Stern Flap Solution to Contain the Speed Performance Loss due to the Ship Weight Growth: an Application on the “De La Penne” Destroyer Class

Lt. CDR. Mario DE BIASE[a] Lt. Vincenzo BASILE [a,1] Simone MANCINI[b]
[a] *General Navy Staff - Ship Design Office; Rome, Piazzale della Marina 4, Italy*
[b] *Force Technology / Danish Maritime Institute, Kgs. Lyngby, Denmark*

Abstract. It is well known that during the lifecycle the growth of the ship’s weight is one of the main sources of the performance-loss. Stern flaps have been used in many recent designs of transom stern vessels, in particular by the US Navy, to increase top speed or to realize improvements in fuel economy over the operating range. Furthermore, stern flap implementation has also become a practical retrofit on the existing platform because significant improvements can be achieved at a minimal cost. According to the US Navy experience, to analyze this aspect, the Ship Design Office of the Italian Navy General Staff performed a preliminary evaluation of the application of this device on own Destroyer hull (De La Penne class), using the CFD U-RANS approach and through experimental test campaign performed at Model Basin of CNR-INM (Council of National Research – Institute of Marine Engineering). This preliminary study was conducted in the model and full scale: several flap angles have been tested with a fixed NACA profile. The results have shown that the major improvements, in terms of power reduction, have been obtained for the interest speed range (Fr = 0.335 – 0.419).

Keywords. Stern Flap, CFD, URANS simulation, Energy-saving devices, Resistance and Self-Propulsion tests

1. Introduction and background

The energy-saving devices are one of the main topics of interest in naval architecture in the last decades. These devices can achieve improvement in terms of fuel consumption reduction, reducing hull resistance. For commercial vessels, this advantage means fuel savings, money savings, and so an increase in competitiveness. While for the Navies this means more endurance or lower fuel storage capability, so more space for the payloads and improvement of the operational capability.

There is a wide comprehensive literature about these devices but in this study, the focus is mainly on stern devices for displacement hulls. There are several stern devices solutions, for instance, the stern flap, stern wedge, or integrated wedge-flap (simplified sketches of these solutions are depicted in Figure 1).

[1]Lt. Vincenzo Basile, Italian General Navy Staff – Ship Design Office; Rome, Piazzale della Marina 4, Italy, Vincenzo.basile@marina.difesa.it.

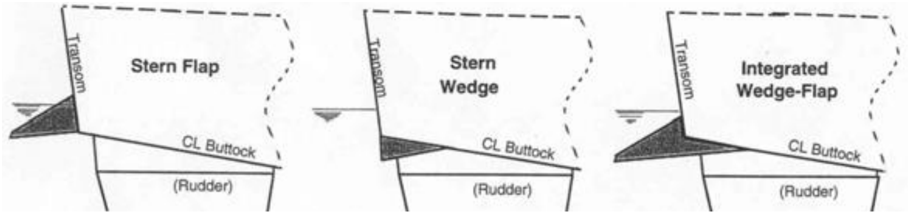

Figure 1. Stern appendage options and configurations from Cusanelli et al. [1].

Has shown in Figure 1, the stern wedge is located beneath the transom (generally inlayed into the hull plating) at an angle relative to the buttock. Stern wedges do not extend aft of the transom and are realistically a local abrupt modification in the aft buttock lines of the ship. A stern flap is an extension of the hull bottom surface which extends aft of the transom. It is a relatively small appendage built of a plate fitted to the transom at an angle relative to the centerline buttock of the ship. Instead, the integrated wedge-flap is a combination of both systems.

All stern flaps and wedges create a lift at the transom and modify the hull pressure distribution on the aft part of the hull. So, for displacement ships, the main advantage of the stern flap or wedge is due to the induced change in the flow field around the hull (Karafiath et al. [2]). The first reported usage of stern wedges on the surface combatant ship was in German Type 34 destroyers which were built before World War II, and later in the eighties, on the Italian Maestrale class frigates, see Karafiath et al. [2].

