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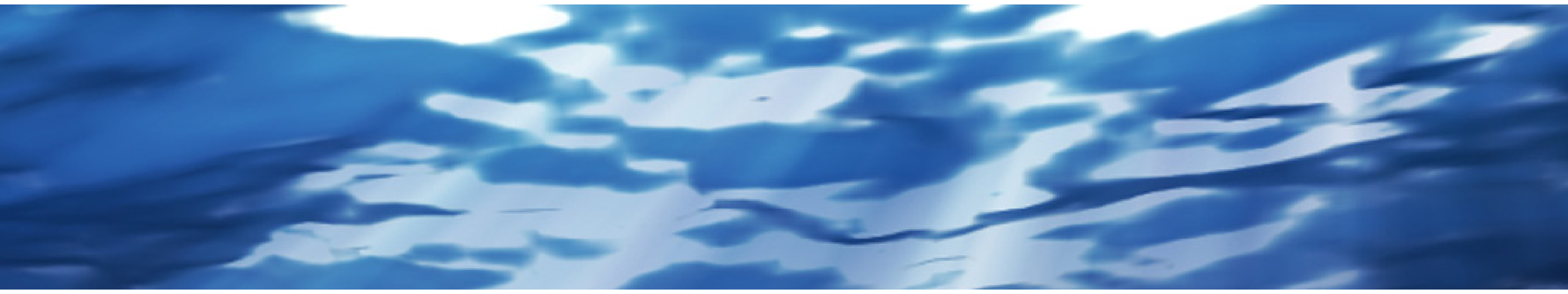
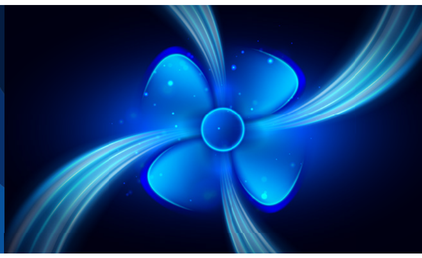


LIGHTHOUSE REPORTS

SailProp
Even sailing vessels need an efficient propeller



An innovation project carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

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HÅLLBAR SJÖFART

SailProp

Even sailing vessels need an efficient propeller

Authors

Ioli Gypa, Chalmers University of Technology

Sofia Werner, SSPA Sweden AB

Rickard Bensow, Chalmers University of Technology

In cooperation with

Robert Gustafsson, Marcus Jansson at Kongsberg Maritime Sweden AB

Carl Fagergren at Wallenius Marine

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Summary

Wind-assisted ship propulsion has large potential to reduce CO_2 emissions in shipping. Much research has the last years been focusing on the different sail technologies, ship-hull design optimisation and weather route optimisation. However, the traditional propulsion system is still needed for wind-assisted vessels and is associated with several challenges, related to the wide range of operating conditions and propeller loads due to the varying degree of wind-assistance that will occur. In this study we develop the use of an interactive design and optimisation methodology for application on propellers of wind-assisted vessels. The methodology involves handling the complete operating profile of the propeller/vessel, an optimisation method for interactive cavitation evaluation by the blade designer, and the use of a new objective, the total energy consumption of the expected operation.

The purpose of the study is to gain an improved understanding of the challenges involved in propeller design for wind-assisted/-propelled vessels, develop new design methodologies to meet these challenges, and to investigate to what extent a new propeller design can offer a significantly lower energy consumption when compared to the existing design.

