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Some practical design aspects of appendages for passenger vessels

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ABSTRACT: *The hydrodynamic effect of appendages for high-speed passenger vessels, such as Ro-Pax, Ro-Ro and cruiser vessels, is very severe and, therefore, it is essential to carry out the design of appendages for high-speed passenger vessels from the preliminary design stage to the final detail design stage through a full survey of the reference vessels together with sufficient technical investigation. Otherwise, many problems would be caused by mismatches between the appendages and the hull form. This paper investigates the design characteristics of some appendages, such as the side thruster, the shaft-strut, and the stern wedge, based on the design experience accumulated at Samsung, on CFD, and on model test results for high-speed passenger vessels. Further to this investigation, some practical and valuable design guidelines for such appendages are suggested.*

***KEY WORDS**:* Passenger vessels; Appendage; Side Thruster; Shaft-Strut; Stern Wedge; Powering Performance

INTRODUCTION

In passenger vessels, various appendages are generally attached to the hull. These appendages are employed to guarantee high comfort and good maneuverability, and the twin shaft type is usually adopted to provide a redundancy in propulsion systems and a high-speed performance in shallow draught since these vessels usually operate in harbors or water channels. Therefore, appendage design requires full technical consideration of hydrodynamic performance aspects such as resistance, propulsion, sea keeping, and maneuvering performance, and strength and structural performance aspects including noise/vibration. In general, it is difficult to establish the dimensions or design of appendages in the early design stage since the detailed design of the vessel is not still fixed.

In this view, appendage design should be carried out with a full preliminary investigation; otherwise, many negative problems would be caused, such as an increase of resistance, a reduction of self-propulsion performance, a possibility of creating harmful cavitation, a delay in the construction schedule by manufacturing problems, among others. Consequently, special attention should be paid to appendage design during the entire design process through sufficient technical investigation and a survey of the reference vessels, and the optimal design of appendages should be performed in accordance with the design progress of the vessel.

This paper investigates the design characteristics of some appendages such as the side thruster, the shaft-strut, and the stern wedge based on the design experience accumulated at Samsung, on CFD, and on model test results for the Ro-Ro Passenger Ferry (hereinafter referred to Ro-Pax) and the cruise vessel(Rhyu et al. 2003). The object of this paper is to suggest some practical and valuable design guidelines for such appendages.

Table 1 Principal Particulars.

Hull Type	Ro-Ro	Ro-Pax			Cruise Vessel
	150*m* Class	154*m* Class	185*m* Class	210*m* Class	50,000 GT Class
LOA [*m*]	152.0	154.0	185.0	212.0	235.0
LBP [*m*]	140.0	144.0	172.0	198.0	211.1
B [*m*]	23.6	24.6	28.4	25.0	29.0
T_d [*m*]	6.37	6.0	6.75	6.6	7.1
GT [*Ton*]	15,000	22,500	34,000	28,000	50,000
Speed [*knots*]	19.8	26.5	25.5	30.0	24.0

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PRINCIPAL PARTICULARS OF PASSENGER VESSELS

The principal particulars of the passenger vessels considered in this paper are listed in Table 1, and they were utilized in the investigation of the characteristics and to suggest the optimal design of appendages.

DESIGN OF SIDE THRUSTER

The resistance performance of the side thruster was first investigated through model tests and studied to obtain a solution to minimize additional resistance

Side thruster

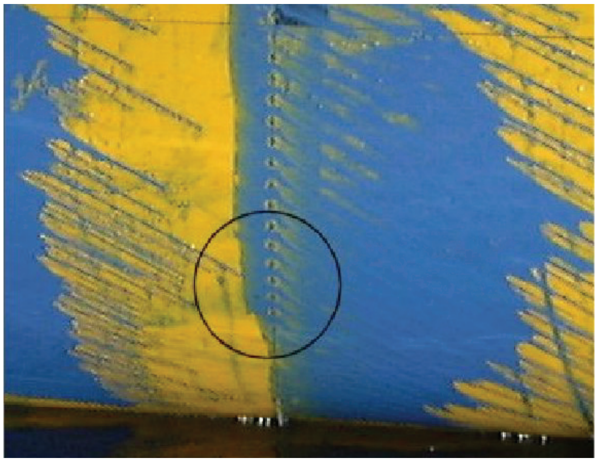
The side thruster is the most universal maneuvering propulsion device (MPD), which assists a ship in maneuvering in cases in which it lacks maneuvering performance from the rudder itself. The side thruster has the advantage of being more able to control a ship in severe winds or currents, but it also has some disadvantages since it causes an increase of resistance, requires additional space for installation and is a source of noise and vibration.