Several Navies are evaluating these solutions. Canadian Navy, for instance, has evaluated the retrofit applications of stern flaps on the Halifax Class Frigates that are in service from the nineties. With the customed optimization of these devices via towing tank tests, the Canadian Navy estimates improvement in the resistance greater than 4% over the existing hull, as exposed in Cummings et al. [3].

U.S. Navy Energy Office has been pursuing many ways to reduce the fuel consumption on the U.S. Navy ships obtaining power saving (and so money savings) between 4% and 19% ([4] and [5]). In a recent survey, several retrofit type devices were identified as potential candidates for reducing the fuel usage of existing ships, the most cost-effective device was the stern flap [4].

Kumar et al. [6] expose that the Indian Defence Shipbuilding and Ship Repair Office found in the stern flap a solution which could lead to significant reductions in power and emissions without compromising the platform’s performance.

Also Italian Navy in the recent past has conducted tests to evaluate the effectiveness of stern devices (especially interceptors), as a power-saving system, particularly for the high speeds, on patrol vessel hull, as shown in De Luca et al. [7].

In this study, the Ship Design Office of the Italian Navy General Staff has investigated the effectiveness of stern flaps as a simple and cost-effective retrofit-way of restoring or improving the performance of ships in service. In particular, this study is focused on a stern flap designed for the *Ammiragli* destroyer class to recover the performance-loss caused by the growth of the ship’s weight about 400 t in 30 years of service, corresponding to 7% of displacement increasing).

2. Ship geometry and conditions

2.1. Hull details

The study was carried out considering the *Ammiragli* destroyer class hull (Figure 2). The *Ammiragli* class is a destroyer class composed of two sister ships: *Luigi Durand De La Penne* and *Francesco Mimbelli*, in service in the Italian Navy since 1993. In the numerical and experimental analysis, two loading conditions are taken into account: the light-displacement condition (5308.14 m^3) and the heavy-displacement one (5717.21 m^3): hull and condition details are available in Table 1.

Figure 2. Side view of the *De La Penne* full appended hull model.

The so-called light displacement represents the design displacement value at ship launching. Instead, the heavy displacement is the last displacement value detected during the last stability check performed on board of the *Francesco Mimbelli* ship at the end of the last dry-docking. Hence, the difference between these two displacements identifies the weight's growth during the ship's life.

Table 1. Hull details tables.

	Unit	Light Displacement	Heavy Displacement
λ	[-]	19.0	19.0
L/B	[-]	8.64	8.67
B/T	[-]	3.22	3.07
C_B	[-]	0.501	0.513
∇	[m^3]	5308.14	5717.21
$L/\nabla^{1/3}$	[m^3]	7.925	7.735

2.2. Stern flap design

The stern flap geometry was designed considering two main parameters: the chord of the section profile (*c*) and the angle of attack (*AoA*). A preliminary evaluation of these two parameters has been done accordingly with the procedures exposed in Parsons et al. [8]. This method is a multi-criterion optimization method based on regressions formulas derived from the performance database of the existing stern flap installations on the U.S. Navy fleet. Based on this approach, the stern flap was designed to reduce the resistance at the highest speeds to recover the performance loss due to the weight increase.

Applying the above-mentioned regression formula to the hull under analysis, the best values for these two parameters are c = 0.5% L_{WL} and *AoA* = 12.5 deg. These values are the best compromise between increasing the total hull resistance at low speeds and reducing it at high speeds and close to the operational speed. Nevertheless, to characterize the stern flap performance, a different *AoA* was tested (*AoA*°= 8.0 deg), as well. The section profile of the stern flap is based on the NACA 0012 profile; the stern flap details (design configuration and the experimental model) are available in Figure 3. Finally, it is noteworthy to observe that the original hull is already provided by an integrated wedge and the stern flap under analysis is not nominally a prolongation of the wedge but the *AoA* was strongly increased.

