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Isolated Consideration of Influence Factors in Open Water Tests of Podded Propulsion Systems

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ABSTRACT
In order to improve the power prediction and propeller design aspects of a podded propulsion system an extensive model test series with four propellers in two scales has been conducted at Potsdam Model Basin (SVA). To isolate the interaction effects between elements of a podded propulsion unit, a range of test setups have been developed including different alternative systems as well as model scale pod units. For all setups, open water tests have been executed. By comparing the results regarding the different setups, interaction coefficients could be determined to describe the influence, isolated parts of the propulsion unit have. The interaction coefficients are calculated analogue to propulsion coefficients in a self-propulsion test. Outcome of this series of model tests is a deeper insight of the effect that especially the shape of the aft fairing can have on the propeller characteristics, causing significant differences. For propeller design purposes of podded drives the knowledge of the interaction between propeller and pod can increase the certainty of the design process significantly. For powering and speed, the prediction of forces acting on the pod housing and the boss cap need to be considered.

Keywords
pod; propeller; model test; open water; propulsion; experiment; pod interaction; geosim

1 INTRODUCTION

Podded propulsion systems are regarded as a useful combination of propeller and rudder. They are commonly used for ships, which require high maneuverability combined with good propulsion efficiency such as cruise ships, ferries or research vessels. Due to the combination of propeller and rudder with a pod gondola, podded propulsion systems lead to a more complex system than a classical propeller-rudder arrangement. The pod strut and pod gondola interact with the propeller and influence the propulsion characteristics in different matters. To determine the propulsion characteristics of a podded propulsion system model scale experiments are customary performed.

In previous research projects different aspects of podded propulsion have been investigated, at SVA by Heinke(2001)/ Heinke(2004) and other research institutes, such as the pod efficiency by Mewis(2001), open water characteristics by Richards et.al.(2011) or gap effects by Islam et. al.(2007).

Model scale experiments and extrapolation of ship hydrodynamics are typically performed following the procedures of the International Towing Tank Conference (ITTC). For podded propulsion systems, the ITTC procedure is marked with the following concern: ‘This Procedure describes the best possible methodology based on information currently available. However, users should be aware that a clear scaling procedure has not yet been developed due to the lack of model-scale and full-scale supporting data in the public domain. The Procedure may be changed when such data becomes available’ (ITTC2017). In order to predict the correct behavior of a podded propulsion system by extrapolating model scale experiment results, a full understanding of the interaction between the components of the system is necessary. For this reason, SVA has conducted an extensive series of model scale experiments for two scales with different setups to isolate interaction effects between hub, propeller, gondola and shaft. Based on these results a procedure has been developed to consider the effects of a podded propulsion system in the design process of the propeller and the performance prediction of the propulsion unit.

2 MATERIALS AND METHODS

2.1 Model test setups

A variable model test setup has been developed, where the standard open water test of a propeller can be modified by varying the shapes of the forward cap, propeller hub, and the aft fairing. The different setups were designed for the Kempf & Remmers open water propeller dynamometer H39. Additional to the alternative setups, a podded drive test setup was used with a z-drive and a measuring shaft to measure the propeller thrust and torque in the propeller hub. This setup was connected to a six-component balance to determine the unit forces and moments. In all setups, the propeller is used in a pull condition. The different model test setups are shown in Figure 1.


(a) original open water test | (b) increased cylindrical hub diameter


(c) conical hub with fixed aft fairing | (d) conical hub with rotating aft fairing


(e) conical hub with gondola aft fairing | (f) pod unit open water test setup

Figure 1. Model test setups

Configuration (a) displays the baseline open water test setup used to measure the isolated open water propeller characteristics. In (b) the cylindrical hub diameter is increased in order to meet the hub ratio of a common podded drive propeller. The inflow cap and aft fairings are designed according to the ITTC Guidelines for open waters tests (ITTC2002). Setup (c) represents the geometrically correct conical hub shape of the propeller for the podded drive unit with a fixed aft fairing. Assembly (d) uses also the geometrically correct hub shape but with a rotating aft fairing as recommended by the ITTC(2017). Configuration (e) represents the alternative system consisting of the propeller with the correct hub shape and a gondola shaped, fixed fairing without a strut. Picture (f) shows the geometrically correct podded propulsion test setup where thrust and torque are measured in the propeller hub and the propeller is driven by a z-drive. The whole unit is connected to a six-component balance to measure the unit forces and moment separately.

