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To cite this article: Peng Zhou *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **219** 012030

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# Model Test Study on Parameter Optimization of Stern Flaps of Series Displacement Ships

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**Abstract.** The design of stern flaps generally pursues the resistance reduction of ships at high speed. Moreover, for some surface warships, the parameter selection of stern flap needs is the key consideration due to the wide range of ship speed from cruising to design speed. In this paper, model ship experiments for a series displacement ship are conducted to optimise the configuration of stern flaps. From the model ship resistance and self-propelled model ship experiments, the stern flap impacts to the lowest effective Froude number, resistance of ship, self-propelled status and voyage status are studied. After the analysis of the results and optimizing of the design, the ship with stern flaps has lower resistance and could save 3% and 5% of energy at cruising and design speed respectively. The authors hope the results of this paper could provide help and reference to the design of ship stern flaps in the future.

## 1. Introduction

For the surface ships, the ship design always pursues to reduce the hull resistance and save energy, especially for navy ships which have high desires for speed and limited resources for equipment arrangement. The stern flaps have the features like: simple structure, easy installation and resistance reduction effects, hence they are widely used in many surface ships [1]. A stern flap is an appendage installed at the stern of hull and extends the hull bottom aft of the transom. Many studies show that stern flaps can provide large resistance reduction and it has already been installed on many operational ships. The hydrodynamic of resistance reduction of stern flaps can be explained (details in Cusanelli, 1999 [2]) as such:

- 1) Developed lift and drag force.
- 2) Increased pressure and decreased flow velocity of afterbody flow.
- 3) Beneficial propulsion interactions.
- 4) Modified ship trim.
- 5) Far field energy reduced.
- 6) Wave energy reduced in near field.
- 7) Alteration of localized transom wave.
- 8) Ship length increased.
- 9) Apparent ship displacement reduced.

Many of existing designs [1-6] of stern flap are mainly aiming to optimize the performance at design speed. With the increasing demands of noisy control of navy ships, on the ships using CODAG (Combined diesel and gas) power system, only diesel engines work at the cruising speed. Hence, the margin of power is highly limited at cruising speed. For this reason, the design of stern flaps should



concern the resistance reduction performance at both of cruising speed and design speed. However, many studies [1-6] show that the stern flaps are only effective above a certain Froude number,  $Fr$ , (or a certain speed for a designed ship), and even increase the resistance at low Froude number. Meanwhile, the varying of stern flap parameters occasionally lead to opposite consequences at low and high Froude numbers respectively [4]. These facts bring the difficulties to the stern flap design which aim to optimize the resistance reduction at cruising and design speed.

The existing studies of stern flap mostly focus on the principle of resistance reduction at design speed, selection of parameters and scale effect. M. Chen [1] and W. Dong [2] studied the principle of stern flaps on round bilge and Deep-Vee hull forms respectively. M Chen and etc. [4-5] studied the stern flaps on round bilge hull ships with various designs using model and real-ship demonstrations. Their results present that the stern flaps can provide impressive ship resistance reduction. Y Zheng, W Dong and etc. conducted model ships experiments to optimize stern flaps design on deep-Vee hull ships. U.S. Navy studied the resistance reduction of stern flaps for Arleigh Burke-class destroyers and FFG-7 frigates at 1990s particularly [7-11] using both model and real ships demonstrations. Gabor Karaflath [10] studied the model ship resistance with different stern flaps shapes and model scales for Arleigh Burke-class destroyers and Perry-class frigates. Comparing with the real ship data, he summarized the principle of stern flaps design for resistance reduction.

At present, the study of the resistance reduction of stern flap mainly uses the methods of theoretical analysis of potential flow [12-14], CFD (computational fluid dynamics) [3] and model ship experiments [4, 6]. For the analysis of potential flow, the wave resistance is calculated using empirical formula or potential flow theory. Therefore the results of ship resistance and wave flow field are inaccurate and unacceptable in some cases. With the development of the computational capacity, CFD has great advantages in many aspects e.g. financial and time costs. Thus, it is suitable for multi-scheme comparison of stern flaps, nonetheless it is difficult to solve the problems such as the detailed prediction of voyage statuses, self-propulsion with stern flaps and nonlinear problems of the large ship movement in wave. The model ship experiment is irreplaceable because of the accurate predictions of resistance in full appendage test, voyage statuses, self-propulsion and ship movement. On the other hand, the huge cost of model ship experiments limits the number of experimental schemes, thus it is difficult to carry out series research on the design of stern flaps.

