

QUANTIFICATION OF EFFICIENCY GAINS DUE TO CONTROLLABLE-PITCH PROPELLERS ON WIND-ASSISTED VESSELS

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ABSTRACT

Maritime regulations are driving innovative technologies to meet stricter environmental standards. In this context, the provision of decision support to ship owners and operators in their consideration of corresponding measures becomes important. Wind-assisted propulsion systems (WAPS) present a suitable solution to enable fuel consumption and emission reductions. Depending on the environmental conditions, commercial vessels equipped with WAPS rely on simultaneous utilization of WAPS and the ship propeller for operation. Conventional fixed-pitch propellers (FPP) are tailored to a specific design point. For a vessel with WAPS, the operation point of the propeller depends on the level of wind assistance, leading to off-design conditions and altered efficiency. Both FPP and controllable-pitch propellers (CPP) can be utilized to leverage this behaviour, however at this point the effect has not been quantified. Furthermore, the pairing of engine type and propeller is of great importance in the context of WAPS, as diesel engines can not easily be operated below a certain minimum power threshold. In this paper, a sailing bulk carrier vessel equipped with WAPS is investigated. Utilizing a set of voyage simulations, the impact of CPP / FPP usage, paired with a diesel or a diesel-electric engine, on propulsion efficiency is investigated. The ship behaviour is captured by means of discrete event equilibrium state calculations accounting for all relevant forces and moments. Voyage simulations are enabled by performing individual calculations along the route, while accounting for the respective environmental conditions. The results suggest that CPP enable overall efficiency gains in the range of up to 10 percent. The impact of engine type is more pronounced, resulting in an increase in energy demand of up to 30 percent for a diesel engine with respect to a diesel-electric configuration.

Keywords: wind-assisted propulsion, efficiency, controllable pitch propeller, route optimization, dynamic programming

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1. INTRODUCTION

Climate change presents a well known threat to the security and prosperity, as well as economic and social development, of the world. A major driving factor is greenhouse gas (GHG) emission. Human activities, namely the burning of fossil fuels for electricity, heat and transportation, are largely responsible for the increase in GHG in the atmosphere over the last 150 years [1]. In this context, waterborne transportation is undergoing a transformation towards defossilization, which enables the implementation of innovative technologies, among them wind-assisted propulsion systems (WAPS). While these technologies pose great opportunities, they are accompanied by challenging tasks regarding their design, assessment and integration on board.

WAPS make use of the wind to, partially or fully, supply the required thrust to propel a ship. Common systems include Flettner rotors, kites and (wing) sails in different variations [2]. If wind conditions are not favorable enough to enable sailing without support of the conventional propulsion system, the propeller will operate at off-design conditions. Depending on the design and maintenance state of hull and propeller, these off-design conditions can yield benefits or drawbacks regarding propeller and fuel efficiency. A typical open water efficiency curve of a fixed-pitch propeller (FPP) is given in Figure 3. In general, unloading the propeller will move the operation point on the curve to the right. This can either result in an efficiency increase if the new operation point is closer to the peak, or severely reduced efficiency if the new operation point is located beyond the peak, to the rightwards end of the curve. In this situation, controllable-pitch propellers (CPP) can enable efficiency gains that exceed those in a conventional vessel configuration.

Only few publications addressing the usage of FPP and CPP in the context of WAPS are available. The research groups around Molland [3] and Reche-Vilanova [4] have performed a corresponding analysis. Both aim for a preliminary study based on minimal input data, which accounts for the WAPS assistance by subtracting a flat percentage of the vessel calm water resistance, without taking into account induced resistance due to drift or the

actual weather conditions. While these assumptions present a sound approach for a preliminary analysis, an improved assessment can be achieved by using an advanced performance model that accounts for the system component specifications and additional effects, such as the drift angle, as well as taking into account realistic weather conditions. Furthermore, many studies, see e.g. [5–8], highlight the importance of weather routing when evaluating systems involving WAPS.

For route optimization, grid-based algorithms including the Dijkstra algorithm and the A* algorithm [9–13], as well as dynamic programming [14–16] are commonly employed. The A* algorithm employs a heuristic approach and is thus not guaranteed to identify the global optimum. Dynamic Programming is based on the optimality principle of Bellman [17] and divides the optimisation problem, in the context of route optimisation, into several sub-problems by separating the route into stages. The space of the sub-problems is limited by constraints and then, provided the constraints have been chosen sensibly, the global optimum is found by analysing all possible combinations.