All setups were mounted to the towing carriage of SVA Potsdam to perform open water tests in the 280 m towing tank

2.3. Model propellers and pod unit

The propellers and the pod housing were developed by SVA Potsdam. The propellers were designed for a thrust coefficient of $K_T^* = 0.184$, which is available at an advance coefficient of about $J^* = 0.85$. The propeller designs with 4 and 5 blades are designed as pull propellers at the pod housing. The geometry of the hub can be adapted to the propeller arrangement by special cone caps. In order to investigate scale effects the propellers were manufactured in two scales. Due to its size the model propellers VP1901 and VP1903 cannot be tested with the pod unit setup shown in Figure 1.(f). Table 1 presents the main data of the propellers.

Table 1. Propeller main data

		VP1900	VP1901	VP1902	VP1903
D	[m]	0.22	0.33	0.22	0.33
$P_{0.7}/D$	[-]	1.144	1.144	1.113	1.113
P_{mean}/D	[-]	1.1138	1.1138	1.0842	1.0842
A_E/A_0	[-]	0.8105	0.8105	0.8109	0.81094
$C_{0.7}$	[m]	0.1002	0.1503	0.0802	0.12033
d_h/D	[-]	0.2545	0.2545	0.2545	0.25455
Skew Θ_S	[°]	24.218	24.218	24.332	24.332
z	[-]	4	4	5	5
Direction of rotation		right-handed			

The geometry of the pod housing is kept simple due to adaptability. The strut is modeled with a NACA-profile. The gondola is an axial symmetric body with the maximum diameter at half of the gondola length. The steering axis of the podded drive lies in the middle of strut and gondola.

2.3. Open water tests

To investigate the effects of the different setups, an extensive series of open water model tests has been conducted in the towing tank of SVA Potsdam. These tests were performed according to the standard procedure of the ITTC(2002) at a constant rate of revolutions. In order to determine Reynolds number effects, every setup was investigated at different revolution rates (5, 10, 15, 20, 25 s^{-1}). The results are expressed by non-dimensional coefficients defined as follows:

Advance coefficient
$$J = \frac{v}{n \cdot D} \tag{1}$$

Propeller thrust coefficient
$$K_{TP} = \frac{T_P}{\rho n^2 D^4} \tag{2}$$

Longitudinal force coefficient
$$K_{TX} = \frac{T_X}{\rho n^2 D^4} \tag{3}$$

Thrust coefficient of the pod housing
$$K_{TPod} = \frac{T_P - T_X}{\rho n^2 D^4} \tag{4}$$

Propeller torque coefficient
$$K_Q = \frac{Q}{\rho n^2 D^5} \tag{5}$$

Propeller efficiency
$$\eta_P = \frac{J}{2\pi} \cdot \frac{K_{TP}}{K_Q} \tag{6}$$

Efficiency in x-direction
$$\eta_X = \frac{J}{2\pi} \cdot \frac{K_{TX}}{K_Q} \tag{7}$$

To determine the hub effects on torque and thrust for all open water tests, idle measurements were carried out with a dummy hub without blades. The idle torque measurements involve all rate of revolutions and all advance coefficients (J = 0 to K_T = 0), including the measurement of the longitudinal force on the hub. Idle torque measurements with forward velocity and the use of the measured torque and thrust, guarantees the isolation of the blade forces in standard open water tests. Since the whole podded propulsion system is considered as one unit, the approach to separate the blades from the hub is questionable in the case of a podded drive. The hub forces are part of the forces acting on the final propulsion system and followingly the pod unit tests are usually considered with a standing idle measurement without the correction of the thrust. To isolate the influence of the hub in connection with a thruster housing as well as to compare to a classical open water setup (Figure 1 (a)), all setups are corrected with standing idle torque measurements with J = 0 and with measurements with forward velocity. Therefore, the effect of pressure forces on the hubcap can be determined and analyzed.