We use two case studies. The first one is the KVLCC2 tanker retrofitted with six Flettner rotor sails, operating between two fixed destinations at constant speed. The second one is a wind powered car carrier with wing sails, operating with a minimum speed requirement. The case studies show that careful consideration of the operating conditions needs to be made. The recommendation is to use the highest loading condition as a starting point for the design; even if the time spent at this high load point is limited the power needed for this dominates. The design process also becomes more cumbersome and demanding as all conditions need to be evaluated, thus a suitable automated optimisation/design methodology will be beneficial. Optimisation should be performed towards minimum total power for the operational profile and not towards single point efficiency which is the normal case. For the cases studied, however, the propeller loads were quite modest from the start and the optimisation led to reduce power of only 1-2 %. It is expected though, that in many applications the choice of propeller will have a larger impact. It is worthwhile to note that in none of the cases, pressure side cavitation was deemed to become a problem; this was somewhat surprising.

The results will be used directly by the industrial partners. The results have helped to shape the ship design process being developed at Wallenius Marine. The optimisation methods developed have been implemented in the design tools of Kongsberg and are being used for commercial projects, both for wind-assisted cases as well as for advanced standard designs.

Sammanfattning

Vindassisterad fartygsframdrivning har stor potential att minska CO_2-utsläppen inom sjöfarten. Mycket forskning har de senaste åren fokuserat på olika segelteknologier, optimering av fartygsskrovsdesign och väderruttoptimering. Det traditionella framdrivningssystemet behövs dock fortfarande för vindassisterade fartyg och är förknippat med flera utmaningar, relaterade till den större variationen av driftförhållanden och propellerbelastningar. I den här studien utvecklar vi en interaktiv design- och optimeringsmetodik för applicering på propellrar av vindassisterade fartyg. Metodiken innefattar hantering av propellerns/fartygets fullständiga driftsprofil, en optimeringsmetod för interaktiv kavitationsutvärdering av bladkonstruktören och användning av ett nytt mål, den totala energiförbrukningen för den förväntade driften.

Syftet med studien är att få en förbättrad förståelse för de utmaningar som är involverade i propellerdesign för vindassisterade/-drivna fartyg, utveckla nya designmetodik för att möta dessa utmaningar och att undersöka i vilken utsträckning en ny propellerdesign kan erbjuda en betydande lägre energiförbrukning jämfört med befintlig design.

Vi använder två fallstudier. Den första är ett VLCC tankfartyg med sex Flettner-rotorsegel, som kör mellan två fasta destinationer med konstant hastighet. Den andra är ett vindframdrivet RoRo-fartyg med vingsegel. Fallstudierna visar att noggrant övervägande av driftsförhållandena måste göras. Rekommendationen är att använda högsta belastningsförhållande som utgångspunkt för designen; även om tiden som spenderas vid denna höga belastningspunkt är begränsad så dominerar den effekt som behövs för detta. Designprocessen blir mer krävande då alla förhållanden behöver utvärderas, därför kommer en lämplig automatiserad optimerings-/designmetodik att vara fördelaktig. Optimering bör utföras mot minimal total effekt för driftsprofilen och inte mot effektiviteten vid en driftspunkt, vilket är normalfallet. För de studerade fallen var dock propellerbelastningen ganska blygsam från början och optimeringen ledde till att effekten endast minskade med 1-2 %. Det förväntas dock att valet av propeller i många tillämpningar kommer att ha större inverkan. Det är värt att notera att i inget av fallen ansågs kavitation på trycksidan bli ett problem; detta var något överraskande.

Resultaten har påverkat arbetsprocesser hos projektets industripartners. Wallenius Marine utvecklar en process för design av vindframdrivna fartyg. Projektet visar hur ruttsimuleringar kan användas i specifikation och design av propeller. De utvecklade optimeringsmetoderna har implementerats i Kongsbergs designverktyg och används för kommersiella projekt, både för vindstödda fall och för avancerade standardkonstruktioner.

Contents

1 Introduction

In conventional propulsion, where the thrust of the vessel comes from the engine, the propeller is optimised for the expected operating point. The efficiency is not optimal at other conditions, but the range of operating conditions is usually narrow, since the engine operates at its optimum power most of the time.

