Pre-Swirl Fins Design for Improved Propulsive Performances

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ABSTRACT

Pre-swirl fins-based Energy Saving Devices (ESDs) have been designed to improve the propulsive performances of a twin-screw ship. To achieve this aim, a combined BEM/RANS method for self-propulsion prediction is required. The approach is included in a framework for a design by optimization, where systematic variations of the ESD geometry have been used to explore the design space and maximize the energy-saving effect of the device. The results show encouraging improvements that reach a promising energy-savings of 2.9%.

Keywords: Pre-Swirl Stators; DEsign by Optimization; SBDO; Energy Saving Devices;

1 INTRODUCTION

The progressive application of stricter environmental regulations, such as the EEDI and the EEOI indexes, has imposed and will soon impose substantial and progressive reductions in the gaseous emissions of pollutants. Combined with the necessity to reduce the ship operative costs (i.e. fuel), this regulatory framework represents one of the most important drivers in the ships innovation, with obvious consequences also in the development of their propulsion systems. Energy Saving Devices (ESDs) fall into this innovation process. These are "simple" and cost-effective solutions capable of improving the overall propulsive efficiency of the ship as a whole: WED, PBCF, Pre- and Post- Swirl stators, as well as highly efficient non-conventional propellers, are some of the recently proposed solutions that have been developed to recover some of the hydrodynamic losses of the propulsion system, for both new projects and retrofits. Some devices act to reduce the propeller load, others to realize a positive interaction with the stern flow of the ship, or to reduce the losses due to strong propeller tip and hub vortexes. Pre-swirl stators, which are the subject of the current study, belong to the class of energy-saving devices devoted to recover the propeller rotational losses.

Pre-swirl stators consist of multiple fins installed in front of the propeller to induce a swirl inflow to the propeller itself in the opposite direction of its rotation, straightening the final wake. Since the first application of these ESDs, literature results have shown very promising saving effects. In the framework of the EU project GRIP (Streckwall and Xing-Kaeding, 2017; Schuiling and van Terwisga, 2017; Prins et al., 2016), pre-swirl stators reached an energy-saving of 6% that in the particular case of a twin-screw passenger vessel was close to 4% Koushan et al. (2020) developed pre-swirl stators for a chemical tanker and their numerical results, claiming a power savings of 2.5%, were confirmed during a dedicated model-scale experimental campaign. The usage of flapped and "controllable" pre-swirl stators was proposed to cope with non-constant operative conditions (slow steaming, fouling, weather, change of draft) and to ensure the highest possible energy-saving, which reached a shaft power reduction of 4% in the case of a bulk carrier (Nielsen and Jin, 2019).

Pre-swirl stators allow for energy saving in the following way. The swirling flow produced by stator fins produces an additional load on propeller blades. Consequentially, the delivered thrust increases and, to achieve the designed speed, the propeller rotation rate (i. e. the delivered power) decreases. Since pre-swirl fins always create resistance, a positive net gain is possible only if the additional thrust (provided by the propeller operating in the wake of the pre-swirl stator) is higher than the resistance added to the ship by the presence of the fins. This aspect must be considered in the design process, selecting for instance merit indexes that are able to simultaneously account for the positive effect of the device and its side effects (flow separation and vortex shedding). The application of pre-swirl stators mainly to slow and fully-blocked ships exactly considers this necessity, since for them the added resistance of these appendages (working in the decelerated flow at the stern) is small compared to the recovery action of the rotational flow.

These considerations sustain the need for dedicated design methodologies capable of embracing conflicting objectives and dealing with the complexity of the problem. The stationary nature of these ESDs potentially requires each fin to be designed to meet the local characteristics of the flow, which is, in turn, influenced by the induced velocities of the propeller in self-propulsion functioning. Opportune design criteria (reduction of the shaft power or reduction of the ship resistance) must be selected to adequately consider the hull/ESD/propeller system as a whole. Moreover, full-scale analyses are mandatory since Reynolds effects can substantially change the flow field and the resulting optimal configuration of the device. Simulation-Based Design Optimization methods, as those already applied for propeller or other ESDs designs (Gaggero, 2020) represent a solid approach to deal with these needs. SBDO, indeed, allows for systematic explorations of enlarged design spaces using the appropriate solvers required for the characterization of the pre-swirl functioning. The combined use of parametric representations of the geometry and optimization algorithms leads finally the convergence to Pareto optimal solutions.

This is precisely the design approach selected in this work. Particularly, the design activity focuses on pre-swirl stators applied to a relatively small (overall length of 32.96 m) and fast (F_n of about 0.45) twin-screw passenger ship, that for its nature represents a demanding application case for pre-swirl devices. The SBDO approach involves a simplified self-propulsion estimation method based on the results of Villa et al. (2019) using a combination of BEM and RANS calculations. The results are the optimal pre-swirl fins parameters ensuring at the same time appreciable energy savings (measured as a delivered shaft power reduction) without worsening the performance (i.e. risk of cavitation) of the propeller. Energy savings, in the order of 3%, are finally verified using self-propulsion calculations based on fully resolved RANS analyses.