2.4 Results, analysis, method

The comparison of the different model test setups was enabled by using an approach similar to the power prediction method combining open water, resistance and self-propulsion test. This present approach is a modified version of the determination of interaction coefficients on podded propulsion systems introduced by Schulze(1999).

Here the open water configuration shown in Figure 1.(a) contributes as baseline open water test and all variations are handled analogue to self-propulsion test to be compared by thrust identity. With this approach, variations between the different model test setups can be expressed by non-dimensional interaction coefficients equivalent to the ones used to describe the interaction between ship and propeller. The basic assumption for this analysis method is thrust identity between the baseline open water test and the variation.

$$K_{T\mathrm{O}} = K_{TT} \tag{8}$$

Based on that assumption the change in design point can be described as shift of the advance ratio J, which leads to a setup induced wake fraction.

$$w_T = 1 - \frac{J_T n D}{v_a} \tag{9}$$

By comparing the torque coefficients between the baseline setup and the adapted setups, a relative rotative efficiency is calculated.

$$\eta_{\mathrm{R}T} = \frac{K_{QT}}{K_Q} \tag{10}$$

These coefficients enable a non-dimensional comparison of the effects acting on the different model test setups. By knowing the different influence factors of the different alternative systems, the propeller behavior can be estimated more accurately. Especially, if there is no stock propeller propulsion test known, meeting the desired design point in propeller design for podded propulsion units can be an issue when the effects of shaft and gondola are unknown.

By considering the shift in advance coefficients due to shaft and gondola with a wake fraction number as described in equation (9) the design advance coefficient for the propeller in open water condition can be estimated as follows:

$$J_{\mathrm{O}} = \frac{J_T}{(1 - w_T)} \tag{11}$$

3. RESULTS AND DISCUSSION

The results are divided in 4 sections to discuss the effects of the different influence factors separately. The shown open water curves are representing propeller VP1900 at a relatively high revolution rate of 20 s^{-1} to minimize Reynolds number effects. The characteristics are similar for all investigated propellers.

3.1 Pod unit boss cap effects

The open water curves of the pod unit shown in Figure 2 are corrected with two different idle measurements.
For the orange curves, the idle measurement with forward velocity is used for correction, to isolate the propeller blade thrust (excluding the forces acting on the thruster housing) and to eliminate the forces acting on the boss cap. Model tests, corrected like this and carried out with an open water dynamometer (such as H39 by Kempf & Remmers) are classical open water tests and are declared accordingly in this paper. This approach is used in order to compare the isolated propeller characteristics in respect to the alternative systems (a) – (e).

The blue curves are corrected differently. For an estimation of the propeller operating at the pod, the pressure forces appearing at the hub need to be included by using the standing idle torque measurement without idle thrust as for example in Figure 5. Model tests with a standing idle correction and a thruster configuration (with z-drive) are usually also mentioned as open water tests, since they test a propulsion unit without wake field (open water) and can be used to evaluate self-propulsion tests. But they differ to the above mentioned open water tests significantly by the fact that the propeller thrust is evaluated with the hub forces, contrary to considering only the forces on the blades. For a better understanding, in this paper such tests are declared as podded propulsion system tests.