In the case of a passenger vessel, the side thruster is required to move the vessel alongside the berth by itself (without the assistance of a tugboat) and in some vessels the side thruster is installed in the stern as well as in the bow. Because it is difficult to install the thrusters on a fine hull form, and because the required thruster capacity is greater than that of a commercial vessel, the number of side thrusters on a passenger vessel is normally more than two. Therefore, it is considered that the resistance increase due to the installation of the side thrust system would be somehow larger than expected, resulting in a severe speed-loss penalty. In this view, it is essential to investigate the effect of the side thruster system on resistance. Systematic model tests, in which the elements of the side thruster were changed, were conducted, and the effects on the resistance were investigated.

Elements of side thruster

The side thruster system includes several components such as the tunnel, the CPP, the grid and, sometimes a scallop. The scallop decreases an additional form resistance by being fitted into the hull to remove a step of the tunnel in the rear, and this is accomplished through a streamline investigation.

The results of a paint test on a 50,000 GT cruise vessel are shown in Fig. 1. Fig. 1(a) shows the streamline test result for the bare hull, and (b) is the case for the hull with the bow thruster (tunnel, grid and CPP). The scallop was not fitted for this ship. Fig. 2 shows the paint test result for a 138K LNGC with the bow thruster, in which case the scallop is applied.



(a) Bare hull

(b) Bow thruster(tunnel, grid and CPP)

Fig. 1 Paint test results of 50,000GT Cruise vessel.

Fig. 2 Paint test result of 138K LNGC with bow thruster (tunnel with scallop, grid and CPP).

Results of model tests

Table 2 shows the comparison of resistances measured for the several cases relative to the percentage of the total EHP for the bare hull. Case 1 is the result for the bare hull. Case 2 is the case of applying the tunnel only, and it is noted that the tunnel-only installation on the hull increases the EHP by 8.9% compared with the result for the bare hull. Case 3, the case of installing the tunnel and CPP, shows an increase of EHP of 1.8% compared with the result of the bare hull, which is much less than that in Case 2. This reason can be explained by the fact that the CPP in the tunnel prevents some in-flow phenomena into the tunnel and thus suppresses the flow separation and vortices generation by the tunnel inlet. It is known that that the grid, installed on the tunnel inlet, suppresses the flow separation, as seen in Case 4, which yields a 3.5% EHP increase, which is still much lower than that of Case 2 with the tunnel only, but somewhat larger than that of Case 3. If the grid and CPP are both installed, as in Case 5, the resultant EHP increase of 1.3% is the lowest among the tested cases, showing the most effective suppression of the flow separation and vortices. In order to confirm this result, the model test result for the 38K LNGC, being the same as that for Case 5 for the cruiser, is shown in Case 5* in Table 2.

It can be seen from the Table that the magnitude of EHP increase is very similar for the two ships, showing that the tested results are reliable. It is noteworthy to mention that Kim et al. (2006) investigated the effect of the grid, installed on the tunnel inlet, on the resistance and suggested a new tunnel grid system giving a lower resistance increase.

Table 2 Comparison of the resistance performance.

Vessel	Case	Tunnel	Grid	Scallop	CPP	EHP/ (EHP)bare (%)	Effect
Cruiser	1	Bare hull		100.0		-	
	2	Yes	No	No	No	108.9	Tunnel
	3	Yes	No	No	Yes	101.8	CPP
	4	Yes	Yes	No	No	103.5	Grid
	5	Yes	Yes	No	Yes	101.3	Grid +CPP
LNGC	5*	Yes	Yes	No	Yes	101.7	Grid +CPP
	6	Yes	Yes	Yes	Yes	104.7	Grid +CPP +Scallop

As mentioned above, two side thrusters were installed for the cruiser and thus, because it was considered that the effect of the scallop in this case would be worse, the scallop was not fitted. In order to understand the effectiveness of the scallop fitting regarding the resistance, the model test result of the 138K LNGC is added to Table 2 as Case 6, showing that the installation of the scallop for this ship results in a resistance increase compared with that of Case 5*, in which the scallop is not installed. In general, it is known that the scallop decreases an additional form resistance due to the reduction of the tunnel step in the rear, but this was not the case. It was also observed from a local flow investigation by an in-house CFD code that the local flow behavior according to the presence of the scallop was not good compared with that of the tunnel without the scallop for this particular ship. Therefore, it is recommended that the scallop should be carefully chosen by investigating the characteristics of local flow phenomena around the hull form with the tunnel inlet.