In this paper, mean and actual weather conditions based on historical data are assessed for a defined transport task and in turn utilized for a preliminary as well as a detailed, space-time resolved analysis. The focus of the analysis lies on comparative simulations regarding the usage of FPP and CPP, paired with either a diesel engine or a diesel-electric engine. The investigations are carried out using the in-house Odyssa Framework (see e.g. [18]). For performance prediction, a steady state approach with 4 degrees of freedom (surge, drift, yaw and heel), which takes into account all relevant components, is employed. This encompasses hull, rudder, propeller, sails, as well as appendages. Route optimization is performed by means of a novel approach that combines Dynamic Programming and the Dijkstra algorithm, for which the required weather data is procured from the European Union's climate data store [19].

The paper is intended to present a suitable tool to support investment decisions regarding novel energy systems and operation strategies by enabling accurate prediction of energy demand with respect to different system configurations and transport tasks. The results show that consideration of the actual system specification and occurring environmental conditions is essential for carrying out a meaningful analysis.

2. EQUILIBRIUM STATE MODEL

A 4-DOF equilibrium state model is employed to determine the operation state of the vessel. Neglecting dynamic effects, balance equations (see Eqs. (1)–(4)) for surge, sway, roll and yaw are set up and solved on the basis of the ship specification as well as the environmental parameters. The ship specification consists of the required parameters to set up the individual models (see Tab. 1) for each component considered in the balance equations, as well as the ship speed through water. A detailed description of the ship specification is omitted for the sake of brevity. The required environmental parameters include true wind speed (TWA), angle between ship course and true wind, significant wave height, angle between ship course and mean wave direction, mean wave period, wave spectral peakedness, as well as wave spreading parameter.

$$\begin{aligned}\sum X &= 0 \\ &= X_{CW} + X_{AW} + X_D(\beta) + X_W + X_S + X_{WMP} \\ &\quad + X_R(\delta, X_T) + X_{CB}(\beta) - X_T\end{aligned}\quad (1)$$

$$\begin{aligned}\sum Y &= 0 \\ &= Y_D(\beta) + Y_W + Y_S + Y_R(\delta, X_T) + Y_{CB}(\beta)\end{aligned}\quad (2)$$

$$\begin{aligned}\sum N &= 0 \\ &= N_D(\beta) + N_W + N_S + N_R(\delta, X_T) + N_{CB}(\beta)\end{aligned}\quad (3)$$

$$\begin{aligned}\sum K &= 0 \\ &= K_D(\beta) + K_W + K_S + K_R(\delta, X_T) + K_{CB}(\beta) \\ &\quad - GM \Delta \sin(\Phi) g\end{aligned}\quad (4)$$

In the equations, X, Y, N, K indicate forces in surge direction, forces in sway direction, yaw moments and roll moments, respectively. The equation system is solved for the variables propulsive force (X_T), drift angle (β), rudder angle (δ) and roll angle (Φ). As evident from the equations, the most relevant interactions between free variables as well as the force and moment contributions are accounted for. This includes primary interactions, e.g. drift angle and drift forces, as well as the influence of the propeller operation state on the rudder forces. However, secondary interactions, such as the influence of heel angle on wind-induced forces on the hull, are neglected. All contributions to the force and moment balance equations, as well as the utilized models, are summarized in Table 1. Subscripts $CW, AW, D, W, S, R, CB, WMP$ refer to calm water, added wave, drift, wind, sail, rudder, centerboard and wind-milling propeller, respectively, while GM is the metacentric height, Δ is displacement and g refers to gravitational acceleration. Calm water resistance, wind-induced forces, rudder-induced forces, as well as the hydrostatic restoring roll moments are modelled by means of empirical approaches which are firmly established within the scientific community. For sail forces, a polynomial approximation based on model tests is employed. The sails are assumed as independent of each other. No interaction effects are accounted for. Added wave resistance is calculated by an advanced empirical model that accounts for wave directionality and an irregular sea state based on the underlying assumption of a JONSWAP spectrum. As corresponding empirical models tend to be error prone, drift forces are obtained from polynomial approximations of CFD calculation results. The force contribution due to the wind-milling propeller is only active in case the complete thrust is supplied via the sails, otherwise zero. It is calculated by an extrapolation of the propeller k_T curve to the advance coefficient at which $J(k_Q = 0)$. For CPP, the design pitch curve is utilized.