In wind propulsion the auxiliary or main source of the thrust comes from the wind, while the propulsion system still operates when needed. The proportion of engine operation versus wind depends on the prevailing wind conditions and can vary from 0% to 100%, which also means that the thrust that the propeller must deliver varies to the same extent. The propeller must therefore be adapted for an operating range that is significantly wider than normal. In addition to this, a wind-assisted/powered ship most of the time has a drift angle, which affects the hull resistance, the inflow to the propeller and needs to be counteracted with the rudder. On those occasions when the ship is solely powered by the wind, it is desirable that the non-operating propeller has as little braking effect as possible. All this places new demands on the optimisation of the ship and the design strategy for the propulsion system.

Therefore, in this project we worked towards:

- Identifying the challenges related to wind propulsion
- Determining the needs for the definition of the operational profile of wind-assisted/powered vessels.
- Developing tools and principles for propeller optimisation in wind propulsion.
- Investigating how the wind-assistance affects the optimal propeller design.

The work has been carried out mainly by SSPA and Chalmers, with SSPA working on operating conditions and ship concepts and Chalmers working on developing propeller design optimisation tools. The industrial partner Kongsberg is a Swedish propeller designer and manufacturer. Their interest in the project was to advance the design methods suitable to wind assisted ships. The other industrial partner, Wallenius Marine, is currently engaged in designing ship concepts that are wind powered, mainly car carriers. Selecting the type of propeller and understanding the consequences of various choices is crucial in the concept development. Therefore, Wallenius Marie was engaged in this project to get concrete knowledge that allows them to take informed decisions. The industrial partners together contributed with the necessary input to connect the work with the industry's standards and continuously participated in the evaluation of results.

At Chalmers, the work was carried out within a doctoral project which has mainly been financed through the Chalmers University of Technology Foundation's investment in wind propulsion in close collaboration with Kongsberg. The combination of partners has ensured both that the results are generally applicable and published according to scientific standards, and that the work is well-connected with the industry and provides concrete added value for the industrial partners.

2 Challenges during the blade design and optimisation of wind-assisted/powered vessels

The main difference between conventional and wind propulsion is that although the weather conditions are always unpredictable, for wind propulsion the power of the wind must be exploited. When designing vessels for conventional propulsion, we typically perform the propeller design work based on one design condition. With wind propulsion there is a broader range of operating conditions for the vessel and a wide load span for the propeller and the engine. Especially for wind-powered vessels, this span can be from 0 to 100% of the engine power. This affects several parts of the propeller design process, such as the:

- engine solution
- propeller type
- propeller operation during 100% sailing
- combination of propeller diameter and propeller speed
- control of cavitation in a broader range of conditions, including pressure side cavitation
- optimisation process, which becomes more complicated

A wrong choice of propeller may lead to a lack of thrust in rough conditions, jeopardising the safety of the vessel, or severe cavitation issues in lightly loaded conditions, with high levels of vibration as a result, or an unnecessary high fuel consumption when there is not enough wind. On a conventional vessel each of these issues might happen, but the wide range of conditions in the case of wind propulsion increases the risk for all to occur on the same vessel. More information about the challenges can be found in (Ref 1, 2). The challenges clearly showed that the propeller design and optimisation process of wind-powered/assisted vessels should be approached in a different way than in conventional propulsion. The operational profile plays a significant role in the design process, while new objectives for blade design optimisation must be considered. Overall, propellers for wind-propulsion are often lightly loaded and should operate well in off-design conditions (Ref 3).

3 Work process

Throughout the project, knowledge from all partners have been needed to understand the needs and the process forwards to meet the challenges. Wallenius has provided their input on the commercial aspects of designing and operating a wind-powered car carrier, and both SSPA and Kongsberg have experiences from working with customers on wind-assisted vessels. The ideas, tools, and processes developed were iterated with the industrial partners to make adjustments and improvements, both on the work within the project and for the respective commercial concepts within industry. The propeller blade design optimisation tools were implemented and evaluated together with Kongsberg within their design tools. Dissemination of results and tutorials for the tools have been offered within Kongsberg to promote the use of the tools in commercial work.