2 COUPLED BEM/RANS FOR PRE-SWIRL STATOR CHARACTERIZATION

The accurate characterization of pre-swirl appendages, that needs self-propulsion estimations, requires ad-hoc tools to be included in a computationally efficient manner into a SBDO approach. Pre-swirl stators realize a substantial interaction with the propeller since they change the inflow to the propeller itself. An estimation of the recovery effect is possible only by the description of the propeller functioning in this updated effective wake, which prevents the use of the simplified actuator disk only, in favour of at least coupled BEM/RANS methods, that are necessary for an accurate propeller performances estimation.

First, the mutual interactions between the wave pattern and the pre-swirl appendages can be considered negligible at least in the preliminary design phase. Therefore, an additional simplification for the self-propulsion estimation regards the calculation of the current ship resistance (also in presence of the ESD) starting from the double-model assumption, as successfully done in many similar cases (Gaggero et al., 2017). A "constant" wave resistance contribution, i.e. independent of the propeller working condition and ESD, can be computed by subtracting the double model drag to the total hull resistance calculated in towing conditions with the free surface. This estimation includes the pure wave resistance and all the double-model approximations, such as the variation of the wetted surface for the reference ship. By adding it to the current drag of the double model equipped with ESD and propellers (or equivalent actuator disks), a reasonable estimation of the total hull drag is possible, allowing for cost-effective self-propulsion predictions.

When a significant interaction with the propeller has to be taken into account, the actuator disk model cannot be applied for pre-swirl devices. As a matter of a fact, while a decent estimation of the thrust deduction factor is possible through these methods, the unsteady functioning of the propeller

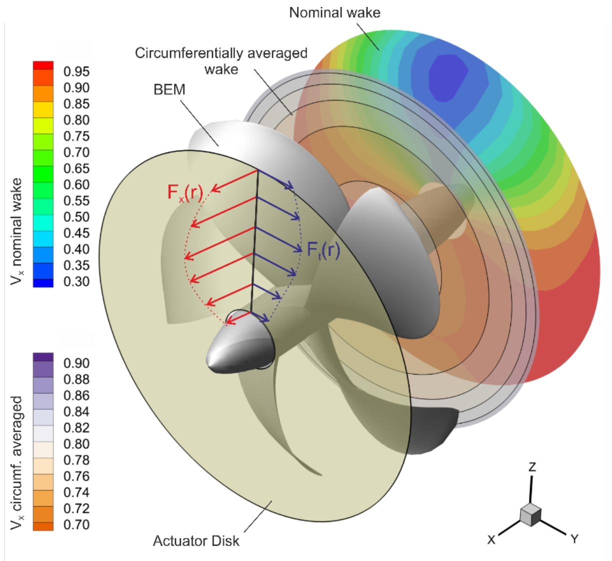


Figure 1. Averaging process for the characterization of the momentum source of the actuator disk: nominal wake – circumferentially averaged wake – axial and tangential radial load distribution of the actuator disk.

is completely ignored. To a certain extent, an estimation of the propeller revolution rate is possible using the open water curves, some auxiliary variables ($\frac{K_T}{J^2}$) and very simplified estimations of the wake fraction. On the other hand, a method capable of accounting for the tangential components of the effective wake modified by the pre-swirl on the propeller loading and unsteady functioning is necessary. Since the computational efficiency is the bottleneck of any SBDO, for this design activity a simplified BEM/RANS coupling method (Villa et al., 2019; Furcas and Gaggero, 2021) is required. RANS analyses characterize the velocity and the pressure field at the stern of the ship employing the actuator disk in place of the propeller. This actuator disk is "loaded" using radial force distributions (axial and tangential) obtained by preliminary BEM steady analyses in the circumferentially averaged nominal wake (as in Figure 1). An unsteady BEM, instead, oversees the calculations of the propeller functioning (absorbed power) under the resulting spatial non-uniform effective wake.