In this study, the main objectives of authors are studying the ship resistance reduction, energy saving and voyage statuses with stern flaps, as well as the optimizing of stern flaps parameters from cruising and design speeds for a series of displacement ships. By means of the two rounds of full appendage model ship resistance and self-propulsion experiments with multi-scheme of stern flaps, the authors provided theoretical analysis, optimized the design of stern flaps, and delivered the suggestions to the stern flaps design which intend to meet the demands of the resistance reduction and energy saving for future surface ships.

## 2. Experimental set-up

### 2.1. Model ship experiments

Two model ships, named M1 and M2, were tested in this study. Both of the displacement model ships have transom sterns, same dimensions, but different hull shapes. The designed displacement of M2 is slightly larger than M1. The model scales of both are 1:21. The range of Froude number is from 0.12 to 0.48 in this study.

The model ship experiments were conducted in the towing tank which located in CSSRC (China Ship Scientific Research Center), Wuxi, China. The length, width and depth of the tank are 474m, 14m and 7m respectively. The accuracy of the measured resistance is believed within 0.5%.

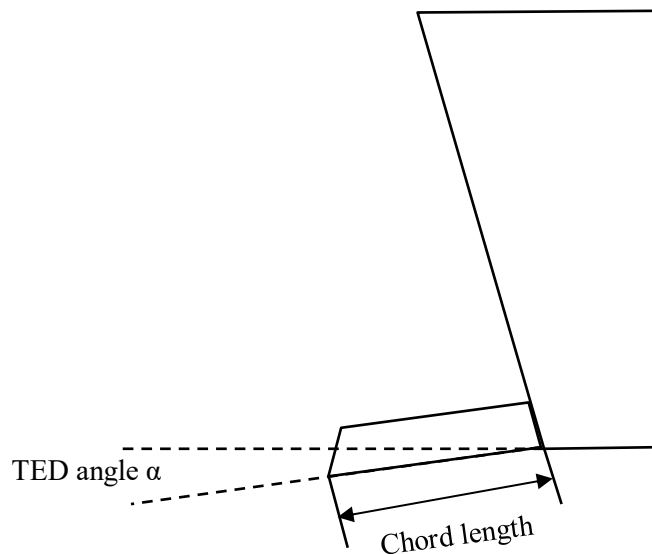
The afterbody flow field changes obviously as a result of the installation of stern flaps. This change could also affect the operational condition of propeller and its efficiency. The ship speed is affected by both of the ship resistance and propulsion, which can be indicated by the received power of propeller.

Therefore, to evaluate the energy saving of the stern flaps, it needs not only model ship resistance experiments but also self-propelled model ship experiments.

For the reasons above, to determine the influence of the different stern flaps to the ship resistance and propulsion, the ship resistance and self-propulsion experiments were conducted with the two model ships with full appendages.

## 2.2. Configuration of Stern flaps

From analysis of the previous studies [1,2], and based on the experience of stern flap design, the key parameters are considered as: chord length  $L_f$ , trailing edge down (TED) angle, span across transom, thickness of flap, shape of flap and shape of flap edge etc. According to the principle of the resistance reduction, the chord length,  $L_f$ , and TED angle,  $\alpha$ , are selected as the variables to optimize the stern flaps design in this study. The schematic of the stern flap is shown in Figure 1.



**Figure 1.** Schematic of the stern flap.

In this study, the main objective is to enhance the effectiveness of stern flaps at both of the ship cruising and design speed. Considering the comprehensiveness of the ship's dimensions, displacement, shape of stern and the characteristics of sailing etc., the range of chord length and TED angle are determined to optimize the stern flap design. Two rounds of experiments are conducted using model ship M1 and M2 respectively. From the previous studies, the impacts from the varying the TED angle with a relatively short chord length stern flap are summarized [1-3,9]. Hence, in round 1, the stern flaps have the same chord length which are determined by the literature review. Their normalized lengths,  $L$ , (i.e. the ratio to the designed water line,  $L_f/L_{wl}$ ) are fixed at 0.006. The total of three groups, including model ship towing and self-propulsion, experiments at different speed were conducted. The TED angles were selected as 6, 8 and 10 degree. In the round 2, five groups of experiments were conducted using model ship M2 based on the results of round 1. Round 2 includes more experiments of  $\alpha$  (i.e. 0°, 8° and 15°) at  $L = 0.006$ , and extended  $L$  (i.e. 0.007 and 0.009) at  $\alpha = 8^\circ$ . The scheme of experiments are shown in table 1.