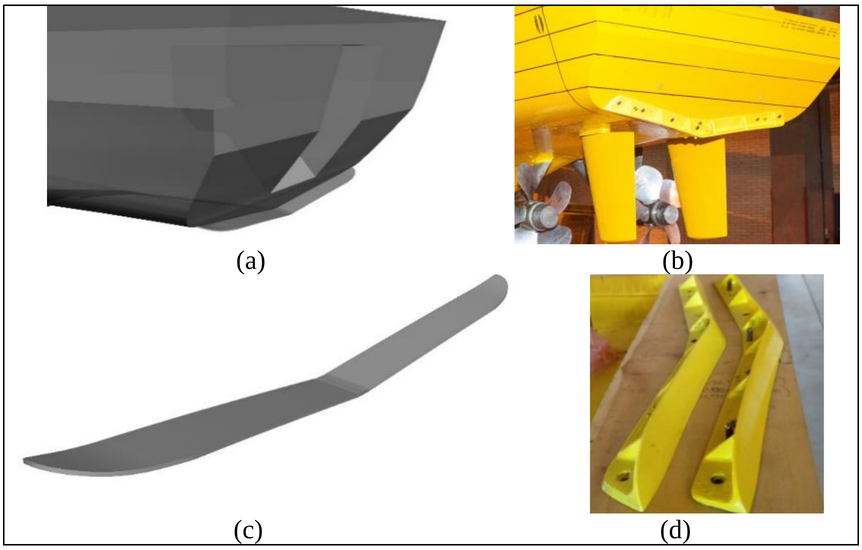

Figure 3. Hull transom stern CAD model with mounted stern flap (a) *vs* towing tank model (b). CAD Stern flap close view– *AoA*= 12.5 deg (c) *vs* towing tank stern flap models - *AoA* = 8 deg and 12.5 deg (d).

2.3. Tests campaign

The analysis has been carried out in two stages. A preliminary analysis (first stage) has been done through CFD (Computational Fluid Dynamics) analysis considering the bare hull at the two displacement conditions with and without the stern flap. The second stage was provided by the CNR-INM (Consiglio Nazionale Delle Ricerche - Istituto di Ingegneria del Mare) to validate the numerical outputs adopting the fully appended hull model at the two displacement conditions with and without stern flap at two different *AoAs* (8.0 deg and 12.5 deg). Table 2 gives a complete overview of the numerical and experimental resistance test performed. The numerical simulation was carried out at 6 speeds: 14.0, 18.0, 22.0, 24.0, 26.0, and 30.0 Kn (*Fr*= 0.196, 0.251, 0.307, 0.335, 0.363, and 0.419). Instead, the experimental tests were done for a wide range of speeds (13 speeds) from 6.0 to 30.0 Kn (*Fr* = 0.084–0.419).

Table 2. Synoptic table of performed resistance tests.

Loading condition	CFD Series Name	Towing Tank Series Name	Stern Flap (yes/no)	Stern Flap *AoA* (deg)
Light Displacement	Series 001_CFD	Series 001	No	//
Heavy Displacement	Series 002_CFD	Series 002	No	//
Light Displacement	Series 003_CFD	Series 003	yes	8.0 deg
Heavy Displacement	Not tested	Series 004	yes	8.0 deg
Light Displacement	Series 005_CFD	Series 005	yes	12.5 deg
Heavy Displacement	Series 006_CFD	Series 006	yes	12.5 deg

3. Numerical setup

The numerical simulations were conducted through the commercially available software Siemens PLM Star CCM+. To solve the time-domain equations, an implicit solver is used to find the field of all hydrodynamic unknown quantities, in conjunction with an iterative solver to solve each time step. The code uses a Semi Implicit Method for Pressure Linked Equations (SIMPLE) to conjugate pressure field and velocity field, and an Algebraic Multi-Grid (AMG) solver to accelerate the convergence of the solution. The free surface is modeled with the two-phase Volume of Fluid (VoF) technique combined with the Interface Capturing (HRIC) scheme based on the Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM). A segregated flow solver approach is used for all simulations.

The Reynolds stress problem is solved using the k-ω SST turbulence model and the *All Wall y+* is the wall treatment approach utilized for all simulations. This is a hybrid approach that attempts to emulate the *high y+* wall treatment for coarse meshes (for $y+ > 30$), and the *low y+* wall treatment for fine meshes (for $y+ \approx 1$). It is also formulated with the desirable characteristic of producing reasonable answers for meshes of intermediate resolution (for *y+* in the buffer layer), as depicted in Siemens PLM Star-CCM+ v 2019.1 User's Guide [9]. The *Wall y+* distribution on the hull at maximum speed tested is available in Figure 7. It can be seen that *Wall y+* values range from 0 to 120, as suggested in International Towing Tank Conferences (ITTC) guidelines [10].