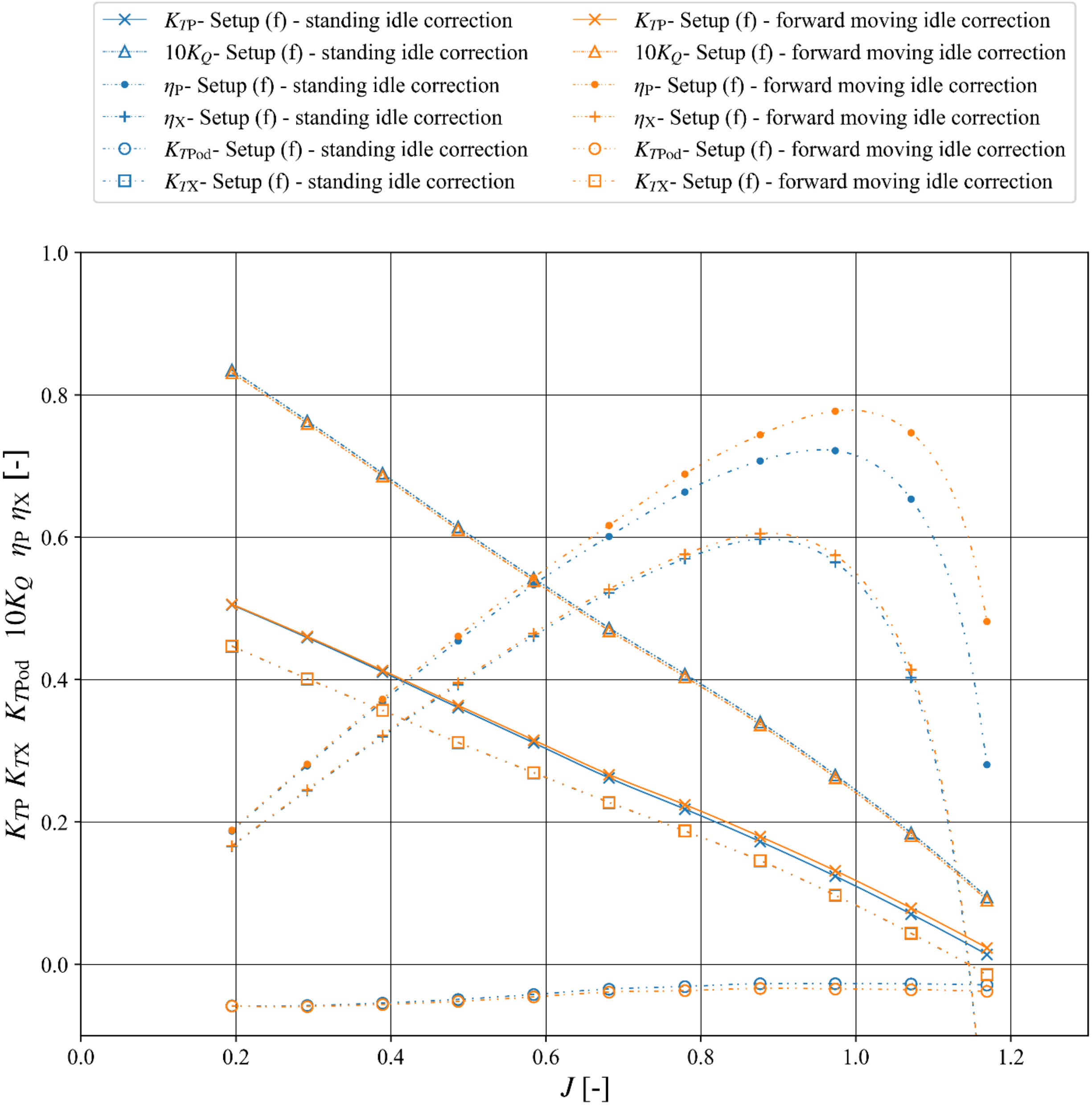

Figure 2. Effect of standing hub correction and forward moving hub correction

As displayed in Figure 2, the boss cap correction has a significant influence on the propeller thrust but almost negligible influence on the torque. The total system thrust is not influenced by the boss cap correction. Open water curves for comparing a propeller in open water condition with a propeller working at a pod unit (comparing only the forces on the blades) have to be corrected by the hub forces and moments from the idle measurements with $J > 0$. To get the correct load sharing between propeller and thruster housing, an idle correction only for the moments (standing idle torque measurement) is necessary.

