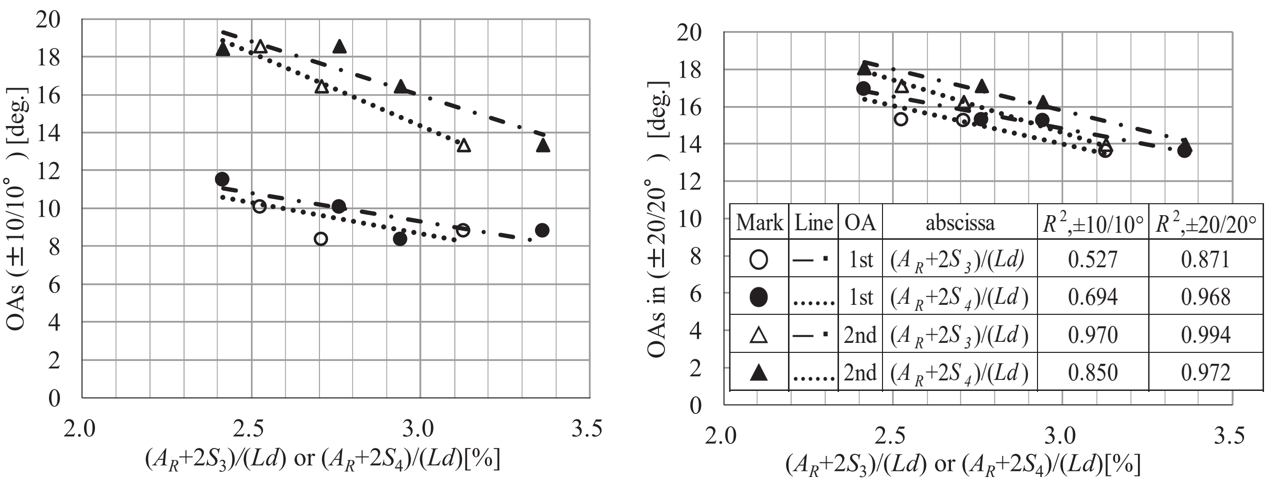


Fig. 10 Variation of OAs depending on $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$

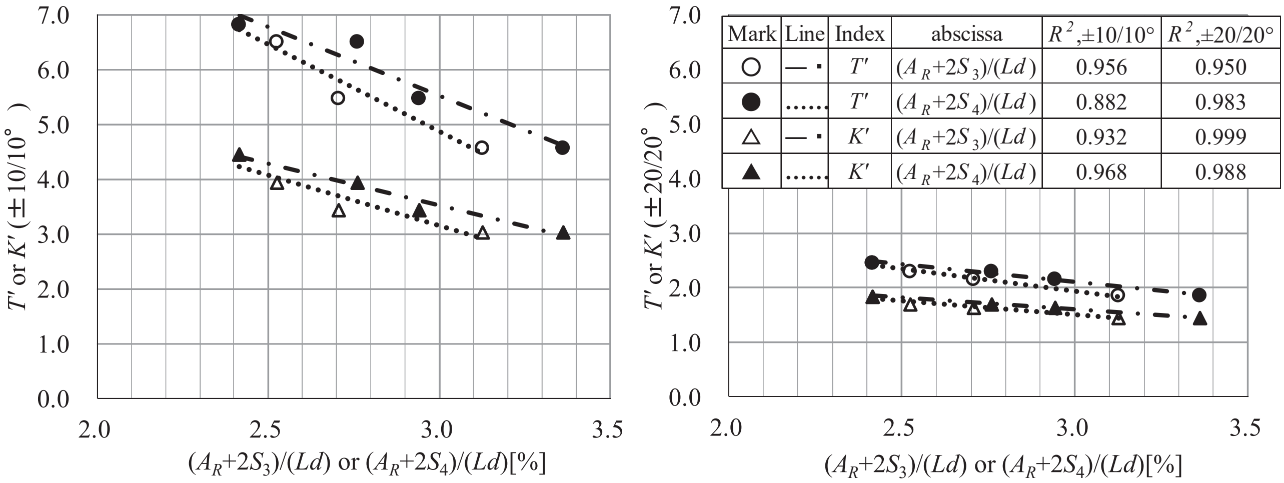


Fig. 11 Variation of T' and K' depending on $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$