Summary

- Some useful conclusions based on the present study into the effect of the side thruster on resistance can be made. The resistance increase due to the tunnel presence on the hull is approximately 10%, but the presence of the CPP and the grid suppress the flow separation and vortex generation, and therefore, the final resistance increase due to the side thruster system is not very significant, being about 1~2%.
- However, the careless installation of the scallop increases the resistance compared with that of the tunnel without the scallop.

In this paper, the investigation was carried out from the perspective of resistance performance, but a study into the effect of the side thruster on noise and vibration should be also performed for passenger vessels. Therefore, more research should be conducted into the above problem to achieve a more optimal design of side thruster.

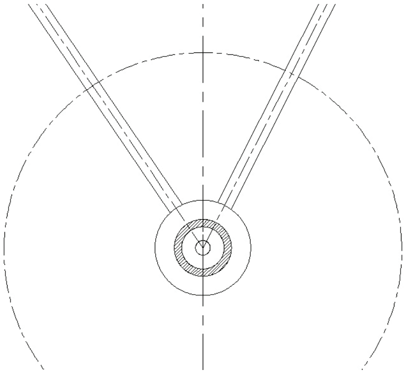
DESIGN OF SHAFT/STRUT

Shaft/strut

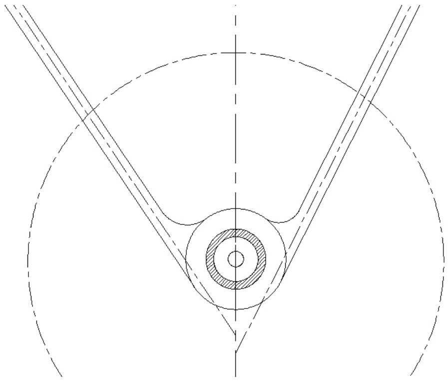
The strut is a kind of bracket that is installed between the hull and the shaft when it is necessary to support the shaft and the propeller. It is also required to sustain its own weight as well as that of the shaft and the propeller. And the strut should be designed to resist the excitation force and moment that are induced by the rotational motions of the propeller and the vibration of shaft. This paper proposes the idea of an optimal design for the shaft/strut through an investigation of the design for the main strut and the arrangement between the strut and the shaft.

Design of main strut

There are generally two types of main strut, the single type and the twin type being usually called the vee type. The vee-strut type having twin struts is more widely used compared with the single-strut type from propulsion and strength points of view. The vee-strut type is classified into a radial type and a tangential type according to the connection method at the barrel. In the case of the radial type, the center of the strut section coincides with the center of the shaft line, as shown in Fig. 3(a). In contrast, in the tangential type, the sideline of the strut arm is linked to the outline of the barrel, as seen in Fig. 3(b).



(a) Radial type struts



(b) Tangential type struts

Fig. 3 Types of vee-struts.

Regarding this difference of connection, Saunders (1957) has stated that tangential arms are well spread at the hub, but they usually involve reentrant angles alongside the barrel which are considerably smaller than 90 degrees, and that radial arms provide good attachments in supporting the shaft, but that the passage between the arms at the hub surface may be somehow constricted if the vee angle is too small. Losee(1957) indicated that the radial arms for the vee-strut are more general. Sometimes, however, in the case of a too small angle between the arms, it may be desirable to provide greater separation between the arms at the barrel, and the outer surfaces of the arms may be made tangential to the barrel. However, this could introduce an additional transverse bending moment on the arms. Occasionally a compromise can be made between the radial and tangential arrangements. In addition, Hackett and Jonk(1999) indicated that the radial strut provides superior strength and stiffness on an unit-weight basis, but that the radial struts tend to reduce the flow between the strut arms more than the tangential struts, causing some other hydrodynamic problems such as wake peak.

