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Optimisation of Unconventional Tip-Rake Propeller using Panel Code Method

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ABSTRACT

This paper aims to optimise an unconventional tip rake design for maximum efficiency. The initial propeller geometry used for the investigation is a conventional single screw design developed for container ships. A parametric model of the initial blade is generated and is further modified to add a raked tip. Raked tip is governed by a set of variables defining the shape and extent of the rake, ensuring smooth transition.

Two initial designs are created, a conventional design and a tip raked design of the conventional design. These are numerically evaluated using RANSE based analysis and panel method to create a correlation factor. The parametrised model is connected to an optimisation tool which systematically varies propeller characteristics and the variables controlling raked tip. OWT of the generated designs is numerical evaluated using panel method and corrected against RANSE based calculation using correlation factors. Tangent search method is used to maximise open water efficiency. Subsequently, a propulsion prognosis is evaluated by interpolation using K_T under the assumption of fixed propulsion coefficients. Constraints are imposed to filter designs outside a certain light running margin. The optimised results are compared against RANSE based results to ensure its validity.

Keywords

Optimisation, Unconventional design, Parameterisation, Tip raked propeller.

1 INTRODUCTION

Conventional propeller geometries have remained the same over past several decades. Although gains in propeller performance have been achieved over this time span, the main driver of these gains were due to progression in computational capacity which made time consuming numerical computations accessible to the marine industry. With these gains in numerical computation capacity, a new way of propeller performance enhancement is viable through multiple iterations of conventional geometries, tailored to a specific performance target, also known as optimisation. But, with the increase in demand for highly efficient propeller spawned by stricter emission regulations, a look towards a more unconventional propeller design is valid.

One of these unconventional designs is a tip raked propeller. A tip raked propeller is a "bended tip design" of conventional propeller. These propellers are designed to reduce losses arising from tip vortices by reducing cross flow near the propeller tip. Originally developed for the aerospace industry, the bended tip design, more commonly known in the aerospace industry as winglet designs were assigned to airplane wings in pursuit of lower drag for the same lift. These designs proved successful and were later adopted to the marine industry in the form of tip raked propellers and came as a bended tip version of the conventional design by Anderson et al. (1986). This design gained popularity as it claimed to have better efficiency compared to similar diameter conventional designs. A similar adaptation of the same concept came from Gomez et al. (1998) by fitting a flat plate to conventional designs. These designs claimed to have better efficiency but suffered high levels of cavitation. Many other attempts at designing tip raked designs are available with designers evaluating performance and cavitation behaviour for raked tip bended in both directions.

With improvement in computational ability, design optimisation has become a main stay in propeller design and is expected to play a major role in the future. Some have attempted to optimise tip loaded designs (Steffano Gaggero et al. 2015) with varying effects. Most recently, these optimisation strategies have moved on to multi objective design strategies and machine learning with focus on both efficiency gain and cavitation reduction (Doijode et al. 2022).

Since multiple variables influence the performance of a tip raked design, an optimisation tool is necessary to generate a design with optimal efficiency. This paper aims to perform an optimisation on tip rake design to understand the efficacy of such a procedure using a panel code method using single objective optimisation.

2 METHODOLOGY

The methodology used for parametrisation of propeller blades and the subsequent strategy used for optimisation are described in this section. The optimisation strategy is limited to open water condition optimisation. A propulsion prognosis is evaluated for each variant created inside an optimisation loop with no change in hull efficiency element considered as an assumption. The hull efficiency elements of conventional initial propeller are used throughout the optimisation. Constraints are applied to ensure the optimised propeller fits within a fixed light running margin (LRM) hence viable to fit in an engine curve.