The estimation of the effective wake proposed in Gaggero et al. (2018) has been used to realize the simplified (weak) coupling between the solvers, avoiding the iterations which are typical of unsteady and spatial non-uniform body forces methods (Gaggero et al., 2017). Momentum sources replace the propeller at the stern of the ship, in terms of pressure (thrust deduction) and velocity (wake fraction) disturbance inside the RANS calculations. The corresponding total wake on the propeller plane is then elaborated to compute the effective wake for the unsteady propeller functioning. The same actuator disk used for self-propulsion (i.e. the same radial distribution of load), when delivering the same thrust in a uniform flow with velocity equal to the averaged nominal wake measured during towing tests, provides a radially varying and circumferentially averaged velocity field, which satisfactorily represents the propeller self-induced velocities. Then, the self-induced velocities under the effective wake are approximated as those produced by the propeller under the nominal wake. Since the propellers (the actuator disks) under both wakes (self-propulsion with the actuator disk behind the ship and equivalent "open water" analysis) deliver the same thrust using the same spatial distribution of load, this approximation seems plausible in the context of these simplified calculations. Without any of the BEM/RANS iterations required by more sophisticated approaches, then the effective wake can be calculated as:

$$V_{\text{effective}}{}^{\text{ship}} = V_{\text{total}}{}^{\text{ship}} - (V_{\text{disk}}{}^{\text{total}} - V_{\text{ship}} * (1-w)_{\text{nominal}}) \quad (1)$$

where:

- ${V_{\text{total}}}^{\text{ship}}$ is the “total” velocity field computed by RANS in self-propulsion condition on the propeller plane with the influence of the actuator disk;

- ${V_{\text{disk}}}^{\text{total}}$ is the “total” velocity field on the propeller plane of an open water analysis where the actuator disk, loaded with the same distribution used in behind ship condition and delivering the same thrust of self-propulsion condition, is subjected to a uniform inflow equivalent to the ship averaged nominal wake (i.e. $V_{\text{ship}} * (1-w)_{\text{nominal}}$);

- V_{ship} is the ship velocity;

- $(1-w)_{\text{nominal}}$ is the nominal wake fraction in towing condition.

The complete coupling algorithm is outlined in the flow chart of Figure 2. The process is described in the most general case, including the pre-swirl stators. The objective of the process is the estimation of the propeller delivered power, which is the design objective to be minimized.
Block 1 considers the double model in towing condition since the evaluation of the ship resistance is required at first. Block 2, instead, is in charge of the analyses that account for the propeller action using entirely actuator disk calculations, which always resulted sufficient for the thrust deduction factor estimation. In both cases, the “wave resistance” simplification described before is used to derive the towed and the self-propulsion resistance. In addition to the thrust deduction and the ship resistance (Block 3), the outputs of these analyses are the nominal and the total wakes on the propeller plane, which in turn are one of the inputs required to assess the propeller self-induced velocities. Block 4 is devoted to this calculation, realizing the weak BEM/RANS coupling. Subtracting these approximated self-induced velocities from the total velocity field obtained in Block 2, the effective wake field can be determined in Block 5. Once the effective wake fraction of the resulting non-uniform field and the thrust deduction factor (from Block 3) are known, a preliminary propeller rate of revolution can also be estimated using the propeller open water curves. These are the “first guessed” propeller performances of Block 6. Finally, Block 7 is in charge of the unsteady characterization of the propeller using BEM calculations. It accepts as input the effective wake evaluated in Block 5 (then considering also the tangential components of the incoming flow to the propeller, neglected in Block 6), the preliminary estimation of the propeller revolution rate, using open water curves, and the target thrust, determined by the self-propulsion analysis using the actuator disk. In this case, the effective wake does not change iteration per iteration, as in the case of the computations using iterative and spatially varying body forces approaches, since the simplified actuator disk is equivalent to the unsteady propeller in terms of both (averaged) self-induced velocities and delivered forces. Iterations, instead, are used to tune the propeller revolution rate accounting for the spatial non-uniformity of the wake and the modification of the tangential components of the inflow caused by the pre-swirl fins. Once the propeller revolution rate, which is necessary to provide an averaged unsteady thrust equal to the ship resistance in self-propulsion (that of Block 3), has been obtained, the time-averaged delivered power can be determined to assess the performance of the propulsive configuration under investigation.

3 THE REFERENCE SHIP

The test case selected for the design activity is a 33 meters long, twin-screw, a mega-yacht designed by Azimut-Benetti. An overview of the shaft/appendages arrangement is provided in Figure 3. The configuration examined in this study account for a displacement of 200 tons and a speed of 15 kn.
At first, RANS analyses (PLM, 2017) have been used to predict the ship resistance in full scale, using a computational mesh of about 3.2 Million cells, a 2-DoF solver with VoF capabilities and the realizable k-ϵ turbulence model. The double model, employed in the optimization activities and to derive