3. PROPELLER MODELLING

Propeller modelling is carried out based on the Wageningen B-Screw Series [26]. The series allows to obtain the open water curves of a propeller within the data basis for given values of blade number, blade area ratio, Reynolds Number and pitch ratio. The Reynolds Number is calculated based on the vessel state at

TABLE 1: FORCE AND MOMENT CONTRIBUTIONS, MODELLING APPROACHES IN EQUILIBRIUM CALCULATIONS

Variables	Description	Modelling Approach
X_{CW}	Hull calm water resistance	Empirical, Holtrop & Mennen [20]
X_{AW}	Hull added wave resistance	Empirical, Kim [21]
X_{WMP}	Resistance due to wind-milling propeller	Extrapolation of k_T from Wageningen Series to $J(k_Q = 0)$
X_D, Y_D, N_D, K_D	Drift-induced forces and moments on hull	Polynomial approximation from CFD calculations, Schmitz [22]
X_W, Y_W, N_W, K_W	Wind-induced forces and moments on hull	Empirical, Blendermann [23]
X_S, Y_S, N_S, K_S	Sail-induced forces and moments	Polynomial approximation from model tests, Bordogna et al. [24]
X_R, Y_R, N_R, K_R	Rudder-induced forces and moments	Empirical, Bertram [25]
$X_{CB}, Y_{CB}, N_{CB}, K_{CB}$	Centerboard-induced forces and moments	Empirical, Bertram [25]
$GM \Delta \sin(\Phi) g$	Hydrostatic restoring roll moment	Bertram [25]

design speed and, since the effect on the coefficient curves is minimal, not adjusted during calculations. For a given propeller specification, thrust coefficient k_T , torque coefficient k_Q and correspondingly open water efficiency η_O can be obtained by means of polynomials for the entire range of advance coefficients J associated with the first quadrant of propeller operation – see Eq. (5) for the respective parameter definitions:

$$J = \frac{v_A}{nD}, \quad k_T = \frac{T}{\rho n^2 D^4}, \quad k_Q = \frac{Q}{\rho n^2 D^5} \quad \text{and} \quad \eta_O = \frac{J k_T}{2\pi k_Q}. \quad (5)$$

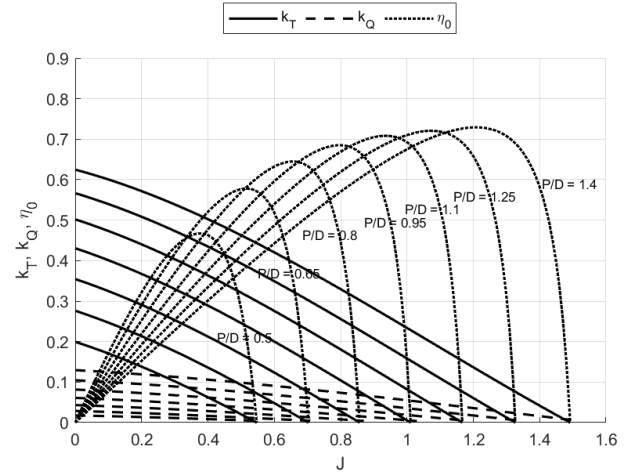
Herein, n is propeller rotation rate, D is the propeller diameter, ρ denotes the water density and T is the propeller open water thrust. The mean inflow velocity to the propeller in the propeller plane v_A is given by Eq. (6)

$$v_A = v_S (1 - w) \quad (6)$$

where v_S is the ship velocity and w is the wake fraction. A potential influence of oblique inflow to the propeller due to vessel drift is not taken into account. Figure 1 illustrates the open water curves for a Wageningen propeller at pitch ratios ranging from $P/D = 0.5$ to $P/D = 1.4$ in intervals of 0.15. Curves of thrust coefficient, torque coefficient and open water efficiency are given for all pitch ratios, while annotations have only been placed for the efficiency curves to preserve visual clarity.

In case of a FPP, only a single set of curves (k_T , k_Q , η_O) is considered. Based on a given required thrust, the advance coefficient that corresponds to the matching thrust coefficient is identified, which also gives the torque coefficient, thus yielding all relevant propeller operation parameters.