2.1 Parameterisation

The parameter model of propeller geometry is carried out using CAESES framework (Praefke et al., 2017). CAESES is a CAD geometry generation software used to develop parametric geometries and its optimisation. The original propeller geometry is used as the input and CAESES develops a parametrised blade based on this input. The inputs are the profile definition at each radius along with propeller parameter distributions such as pitch, chord length, skew, rake etc. The parametrised conventional blade is further modified to produce a raked tip. The raked tip is also parametrised and controlled by a set of variables which define the radius of transition to the raked tip (split radius), the length of the raked tip (dTtip) and rotation of the profile section at the raked tip (tip Tilt). Transition radius or split radius is defined as relative radius (r/R) at which the transition occurs, length of bend or dTtip is defined as the ratio between length of bend and the propeller diameter while the rotation of profile or tip tilt is defined as angle of rotation in degrees with the pivot point defined at the leading edge of the profile. The combination of parametrised conventional blade with parametrised raked tip ensures a consistent generation of parametric tip raked design, even when the underlying conventional propeller geometry changes. Examples of tip rake variables and their effect on tip rake geometry are shown in Figure 1.

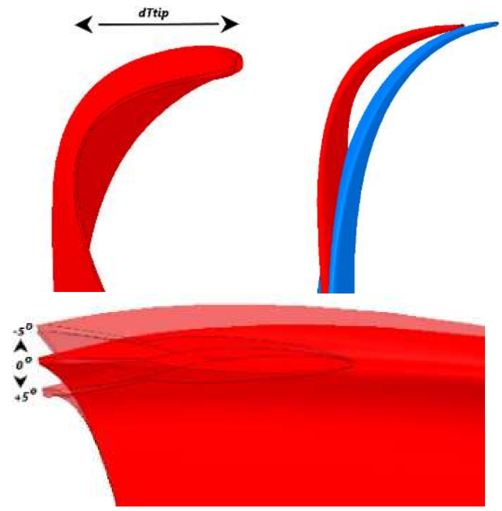


Figure 1: Illustration of dTtip (Top left) , split radius (Top right) and Tip Turn (Bottom)

2.2 Optimisation

The parametrised blade is converted into a panel mesh and is used as input geometry for panel code (Boundary element method) panMARE (Berger et al., 2016). To optimise the propeller a single stage optimisation procedure is used. Optimisation utilizes a single objective tangent search method (Hilleary, 1966) to maximise propeller efficiency with applicable constraints. It is a gradient-free method which can efficiently solve a single objective optimisation for local optimisation problems. Initial exploratory moves are performed by the algorithm by changing each variable at a time to identify promising directions which are followed by global moves by combination of many variables to make steps towards improvement of objective. Tangent search method gives good results with efficient operation. Usually, tangent search method is combined with Design-of-Experiments to identify a good starting point. In this paper, it is assumed that the initial propeller is a very good starting point, as all criteria set for optimisation are met by the initial geometry. Each optimisation loop is allowed to change tip rake variables within a certain range. For this paper, the investigation is limited to geometries of propeller with tip raked towards suction side. Since, certain extreme values for each tip rake variable generates unfavourable geometries, the tip rake variables are also limited to a certain range. Other inputs used are nominal propeller curve, light running margin (LRM), hull efficiency elements, ship speed and correlation factor. The correlation factors are assigned based on the grid dependency study of panMARE and benchmarked against RANSE based calculations. In this paper, all RANSE based evaluations are carried out using commercially available RANSE based software, ANSYS CFX. The LRM is derived from propulsion prognosis of initial conventional geometry and is allowed to deviate 1% from original value during optimisation. The allowed deviation generates limits on RPM for power consumed at a particular vessel speed and is considered as a constraint. To interpolate the propulsion point from each generated variant's open water curve, K_T/J^2 value from initial propeller's power prognosis is used. The objective of the optimisation loop is to maximise open water efficiency at the interpolated ship operational point.

3 GRID DEPENDENCY

The propeller used for calibration is a five bladed single screw propeller designed for a container vessel. The propeller characteristics of the initial geometry (Orig) are shown in Table 1 and geometry shown in Figure 2.

Figure 2: Orig Propeller Blade

Table 1: Propeller characteristic of Orig

Parameters	Value	Units
Diameter	9.6	m
Number of blades	5	-
EAR	0.584	-
Mean Pitch	1.083	-
Mean Skew	36.29	degrees

For this conventional design, the initial geometry is discretised with varying configurations of number of panels in chord wise direction (Ni) and number of discretised panels in radial direction (Nj). For this study, the discretisation ratio between Ni and Nj are kept constant at 1, but type of panel distribution is varied between uniform distribution in Ni and Nj direction to biased refinement towards leading and trailing edge in Ni direction (Figure 3).