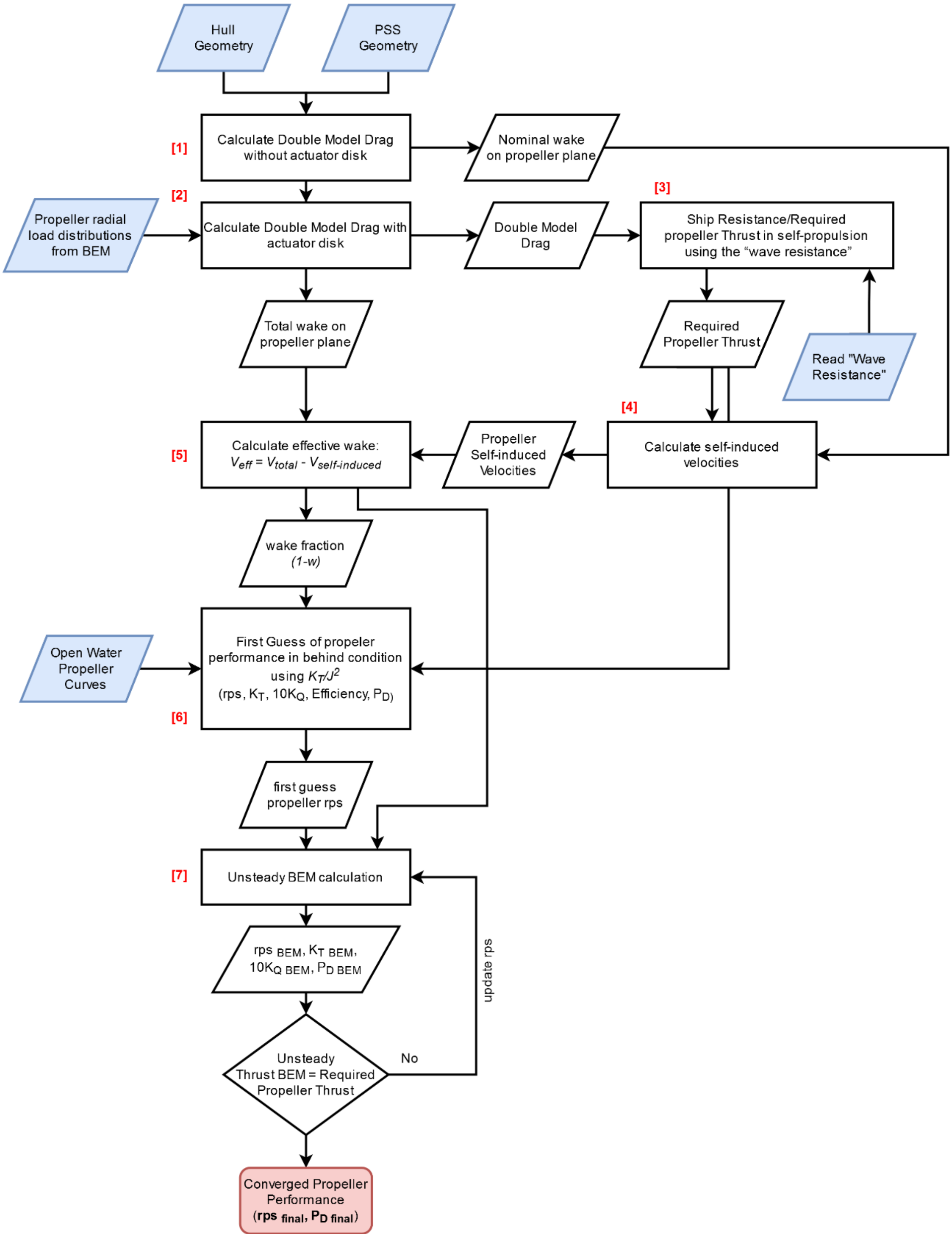


Figure 2. Flow chart of the simplified self-propulsion evaluation process.

Table 1. Self-propulsion coefficients from coupled BEM/RANS and fully RANS analyses at the design ship speed for the reference configuration. Propeller revolution rate and delivered shaft power of coupled BEM/RANS in the percentage of reference values (n_{Ref} and $P_{\mathrm{D_{Ref}}}$) computed using fully RANS analyses.

	$\frac{n}{n_{\mathbf{Ref}}}$[%]	**(1-t)**	**(1-w)**	K_{T}	$10K_{\mathrm{Q}}$	η_{o}	$\frac{P_{\mathrm{D}}}{P_{\mathrm{D_{Ref}}}}$[%]
Coupled BEM/RANS	99.8%	0.947	0.930	0.231	0.381	0.636	94.4%
Fully RANS	100%	0.933	0.932	0.240	0.413	0.612	100%

the “wave resistance” discussed in the previous section, reduces the cells count to about 2 Million, avoiding the refinements in correspondence of the free surface. With this setup, ship performances compare reasonably well with the experimental data scaled to ship size using the ITTC’57 procedure. Ship resistance, particularly, has been predicted in the proximity of the design speed with a margin of error lower than 4%. Sinkage and trim show trends qualitatively in agreement with measurements. Propeller performances have been evaluated using both RANS and the BEM developed at the University of Genoa. BEM was used to identify the radial distributions of axial and tangential forces for the actuator disk, and to perform the unsteady analyses required to determine the propeller delivered power (Block 7 of Figure 2). The reference surface mesh consists of 1250 panels per blade, solved with an equivalent time step of 6° and a steady wake alignment, realized with the circumferentially averaged inflow of the nominal wake. The comparison with measurements (open water diagram, in this case) was good for both the solvers. In the operative range of $J = 0.6$–0.8, thrust has been slightly underestimated (3-5% respectively for RANS and BEM). Unexpectedly, torque has been better predicted especially for RANS (less than 1% discrepancy), while BEM calculations show the well-known limitations in heavily loaded conditions.