4 Methodology

4.1 Operational profile

It has been highlighted that due to the sail assistance, there is a wide propeller load variation, from very lightly to highly loaded propellers. For the blade design of such propellers, blade designers need to consider this variation at an early design stage.

A key input for the definition of the operational profile are route simulations, which are provided for the WASP vessel, often together with probability functions for the required delivered power, propeller revolutions, rudder-heel-leeway angles, and the thrust, with and without the sail assistance. From this information, the designer can decide which conditions will affect the blade design and the engine selection the most.

There are specific conditions, off-design or not, with high operating probability during the route and the designer should certainly consider them. At the same time, there are several off-design conditions that should be considered as well. For example, when the wind propulsion technology offers a significant amount of thrust to the vessel, even if the probability for this weather condition is low, the designer should check whether reducing the power considerably, would lead to reaching the engine's lower torque limits. In parallel, in high sea states, the upper torque limits should be checked as well (Ref 3). See examples in the case studies presented below.

4.2 Optimisation objectives and constraints

The objectives and constraints in blade design optimisation processes are usually related to efficiency, cavitation, pressure pulses and strength, among others. Most of these objectives are relevant in wind propulsion, but now there are several conditions that represent the operational profile with varying propeller loads, which affect the blade design work. All these conditions must be considered in the optimisation and therefore, the following two objectives are proposed for blade design optimisation within wind propulsion:

$$total\ energy\ consumption = \sum_{i=1}^{n} P_{Di} * t_i$$

where P_{Di} is the delivered power to the propeller for each condition i and t_i is the operating time for each condition.

When there is detailed engine information with specific fuel consumption available, it is possible to calculate the TFC, according to:

$$total\ fuel\ consumption = \sum_{i=1}^{n} P_{Di} * t_i * SFC_i$$

where SFC_i is the specific fuel consumption for each operating condition.

The objective in blade design optimisation for vessels within wind propulsion is therefore to minimise either the total energy consumption (TEC) or the total fuel consumption (TFC), so that all selected conditions of the operational profile are taken into consideration. A flowchart of the process is shown in Figure 1, where a number of operational conditions have been chosen, each condition is used both for a baseline design and as analysis conditions during optimisation, causing the complexity of the design process.

