ISSN 0554-6397
Pregledni članak
(*Review article*)

Ines Bezić
E-mail: Ines.Bezic@fesb.hr
University of Split, FESB, Ruđera Boškovića 32, Split, Croatia
Petra Tepić
E-mail: petra.tepic@adriaprop.hr
Adriatic Propeleri d.o.o, Poslovna Zona Ionići 44, Bibinje, Croatia
Josip Bašić
E-mail: jbasic00@fesb.hr
Branko Blagojević
E-mail: bblag@fesb.hr
University of Split, FESB, Ruđera Boškovića 32, Split, Croatia

Comparative Analysis of Energy Saving Devices for Retrofitting Existing Ships

Abstract

This study investigates the application of Energy Saving Devices (ESDs) on existing ships up to 50 m in length, with a focus on retrofitting options. A key inefficiency in marine propellers is the rotational (swirl) flow in the wake, which increases vibration, cavitation, and underwater radiated noise (URN). ESDs have been developed to mitigate swirl losses, including pre-swirl devices (stators, ducts) and post-swirl devices (Propeller Boss Cap Fins (PBCF), twisted rudders, Grim Vane Wheel). A comprehensive comparison was conducted among various ESDs regarding their impact on propulsion efficiency, vibration and noise levels, and installation complexity. While pre-swirl devices provide higher efficiency gain, the results show that the PBCF is the preferable device, with significant reductions in hub vortex losses. The findings provide guidance for selecting optimal ESD configurations for existing vessels seeking improved efficiency with minimal structural changes.

Keywords: Energy Saving Devices (ESDs), Propulsion Efficiency, Vibrations, Noise, Retrofitting Ships

1. Introduction

Among the many components influencing the performance of marine propulsion systems, propellers play a pivotal role in converting engine power into thrust. Traditional propeller designs often face challenges such as flow separation, cavitation and energy losses, which can reduce efficiency and increase operating costs [1]. One promising approach to these challenges is use of ESDs, which are designed to manipulate the incoming flow to the propeller and improve its overall performance [2]. In 2023, International Maritime Organization (IMO) represented strategy which has the objective of achieving net-zero greenhouse gas emissions (GHG) by 2050. After introduction of Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), studies have shown a decrease in shipping carbon intensity in 2023, compared to previous years.

By analysing the results from multiple studies, we aim to provide a comprehensive understanding of how ESDs contribute to the optimization of propeller performance, identify the most effective design strategies, and highlight potential areas for future research.

Nicorelli et al. [3] discuss a simulation-based design optimization (SBDO) method applied to ESDs for a specific hull test case. The focus is on devices like pre-swirl ducts (PSD), pre-swirl fins (PSF), and wake-equalizing ducts (WED). For PSD and PSF up to a 4% reduction in delivered power was achieved, which is significant given the vessel's characteristics and operating conditions. Alizadeh et al. [4] investigate ship noise emissions, identifying the propeller as a major source and evaluating ducted propellers as a noise-reduction solution. Numerical simulations and experimental measurements show that ducted propellers reduce sound pressure levels, with reductions of 28% and 37% respectively compared to unducted propellers. Another study [5] explores the use of ESDs to reduce fuel consumption and increase the efficiency of ship propulsion systems. The study focuses on the Pre-Swirl Stator (PSS), resulting in a 4.7% increase in thrust. The research also investigates the combination of PSS with Propeller Boss-Cap Fins (PBCF), which further reduces hub vortex and enhance propeller efficiency by 1-1.5%. Zou et al. [6] present numerical simulations of open water and self-propulsion tests. A standard propeller model was validated against experimental data, showing good agreement. Nowruzi & Najafi [7] tested 3D CFD simulations by applying the Reynolds-averaging approach for the turbulence modeling.

The numerical uncertainties and limitations in simplified models, such as approximated propeller slipstream, highlighted the need for careful final configuration selection and additional validation. Study by Gaggero & Martinelli [8] demonstrated the flexibility and potential of optimization-based design methods to achieve energy savings. J. M. Baltazar et al. [9] implemented a wake alignment model with empirical corrections for blade wake pitch and tip gap flow and showed that the approach significantly improves agreement with experimental data, providing reliable open-water performance predictions. Cheng et al. [10] towing tank tests and CFD simulations showed strong agreement, confirming that optimization improves speed performance compared to the initial design. Nadery & Ghassemi [12] applied the Taguchi method to optimize duct design parameters, revealing that poor designs may decrease efficiency by up to 3.25%.