The self-propulsion functioning has been similarly predicted in both cases (fully RANS and coupled BEM/RANS analyses), especially focusing on the propeller revolution rate and the propulsive coefficients of the ship in this reference functioning condition (i.e. no ESD). As extensively discussed in Furcas and Gaggero (2021), some discrepancies can be ascribed to differently computed propeller performances, particularly in highly non-uniform wakes (Gaggero et al., 2014), to a different interaction of the actuator disk/fully resolved propeller with the hull and to different ways of calculating the effective wake. Particularly for the latter, it is worth noting that the coupled BEM/RANS method computes the effective wake as the average of the local velocity field. On the other hand, fully RANS analyses rely on the open water propeller performances equivalence, as in the case of towing tank measurements. In the case of very uneven behaviour of the port/starboard tangential flow, i.e. as the result of the action of the pre-swirling fins, this could lead to very different values of wake fraction, and consequently of propeller efficiency. In this specific case, the predicted shaft delivered power has shown a difference between the methods of about 5%. The coupled BEM/RANS has predicted a weaker propeller/hull interaction using the actuator disk, that combined with the underestimation of the averaged torque coefficient, leads to the above mentioned shaft power under-prediction. As a whole, however, accounting for the severe approximations needed for these computationally efficient calculations, these results seem more than acceptable to legitimize the use of the simplified self-propulsion procedure into the optimization loop.

4 RESULTS AND DISCUSSION

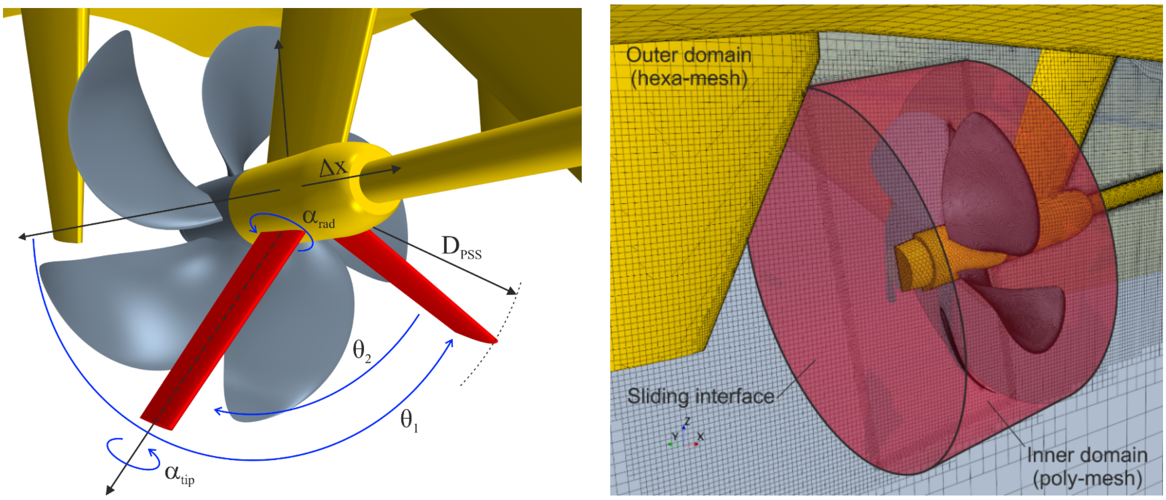
All design processes based on an SBDO approach are built upon a parametric description of the geometry and an automatic “try-and-error” process using appropriate algorithms, such as genetic or gradient ones, to realize (Pareto) convergence towards design objectives and constraints. Current preswirl ESDs have been designed following this paradigm, then starting from a parametric description of the device. A method capable of enlarging the design space as much as possible, allowing for local

Table 2. Ranges of design parameters and geometry of the optimized pre-swirl device.