3.2 Influences of different alternative setups

In the first step, the different alternative setups on the open water dynamometer H39, simulating different effects of the characteristics of a podded propulsion system, were investigated. The resulting open water curves for the different setups, described in chapter 2.2, are shown in Figure 3.

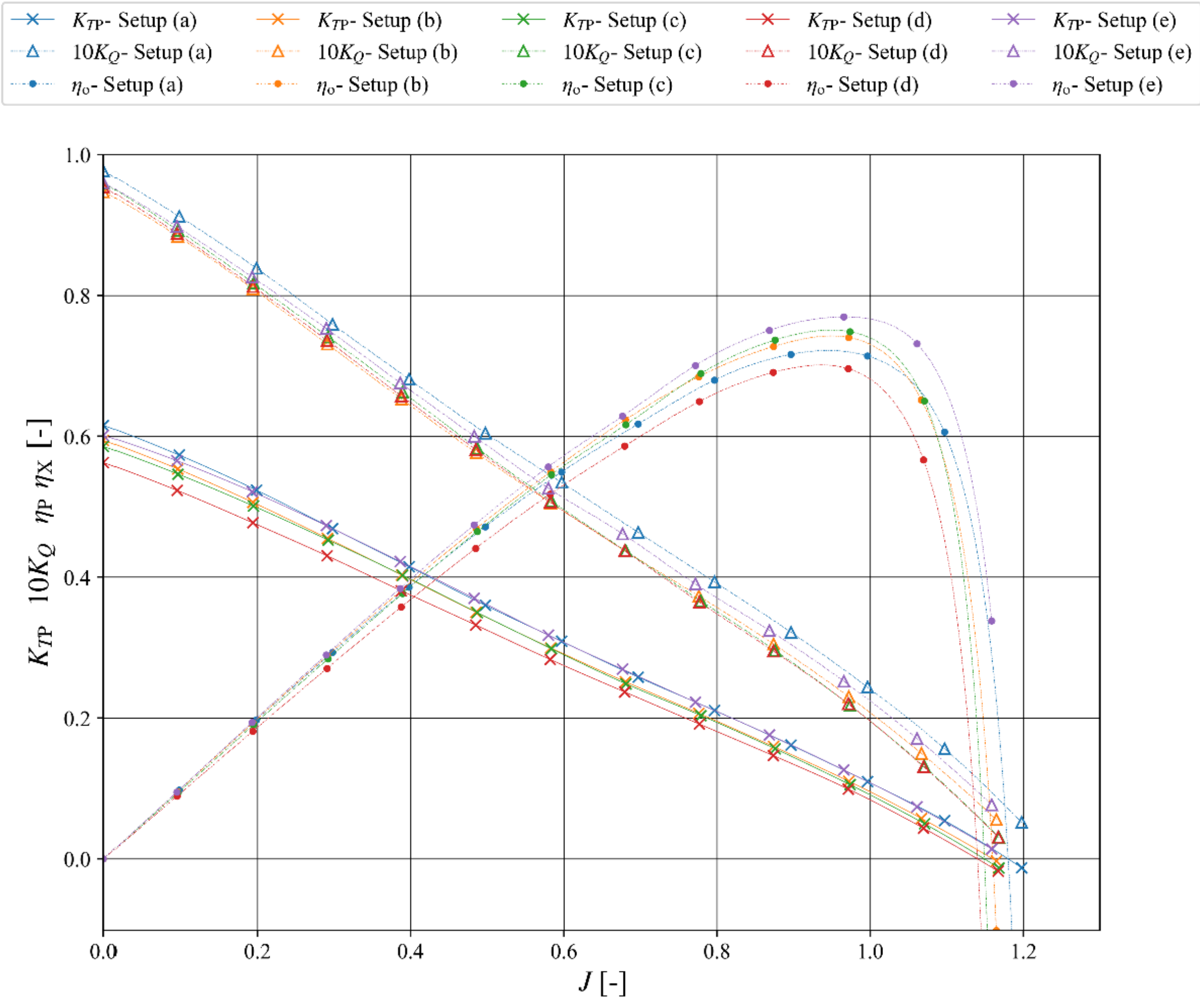

Figure 3. Open water curves of different alternative setups on open water dynamometer H39