The ship designer usually considers that for the main strut, the structural aspect is more important than the hydrodynamic aspects. Therefore, an investigation of the strength of the strut in the preliminary design stage is required. The Finite Element Method (FEM) is generally used in this structural analysis, but it requires significant time and special knowledge. For this reason, the guidance of Design Data Sheets (DDS) proposed by Losee is usually in use in the preliminary design stage for naval and commercial ships. Table 3 shows a comparison of the safety factors for the longitudinal section modulus calculated by FEM and DDS, respectively, for a 210*m* Class Ro-Pax. The two safety factors are similar to each other and therefore, the use of DDS method in the preliminary design stage is justified to predict the strength of the strut.

Table 3 Comparison of safety factors obtained by two methods.

Calculation method	Strut type	Safety factor for longitudinal section modulus
FEM	Tangential	3.1
DDS		3.2

Table 4 shows the results by DDS for a 185*m* Class Ro-Pax in order to compare the strengths of the tangential and radial struts. The EPH section proposed by DTMB is applied to the strut arm and is 5.0 in chord/thickness ratio. The result shows that the strengths of the tangential and radial struts are very similar to each other.

Table 4 Strength between radial and tangential strut.

Ship type	Strut type	Safety factor for longitudinal section modulus
185*m* Class Ro-Pax	Tangential	2.93
	Radial	2.97

As shown above, DDS is usefully and practically used for structural analysis of the strut in the preliminary design stage, but it is known that DDS is inadequate in evaluating the vibration performance and that there is no such guidance in LR(2003) or ABS(2003). In order to confirm this fact, the vibration characteristics of the tangential and radial strut arms for the 185m Class Ro-Pax were investigated by DDS and FEM analyses. The results estimated by DDS showed that the safety factors for vibration are 1.53 and 2.25 for the tangential and radial types, respectively. The safety factor for vibration is defined as the natural frequency of the strut arm divided by the propeller blade frequency. However, the results by FEM show safety factors of more than 10 and therefore, it was confirmed that DDS cannot be used in vibration analysis.

According to the recommendation of Hackett and Jonk (1999), it is desirable to minimize the wake peak by applying the tangential strut instead of the radial strut, since passenger vessels require low noise and vibration performances to guarantee a high degree of comfort for the passenger. Based on the design experience and knowledge accumulated from model test results, the authors would like to recommend the tangential type to be generally used for passenger vessels.

Shaft arrangement

Shaft arrangement is an important factor in appendage design for passenger ships. Fig. 4 shows the results of resistance tests according to a change of shaft arrangement for a 154*m* Class Ro-Pax. Two struts, the main and intermediate struts, are generally in use in the case of a long shaft case. Fig. 4 shows a comparison of the resistances in three cases, bare hull, hull with main strut, and hull with intermediate and main struts. It can be seen that the resistance in the last case, hull with two struts, is about 18% larger than that of the bare hull, whereas the second case, hull with one main strut, is about 13% larger than that of the bare hull. In the second case, in which the bossing being made somewhat longer to support the shaft more rigidly, it is noteworthy to see some resistance gain compared with the last case with two struts.

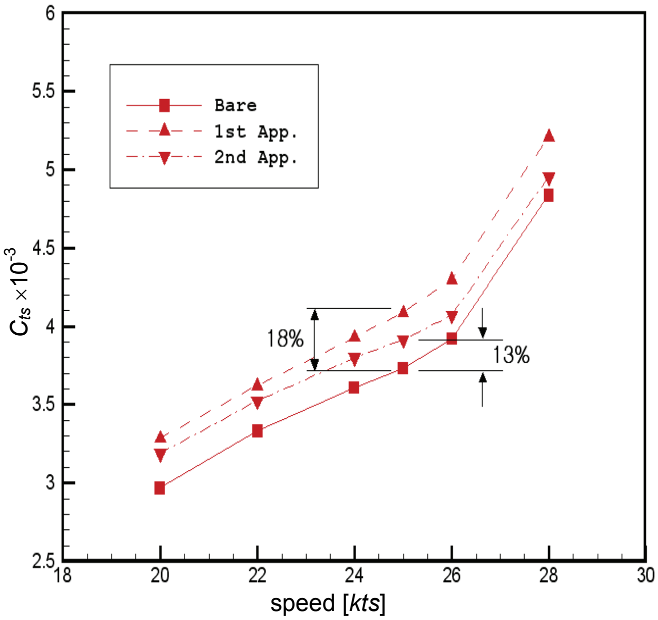


Fig. 4 Comparison of resistance for three cases: bare hull, bare hull with one main strut (2nd App.) and bare hull with intermediate and main struts (1st App.).