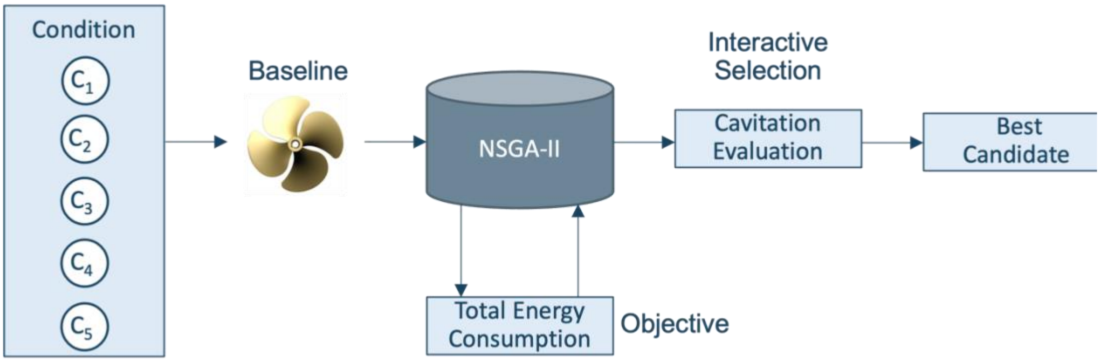

Figure 1 *Simplified flowchart of the design process developed.*

An important constraint in blade design optimisation problems within wind propulsion is related to cavitation. In lightly loaded conditions, there is high probability of having pressure side cavitation, and in middle and highly loaded suction side cavitation appears. This is the case also in conventional propulsion, but in wind propulsion there are more conditions for which the cavitation should be controlled. The final design should be such so that the cavitation is within the acceptable limits in all conditions (Ref 3). The cavitation constraints are difficult to formulate reliably in mathematical terms. In order to achieve that, cavitation is controlled by the blade designer during the optimisation with an interactive optimisation methodology, see Figure 2, which has previously been developed in associated projects and presented in (Ref 4). The benefit is that the blade designer influences the optimisation, guiding it (black arrows in Figure 2) towards good variants and thus yielding more feasible solutions.

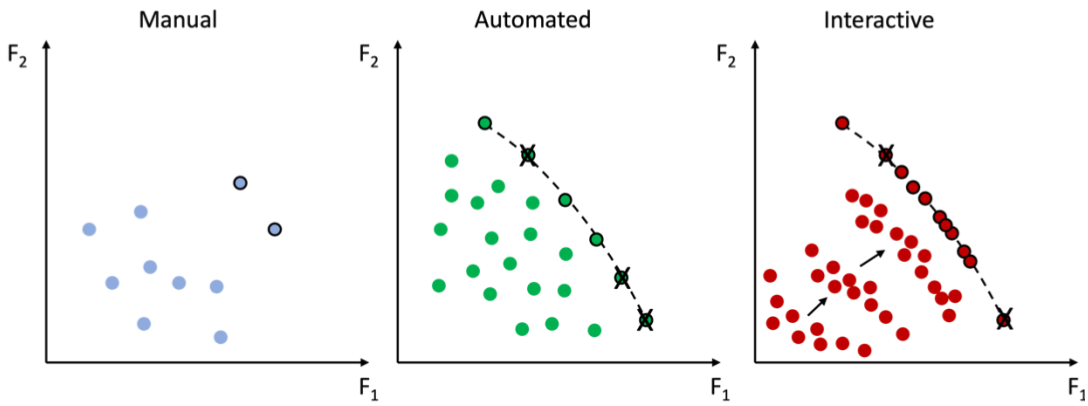

Figure 2*. The interactive optimisation mixes the manual and automated design approaches to yield high quality solutions with minimal user effort.*

5 Case Studies

Two case studies have been investigated in this project. The first study regards the KVLCC2 vessel, which has been retrofitted with six Flettner rotor sails and the design and optimisation of a fixed-pitch propeller (FPP) is investigated. The second case study regards a wind-powered car-carrier (wPCC), which is equipped with four rigid wing sails, and the design and optimisation of a controllable-pitch propeller (CPP) is investigated. Overall aim for both case studies has been to propose and describe a methodology for designing suitable propellers for wind-assisted/powered ships in order to cover the demanding operating needs of wind propulsion.

5.1 KVLCC2 vessel

The case study for the KVLCC2 (KRISO Very Large Crude carrier) vessel, along with the description of the methodology and the results have been published in (Ref 1), some of which are presented in this report. SSPA performed the route simulations for the KVLCC2 using a velocity prediction programme as outlined in (Ref 5) and the results have been provided and are the input to the blade design and optimisation methodology.

The KVLCC2 vessel has been investigated for the route Qingdao-Singapore-Qingdao, which is a typical route for a VLCC. The vessel was equipped with six rotor sails and the speed was kept at 15 kn. Specifically, from a commercial perspective, it was investigated whether the existing propeller was sufficient for the operating profile of the retrofitted KVLCC2 and in parallel it was examined whether a new propeller design could offer a significantly lower total energy consumption (TEC) or total fuel consumption (TFC) for the route compared to the existing propeller.