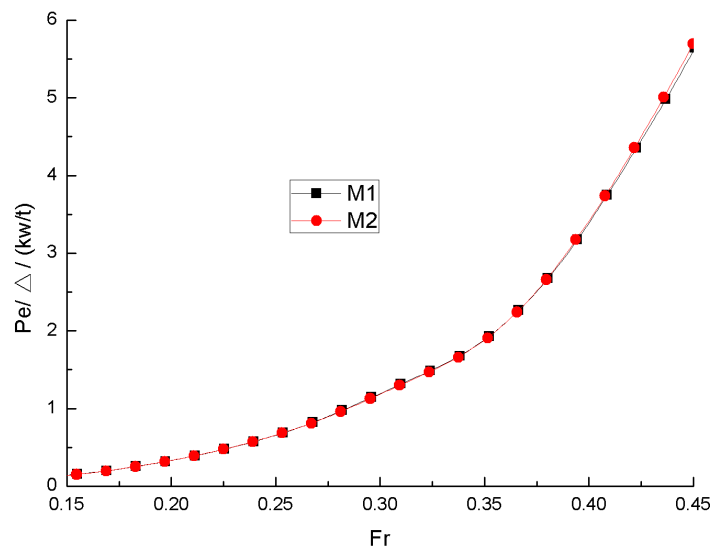
**Table 1.** The model tests

Number of ship models	Number of stern flaps	Parameters of stern flaps $L_f/L_{wl} - \alpha$
M1	F11	0.006-6
	F12	0.006-8
	F13	0.006-10
M2	F21	0.006-0
	F22	0.006-8
	F23	0.006-15
	F24	0.007-8
	F25	0.009-8

### 3. Results and analysis

#### 3.1. Results without stern flap

First of all, the stationary resistance of model ships M1 and M2 at different speed were measured. The equivalent resistance of real ships are expressed using quadric conversion. The resistance per unit displacement,  $Pe$ , verses Froude number is shown in Figure 2. From the results, the two model ships have very similar resistance performance.

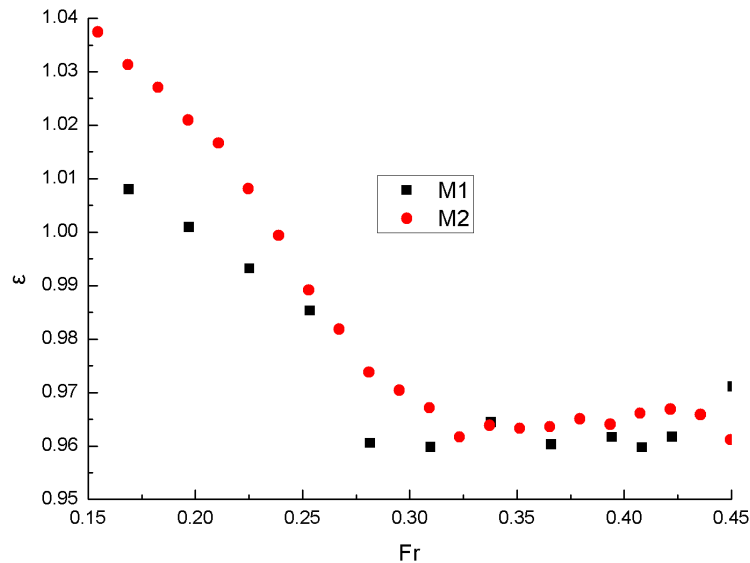
**Figure 2.** The resistance of model ships M1 and M2 without stern flaps.

#### 3.2. Ship resistance

From the results of the model ship resistance experiments, the resistance reduction of stern flaps occurs above a critical Froude number, called as *the lowest effective Froude number*,  $F_{LE}$ . Comparing with the model ship without stern flaps, the ship resistance with stern flaps increases below  $F_{LE}$  and decreases above  $F_{LE}$ . This results agree with most of existing studies [4,6,12]. For surface ships, the Froude number of cruising speed is always near or slightly lower than the  $F_{LE}$ . Hence, to reduce resistance at cruising speed, the optimizing of stern flaps is attempting to decrease  $F_{LE}$  of stern flap.