2. Energy Saving Devices for Retrofitting

2.1. Pre-Swirl Stator

Muhammad et al. [13] showed that the use of a pre-swirl stator (Figure 1) could increase the propeller efficiency by 6.64% at a stator diameter of 1.1 DP propeller model. The optimization in [8] led to significant energy savings, even for the challenging test case, which was not a typical full-blocked ship. Król & Tesch [14] discuss ESDs for marine propulsors, focusing on fixed lifting foils mounted in front of the screw propeller, known as pre-swirl stators or guide vanes. The results showed 4% efficiency improvement over the original propeller in model tests. J. H. Kim et al. [15] focused on developing an ESD for slow-speed ships to mitigate performance drops caused by vortices transferring from the ship's middle body to the stern. Sakamoto et al. [16] aimed to demonstrate the comprehensive validity of viscous CFD simulations for evaluating the hydrodynamic performance of energy-saving devices (ESDs) across different hull forms.

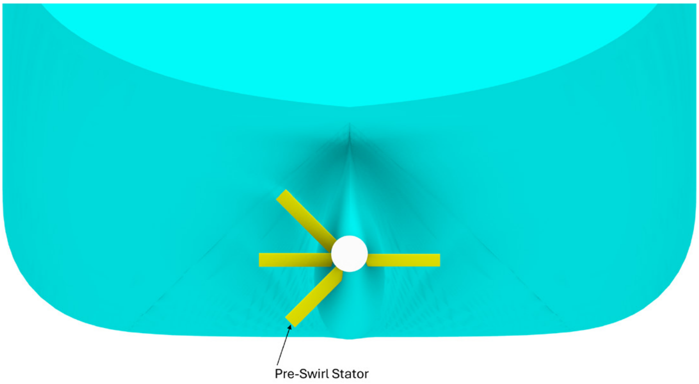

Figure 1: Pre-Swirl Stator Positoning

2.2. Ducted Propellers

Ducted propellers improve the inflow and recover part of the losses in the stern flow. Mewis duct, which combines a pre-swirl stator with a duct that accelerates the flow into the propeller disk, straightens and equalizes the wake in full-form vessels with strong boundary layer thickening at the stern. The stator vanes generate a counter-swirl that reduces propeller rotational losses. By redistributing the velocity field, ducts help to increase the thrust while reducing the power demand. They are especially effective for vessels with blunt stern forms, where the wake is highly non-uniform. They can also introduce additional appendage resistance and may become less effective at higher speeds, making their benefits strongly dependent on ship type and design conditions.

A computational study by J. M. Baltazar et al. [9] compared the performance of ducted and open propellers, indicating improved efficiency and reduced vibration under certain conditions. Chamanara et. al [17] investigated the effects of duct angle and propeller location, emphasizing the importance of precise geometric configurations. Nadery & Ghassemi [12] used CFD simulations to evaluate the hydrodynamic performance of a propeller with and without a wake equalizing duct (WED) on a container ship, showing that a well-designed duct can improve efficiency by 1.67% and significantly reduce pressure pulses. Ghassemi et al. [18] conducted experimental and numerical studies on ducted propeller performance under varying operating conditions, highlighting the trade-offs involved in different speed regimes. Tarafder et al. [19] used RANSE-based CFD simulations to estimate the open water characteristics of a Wageningen-B series propeller and compared the results to traditional regression formulas, finding less than 5% error in most cases. Winaro et al. [20] examined how tip clearance in ducted propellers affects thrust and torque. B. Liu & Vanierschot [21] compared the hydrodynamic performance of a ducted propeller (DP) and a rim-driven thruster (RDT) using CFD simulations. Bahatmaka et al. [22] used CFD simulations with the RANSE to predict the performance of a Kaplan-type ducted. The simulations, validated against experimental data, showed good agreement in thrust, torque, and efficiency trends. Munazid et al. [23] investigated the impact of different pre-duct shapes on propeller performance as an ESD. Results showed that pre-ducts significantly improve propeller performance at low rotation speeds, while improvements at high speeds are less pronounced, highlighting the importance of geometry and placement in maximizing energy savings. S. Kim & Kim [24] focused on the design and performance of a ducted propeller, based on Kaplan-series propellers. He et al. [25] introduced a new method combining Multi-Block Hybrid Mesh (MBHM) and the Reynolds Stress Model (RSM) to analyze the hydrodynamic performance of ducted propellers with high accuracy. The results align well with theoretical predictions, confirming the method's effectiveness and providing valuable insight for underwater thruster design. J. Baltazar et al. [26] examined key modeling factors affecting the performance prediction of ducted propulsors using a low-order Panel Method. Results showed that accurately accounting for the duct boundary layer significantly improves alignment and prediction accuracy, with strong agreement between numerical and experimental thrust and torque data.