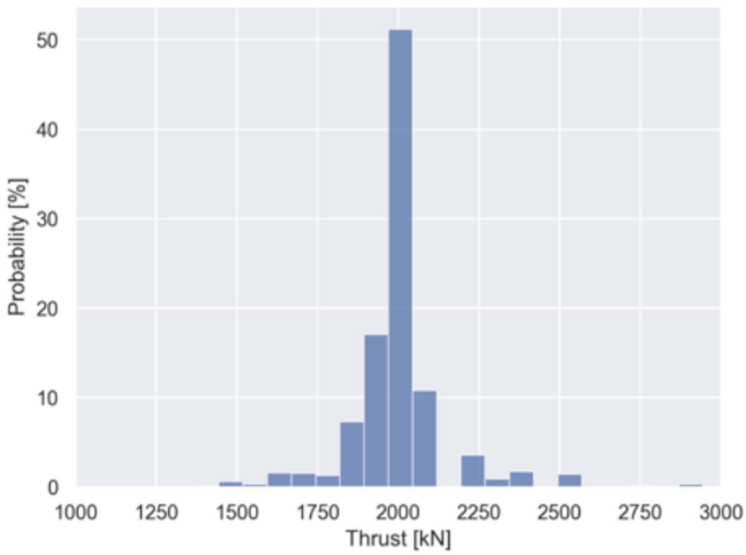

Figure 3. *Propeller thrust requirements for the KVLCC2 based on performance simulations for the route Qingdao-Singapore-Qingdao.*

As can be noted in Figure 3, the range of conditions encountered is wide, from about 1500 kN to almost 3000 kN in the extreme. For most of the time however, the vessel operates in a much more limited range. For this case, three conditions were chosen; a low one, a medium frequent one, and a high load condition.

From the route simulations, it was found that the sails lead to a reduction in fuel consumption of 9%. According to the blade design exercise, the optimal propeller design offered approximately further 0.9% reduction in TEC with the proposed methodology. This suggested that the existing propeller was sufficient, and a new propeller should not be retrofitted. Although the savings with propeller optimisation is not substantial, it is expected as the change in operation for the vessel is limited. If the potential customer had chosen to also reduce speed to make greater use of the wind, the propeller choice would have become more important.

Moreover, it was indeed possible to control the cavitation in all conditions through the interactive optimisation. No issues with cavitation appeared on the suction side of the blade, while no pressure side cavitation appeared at all, even at the most lightly loaded conditions.

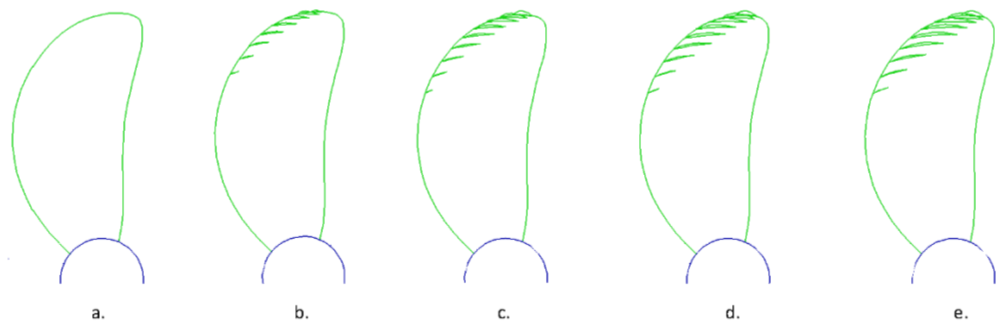

Figure 4. *Suction side cavitation at critical angle for five conditions.*

5.2 wPCC

The case study of the wPCC (wind-powered car carrier) vessel, along with the description of the methodology and the results have been published in (Ref 2), some of which are presented in this report. SSPA performed resistance and propulsion tests, load variation tests, CFD simulations at a matrix of drift and rudder angles, and route predictions and provided the results (Ref 6), which are the input needed for the blade design and optimisation methodology.