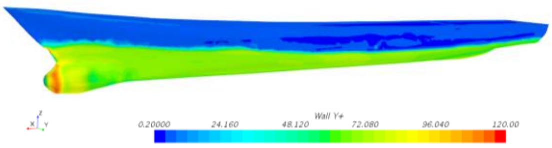

Figure 4. *Wall y+* distribution on the hull at maximum speed (*Fr*= 0.419 – heavy displacement).

The *U-RANS* simulations were carried out using the Overset/Chimera grid method to take into account the hull motion. The Overset mesh is a dynamic meshing approach in which the mesh follows the motion of the "object" through a fixed background mesh. More details about this approach are available, for instance, in Tezdogan et al. [11], De Luca et al. [12], and Begovic et al. [13]. The boundary conditions applied and the computational domain dimensions are shown in Figure 6 and these dimensions comply with the ITTC [10] guidelines. Furthermore, the time step size is determined by the formula suggested by the ITTC guidelines [10].

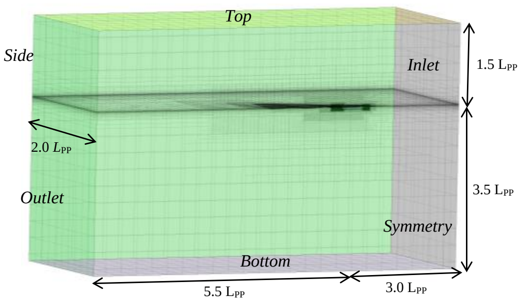

Figure 5. Domain dimensions and boundary conditions

4. Results and Discussions

4.1. Results of CFD and experimental analysis

The CFD analysis was performed at the early stage of this analysis, so only the bare hull configuration was tested. The addendum of the appendages on the resistance was evaluated through the comparison between the bare hull and full appended hull test carried out at the CNR-INM (Consiglio Nazionale delle Ricerche – Istituto di Ingegneria del Mare) Towing Tank during the design stage of the *Ammiragli* class (1986 - 1988).

The working principle of the stern-flap is clearly detected in the tests performed. The stern-flap causes the flow to slow down under the hull at a location extending from the aftmost portion of the stern to a point generally forward of the propellers. This decreased flow velocity determines an increase in pressure, which in turn causes the following: a drag on the flap; a forward thrust on the ship's afterbody; an upward force on the ship's afterbody; a decreased flow velocity and a consequently increased of the pressure.The results of the experimental and CFD tests, in terms of residuary resistance coefficient (C_R), are shown in the graphs in Figures 6 and 7 for light and heavy displacement respectively Furthermore, the grid uncertainty assessment has been done accordingly to the procedures suggest in Roache [14] and the ITTC guidelines for Verification and Validation [15]. The value of the grid uncertainty for resistance is found to be equal to 2.4% and the other sources of uncertainty, as iteration and time-step uncertainty, were found to be negligible concerning grid uncertainty, as indicated, for instance, in De Luca et al. [12].

The comparison between the experimental test and numerical simulations shows that the CFD simulations give reliable output especially at Froude Number (*Fr*) greater than 0.25. The comparison error is summarized in Table 3 and many cases are less than the grid uncertainty value. The residuary resistance is also reliably captured by CFD compared with experimental data. The effectiveness of stern flap estimated numerically is confirmed by the experimental tests and the performance estimated fairly agreed at the high speed ($Fr > 0.30$) for both loading conditions. Instead of the heavy condition, it is well-predicted trough all speed range.

Table 3. Comparison error between the experimental and numerical tests for hull resistance (maximum, minimum, and average error in all speed range).