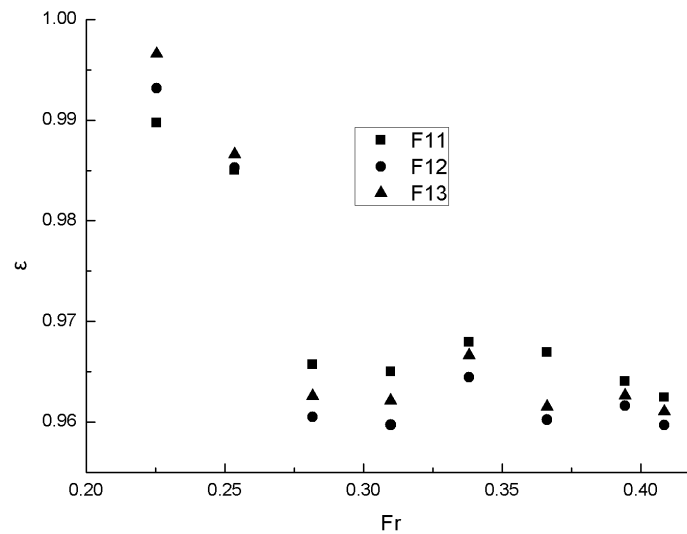
The resistance reduction is defined as  $\varepsilon = \frac{R_{\text{with-sternflap}}}{R_{\text{without-sternflap}}}$ , where  $R_{\text{with-sternflap}}$  and  $R_{\text{without-sternflap}}$  are the ship resistances with and without stern flap respectively. Apparently,  $\varepsilon$  is smaller than 1 when stern flaps reduce the resistance, otherwise the resistance are increased.

Comparing the results, which are shown in Figure 3, of the resistance experiments with the same stern flaps F12 and F22,  $F_{LE}$  for model ship M1 and M2 are around 0.20 and 0.23 respectively. It indicates that the design of stern flaps depends on the hull form design and  $F_{LE}$  changes much with the hull form even for the same series ship with same stern flap.

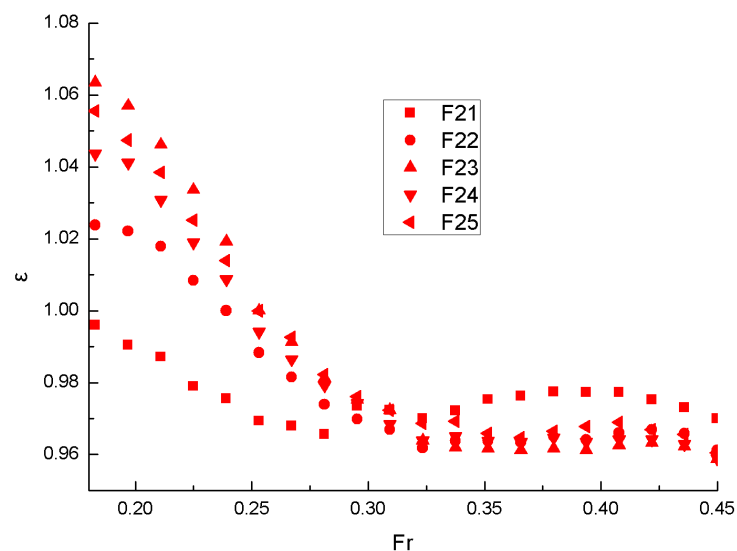


**Figure 3.** The resistance reduction of model ship M1 and M2 with same stern flaps ( $\frac{L_f}{L_{wl}}=0.006$  and  $\alpha=8^\circ$ ).

The resistance results of model ships M1 and M2 with different stern flaps are shown in Figure 4 and Figure 5. From the results, for the same ship with different stern flaps, the resistance reduction are similar, in the range of 3% to 4%, at design speed where Froude number is around 0.42. At cruising speed, where Froude number is around 0.25, the resistance reduction changed by different stern flaps. Due to the narrow range of the varying of TED angle, the difference of  $\varepsilon$  is negligible in the experiments of M1. In the experiments of model ship M2, the changing of TED angle was expanded, from  $0^\circ$  to  $15^\circ$  (F21, F22 and F23), resulting  $\varepsilon$  varies from 0 to 3%. When Froude number is lower than 0.25, the stern flaps with smaller TED angle and shorter chord length result in lower resistance in both round of experiments.