The specific case study is based on the Oceanbird research concept for a wPCC. The wPCC has a length of 200 m, the displacement is 30 000 tons, and the cargo is 7 000 cars. It follows a route between two fixed destinations (Southampton - New York) across the Atlantic Ocean in 12 days, for a constant speed of 10 knots. It is a twin-screw vessel with open shafts and brackets. The hull has specifically been optimised for sailing.

Since the specific vessel was wind-powered, the operational profile of the propeller was wide. 50% of the time the vessel was sailing, meaning that the engine and propulsion system did not operate. The remaining 50% of the time, five operating conditions were selected as the most important by the blade designers, with the thrust ranging between 50-390kN. These conditions were investigated for two different operational profiles, where each condition operated for a different amount of time in each operational profile.

Condition	% of time	Hours/year
1	9.8%	858
2	13.8%	1209
3	12.2%	1069
4	9.2%	806
5	5%	438

(a)

Condition	% of time	Hours/year
1	10.3%	902
2	15.5%	1358
3	12.2%	1069
4	7.5%	657
5	4.5%	394

(b)

Figure 5. *The five conditions for the two tested operational profiles for the wPCC.*

Given that the thrust from the propeller ranged from 0% to 100% of the required thrust (rest given by the sails), a part of the investigation was to look into the choice of a fixed pitch propeller (FPP) or a controllable pitch one (CPP). It became however early evident that a CPP is a natural choice, also requiring a large pitch range to operate in the most beneficial conditions. This also influences the engine choice, requiring very low shaft rotation rate to handle to low load conditions in a good.

For the 50% of the time that the vessel was fully sailing, the windmilling position of an FPP and a CPP, the feathering position of a CPP and the harvesting function of a CPP were investigated for two different ship speeds. The results showed that a feathering CPP offered the lowest drag over ship resistance compared to a windmilling FPP and CPP. Regarding the harvesting operation, it was demonstrated that the shaft losses affected the efficiency of the propeller significantly and should be considered early in the design process. These results were the outcome of open water model test data.

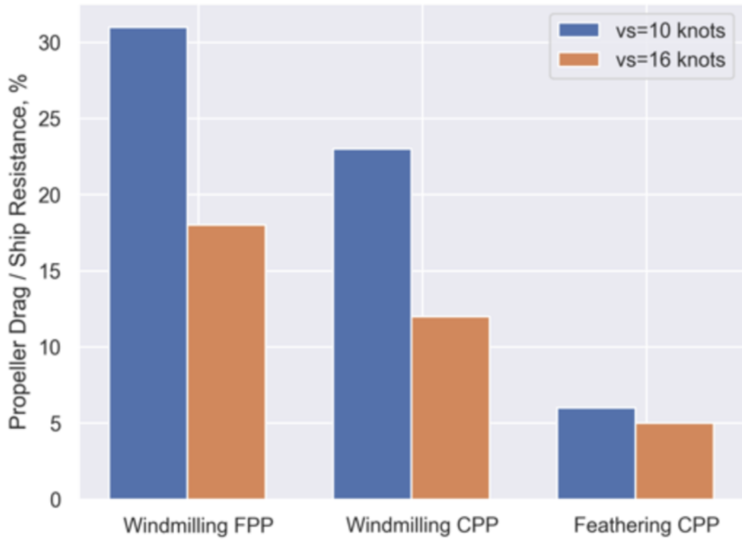

Figure 6. *Propeller drag over ship resistance in windmilling and feathering positions.*

Several optimisation runs were performed for the two operational profiles. The best design of operational profile 1 offered a 1.7% TEC reduction compared to the baseline (starting point of the optimisation) design of the optimisation, while the best design of operational profile 2 offered a 1.1% TEC reduction compared to the baseline.