Summary

Some useful conclusions based on the present study into strut type and arrangements can be made.

- The tangential type strut is preferable to the radial type strut in that it minimizes the wake peak.
- Losee's method (the DDS method) is used effectively to evaluate the strength of strut arm for a passenger vessel in the preliminary design stage.
- Shaft arrangement can be carefully considered to minimize an additional resistance increase.

DESIGN OF STERN WEDGE

Technical investigation and model tests of the stern wedge were performed to improve the resistance and self-propulsion performances. Based on this study, some useful design guidelines are provided.

Transom appendages are classified into ducktail, stern flap, and stern wedge in accordance with the elements of installation, as shown in Fig. 5. For high speed small vessels, the transom appendages are usually installed to control trim at high speeds, resulting in some improvement in powering performance. These transom appendages are also applicable to medium or large vessels to smooth the stern waves and also to decrease the pressure drag due to flow field change, resulting in overall powering performance improvement. It was reported in Cumming et al. (2006) that 5 to 10% fuel savings for warships with the stern flap can be achieved from the sea trials. Recently, Thornhill et al. (2008) validated the drag reduction due to the presence of the stern flap by showing good correlations between CFD and experimental results.

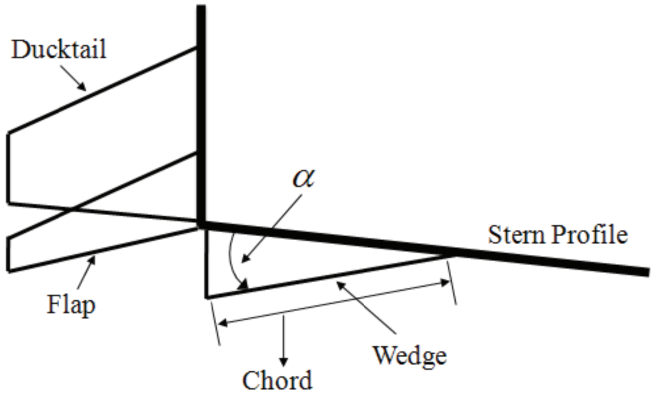


Fig. 5 Schematic drawing for various transom appendages.

The ducktail appendage has been generally applied to passenger vessels for a long time as a function of ramp and it was also known that this can reduce the wave-making resistance due to a lengthening effect. It would be difficult to install the stern flap appendage on passenger vessels due to the problem of berthing backward on the quay. Recently, the stern wedge has been used as a transom stern appendage since there is no protrusion beyond the stern. In this paper, the effect of the stern wedge on the resistance and propulsion of the 154*m* class Ro-Pax is investigated.

Numerical Calculation

Karafiath et al. (1999) reported the effect of the adoption of the stern wedge by model tests for amphibious and sealift hull forms, summarizing that the adoption of the stern wedge can improve the resistance and self-propulsion performances for speeds faster than Fn = 0.3 and up to a 7% gain in the self-propulsion performance at Fn = 0.35 is achieved.

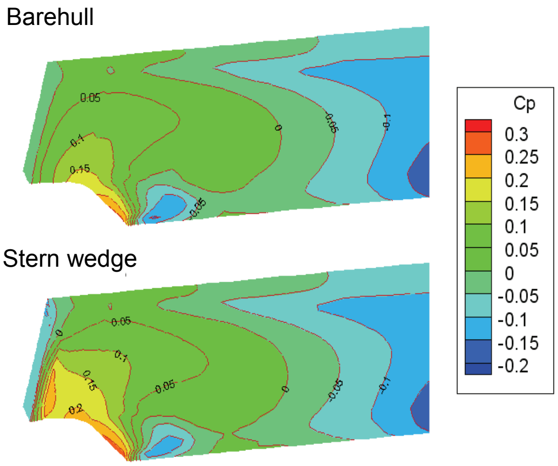


Fig. 6 Distribution of hull surface pressure at Fn = 0.36.

Table 5 Comparison of the resistance calculations.