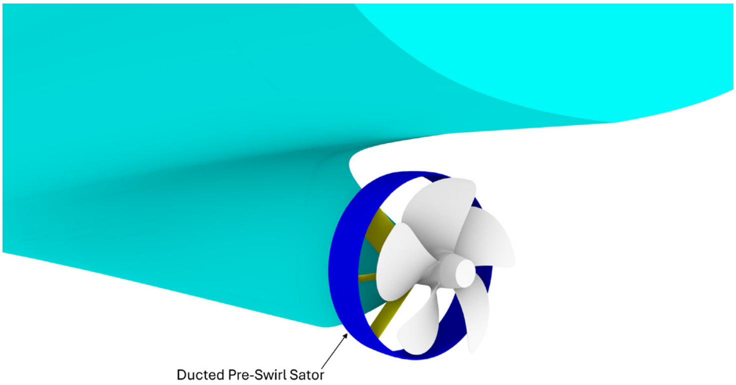

Figure 2: Ducted Pre-Swirl Stator Design

2.3. Propeller Boss Cap Fin (PBCF)

The PBCF replaces the conventional propeller boss cap. It is fitted with small, fin-like blades that extend radially from the cap. These fins work by breaking up the hub vortex that results in energy loss and vibration. By eliminating or reducing this vortex, the PBCF enables more of the engine's power to be converted into forward thrust, improving propulsion efficiency. Efficiency improvements using a PBCF can be achieved by varying the fin type and pitch angle of the PBCF, adjusting the phase lag angle, optimizing the propeller and PBCF diameter ratio, or selecting different cap types (straight, convergent, or divergent) along with their respective pitch angles.

Six PBCF design parameters as suggested in [31] are fins shape, radius ratio of PBCF and the propeller, installation position, angle of the fins, number and inclination of the fins. Most of the studies analyze convergent caps and report an increase in propeller efficiency of up to 8% for advance coefficients between 0.8 and 1. Lim et al. [32] analyzed the impact of various design parameters on propeller efficiency, finding that pitch and chord-to-span ratio had the most significant effects. The analyses of divergent caps generally showed a decrease in efficiency [33], some studies [34] reported increased efficiency at high speeds only. Studies [35], [36] and [37] conducted propeller-PBCF radius ratio impact on propeller efficiency by changing cap diameter. Trimulyono et al. [37] concluded that the highest efficiency increase is for 0.2 radius ratio, Sunarsih et al. [36] for 0.25 ratio, while Arief et al. [35] got highest increase for 0.3 ratio. Kobayshi et al. [38] investigated the energy-saving effects of the Eco-Cap, a propeller hub cap with fins (HCWF). It was found that suppresed hub vortices improve propulsion efficiency up to 4.7%.

2.4. Rudders

A rudder as an energy saving device makes use of the flow behind the propeller to recover swirl energy and improve overall propulsive efficiency. A conventional rudder experiences drag as it interacts with the propeller slipstream, but by modifying its shape or adding appendages, this drag can be turned into useful thrust. Their effectiveness is closely tied to the ship's propeller and stern arrangement, and poorly optimized designs can lead to increased resistance or cavitation on the rudder surface. Installation of such devices also demands careful structural integration with the steering system and consideration of loads transmitted during operation (Figure 3).