If a CPP is considered, the process is carried out for all permissible pitch ratios and the propeller pitch corresponding to the highest open water efficiency is chosen as the operation point. The identified open water efficiency is reduced by 1 % to account for the increased hub size for CPPs [27]. For the matching process, the range of pitch ratios is discretized in steps of 0.01. It should be noted that the described approach does not perfectly reflect conditions on an actual ship, since CPP are usually operated in a combinator mode, which relates rotation

**FIGURE 1: WAGENINGEN PROPELLER OPEN WATER CURVES AT MULTIPLE PITCH RATIOS**

rate and propeller pitch, or in a fixed mode, where rotation rate is fixed and propeller pitch is varied. Since combinator mode curves are not readily available, the current approach was pursued.

These control strategies are designed with respect to various criteria, such as engine limitations and propeller cavitation. Nevertheless, fuel efficiency is naturally also targeted and it is thus expected that the present approach mimics the actual behaviour to an acceptable degree. Occurrence of propeller cavitation as well as power demand due to operation of the hydraulic system of the CPP is not considered. Furthermore, the authors are aware that modern CPP display significantly altered shapes in comparison with the Wageningen B series. As this also holds true for FPP, it is expected that a comparative investigation still delivers meaningful results.

4. POWER PREDICTION

In order to set up Eqs. (1)–(4), the complete system specification, including the sail trim angle, needs to be given. At this

point, however, it is not known which sail trim angle is associated with the optimal vessel state, therefore requiring an optimization procedure. The optimization is realized as a sweep across all feasible trim angles. The sail trim angle for which the minimal power is calculated is chosen. If there is no solution to the equation system (e.g. because hull, rudder and appendages could not produce enough side forces to counteract the sails), or if the operation limits are exceeded, the power for the respective trim angle is set to positive infinity. This prevents consideration of the respective operating state in the routing algorithm, see Sect. 5. The operation limits are summarized in Tab. 2.

Among others, solution of the equation system detailed in Sect. 2 yields the required propulsive force X_T . If X_T equals zero, the required power is taken as zero. For all positive values of X_T , the required propeller open water thrust T follows from

$$T = \frac{X_T}{1 - t}, \quad (7)$$

with t as the thrust deduction factor. The corresponding torque is then calculated according to the considerations in Sect. 3, which enables

$$P_T = 2\pi Qn \quad (8)$$

as the power to be delivered to the propeller. Taking into account relative rotative efficiency η_R , shaft efficiency η_S and gear efficiency η_G delivers the engine brake power

$$P_B = \frac{P_T}{\eta_R \eta_S \eta_G}. \quad (9)$$

After power calculations, it is checked if they are within the operational limits of the system. For the present work, minimum and maximum RPM values, as well as maximum engine power need to be respected. For electric engines, no minimum threshold of power is imposed, while for diesel engines a minimum power of 10 % MCR is admissible. If system limits are violated, the power is taken as positive infinity. To minimize calculation times during routing, the power calculation results are made available to the routing algorithm through a matrix that holds the calculation results for all combinations of ship speed and environmental parameters.

5. ROUTING ALGORITHM

For routing purposes, a novel probabilistic roadmap based approach [28], which makes use of Dynamic Programming and the Dijkstra Algorithm, is employed. Schwedt et al. [28] provide an in-depth analysis on the impact of route optimization on WAPS vessels. In the algorithm, the spatial domain is discretized by a set of nodes and feasible connections between them. Furthermore, each node is augmented with a discrete time coordinate to account for the change in weather conditions along considered routes. The algorithm determines the cost optimal route with regard to space and time in the sense of overall consumed energy, while respecting a given maximum travel duration. In this case, the cost (energy) to traverse a connection is given by the respective travel time and the required power, with the power being obtained by means of interpolation within the matrix calculated according to the considerations in Sect. 4.