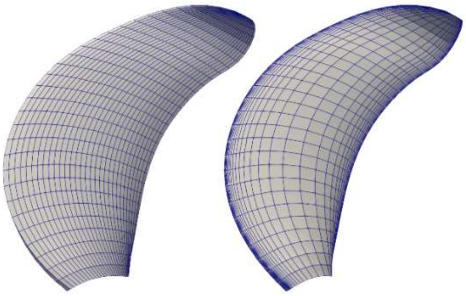


Figure 3: Panel refinement in uniform (left) and biased (right)

To calibrate panMARE results, RANSE based OWT are evaluated and are used as benchmark. The CFX based OWT uses the same grid and numerical setup as used for open water evaluation by Asif et al. (2023). The varied panel mesh configurations are compared against RANSE based OWT to obtain the best mesh configuration. The correlation is then calculated between the best mesh and benchmarked CFX calculation and is applied to all generated variants open water results in the optimisation loop. One of the objectives here is to observe whether this correlation is valid for the final optimised propeller at the end of optimisation loop. Table 2 shows the comparison in deviation of K_T and K_Q of panMARE results against CFX results for varying panel mesh configuration and refinement type. The values shown are averaged deviation of K_T and K_Q for J values between 0.6 to 1.0.

Table 2: Deviation of K_T and K_Q for different Panel configuration and refinement type for conventional design

Configuration	Refinement	Average ΔK_T (%)	Average ΔK_Q (%)
15x15	Biased	0.3675	-3.205
20x20	Biased	-1.615	-4.71
30x30	Biased	-3.85	-7.7575
15x15	Uniform	5.805	3.07
20x20	Uniform	6.34	3.6
30x30	Uniform	3.3725	1.2025
40x40	Uniform	2.245	0.365

Since the unconventional designs are to be optimised with each variable having a range of values (Table 3), a variant is generated with averaged values (Orig-TR) for correlation. This corresponds to split radius, dTtip and tip turn having values 0.8625, 0.1125 and 0, respectively. Table 4 shows the comparison in performance with varying panel configuration and refinement type. The relevance of a correlation factor is evident from this table, as the deviations are very high. A propulsion prognosis using such highly deviated (or non-calibrated) panMARE results will lead to very unrealistic results and will mislead the optimisation algorithm to make unwanted changes to geometry. The reason for such high deviations could be spawned from the inability of the panel code method to capture complex flows arising from drastic tip rake geometries used in this paper. But, if the correlation factors can mitigate the high deviations and panMARE can predict the tendencies in efficiency gain or loss, this approach could lead to a highly computationally efficient and accurate way to optimise a propeller.

Table 3: Tip-raked propeller variable range and average value.

Variables	Lower limit	Average	Upper Limit
Split Radius	0.8	0.8625	0.925
dTtip	0.075	0.1125	0.15
Tip Turn	-10	0	10

Table 4: Deviation of K_T and K_Q for different Panel configuration and refinement type for tip rake design

Configuration	Refinement	Average ΔK_T (%)	Average ΔK_Q (%)
15x15	Biased	-20.0075	-21.325
20x20	Biased	-20.0075	-20.6625
30x30	Biased	-19.2175	-22.16
15x15	Uniform	-20.7125	-21.88
20x20	Uniform	-17.22	-18.7525
30x30	Uniform	-15.8175	-17.1575
40x40	Uniform	-15.5125	-16.63

According to Table 2 and 4, a 40 by 40 configuration with uniform panel distribution has the least average deviation against RANSE based results for conventional and unconventional designs. Therefore, a correlation corresponding to this configuration is carried forward for all remaining cases. Although, the tables show average deviation, when correlation factor is used to calibrate the panMARE results, individual corrections corresponding to each J value are applied.

4 EVALUATION AND PERFORMANCE ANALYSIS

Performance prognosis of all versions evaluated are based on the hull efficiency elements of the Orig propeller. These values are obtained from model tests performed on Orig. The hull efficiency elements are shown in Table 5. No mechanical losses are considered for the evaluation and all performance analysis is based on direct full scale open water results. The target speed to be achieved is 22.8 knots and hence all optimisations will be aimed at optimising efficiency for this vessel speed.