Design Parameter	Min	Max	Pre-4491
Pre-swirl diameter/Propeller diameter	0.85	1.25	1.08
Fins chord (same for both)	0.15 m	0.30 m	0.22 m
Max camber/Chord (first fin)	-0.05	0.05	-0.002
Max camber/Chord (second fin)	-0.05	0.05	-0.047
Max thickness/Chord (same for both)	0.075	0.15	0.125
Position of max camber/chord (first fin)	0.30	0.60	0.40
Position of max camber/chord (second fin)	0.30	0.60	0.60
α at root (first fin)	-17.5°	17.5°	-0.5°
α at tip (first fin)	-17.5°	17.5°	0.5°
α at root (second fin)	-17.5°	17.5°	11.5°
α at tip (second fin)	-17.5°	17.5°	-9.5°
Θ_1	0°	230°	220°
Θ_2/Remaining angular space	0	1	0.28
DX/Hub length	0	1	0.11

variations of the geometry compatible with the local features of the flow, with the minimum possible number of design parameters, would be preferable. To comply with this aim, each fin of the pre-swirl stator has been designed with a linear variation of the angle of attack, based on the values at root and tip, a NACA 4-digit sectional hydrofoil (maximum thickness, camber and position), a span-wise constant value of chord (equal for both the fins) and the diameter of the device (Figure 3). The position of the fins has been handled by the distance from the propeller plane and by their angular location around the shaft. Therefore, the total number of design parameters was equal to 14 (Table 2). The reduction of the delivered shaft power is the objective of this design case, since it summarizes the effectiveness of this device as a compromise between the additional resistance of the fins and their positive influence on the propeller functioning. However, the application to a mega-yacht requires particular attention to the propeller functioning, and to a possible increased risk of cavitation (i.e. worsening of radiated noise/vibrations) as a consequence of the modification of the effective wake. The unsteady calculations of the propeller functioning, introduced in the optimization workflow, permit the monitoring of the pressure distribution on the propeller blades, which can be easily translated into a new set of design objectives dealing with the risk of cavitation. Then, the final process accounts even for the risk of cavitation collecting the maximum value of suction (i.e. the computed inception index) on the back of the blade during a complete revolution (for the reference case: ${C_{\mathrm{PN}}}^{\mathrm{MAX}}$ equal to 2.08). Besides, the C_{Pn} average value (for the reference case: ${C_{\mathrm{PN}}}^{\mathrm{AVG}}$ equal to 1.68), which in some way gives an idea of the extent of the flow disturbance induced by the fins, is gathered as well. For this analysis, a multi-objective optimization algorithm (of genetic type) is mandatory. The design space has been filled with 140 initial configurations (Latin Hypercube Sampling) and a total of 2800 cases (20 times the initial population) have been derived. The results of the optimization activity are summarized in the Pareto diagram of Figure 4.

The effectiveness of the pre-swirling action of the device in reducing the propeller delivered power, within the limitations of the approximated self-propulsion estimation method, is clear already by these simplified analyses. As usual, when dealing with contrasting objectives, the highest reduction of absorbed power corresponds to the cases where the risk of cavitation is higher. Luckily, there are also several geometries capable of ensuring a simultaneous reduction of both the design objectives. Among these, Pre-4491 is the configuration that realizes the maximum reduction of delivered power at a slightly lower risk of cavitation. Based on this, it has been chosen as the optimized configuration to be further analysed using full RANS calculations.



(a) Design parameters (b) Reference mesh (fully RANS)

Figure 3. Parametric description of the pre-swirl fins and mesh arrangement for RANS calculations (fully RANS case).

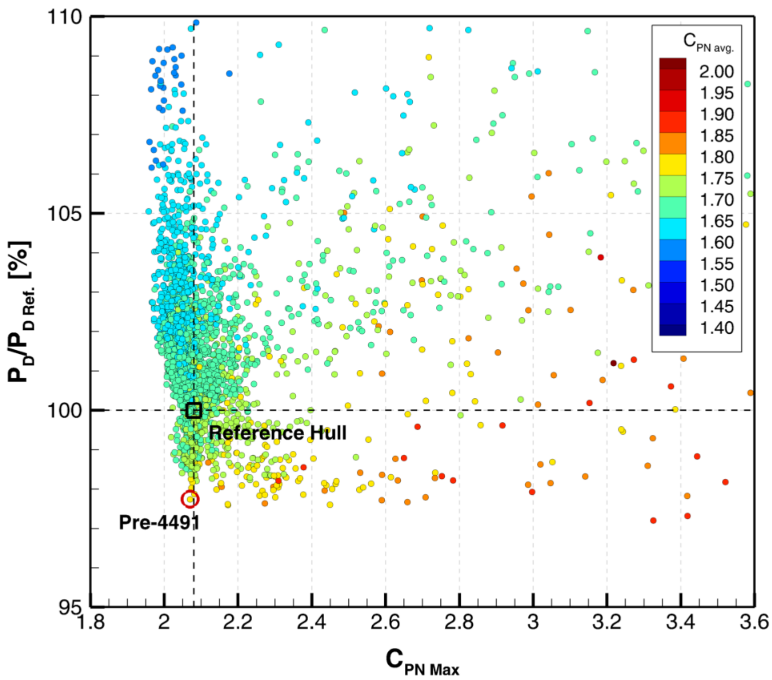
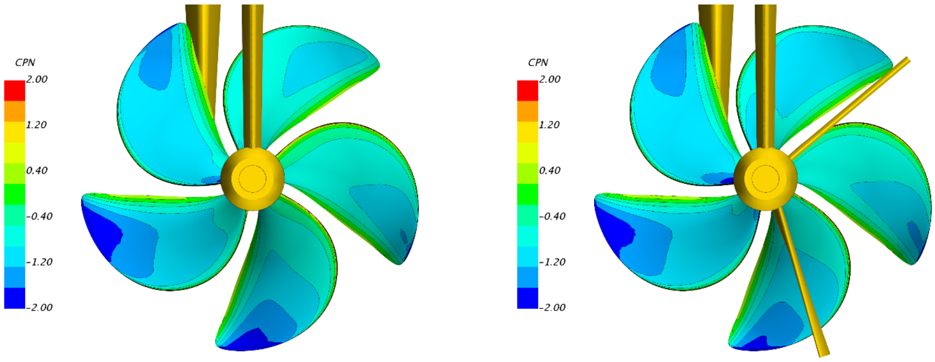