**Figure 4.** Resistance reduction of model ship M1 with different stern flaps.



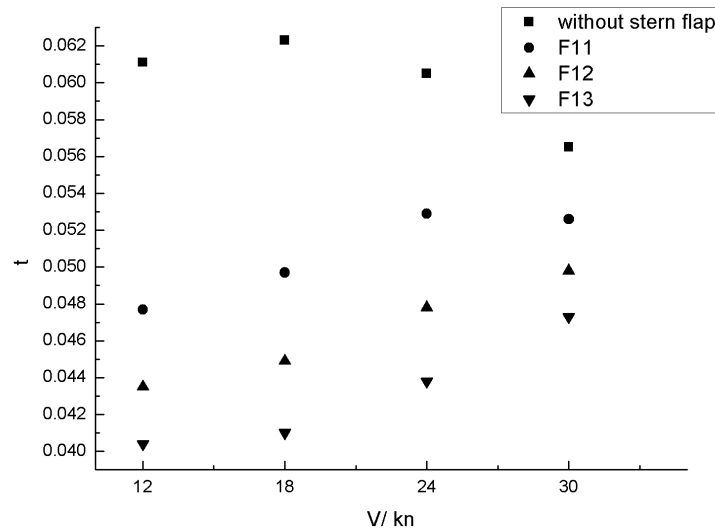
**Figure 5.** The resistance reduction of model ship M2 with different stern flaps.

In general, all configuration of stern flaps, which are tested in this study, can provide obviously resistance reduction at design speed and the difference between them is relatively small. It indicate that, at the range of  $L_f$  and  $\alpha$  selected in this study, the change of configuration of stern flap has small impact to the resistance reduction. For the series ship in this study, the appropriate combination of  $L_f$  and  $\alpha$  can achieve same resistance reduction. At cruising speed, the varying of  $L_f$  and  $\alpha$  has significantly impact to the resistance reduction, the excessive  $L_f$  and  $\alpha$  could increase the resistance at this speed.

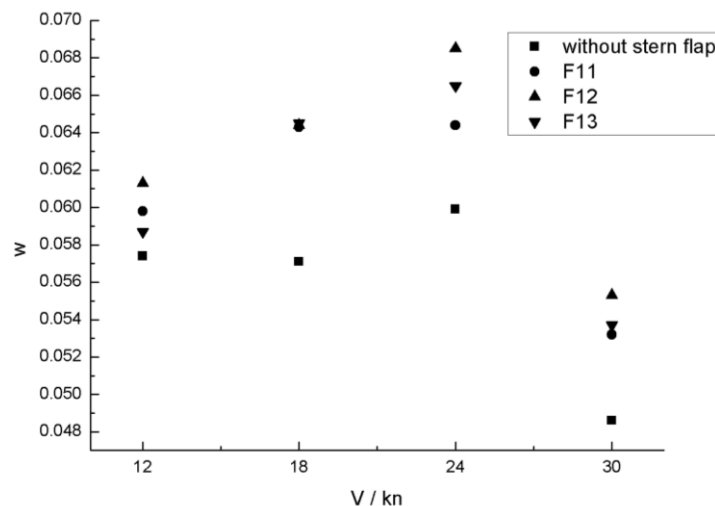
### 3.3. Self-propulsion tests

The installation of stern flaps affects the afterbody flow field directly, and the operational condition of propellers are changed as a result. The self-propulsion factors, trust deduction coefficient  $t$  and wake factor  $\omega$ , measured from self-prolusion experiments of model ship M1 with and without stern flaps are shown in Figure 6 and Figure 7. From the figures,  $t$  of all experiments were decreased and  $\omega$  were increased by the installation of stern flaps. Comparing the results,  $t$  is decreasing with the increasing of

$\alpha$ . In addition, the curvature of  $t$  versus ship speed was modified to an increasing relationship by the installation of stern flaps. The varying of these two factors affects the hull efficiency  $\eta_H$  (i.e.  $\eta_H = \frac{1-t}{1-\omega}$ ), and the total ship propulsive efficiency  $\eta_D$  (i.e.  $\eta_D = \eta_H \cdot \eta_0 \cdot \eta_R$ , where  $\eta_R$  and  $\eta_0$  are the relative-rotative efficiency and propeller efficiency respectively.) Furthermore, the impacts to the self-propulsion factors from different stern flaps are altered. For a certain  $L_f$ , with increasing  $\alpha$ ,  $t$  is decreasing and  $\eta_H$  is increasing.