Table 5: Hull efficiency elements of Orig

Parameter	Value
Thrust deduction	0.111
Wake fraction	0.166
η_R	1.003

4.1 Initial versions

The CFX based open water test comparison between Orig and Orig-TR is shown in Figure 4.

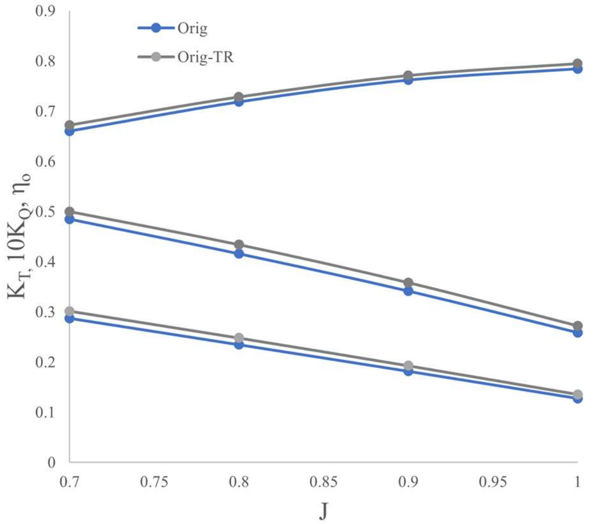
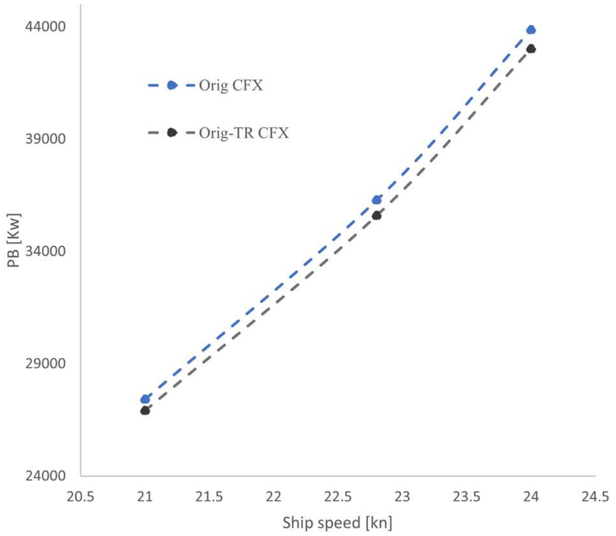


Figure 4: OWT comparison between Orig and Orig-TR

Based on these performance characteristics a propulsion prognosis is evaluated and shown in Figure 5.



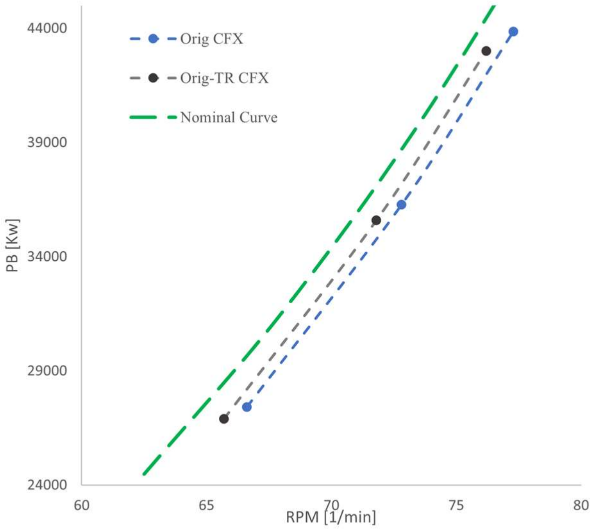
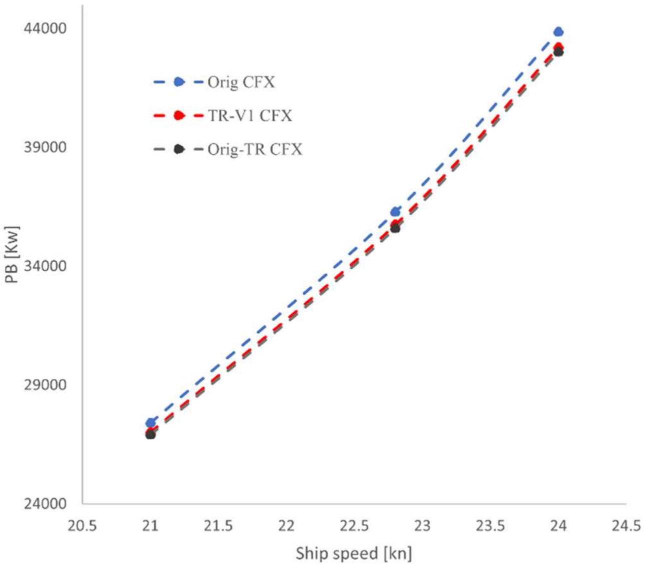