Drag	Original Hull	Hull with wedge
C_d (%)	100	94.4
C_{df} (%)	100	99.5
C_{dp} (%)	100	79.7

(C_d : total drag coefficient, C_{df} : frictional resistance coefficient, C_{dp} : pressure resistance coefficient)

The flow fields for the 154*m* class Ro-Pax with an in-house CFD code were computed to confirm the pressure change due to the stern wedge. Fig. 6 shows that the surface pressure on the stern with the stern wedge is higher than that on the hull without the stern wedge. Table 5 shows the computational drag components, and it can be understood that the decrease in the pressure resistance is somewhat large, as reflected in the pressure distribution in Fig. 6, resulting in about a 5 ~ 6% decrease in the total resistance.

Model tests

In order to evaluate the effect of the stern wedge on the resistance and self-propulsion performance, the model tests were carried out for the 154*m* class Ro-Pax and these results can be also confirmed the validity of the numerical results. Fig. 7 shows the wave-making resistance coefficients tested for the two cases, showing that the wave resistance of the hull with the stern wedge is lower than that of the bare hull by 17% at Fn = 0.36. Table 6 shows that the required power is reduced by the stern wedge installation whereas the hull efficiency is somehow worsened. This fact can be supported by the aforementioned numerical result that most of the drag reduction is due to the pressure drag reduction including the wave-making resistance. In fact, it was observed from the model test that the stern waves of the hull with the wedge are much smoothened compared with that of the bare hull.

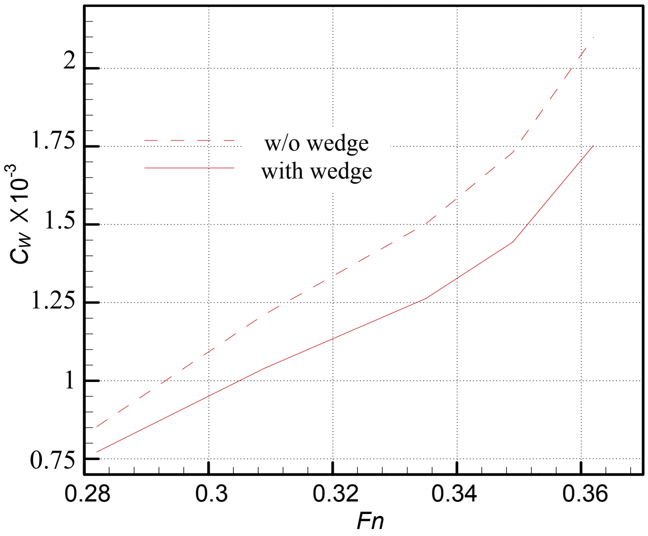


Fig. 7 Effect on wave resistance by stern wedge (model test).

Table 6. Effect on powering by stern wedge (model test).

Item	Original Hull	Hull with wedge
P_E	100	93.1
P_D	100	93.0
w	100	108.2
t	100	121.0
η_h	100	99.2
η_r	100	100.2
η_o	100	100.6

(P_E : effective power, P_D : delivered power, w : wake fraction, t : thrust deduction fraction, η_h : hull efficiency, η_r : relative rotative efficiency η_o : open water efficiency)

Summary

It was proved by the CFD and experimental results that the stern wedge can improve the powering performance by reducing mainly the pressure drag and also some the wave-making resistance decrease. The stern wedge has several advantages compared with the ducktail and the stern flap with regard to structure and shape without protrusion beyond the stern. It is recommended that the length and the angle of the stern wedge should be optimized in accordance with the stern profile in order to achieve the maximum gain, and this can be effectively accomplished by parametric studies with a proven CFD code.

CONCLUSIONS

The hydrodynamic effect of appendages for high speed passenger vessels are very severe and sensitive to the local hull form variations and thus, it is essential to carry out the design of the appendages for passenger vessels from the preliminary design stage to the final design stage through a full survey of the reference vessels together with sufficient technical investigations.

As explained in this paper, studies on appendage design for passenger vessels was conducted through various means such as reference review, empirical and numerical calculations and model tests. Some practical design aspects and guidelines for appendages such as the side thruster, the shaft-strut and the stern wedge in order to achieve good overall performance are summarized at the end of each section covering each appendage.

It was demonstrated that such appendages, well designed, can minimize an additional powering requirement or can render it even less than that of the bare hull. In this respect, some guidelines suggested in this paper can be effectively and usefully employed in the optimal design of passenger vessels with appendages.

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