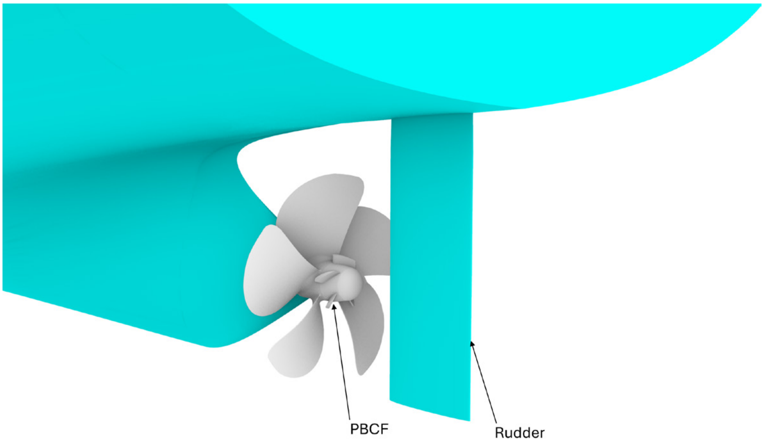

Figure 3: PBCF

Karim & Naz [39] focused on reducing fuel consumption by analyzing the interaction between the hull and propeller using CFD. The impact of different rudder positions on propeller efficiency was assessed, showing that rudder placement significantly influences overall propulsion performance. Kumar et al. [40] investigated the interaction between the rudder and propeller in open water, including the impact of a duct placed ahead of the propeller. The study showed that the presence of the propeller enhances rudder lift performance, with optimal lift observed up to a stall angle of 25 degrees. The duct was found to improve the propeller's open water efficiency by 2–3%, and both the rudder and duct significantly influenced the propeller's thrust, torque, and efficiency. Phillips et al. [41] explored methods to evaluate rudder performance by incorporating the flow effects generated by a propeller, specifically its accelerated and swirling wake. Hu et al. [42] investigated how different rudder angles affect the interaction between the propeller and rudder. At a 30° rudder angle, these fluctuations become asymmetrical between the port and starboard sides of the rudder. In [43], Detached Eddy Simulation (DES) is employed to analyze the structural response of a rudder within the context of propeller–rudder interaction.

2.5. Energy saving devices overview

The ESDs, based on reviewed literature, are listed in the Table 1 for pre-swirl devices, and Table 2 for post-swirl devices.

Table 1: Pre-swirl ESDs Review

	Wake Equalizing Duct	**Pre-Swirl Fins**	**Mewis Duct**
Mode of action	Duct straightens inflow and reduces wake non -uniformity	Fins induce counter-swirl in wake to reduce propeller-induced swirl losses	Combines duct and pre-swirl fins
Efficiency increase	2–4%	2–5%	6–8%
Advantages	Simple geometry; reduces cavitation & vibration; well-proven	Relatively simple to retrofit; effective across range of ship sizes	Reduces propeller cavitation and pressure pulses Widely adopted
Disadvantages	Effectiveness depends on hull form. Installation requires hull modifications	Requires precise angle/placement Potential added resistance at off-design speeds. Hull welding needed	More complex to install Best results at low speeds (<20 kn). Better on slender hulls
Recommended Application	Older bulkers/ tankers	Single-screw ships with strong rotational wake	Bulk carriers, tankers, general cargo

Table 2: Post-swirl ESDs Review

	Grim Vane Wheel	**Hub Vortex Absorbed Fins**	**Fixed Post-Swirl Stator**	**Rudder**
Mode of action	Swirl into thrust by rotating vanes	Suppresses hub vortex to reduce torque loss	Straightens rotational wake flow	Reduces swirl and improves flow uniformity
Mechanism	Free-spinning vanes	Fixed radial fins on boss cap	Stationary vanes aligned with flow	Rudder or fins aligned with swirl
Efficiency increase	3–5%	1–3%	2–4%	1–2.5%
Design Complexity	High (rotating components, alignment required)	Low (simple retrofit)	Moderate (requires integration into hull or propulsion design)	Low to moderate (rudder profile or fin adjustments)
Advantages	Improved rudder inflow and reduced vibration	Reduction in noise and cavitation	Potential for rudder performance boost	Enhanced maneuverability and wake flow stability
Disadvantages	Complexity and alignment sensitivity	Less effective for weak hub vortex	May add drag	Lower efficiency
Recommended Application	Newbuilds / major retrofits	Retrofits and newbuilds	Vessels with available aft space	Integrated with rudder design / retrofit