Figure 5: Illustration of predicted power vs. ship speed and predicted power vs. RPM between Orig and Orig-TR

Orig-TR has a reduced power consumption of 1.89% compared to Orig at 22.8 knots, but the light running margin reduced to 1.4% from 2.2% when evaluated against nominal propeller curve. Therefore, to have a good starting variant for optimisation, the Orig version is adjusted in pitch to produce a new base propeller for tip raked versions. The new tip raked propeller (TR-V1) has a reduced power consumption of 1.45% compared to Orig at 22.8 knots, but the light running margin increased to 2.7% from 1.4% when evaluated against the nominal propeller curve. Figure 6 shows the comparison of power and light running margin between Orig, Orig-TR and TR-V1. It is evident from Figures 5 and 6 that, both tip raked variants produce better performance compared to conventional design.



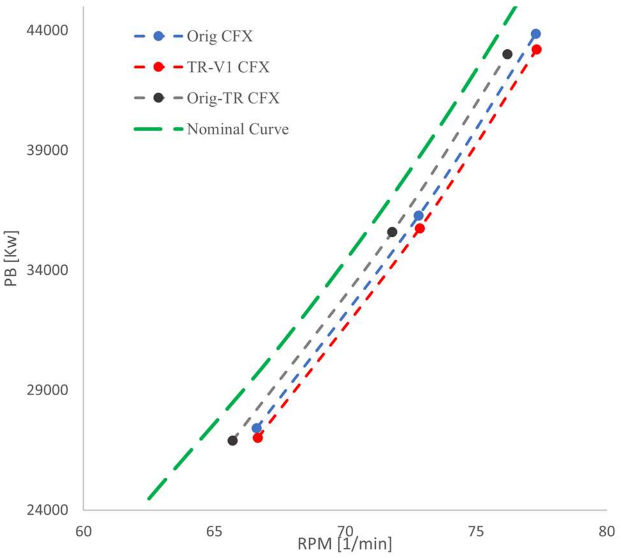


Figure 6: Illustration of predicted power vs. ship speed and predicted power vs. RPM between Orig, Orig-TR and TR-V1.

4.2 Optimisation: Case 1

In case one, TR-V1 is assigned to the optimisation loop. To optimise the propeller, variants are generated within the optimisation loop, but variables allowed to change for variant generation are limited to split radius, tip turn and dTtip. An optimisation is performed using CAESES-panMARE framework to maximise η_O with constraints applied to light running margin. Based on LRM values of Orig and TR-V1, a mid-way value of 2.5% LRM from nominal propeller curve is selected as the base value. The constraints applied allow a deviation of +/-1% from this central value and all variants within this range are considered as acceptable design. Figure 7 shows the evolution of interpolated η_O as different variants are generated.

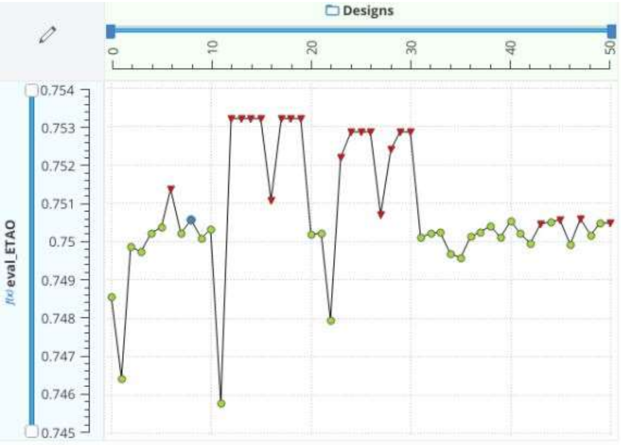


Figure 7: Evolution of η_O during variant generation (red – infeasible, green – feasible, blue – optimum).