In theory, the defined problem could be solved solely through Dynamic Programming, which evaluates all possible connections within the given space, by assuming a discrete set of permissible velocities. In practice, this is prevented by the associated computational resources. Therefore, prior to employing Dynamic Programming, the problem space is limited by usage of the Dijkstra Algorithm. A forward shortest-path search is performed from start and goal node, assuming the maximum admissible speed of the vessel, yielding a time interval of feasible arrival times for each node. Only nodes with a feasible arrival time interval above a defined threshold are considered for further analysis. For the remaining nodes, this time interval is discretized and each combination of a spatial node and a discrete time instant is then treated as a vertex in a time-expanded graph. Each combination of spatial node and discrete time is considered as a vertex available for the routing algorithm.

6. CASE DESCRIPTION

For the present work, a modern sailing bulk carrier is considered, see Fig. 2. The vessel has originally been conceived in the



FIGURE 2: INVESTIGATED VESSEL

scope of a feasibility study for an energy self-sufficient system, see also Fitz et al. [18] for a summary of the approach and findings. Contrary to the configuration investigated by Fitz et al. [18], in this work the vessel is not equipped with hydrogenerators and is thus not capable of energy recuperation.

The ship is mainly propelled by four large Dynarig sails [29], which constitute the primary propulsion system of the ship. While wind-assisted propulsion is intended to serve as the main method of propulsion, the conventional propulsion system is designed to fully support maneuvering the ship in a safe and efficient manner at its design speed. The ship is equipped with a standard rudder. For the present investigations, a FPP as well as a CPP are considered. To balance the high side forces of the wind propulsors, the ship is equipped with a centerboard. The engine is assumed either as a diesel engine or a diesel-electric system, with both options being considered in the analysis. In case of the diesel engine, it is assumed that the system can not be operated below 10 % MCR while full sailing without propeller support is, of course, still

permissible. An overview of the system specification is given in Table 2.

TABLE 2: VESSEL MAIN SPECIFICATIONS

Component	Symbol	Description	Value
Hull	L	Length overall	130 m
	B	Beam	18.86 m
	T	Draft	7.9 m
	V_D	Design speed	10 kn
	V_{min}	Minimum speed	3 kn
	V_{max}	Maximum speed	18 kn
	Δ	Displacement	12 618 m ³
	C_B	Block coefficient	0.6627
	w	Wake fraction	0.13
	t	Thrust deduction factor	0.15
	η_R	Relative Rotative Efficiency	1
	GM	Metacentric height	1.116 m
Propeller	β_{max}	Maximum drift angle	10°
	Φ_{max}	Maximum heel angle	12°
	Z	Number of blades	4
	D	Diameter	4 m
FPP	A_E/A_0	Blade area ratio	0.7
	P/D	Pitch ratio	0.8
CPP	P/D	Pitch ratios	0.5...1.4
Rudder	A_R	Cross section area	21 m ²
	δ_{max}	Maximum rudder angle	20°
Sails	A_s	Sail area	1000 m ²
	N_s	Number of sails	4
Engine	n_{min}	Min. engine speed	20 rpm
	n_{max}	Max. engine speed	200 rpm
	MCR	Max. continuous rating	1.5 MW
	η_G	Gear Efficiency	0.99
	η_S	Shaft Efficiency	0.97

For routing calculations, the vessel is assumed to traverse the Atlantic Ocean from Lisbon to New York. A mean travel speed equal to the design speed of the vessel is imposed through the routing algorithm, while the minimum and maximum allowable travel speeds are given in Tab. 2. Routing start events are set daily at 12:00 for the first 345 days of the year 2019. Start events beyond this date would possibly lead to travels extending to the year 2020. As the analysis is limited to the year 2019, no start events are placed in the last 20 days of the year. Furthermore, start and goal nodes are situated in the ocean in close vicinity to the respective harbors. Thus, any port call activities and corre-

sponding operation states and power demands are excluded from the analysis. The shortest distance when traveling between start and goal node within the utilized roadmap equates to 5351.8 km.