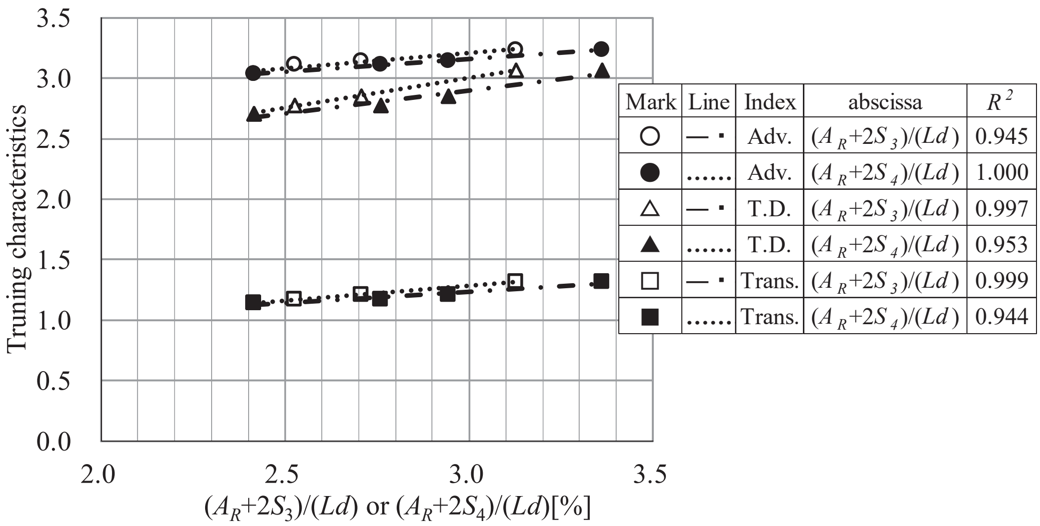


Fig. 12 Variation of TCs depending on $(A_R+2S_3)/(Ld)$ and $(A_R+2S_4)/(Ld)$ (Indies of the legend are as follows. Adv.: advance, T.D.: tactical diameter, Trans.: transfer.)

4. Conclusions

In order to investigate fundamental effects of a stern duct located in front of a propeller to improve propulsion performance on manoeuvrability, the authors carried out turning circle tests and zigzag tests, using a free-running model ship of a bulk carrier with WAD as a stern duct. This is a case study using a bulk carrier and a stern duct. Manoeuvring characteristics of the model ship have been compared between following four kinds of stern-appendages condition; (1) with a stern duct, (2) with the stern duct and a small skeg, (3) with the stern duct and a large skeg, and (4) with no stern-appendages. The comparison shows that a stern duct decreases overshoot angles, course stability index, and turning ability index, and increases turning characteristics in terms of advance, tactical diameter and transfer. In other words, a stern duct improves course stability and reduces turning ability. These effects are similar to those of a stern-skeg.

The authors have been compared the effects of a stern duct and a skegs with two kinds of their lateral projected areas quantitatively. One is rudder-skeg-are ratio proposed by Yamada, the other is rudder-stern-appendage area ratio. As the result, it is clarified that the manoeuvring characteristics vary almost linearly to rudder-skeg-are ratio and rudder-stern-appendage area ratio. Moreover, increase of lateral projected area of a stern duct has almost equivalent effects on manoeuvrability to those of a skeg quantitatively. Thus, both rudder-skeg-are ratio and rudder-stern-appendage area ratio can correlate lateral projected area of a stern duct with the manoeuvring characteristics quantitatively.

Considering the researches on a ducted propeller mentioned in the Introduction, further manoeuvring tests or numerical calculation by reliable models using various types of ships and those with various dimensions of stern ducts are necessary to generalize their effects on manoeuvrability.

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