The tip rake variant with maximum η_O is selected and its propulsion prognosis evaluated. Figure 8 shows the performance comparison between optimised tip raked variant (TR-V1-Opt), TR-V1 and Orig. Table 6 shows the gain in power reduction and change in LRM between these variants. All values shown in Table 6 and Figure 8 are comparisons between panMARE results.

Table 6: Power and LRM change between Orig, TR-V1 and TR-V1-OP.

Version	Power (%)	LRM (%)
Orig	-	2.20
TR-V1	-1.16	2.60
TR-V1-OP	-1.60	3.30

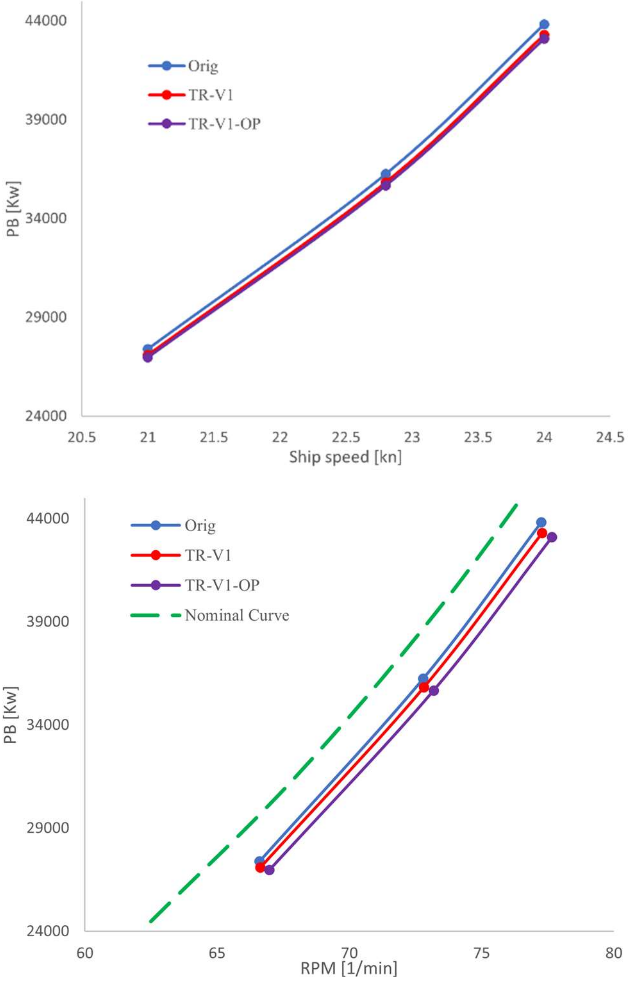


Figure 8: Predicted power vs. ship speed and predicted power vs. RPM between Orig, TR-V1 and TR-V1-OP

Results show a reduced power consumption with optimised variant with LRM staying within allowable deviation. A comparison between initial and optimised tip rake variables is shown in Table 7.

Table 7: Initial vs Optimised tip rake variables

Variables	Initial	Optimised
Split Radius (Sp)	0.8625	0.85625
dTtip	0.1125	0.1214
Tip Turn	0	-1

4.3 Optimisation: Case 2

In case two, a similar procedure to case one is followed but with variant generation allowed to also change propeller pitch distribution and camber distribution. The aim is to study whether a combination of tip rake parameter and conventional propeller parameter can be more beneficial than case one. To make the results fairer and more meaningful, the conventional propeller is also optimised within an optimisation loop with changes allowed in pitch and camber distribution. The results comparing Orig, TR-V1 optimised with distribution change and tip parameter change (TR-V1-OP2) and Orig optimised with distribution change (Orig-OP) are shown in Figure 9. Table 8 shows the gain in power reduction and change in LRM between these variants. All values shown in Table 8 and Figure 9 are comparisons between panMARE results.