7. PRELIMINARY ANALYSIS

Prior to calculations involving the routing algorithm, a preliminary analysis akin to the work that has been conducted by Reche-Vilanova et al. [4] is carried out. The operation state of both propeller types, FPP and CPP, as well as the corresponding engine brake power is obtained according to the considerations in Sect. 3 and Sect. 4. Here, the required thrust is obtained only accounting for calm water resistance and thrust deduction. No equilibrium calculations, see Sect. 2, are performed. Figure 3 presents the curves of propeller open water efficiency for the FPP with fixed pitch ratio of $P/D = 0.8$ and for the CPP. Along with

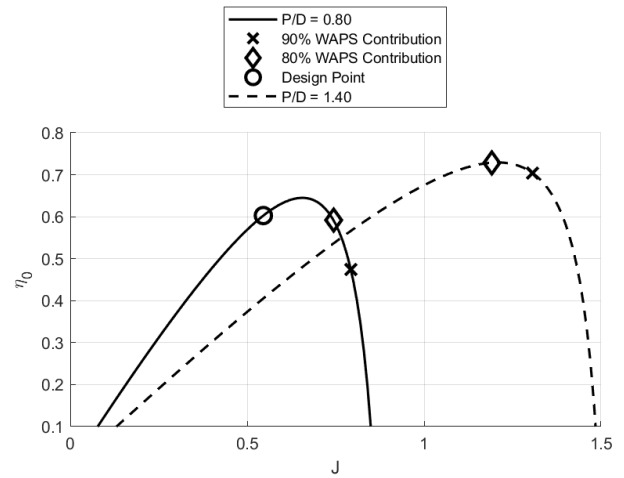
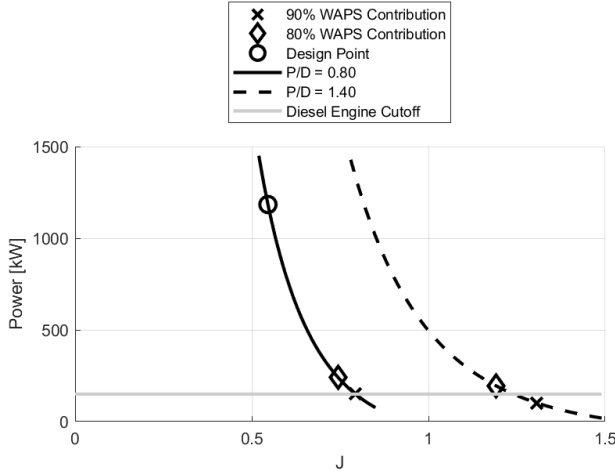


FIGURE 3: OPEN WATER EFFICIENCY AT DIFFERENT OPERATION POINTS

the efficiency curves, the resulting operation points for design point, 80 % WAPS contribution and 90 % WAPS contribution are shown. Here, a given WAPS contribution percentage is taken as a likewise reduction in ship resistance. For both WAPS contribution levels, it is found that the CPP operates optimally at a pitch ratio of $P/D = 1.4$ and thus only the corresponding efficiency curve is included in Fig. 3. For the design point, optimal open water efficiency is obtained at the base pitch ratio of the propeller, yielding the same operation point for FPP and CPP, with $\eta_0 \approx 0.6$. This value can be considered typical of a well designed propeller at vessel design speed. For the cases with WAPS contribution, the propeller is unloaded, thus moving the resulting operation points rightwards on the efficiency curves. A summary of the results is given in Table 3. In case of the FPP, this leads to reduced efficiency, while for the CPP, the open water efficiency assumes values of higher magnitude. This contrasts the results obtained by Reche-Vilanova et al. [4]. Due to a base propeller design for which the design point was located further away from the peak of the efficiency curve, a WAPS contribution of 80% still yielded efficiency gains in their work. This highlights the need for a differentiated analysis, taking into account the actual

TABLE 3: EFFICIENCY AND POWER

Case	η_O	P_B [kW]
Design, FPP	0.6	1184.07
Design, CPP	0.6	1184.07
80 % WAPS, FPP	0.59	241.23
80 % WAPS, CPP	0.72	195.87
90 % WAPS, FPP	0.473	150.69
90 % WAPS, CPP	0.7	99.74