Figure 4. Pareto convergence of the optimization process.

Table 3. Self-propulsion coefficients from coupled BEM/RANS and fully RANS analyses at the design ship speed for the optimal pre-swirl configuration. Propeller revolution rate and delivered shaft power always in the percentage of the values (n_{Ref} and $P_{\text{D}_{\text{Ref}}}$) of the reference ship computed using respectively the BEM/RANS coupled solver (B/R) and the fully RANS analyses (F-R).

	$\frac{n}{n_{\text{Ref}}}$[%]	$(1-t)$	$(1-w)$	K_{T}	$10K_{\text{Q}}$	η_{o}	$\frac{P_{\text{D}}}{P_{\text{D}_{\text{Ref}}}}$[%]
Ref. Ship B/R	100%	0.947	0.930	0.231	0.381	0.636	100%
Ref. Ship F-R	100%	0.933	0.932	0.240	0.413	0.612	100%
Pre-4491 B/R	97.2%	0.948	0.929	0.247	0.408	0.656	97.8%
Pre-4491 F-R	97.1%	0.940	0.866	0.255	0.438	0.588	97.1%



(a) Reference hull (b) Pre-4491

Figure 5. Optimal pre-swirl fins arrangement and pressure coefficient (C_{PN}) on the propeller blades, seen from bow (suction side).

Complete full-RANS analyses confirms the reductions of delivered power observed in the optimization process, predicting a saving of about 2.9% (Table 3). Fully RANS analyses of this final configuration highlight once more the limitations of the BEM/RANS calculations already discussed for the reference ship, but confirm the trends evidenced by the simplified calculations during the optimization. As for the reference case, the coupled BEM/RANS approach underestimates the hull/propeller interaction, which is on average 1% higher when computed with the fully resolved propeller. Delivered thrust and absorbed torque by the propeller reflect this discrepancy that is further intensified by the limitations of BEM in dealing with strongly non-homogeneous inflow wakes, as those from the pre-swirl stators. The most significant difference between the two approaches can be observed in the predicted effective wake fractions and, consequently, in the propeller efficiency.

As discussed in similar analyses (Furcas and Gaggero, 2021), the reduction of the effective wake fraction up to 7-8% (fully resolved propeller calculations) compared to the marginal reductions observed using the simplified BEM/RANS approach in presence of the pre-swirl stators is due to the different computational strategy. Using the coupled BEM/RANS method, the wake fraction estimation is carried out directly through an average over the effective wake (which is calculated by the coupling algorithm) on the propeller disk. On the other hand, fully RANS analyses exploit the open water propeller diagram and the information from the self-propulsion calculations (propeller delivered thrust and revolution rate) to assess the wake fraction required to meet the thrust identity between the thrust coefficient delivered in open water conditions and the one delivered behind the hull. However, except for a certain difference between these two approaches (i.e. body forces tendency to underestimate the flow deceleration), in this case the port/starboard non-symmetrical tangential components of the flow to the propeller, due to the pre-swirl fins, have to be considered. Tangential flow contributes to the blade delivered thrust increasing by changing the local angle of attack without any change in the axial flow that, instead, is the only parameter responsible for the thrust identity when the usual definition of wake fraction, based on equivalent open water propeller performance, is adopted. This causes an overestimation of the wake fraction/flow deceleration when its calculation is based on the thrust identity assumption. As a matter of fact, the effect of the port/starboard uneven tangential flow in increasing the propeller delivered thrust is not considered and is consequently balanced by a false deceleration of the axial wake. The wake fraction computed by averaging the effective wake accounts only for the current local axial velocity (and not of the influence on the thrust of the tangential flow), instead, results in a significantly faster average inflow. The calculation of the propeller efficiency, which is strictly correlated to the wake, appears to depend on these differences. Since the operative point of the propeller significantly moves towards lower advance coefficients, the propeller efficiency (predicted using fully resolved RANS analyses) is reduced, but it is largely compensated by a significant increase of the hull efficiency (not observable in the case of BEM/RANS coupled analyses), which implicitly accounts for the different calculation methods.