As displayed in Figure 3 the baseline setup for a standard open water test tends to have the highest thrust and torque. The increased hub diameters of the cylindrical and conical setups (b) and (c) show a relatively similar behavior, which is accountable by the similar, but in respect to (a) increased hub diameter, while the effect of the conical shape seems to be relatively small in this case. The larger hub diameter increases the adjacent velocity, which results effectively in an increase of J and at the same time a reduced blade area, which both leads to lower thrust at the same inflow speed. The rotating aft fairing, as it is recommended by the ITTC(2017), setup (d), shows significantly less thrust than the setups (b) and (c) with a similar amount of torque, leading to a smaller efficiency. This behavior can be explained by the attachment of the aft fairing directly to the propeller hub. Forces on the fairing are here included in the measurement. The working propeller hardly influences torque effects on the aft fairing so that the rotational influence on torque is corrected by the idle measurement correctly. In contrast to the torque, the thrust forces on the aft faring are strongly influenced by the effects of the working propeller. Due to higher velocities in the propeller jet and the conical aft shape, a high speed and low pressure zone on the surface of the aft fairing occurs due to the equation of continuity as well as momentum conservation, which causes additional suction forces on the fairing.

Since the fairing is connected to the propeller, the additional forces on the fairing are included in the thrust measurement and cannot be corrected with the idle measurements, which explains the lower thrust of this setup.

Setup (e) with the gondola shaped, fixed aft fairing shows an opposite behavior. Thrust and torque are higher compared ot the other setups with similar hub ratio. This can be explained by the shape of the fairing, which increases the diameter of the propeller jet stream and thus reduced the jet velocity and therefore increasing the thrust. Torque is less affected by this phenomenon, so the pure propeller efficiency is higher with a gondola shaped aft fairing. Nevertheless, the forces acting on the gondola are not included in this measurement, so the total efficiency can be much lower. The effects of forces on the whole unit are discussed below.

3.3 Comparison alternative setups with pod unit

The results of the alternative setups, displayed in Figure 1.(a)-(e), are compared with the complete unit, shown in Figure 1.(f). The results of the different open water tests are presented in Figure 4, where only the propeller blade thrust, the propeller efficiency (excluding the pod and hub forces) and the torque curves of the pod setup (f) are outlined in brown. The propeller thrust is corrected with the idle measurement with forward velocity. Thus, the propeller thrust represents only the propeller blades at the pod housing. This unusual approach (see chapter 3.1) is used at this point to be able to compare the propeller blade behavior with the open water setups (a) – (e).

As featured in Figure 4 the propeller of the podded propulsion unit shows the most similarities to the alternative system with the gondola shaped aft fairing. Additionally, the effects of the shaft can be experienced by a slight advance coefficient shift, leading to an even higher propeller (excluding the forces on the thruster housing) efficiency.