Figure 4: a) HVAF [44], b) Rudder [45], c) Grim Vane Wheel [46]

3. Results and discussion

Pre-swirl devices such as wake-equalizing ducts, pre-swirl fins and Mewis Duct are effective on large, slow-moving vessels, achieving significant fuel savings when properly designed. Installation complexity often limit their use for smaller vessels and retrofitting. For vessels under 50 meters, the post-swirl devices are found to be the best cost/benefit option. The PBCFs offer a favorable balance between retrofit simplicity and measurable fuel savings, typically in the range of 2–4%. They are less sensitive to hull form variations and can be installed without extensive hull modifications, making them a cheaper and efficient solution for small vessel operators.

Overall, the choice of ESD should consider vessel size, hull form, operational profile, and cost–benefit ratio. For small vessels, PBCF represents a highly recommended retrofit strategy, while pre-swirl devices remain more appropriate for large ships.

Table 3: ESDs comparison for ships less than 50 meters

ESD	**Pre-swirl devices**	**Post-swirl devices**
Vessel type	Tugs, fishing and patrol boats	Small ferries, yachts
ESD types	Stator fins, ducts, strut	GVW, PBCF, rudder
Flow effects	Modifies inflow	Acts on swirl in the wake
Suitability	Benefits only on single-screw workboats	PBCF and small rudder bulbs scale down well
Efficiency gains	2–4% possible on slow, full-form hulls, very sensitive to design	2–3% with PBCF Rudder bulbs may add another 1–2%
Advantages	Can smooth inflow and reduce cavitation on h.loaded propellers	Easy to retrofit. Short yard time

Disadvantages	Requires hull integration May increase resistance if mis-designed	Rudder area is limited on small vessels
Retrofit practicality	Rarely justifiable unless vessel has very high annual fuel use	Highly practical

Smaller vessels require affordable, practical energy-saving solutions that offer a quick return on investment. As presented, the PBCF offers a range of benefits. One of the most significant advantages of the PBCFs is simple retroffit installation. The PBCFs require no structural modifications to the hull or major mechanical systems; it is typically mounted directly onto the existing propeller boss. The process is quick and efficient, often completed during routine ship maintenance. Compared to larger and more complex energy-saving devices such as ducts or contra-rotating propellers, the PBCF involves a relatively low upfront investment. It also contributes to a more comfortable and quieter onboard environment by reducing vibration and noise. By minimizing the formation of the hub vortex behind the propeller, it significantly lessens propeller-induced vibration. This is especially beneficial for vessels that carry passengers, such as ferries and yachts, as well as for patrol boats where low noise signatures may be desirable. It offers a superior combination of performance, ease, and cost-effectiveness. Unlike pre-swirl stators or ducts, it requires no alteration to the hull or propulsion layout, making it particularly suited to vessels where space and budget are limited.

Reviewed studies used different methodologies (CFD, model test, sea trials), advance coefficients, hull forms, and propeller designs. Therefore, efficiency gains cannot be directly compared to each other as absolute metrics, but rather viewed as maximum value under certain conditions. While most of the empirical studies are based on large vessels, the hydrodynamic principles provide a strong theoretical base for recommending PBCF for smaller vessels. For example, smaller vessels often operate with heavily loaded propellers that generate strong hub vortices. Since the PBCF suppresses the hub vortex, regardless of the variable upstream wake field, it offers a reliable performance improvement. Combined with the fact that PBCF doesn't require structural hull modifications, it emerges as preferable retrofitting recommendation for smaller vessels.

4. Conclusion

Energy Saving Devices (ESDs) improve propulsive efficiency by reducing energy losses in the propeller wake, leading to measurable fuel savings and lower greenhouse gas emissions. An overview of common devices leads to the conclusion that ESD performance is strongly dependent on vessel size and hull geometry. Since most of the reviewed studies focus on large vessels, this review study highlights the lack of research on vessels smaller than 50 m.