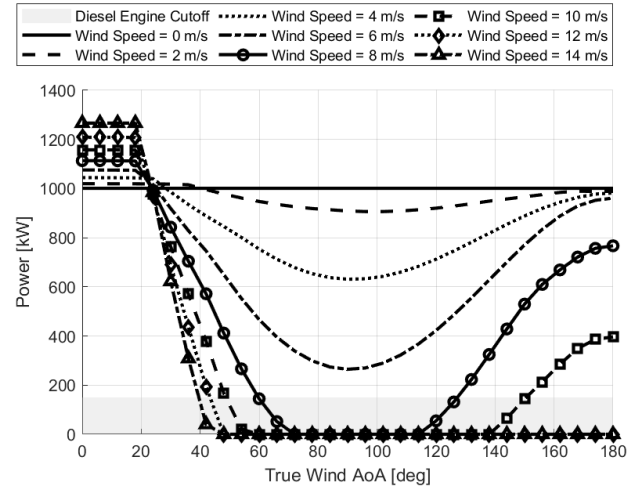
**FIGURE 4: ENGINE BRAKE POWER AT DIFFERENT OPERATION POINTS**

vessel and component specification. Comparing the open water efficiency of FPP and CPP in the cases with WAPS contribution suggests the potential for considerable savings due to usage of a CPP. However, since in these cases the propeller is unloaded to a large degree, actual power savings are small with respect to the power at design speed. Figure 4 shows the engine brake power over propeller advance coefficient, as well as the respective operation points, for the FPP and the CPP. Additionally, the minimum power (10 % MCR) for the investigated system configuration, in case a diesel engine is considered, is given. While a WAPS contribution level of 90 % is still permissible for the FPP configuration, the CPP would have to be operated at a sub-optimal pitch ratio to comply with engine limitations. It should be noted that these sub-optimal operation states are not included in this work and corresponding operation states are disregarded. In practice, a ship with a diesel engine would be required to either increase speed until engine power is above the threshold or decrease speed until sail only operation is possible.

8. DETAILED ANALYSIS

In the following, results are obtained under consideration of all deliberations in Sect. 2 – Sect. 5. Power prediction is performed taking into account the equilibrium state of the vessel as well as corresponding effects, such as additional resistance due to vessel drift.

At this point it is not clear to what extent the limitations

**FIGURE 5: REQUIRED POWER OVER TWA AT DESIGN SPEED**

associated with a diesel engine affect vessel operation. As the ship was designed aiming at usage of the sails as the main means of propulsion, it is expected that high WAPS contribution levels commonly occur. The engine brake power at design speed, plotted against true wind angle of attack relative to the course of the vessel, is given in Fig. 5 for multiple wind speeds at calm water conditions. Here, an angle of attack of zero relates to frontal winds. At small angles of attack, the sails can not be utilized and the conventional propulsion system needs to be utilized. The reason for the variation in engine brake power at the respective wind speeds lies in the vessel superstructure wind resistance. For moderate angles of attack, sail assistance is possible. Naturally, the magnitude of required engine power depends on the wind speed. If wind speeds above 6 m s^{-1} are considered, sail only propulsion is enabled. Here, the wind speed governs the width of the angle of attack range for which no engine support is needed. Figure 5 also displays the area a diesel engine could not be operated in, colored in grey. As the minimum power limitations will affect permissible vessel operation ranges for all wind speeds above 6 m s^{-1} for certain wind angles of attack, a considerable effect on energy demand is expected.

A plot of all the route trajectories obtained by route optimization of the routing events is given in Fig. 6. The trajectories cover a considerable part of the Atlantic Ocean, highlighting the need to diverge from the shortest distance route to fully exploit the potential of WAPS. The figure also reveals current shortcomings of the routing algorithm. At present, the algorithm does not take into account ice, safety considerations or otherwise restricted areas. As a result, some routes traverse the waters close to Newfoundland, which might not be safely operable during winter. A box-and-whisker plot of overall consumed energy during all routing events is displayed in Fig. 7. It shows the respective values for CPP and FPP in case of a diesel-electric engine as well as for a diesel engine, but is augmented by the data mean values, see black dots. The results are within the expected range. In theory, the vessel could traverse the route exclusively utilizing propulsion via the sails, leading to zero consumed energy, which