**Figure 6.** Thrust deduction coefficient of model ships M1 with and without stern flaps versus equivalent ship speed.

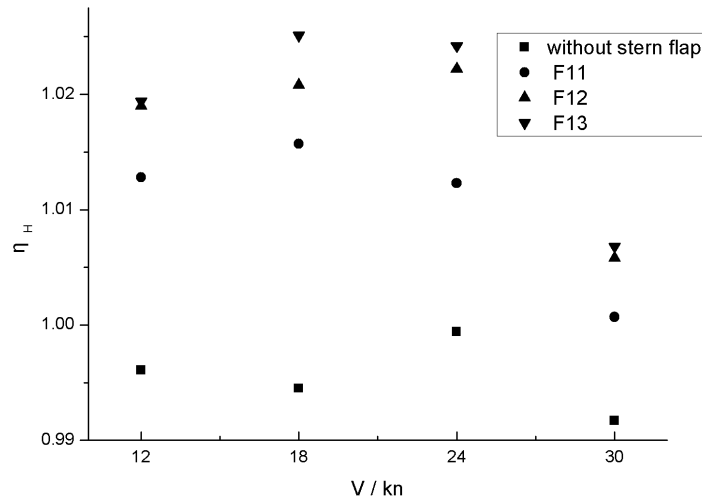


**Figure 7.** Wake factor of model ships M1 with and without stern flaps versus equivalent ship speed.

The hull efficiency  $\eta_H$  versus ship speed is shown in Figure 8. At the design speed,  $\eta_H$  is increased around 1% to 2% by the installation of stern flap. Including the minor changes of the relative-rotative efficiency  $\eta_R$  and propeller efficiency  $\eta_0$ , the received power of propeller  $P_D$  is decreased around 5% to 6% and the total propulsion efficiency  $\eta_D$  is increased around 2% caused by the stern flap with the range of  $\alpha$  which was selected experiments of model ship M1. In general, the energy is saved around 5%.



At cruising speed,  $\eta_H$  is increased (around 3% to 4%) more than which at design speed,  $P_D$  is decreased around 3% and  $\eta_D$  has no significant change. Over all, the total energy is saved around 3%.



**Figure 8.** Hull efficiency of model ships M1 with and without stern flaps versus equivalent ship speed.

In addition, the installation of stern flaps affects the pressure distribution of the ship bottom, especially for the stern area. It could change the trim and the draft of bow and stern. From the results of this study and another group of model ship experiments using a smaller model-scale ship with same type of stern flaps. It can be found that the stern flaps can deescalate the difference of the bow and stern which benefit the voyage status and resistance reduction.

#### 4. Conclusions

In this study, the experiments of series displacement model ships are conducted to optimize the stern flap design at both cruising and design speed. From the results and analysis of two rounds experiments including multi-configuration of stern flaps, there are a few conclusions can be summarized as below:

1) The effectiveness of stern flap is decided by the lowest effective Froude number,  $F_{LE}$ . From this study, it is found that  $F_{LE}$  is affected by the combination of characteristics of hull form and configuration of stern flaps. For the same hull, the short chord length and smaller TED angle of stern flap result a lower  $F_{LE}$  (the lowest  $F_{LE}$  was measured as 0.20 in this study). The increasing of one or both of them would increase the  $F_{LE}$ .

2) For the hull form tested in this study, the installation of stern flap significantly changed the resistance and the impacts are different at cruising and design speed. At design speed, the effects from stern flaps are obvious, however the effects from the varying of the stern flap configuration are not significant. Generally speaking, the different combination of  $L_f$  and  $\alpha$  can achieve same resistance reduction. At cruising speed, the resistance reduction is sensitive to the varying of the stern flap configuration, longer  $L_f$  and larger  $\alpha$  result an increasing of resistance.

3) For the surface ship in this study, the appropriate stern flaps benefit both of the propulsion performance and voyage status. Using optimized stern flap, the energy saving can achieve 3% and 5% at cruising and design speed respectively.

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