The literature shows that pre-swirl devices remain highly effective on large bulk carriers and tankers, while post-swirl devices directly reduce the hub vortex without requiring hull welding or major modifications. Based on hydrodynamic principles and simple installation procedures, it is concluded that the PBCF is the preferred device for small vessel retrofits.

Future work should focus on optimizing PBCF design for varying propeller types, and integrating CFD and experimental data to maximize energy efficiency gains. Furthermore, a detailed economic analysis is essential to gain real insight into the profitability of these devices.

5. Abbreviations

Et al.	*Et Alia*	GHG	Greenhouse Gas Emissions
ESD	Energy Saving Device	MBHM	Multi-Block Hybrid Mesh
URN	Underwater Radiated Noise	RSM	Reynolds Stress Model
CFD	Computational Fluid Dynamics	RANS	Reynolds-Averaged Navier-Stokes
PBCF	Propeller Boss Cap Fins	k	Turbulence Kinetic Energy
IMO	International Maritime Organization	ω	Specific Dissipation Rate
GVW	Grim Vane Wheel	CII	Carbon Intensity Indicator
HVAF	Hub Vortex Absorbed Fins	EEXI	Energy Efficiency Existing Ship Index
SBDO	Simulation-based Design Optimization	CO_2	Carbon Dioxide
PSD	Pre-swirl Ducts	ITTC	International Towing Tank Conference
PSF	Pre-swirl Fins	HCWF	Hub Cap With Fins
WED	Wake-equalizing Ducts	DES	Detached Eddy Simulation
PSS	Pre-Swirl Stator	e.g.	*Exempli Gratia*
3D	Three Dimensional	m	Meters
RANSE	Reynolds-Averaged Navier-Stokes Equations	kn	Knots

6. References

1. Q. Tan, Y. Ding, C. Sui and L. Xiang, *Effects of propeller cavitation on ship propulsion performance in off-design operating conditions*, Ocean Engineering 313 (2024), pp. 119430.
2. K. Koushan, V. Krasilnikov, M. Nataletti, L. Sileo and S. Spence, *Experimental and numerical study of pre-swirl stators PSS*, J Mar Sci Eng 8 (2020), .
3. G. Nicorelli, D. Villa and S. Gaggero, *Pre-Swirl Ducts, Pre-Swirl Fins and Wake-Equalizing Ducts for the DTC Hull: Design and Scale Effects*, J Mar Sci Eng 11 (2023), .
4. V. Alizadeh, M. Abbaspour, A. Mohseni Arasteh, K. Lari and M. Torabi Azad, *Numerical solution and experimental investigation for hydro-acoustic analysis and noise reduction assessment of ship ducted propeller*, Heliyon 10 (2024), pp. e29632.