Regarding the geometry of the optimal designs, they had decreased pitch values at 0.7R, high camber values at 0.7R and 0.95R and minimum chord length. Also, the optimisation runs that were carried out with wider limits in the design variables led to lower TEC, but the variable curves should be controlled by the designer so that the result is not infeasible geometries. This finding has triggered further studies at

Chalmers and Kongsberg looking into the design of a propeller with even lower blade area than the ones developed here, with the potential for significantly larger energy savings. This range of designs is well beyond the current understanding of design and evaluation tools, including model testing and ITTC-procedures for performance predictions.

It was expected that there would be cavitation issues in such a wide operational profile, but since the hull was specifically optimised for sailing, almost no cavitation was predicted during the entire operation.

6 Dissemination

The work has been publicly presented in the following ways:

Conference presentation:

- DNV Nordic Maritime University Workshop 2022 (30 March – 1 April 2022)
- PRADS 2022 (9-13 October 2022) Gypa I, Jansson M, Gustafsson R, Werner S, Bensow R, editors. *Propeller design procedure for a wind-assisted KVLCC2*. 15th International Symposium on Practical Design of Ships and Other Floating Structures; 2022; Dubrovnik, Croatia

Popular presentation

- Västerhavsveckan, August 11, 2022, Chalmers Lindholmen.

Journal article:

- Gypa I, Jansson M, Gustafsson R, Werner S, Bensow R. *Controllable-pitch propeller design process for a wind-powered car-carrier optimising for total energy consumption*. Ocean Engineering, Volume 269, 2023, https://doi.org/10.1016/j.oceaneng.2022.113426.
  Available as Open Access.

PhD thesis:

- Gypa, I, *Marine propeller optimisation tools for scenario-based design*. December 19, 2022. Chalmers. Available for download via https://research.chalmers.se/publication/533185

7 Concluding remarks

With the completion of this project, the challenges and needs of propeller selection, design and optimisation within wind propulsion have become clearer. It has been found that design for single point design for efficiency, commonly used in regular propulsion system design, is not appropriate but the range of operation needs to be considered. This leads to several aspects that need consideration for the industry: (i) The decision on how to operate the vessel needs to be developed together with the design of the propulsion system; (ii) The quality of the predictions of operational profile needs to be high to make the best design possible; (iii) A large number of design points needs to be evaluated in the blade design process, putting higher requirements on automated design tools.

Overall, the proposed methodology and developed tools proved to be straightforward and useful for both case studies and fulfilled the goals of propeller design in wind propulsion. The systematic approach to organise and automate the design process through the combined operating points has been shown to be useful (and necessary) for the industry, reducing the need for labour intensive work for the propeller design team. The objective of TEC guided the optimisation towards areas of the design space with improved performance over a wide range of operating conditions, further improving the quality of the final design as well as the process towards the delivered product.

The experiences from the case studies indicate that the operational choices may have larger influence on the ship design process than for conventional vessels. An example is the very low shaft rate that would be required in some conditions; if this is not attainable one may have to accept a lower speed in these conditions which again changes design specifications. For the decision support it is then clear that high quality route simulations are needed to determine the probability distribution of conditions for the vessels.

The results have been used at Wallenius Marine when building up the new process for ship concept development of wind ships in the following ways:

- The importance of using route studies in the design phase. This can now be requested from suppliers.
- When, and when not, it is useful to request wind propulsion to be considered in the propeller design.
- How to take better informed decisions when deciding propeller type, for example whether the propellers to have controllable or fixed pitch, and which consequences that will have.

At Kongsberg, the tools and procedures developed have been implemented in the Kongsberg design tools and are being put into use within the company.

8 References

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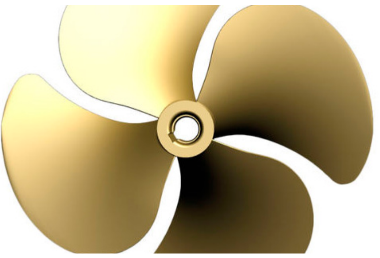
Lighthouse – for a competitive, sustainable and safe maritime sector with a good working environment



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