The snapshots of the pressure distributions on the propeller blades of Figure 5 confirm the influence of the pre-swirl device on the cavitation inception. The time histories of the pressure field have not been collected during the fully resolved RANS analyses, excluding the possibility of a direct time step per time step comparison with the quantities extracted during the optimization process. However, these pressure distributions are qualitatively sufficient to demonstrate the reliability of the design process. As expected from the simplified analyses, also when using fully resolved RANS, Pre-4491 is the configuration capable of even a small reduction of the cavitation inception risk, which is evident in current calculations by the significant reduction of suction when the blade passes through the lower portion of the disk.

5 CONCLUSIONS

In the present work, the design of energy-saving devices based on the pre-swirl stator concept has been illustrated using an optimization process. Thousands of different configurations have been analyzed and automatically modified, based on the feedback of previous calculations to comply with the design objectives and constraints, which in this case were only of geometrical type. To estimate the delivered power, a dedicated BEM/RANS coupled method has been developed to comply with the need for accurate predictions in a computationally efficient way. The extensive exploration of the design space, possible thanks to the design frameworks specifically developed for, allowed for substantial energy savings also for this peculiar test case, which is not the usual full-blocked ship for which these ESDs have already demonstrated their effectiveness. The versatility of the design method appears also in the possibility of monitoring side effects, such as the risk of cavitation, which were explicitly and quantitatively accounted for in the whole design process. The verification with fully resolved propeller RANS analyses has confirmed the validity of the design, which was capable of a 2.9% energy saving.

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References

Furcas, F. and Gaggero, S. (2021). Pre-Swirl Stators Design using a Coupled BEM-RANSE Approach. *Ocean Engineering*, 222:108579.

Gaggero, S. (2020). Numerical Design of a RIM-Driven Thruster using a RANS-Based Optimization Approach. *Applied Ocean Research*, 94:101941.

Gaggero, S., Gaggero, T., Tani, G., Vernengo, G., Viviani, M., and Villa, D. (2018). Ship Self-Propulsion Performance Prediction by Using OpenFOAM and Different Simplified Propeller Models. In *Progress in Maritime Technology and Engineering: Proceedings of the 4th International Conference on Maritime Technology and Engineering (MARTECH 2018), May 7–9, 2018, Lisbon, Portugal*, page 195. CRC Press.

Gaggero, S., Villa, D., and Viviani, M. (2014). An Investigation on the Discrepancies between RANSE and BEM Approaches for the Prediction of Marine Propeller Unsteady Performances in Strongly non-homogeneous Wakes. In *ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection.

Gaggero, S., Villa, D., and Viviani, M. (2017). An Extensive Analysis of Numerical Ship Self-Propulsion Prediction via a Coupled BEM/RANS Approach. *Applied Ocean Research*, 66:55–78.

Koushan, K., Krasilnikov, V., Nataletti, M., Sileo, L., and Spence, S. (2020). Experimental and Numerical Study of Pre-Swirl Stators PSS. *Journal of Marine Science and Engineering*, 8(1):47.

Nielsen, J. and Jin, W. (2019). Pre-Swirl Fins Adapted to Different Operation Conditions. In *Proceedings of the 6th International Symposium on Marine Propulsors smp*, volume 19.

PLM, S. (2017). StarCCM+ users' manual. Technical report.

Prins, H., Flikkema, M., Schuiling, B., Xing-Kaeding, Y., Voermans, A., Müller, M., Coache, S., Hasselaar, T., and Paboeuf, S. (2016). Green Retrofitting Through Optimisation of Hull-Propulsion Interaction–GRIP. *Transportation Research Procedia*, 14:1591–1600.

Schuiling, B. and van Terwisga, T. (2017). Hydrodynamic Working Principles of Energy Saving Devices in Ship Propulsion Systems. *International Shipbuilding Progress*, 63(3-4):255–290.

Streckwall, H. and Xing-Kaeding, Y. (2017). On the Working Principle of Pre-Swirl Stators and on their Application Benefit and Design Targets. *International Shipbuilding Progress*, 63(3-4):87–107.

Villa, D., Gaggero, S., Gaggero, T., Tani, G., Vernengo, G., and Viviani, M. (2019). An Efficient and Robust Approach to Predict Ship Self-Propulsion Coefficients. *Applied Ocean Research*, 92:101862.