5. A. Trimulyono, A.A. Ariamukti, I.P. Mulyatno, B.A. Adietya and M. Iqbal, Investigation of Propeller Performance KM. Dharma Kartika After The Installation of PBCF and Pre-Swirl Stator, in E3S Web of Conferences, 576 (2024).
6. J. Zou, G. Tan, H. Sun, J. Xu and Y. Hou, *Numerical Simulation of the Ducted Propeller and Application to a Semi-Submerged Vehicle*, Polish Maritime Research 27 (2020), pp. 19–29.
7. H. Nowruzi and A. Najafi, *An experimental and CFD study on the effects of different pre-swirl ducts on propulsion performance of series 60 ship*, Ocean Engineering 173 (2019), pp. 491–509.
8. S. Gaggero and M. Martinelli, *Pre-Swirl Fins Design for Improved Propulsive Performances*, 2021.
9. J.M. Baltazar, D. Rijpkema, J.F. de Campos and J. Bosschers, *Prediction of the open-water performance of ducted propellers with a panel method*, J Mar Sci Eng 6 (2018), .
10. X. Cheng, X. Huang, D. Xu, Z. Zhao, H. Liu, M. Kong et al., *Ship Optimization Based on Fully-Parametric Models for Hull, Propeller and Rudder*, J Mar Sci Eng 12 (2024), .
11. H. Ghassemi and R. Shademani, *Hydrodynamic Performance of the Modern Ship Propulsion System*, Journal of Mechanical Research and Application, JMRA/2010.
12. A. Nadery and H. Ghassemi, *Numerical Investigation of the Hydrodynamic Performance of the Propeller behind the Ship with and without Wed*, Polish Maritime Research 27 (2020), pp. 50–59.
13. A.H. Muhammad, M.I. Nikmatullah and U. Kalsum AL, *IMPROVED PROPELLER EFFICIENCY OF A FERRY SHIP WITH ASYMMETRIC PRE-SWIRL STATOR*, Journal of Marine-Earth Science and Technology 2 (2021), pp. 11–17.
14. P. Król and K. Tesch, Pre-swirl energy saving device in marine application, in Journal of Physics: Conference Series, 1101 (2018).
15. J.H. Kim, J.E. Choi, B.J. Choi, S.H. Chung and H.W. Seo, *Development of energy-saving devices for a full slow-speed ship through improving propulsion performance*, International Journal of Naval Architecture and Ocean Engineering 7 (2015), pp. 390–398.
16. N. Sakamoto, K. Kume, Y. Kawanami, H. Kamiirisa, K. Mokuo and M. Tamashima, *Evaluation of hydrodynamic performance of pre-swirl and post-swirl ESDs for merchant ships by numerical towing tank procedure*, Ocean Engineering 178 (2019), pp. 104–133.
17. M. Chamanara, H. Ghassemi, M. Fadavie and M.A. Ghassemi, *Effects of the Duct Angle and Propeller Location on the Hydrodynamic Characteristics of the Ducted Propeller*, Ciencia y tecnología de buques 11 (2018), pp. 41.
18. H. Ghassemi, S. Majdfar and H. Forouzan, *Calculations of the Hydrodynamic Characteristics of a Ducted Propeller Operating in Oblique Flow*, Ship Science & Technology/2017.
19. S. Tarafder, M. Imdadul Haque, M. Asaduzzaman, M. Zahidul Islam Laku and M. Shahjada Tarafder, *NUMERICAL INVESTIGATION OF HYDRODYNAMIC PERFORMANCE OF CONVENTIONAL AND DUCTED PROPELLER*, 2022.
20. A. Winaro, Gedhe Angkoso Nur Sofa Sakti and E. Sugianto, *Kapal: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan, 21 (3) (2024):156-170 The Effect of Tip Clearance Kaplan Ducted Propeller in Offshore Supply Vessel (OSV) on Hydrodynamics H)*, (2024), .
21. B. Liu and M. Vanierschot, *Numerical study of the hydrodynamic characteristics comparison between a ducted propeller and a rim-driven thruster*, Applied Sciences (Switzerland) 11 (2021), .
22. A. Bahatmaka, D.J. Kim, D. Chrismianto, J.D. Setiawan and A.R. Prabowo, Numerical investigation on the performance of ducted propeller, in MATEC Web of Conferences, 138 (2017).
23. A. Munazid, M. Ariana and I.K.A.P. Utama, *CFD Analysis on the Development of Pre-Duct Shape to Improve Propeller Performance*, CFD Letters 16 (2024), pp. 118–132.
24. S. Kim and J. Kim, *Design and Performance Analysis of Ducted Propeller for 10kW-class Autonomous Underwater Vehicle*, Journal of the Korea Institute of Military Science and Technology 28 (2025), pp. 81–91.
25. X. He, H. Zhao, X. Chen, Z. Luo and Y. Miao, *Hydrodynamic Performance Analysis of the Ducted Propeller Based on the Combination of Multi-Block Hybrid Mesh and Reynolds Stress Model*, Journal of Flow Control, Measurement & Visualization 03 (2015), pp. 67–74.
26. J. Baltazar, J.A.C. Falcão De Campos and J. Bosschers, *Open-water thrust and torque predictions of a ducted propeller system with a panel method*, International Journal of Rotating Machinery 2012 (2012), .
27. L. Zhenhua, Z. Yan and H. Junsong, *Strut optimization analysis of azimuth thruster with contra-rotating propellers*, Chinese Journal of Ship Research 19 (2024), pp. 35–41.