Table 8: Power and LRM change between Orig, TR-V1 and TR-V1-OP.

Version	Power (%)	LRM (%)
Orig	-	2.20
Orig-OP	-0.27	2.50
TR-V1-OP2	-1.73	3.50

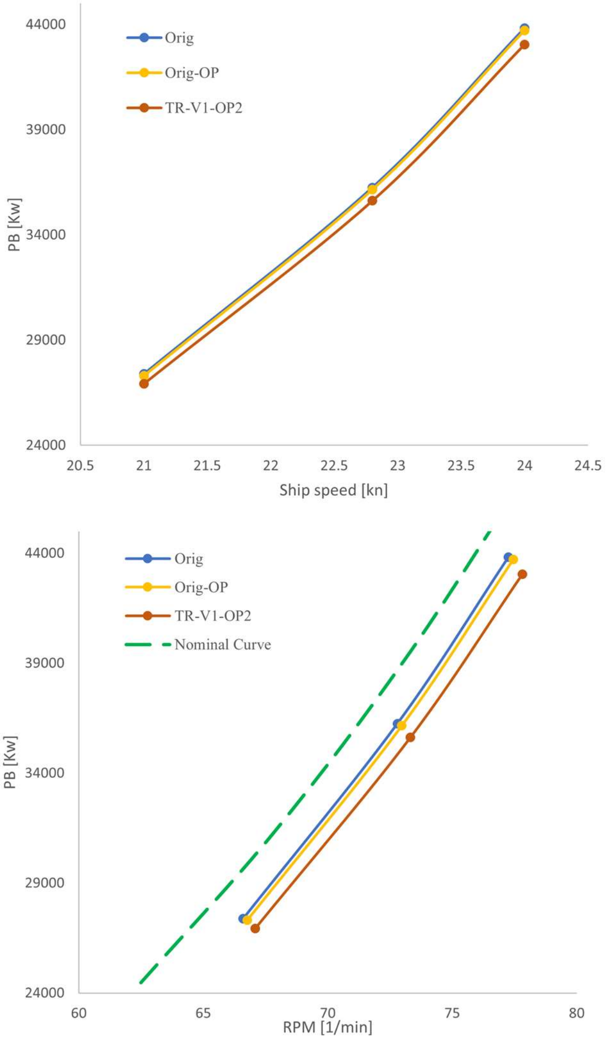


Figure 9: Predicted power vs. ship speed and RPM between Orig, Orig-OP and TR-V1-OP2

It can be inferred that, even though the TR-V1-OP2 gained higher power reduction compared to Orig, the margin of gain between the optimised propellers, Orig-OP and TR-V1-OP2 remains almost constant when compared to gains between Orig and TR-V1-OP. Table 9 shows the final tip rake parameters and Figures 10, 11 and 12 show the difference in distribution. No changes are made to pitch distribution by optimisation algorithm for TR-V1-OP2.

Table 9: Optimised tip rake variables vs. Initial for TR-V1-OP2

Variables	Initial	Optimised
Split Radius (Sp)	0.8625	0.8608
dTtip	0.1125	0.1139
Tip Turn	0	-0.9748