	Average Error (%)	Maximum Error (%)	Minimum Error (%)
Series 001 *vs* Series 001_CFD	3.45%	9.13%	1.37%
Series 002 *vs* Series 002_CFD	2.76%	5.30%	0.18%
Series 003 *vs* Series 003_CFD	1.32%	2.57%	0.29%
Series 004 *vs* Series 004_CFD	Not tested in CFD		
Series 005 *vs* Series 005_CFD	1.85%	2.68%	0.67%
Series 006 *vs* Series 006_CFD	3.39%	4.94%	1.70%

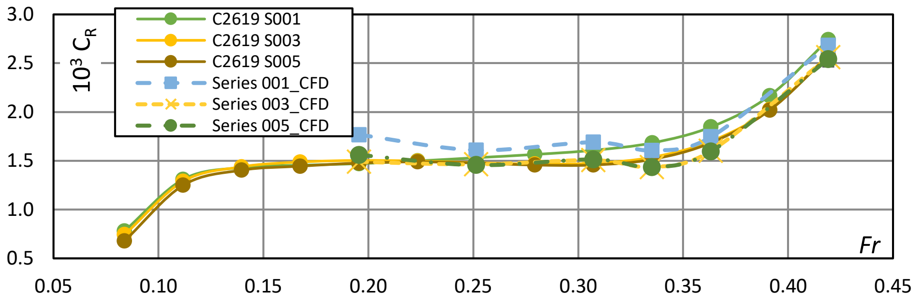

Figure 6. Residuary resistance coefficient (C_R) for the CFD simulations with and without stern flap (*AoA*°=°8.0 deg and 12.5 deg) at light displacement.

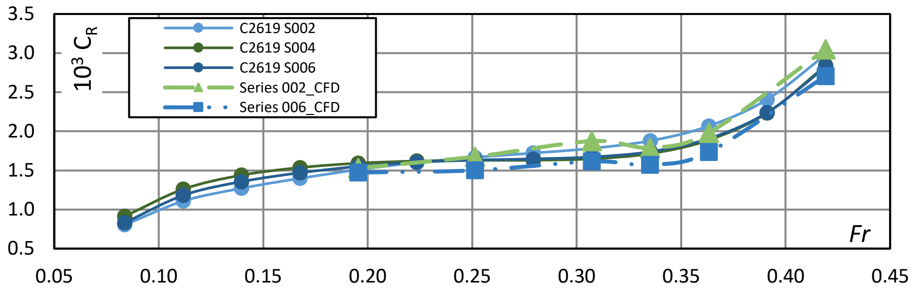

Figure 7. Residuary resistance coefficient (C_R) for the CFD simulations with and without stern flap (*AoA*°=°12.5 deg) at heavy displacement

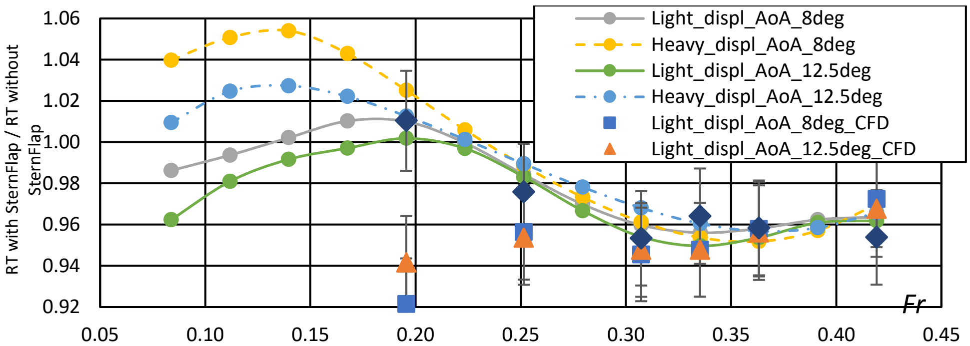

Figure 8. Effectiveness of stern flap at different loading conditions and angles of attack experimental *vs* CFD results (with uncertainty bars).

The stern flap performance improvements observed are up the 5.5% of resistance reduction, similar to what was detected in Cumming et al. [3]. Anyway, has to be taken into account, as stated before, that the original hull is already provided by the stern wedge and so the improvement values cannot be directly compared with the improvement results suggested in Karafiath et al. [2] and Cusanelli [4].