28. C. Guo, P. Dou, T. Jing and D. Zhao, *Simulation of hydrodynamic performance of drag and double reverse propeller podded propulsors*, Journal of Marine Science and Application 15 (2016), pp. 16–27.
29. *Hydrodynamics of marine propulsion*. SAGE Publications Ltd, 2019.
30. Y. Liu, Q. Gong, Y. Bian and Q. Suo, *Effect of ducts on the hydrodynamic performance of marine propellers*, Eng Comput (Swansea) ahead-of-print (2021), .
31. K. Ouchi, M. Ogura, Y. Kono, H. Orito, T. Shiotsu, M. Tamashima et al., *A Research and Development of PBCF (Propeller Boss Cap Fins) - Improvement of Flow from Propeller Boss*, Journal of the Society of Naval Architects of Japan 163 (1988), .
32. S.S. Lim, T.W. Kim, D.M. Lee, C.G. Kang and S.Y. Kim, *Parametric study of propeller boss cap fins for container ships*, International Journal of Naval Architecture and Ocean Engineering 6 (2014), pp. 187–205.
33. I.A.C. Abar and I.K.A.P. Utama, *Effect of the incline angle of propeller boss cap fins (PBCF) on ship propeller performance*, International Journal of Technology 10 (2019), pp. 1056–1064.
34. B.A. Adietya, H. Syahab, M. Indiaryanto, W.D. Aryawan and I.K.A.P. Utama, *Influence Evaluation of Open Propellers with Boss Cap Fins: Case Studies on Types B4-70 and Ka4-70*, CFD Letters 16 (2024), pp. 143–177.
35. I.S. Arief, E. Jadmiko and I. Fikry, *The Effect of Span to Chord Ratio PBCF on C4-40 Wageningen Series Propeller with CFD Method*, International Journal of Marine Engineering Innovation and Research/2019.
36. Sunarsih, N.M. Majid, I.S. Arief, A. Baidowi, E. Jadmiko and Amiadji, *Propulsion Performance and Hub Vortex Reduction on Various Propeller Boss Cap Fins Designs*, International Review on Modelling and Simulations 16 (2023), pp. 360–369.
37. A. Trimulyono, A.B. Jatmiko, I.P. Mulyatno and H. Yudo, The effect of propeller cap angle and fin size of PBCF on propeller performance, in IOP Conference Series: Earth and Environmental Science, 972 (2022).
38. Y. Kobayshi, Y. Okada, K. Katayama, T. Hiroi, D. Wako and Y. Ichinose, *Effects of Propeller Pitch and Number of Blades on Energy Saving of an ECO-Cap MARINE 2021*, 2021.
39. Md.M. Karim and N. Naz, *Numerical Study on Flow Around Modern Ship Hulls with Rudder-Propeller Interactions*, Journal of Marine Science and Application 18 (2019), pp. 400–416.
40. A. Kumar, M. Daluar Hussain and M. Mezbah Uddin, *NUMERICAL INVESTIGATION OF THE RUDDER-PROPELLER INTERACTION IN OPEN WATER WITH AND WITHOUT DUCT*, 2022.
41. A.B. Phillips, S.R. Turnock and M. Furlong, *Accurate capture of propeller-rudder interaction using a coupled blade element momentum-RANS approach*, Ship Technology Research 57 (2010), pp. 128–139.
42. J. Hu, Q. Wan, X. Li, W. Zhang, X. Ning and C. Duan, *Propeller-rudder interaction under different rudder angle*, Ocean Engineering 306 (2024), pp. 118104.
43. W. Zhang, C. Chen, Z. Wang, Y. Li, H. Guo, J. Hu et al., *Numerical simulation of structural response during propeller-rudder interaction*, Engineering Applications of Computational Fluid Mechanics 15 (2021), pp. 584–612.
44. *Propeller-Hub Vortex Absorbed Fins*. accessed April 16, 2025., https://china-propeller.en.made-in-china.com/product/hazRcOwCALVA/China-Made-in-China-Zhenjiang-Jinye-Propeller-Hub-Vortex-Absorbed-Fins.html, .
45. *Propulsion Improving Devices*. Energy Efficiency Technologies Information Portal, accessed April 16, 2025., https://greenvoyage2050.imo.org/technology/propulsion-improving-devices-pids/, .
46. *Boat Design*. accessed April 16, 2025., https://www.boatdesign.net/threads/new-propulsion-sytems-for-ships.9630/page-27, .