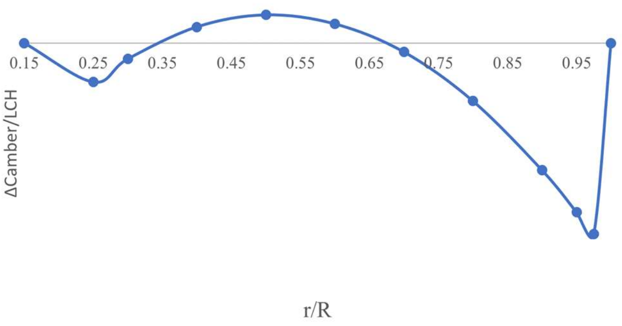


Figure 10: ΔCamber/LCH distribution between TR-V1 and TR-V1-OP2

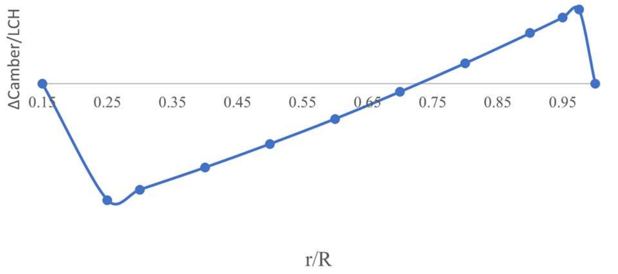


Figure 11: ΔCamber/LCH distribution between Orig and Orig-OP

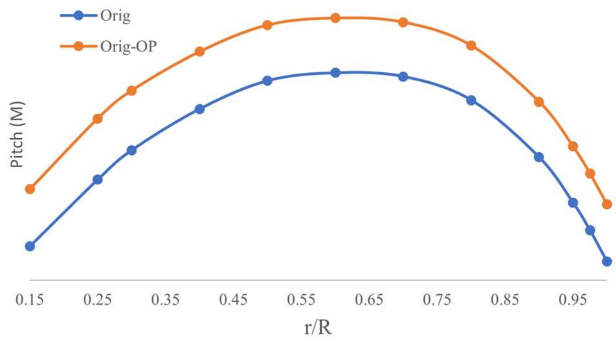


Figure 12: Pitch distribution between Orig and Orig-OP

5 INFERENCES

All propeller's initial and optimised versions are further calculated with CFX to validate the results. Since panMARE results shown in sections above have been calculated by panMARE with correlation factor, a comparison to CFX results is necessary to understand if the factors are relevant after the optimisation loop. Table 10 shows the overall power prediction by panMARE and Table 11 shows all power prediction by CFX.

Table 10: Power prediction by panMARE

Version	Power (%)	LRM (%)
Orig	-	2.20
Orig-OP	-0.27	2.50
TR-V1	-1.16	2.60
TR-V1-OP	-1.60	3.30
TR-V1-OP2	-1.73	3.50

Table 11: Power prediction by CFX

Version	Power (%)	LRM (%)
Orig	-	2.20
Orig-OP	-0.60	2.00
TR-V1	-1.45	2.70
TR-V1-OP	-1.51	3.20
TR-V1-OP2	-1.44	3.50

It can be inferred that there are slight variations between the analysis methods. Major differences in power occur between CFX based Orig-OP vs. panMARE based Orig-OP. CFX based results show higher savings compared to panMARE, but when comparing TR-V1-OP2 between the methods, there is net loss from TR-V1-OP. The difference between optimised propellers and evaluation methods are shown in Table 12.

Table 12: Comparison of optimised propeller versions and their method

Version	Method	Power (%)
TR-V1-OP	CFX	-
TR-V1-OP	panMARE	-0.37
TR-V1-OP2	CFX	-
TR-V1-OP2	panMARE	-0.17
Orig-OP	CFX	-
Orig-OP	panMARE	0.26

All negative values indicate an overprediction of gain in power reduction by panMARE. Since the gain in power reduction is very small from its base variant (TR-V1) for tip raked designs, these differences imply no net gain through optimisation. But it can be noticed that tip raked propellers consistently show higher efficiency compared to conventional design. The lack of gain through optimisation could be the result of either having a very good initial version or could be due to the algorithm's inability to overcome local optima. For the later scenario, it would be beneficial to use a different optimisation strategy to obtain global optima.

In case of correlation factors, it is observed that these initial factors are still valid at the end of optimisation loop.

6 CONCLUSIONS

A decoupled way of designing a tip raked propeller and its parameterization is discussed. The generated CAD model is smooth and can easily be controlled by very few tip parameters. Extreme values of these variables are to be avoided to negate unfavorable geometries. An optimisation strategy using a combination of Tangent search method and panel code method for evaluation with correlation factor is tested. The results showed no significant gain in power through optimisation.

An alternate approach using different optimisation strategies is recommended to obtain global optima. It is shown that an initial correlation factor can be used throughout an optimisation loop without significant deviation in result and holds well inside an optimisation loop. The study should be widened to multi objective optimisation to reduce cavitation and noise. Some assumptions such as constant hull efficiency elements could lead to unfavorable results during actual propulsion test.

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