At low speeds (*Fr* < 0.25) the increase of resistance due to the stern flap is not negligible, in particular for the stern flap with *AoA* = 8.0 deg at heavy displacement condition. So, based on a trade-off analysis considering all the speed range of the vessel, the stern flap with *AoA* = 12.5 deg is more cost-effective in terms of power-saving.

5. Conclusions

This paper presents the results of the analysis, carried out by the Ship Design Office of the Italian Navy General Staff, on the effectiveness of the stern flap solution as a simple and cost-effective retrofit device to restore and/or improve the performance of ships in service. The stern flap was applied to the *Ammiragli* destroyer hull to recover the performance-loss due to the displacement increasing during the life of the ship. This study was performed using CFD U-RANS simulations and experimental tests. The study confirmed the reliability of the CFD simulations, especially in the preliminary design stage to find and optimize the shape of this device. Furthermore, the experimental test confirmed the effectiveness of these devices at high speeds, starting from Froude numbers greater than 0.25. The cost-effective solution for all the speed range was the stern flap with angles of attack equal to 12.5 deg.

References

[1] Cusanelli D. S. and Percival S., CFD Development and Model Test Evaluation on an Integrated Wedge-Flap for the DDG 79 Flight IIA, NSWCCD-50-TR—2001/024, 2001.

[2] Karafiath G., Cusanelli D. S., and Lin C. W., Stern Wedges and Stern Flaps for Improved Powering - U.S. Navy Experience, *SNAME Transactions,* vol. 107, pp. 67-99, 1999.

[3] Cumming D., Pallard R., Thornhill E., Hally D., and Dervin M., Hydrodynamic Design of a Stern Flap Appendage for the HALIFAX Class Frigates, in *MARI-TECH*, Halifax, June 2006.

[4] Cusanelli D. S., Stern Flaps - A Chronicle of Succes at Sea (1989 - 2002), in *SNAME Innovations in Marine Transportation*,, Pacific Grove, California, USA, 2002.

[5] Karafiath G., Stern End Bulb for Energy Enhancement and Speed Improvement, *Journal of Ship Production and Design,* vol. 28, n. 4, pp. 172-181, 2012.

[6] Hemanth Kumar Y. and Vijayakumar R., Stern flaps: A Cost-Effective Technological Option for the Indian Shipping Industry, *Maritime Affairs: Journal of the National Maritime Foundation of India,* vol. 14, n. 2, pp. 26-37, 2018.

[7] De Luca F., Mancini S., Manfredini A., Pensa C., and Scognamiglio R., Interceptor Device for a High-Speed Displacing Craft (Comparison Between CFD Simulation and Experimental Data), in *18th International Conference on Ships and Shipping Research (NAV 2015)*, Lecco, Italy, 2015.

[8] Parsons M. G., Singer J. D. e Gaal C. M., Multicriterion Optimization of Stern Flap Design, *Marine Technology,* vol. 43, n. 1, pp. 42-54, 2006.

[9] Siemens PLM, «STAR CCM+ User's Guide Version 2019.1,» 2019.

[10] ITTC, Recommended Procedures and Guidelines 7.5-03-02-03, Practical Guidelines for Ship CFD Applications, 2011.

[11] Tezdogan T., Demirel Y. K., Kellet P., Khorasanchi M., and Incecik A., Full-Scale Unsteady RANS-CFD Simulations of Ship Behaviour and Performance in Head Seas due to Slow Steaming, *Ocean Engineering*, n. 97, pp. 186-206, 2015.

[12] De Luca F., Mancini S., Miranda S., and Pensa C., An Extended Verification and Validation Study of CFD Simulations for Planing Hulls, *Journal of Ship Research,* vol. 60, n. 2, pp. 101-118, 2016.

[13] Begovic E., Bertorello C., and Mancini S., Hydrodynamic Performances of Small Size Swath Craft, *Brodogradnja Shipbuilding,* vol. 66, n. 4, December 2015.

[14] Roache P. J., Verification and Validation in Computational Science and Engineering, New Mexico: Hermosa Publishers, 1998.

[15] ITTC, Uncertainty Analysis in CFD Verification and Validation 7.5-03-01-01, 2008.