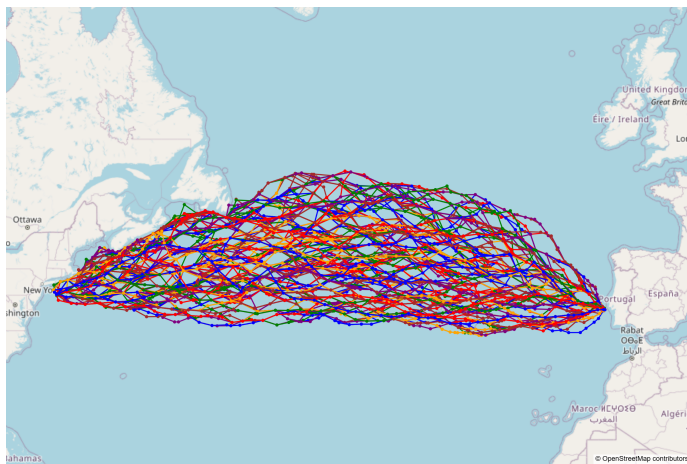


FIGURE 6: TRAJECTORIES OF ALL ROUTING EVENTS

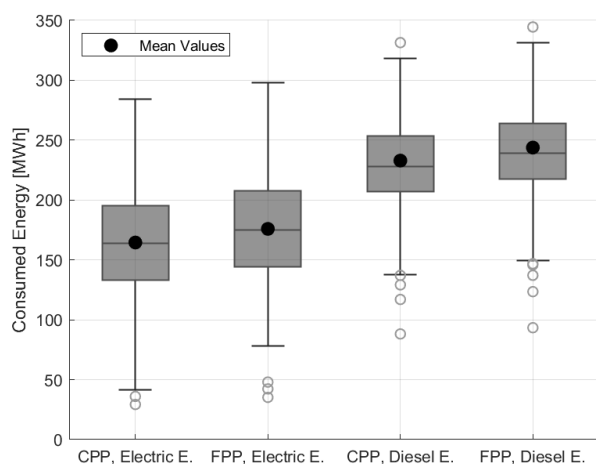


FIGURE 7: CONSUMED ENERGY FOR ROUTING SIMULATIONS

does not occur here. An upper limit for consumed energy is given by the engine MCR and the maximum allowed travel time, yielding 433.46 MW h. The present outliers are located below this limit. For both engine types, usage of a CPP does enable energy savings with a difference in mean and median values of approximately 11 MW h, yielding savings of about 6 % and 4.5 % for diesel-electric and diesel engine, respectively, each taken with respect to the energy demand of the FPP. As these values are in line with savings reported for conventional ships [30], the results suggest that installation of a CPP does not enable considerably larger savings on heavily wind-assisted vessels. Comparing mean and median values of both engine types, it is apparent that utilization of a diesel-electric engine enables significant energy savings, yielding savings of about 28 % and 26 % for CPP and FPP, respectively. The interquartile range is similar for both propeller types, but, in comparison with the diesel-electric engine, smaller for the diesel engine. This reflects the reduced availability of operation states for the diesel engine. Outliers are primarily found with regard to minimum energy consumed and correspond to routing events with highly favorable wind conditions. The diesel engine

seems to prevent full utilization of these, with outliers assuming values of higher energy demand with respect to the electrified system.

9. SUMMARY AND CONCLUSION

In this work, a methodology to assess efficiency gains on wind-assisted vessels is presented. Different configurations, namely FPP and CPP propellers paired with either a diesel-electric or a diesel engine, were investigated. A preliminary analysis revealed that CPP enable a potential for considerable relative gains in open water efficiency and power demand, however, absolute savings are small with respect to the power demand without sail assistance at design speed. Furthermore, comparison with the work of Reche-Vilanova [4] suggested that FPPs, designed with utilization in the context of a WAPS in mind, might be able to leverage efficiency gains up to large levels of WAPS contribution.

For the routing analysis, a sailing bulk carrier was considered on a route from Lisboa to New York. For each setup, a 4-DOF equilibrium state model accounting for the relevant components and effects was set up and utilized to calculate the matrix holding the ship response with respect to all feasible combinations of environmental conditions. The matrix was supplied to a routing algorithm based on Dynamic Programming and the Dijkstra Algorithm to identify energy-optimal routes for the defined transport task. While utilization of a CPP did not enable savings for the WAPS vessel beyond those expected for a conventional system configuration, taking into account the minimum power limitations of a diesel engine severely affected overall energy demand. However, these findings mainly pertain to WAPS vessel new-builds for which high levels ($\geq 80\%$) of WAPS contribution can be expected. In case of retrofits, a diminished influence is anticipated although this naturally also depends on the installed engine MCR and the corresponding minimum power.

The results indicate that full or partial electrification of the propulsion system is highly beneficial for wind-assisted vessels. Further research might investigate installation of a power take-off (PTO) / power take-in (PTI) system with a battery to alleviate shortcomings of diesel engine.

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