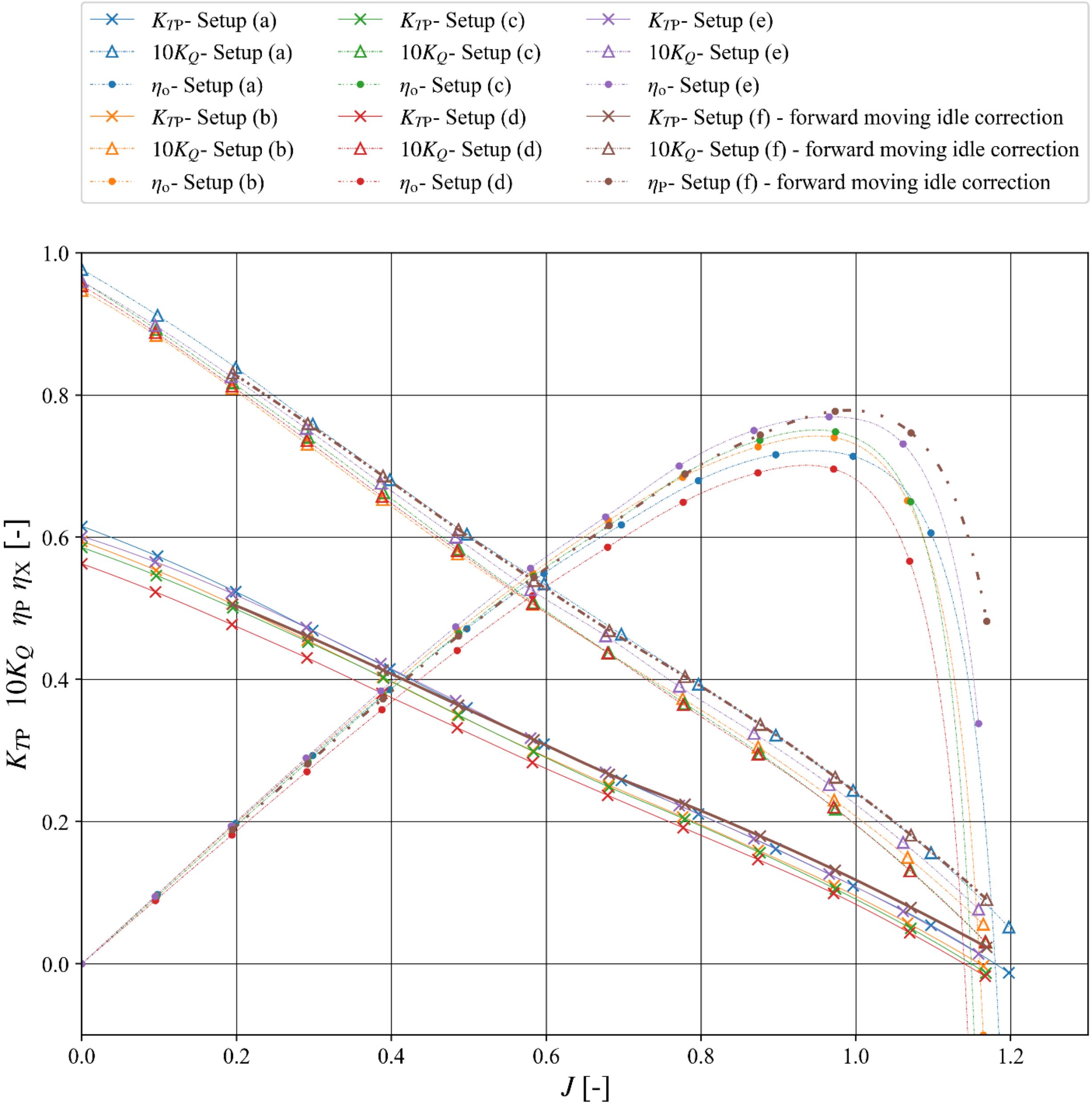

Figure 4. Open water curves of podded propulsion (f) unit and alternative systems (a) – (e)

Additional to the pure propeller behavior for the podded propulsion unit setup, the forces acting on the pod can be measured separately. Subsequently, the general efficiency and performance of the pod unit shall be compared to the open water behavior of the setups (a) – (e). According to chapter 3.1, here standing idle torque measurements without the use of the measured idle thrust must be used for the correction of the pod unit. In the following diagram (Figure 5) next to the open water curves of setup (a) – (e), the total efficiency of the podded propulsion unit, the resistance of the pod housing and the total thrust, the propeller thrust as well as torque of the podded propulsion unit are plotted.

By evaluating the forces acting on the pod, it is illustrated that the pod thrust coefficient K_{TPod} is constantly negative, resulting in a thrust reduction for the complete system, whose total thrust coefficient results in K_{TX}. This indicates that for propulsion prognoses, the whole podded propulsion system including the thruster housing and the correct idle torque correction have to be taken into account to evaluate correct propulsion coefficients from self-propulsion tests with such units.

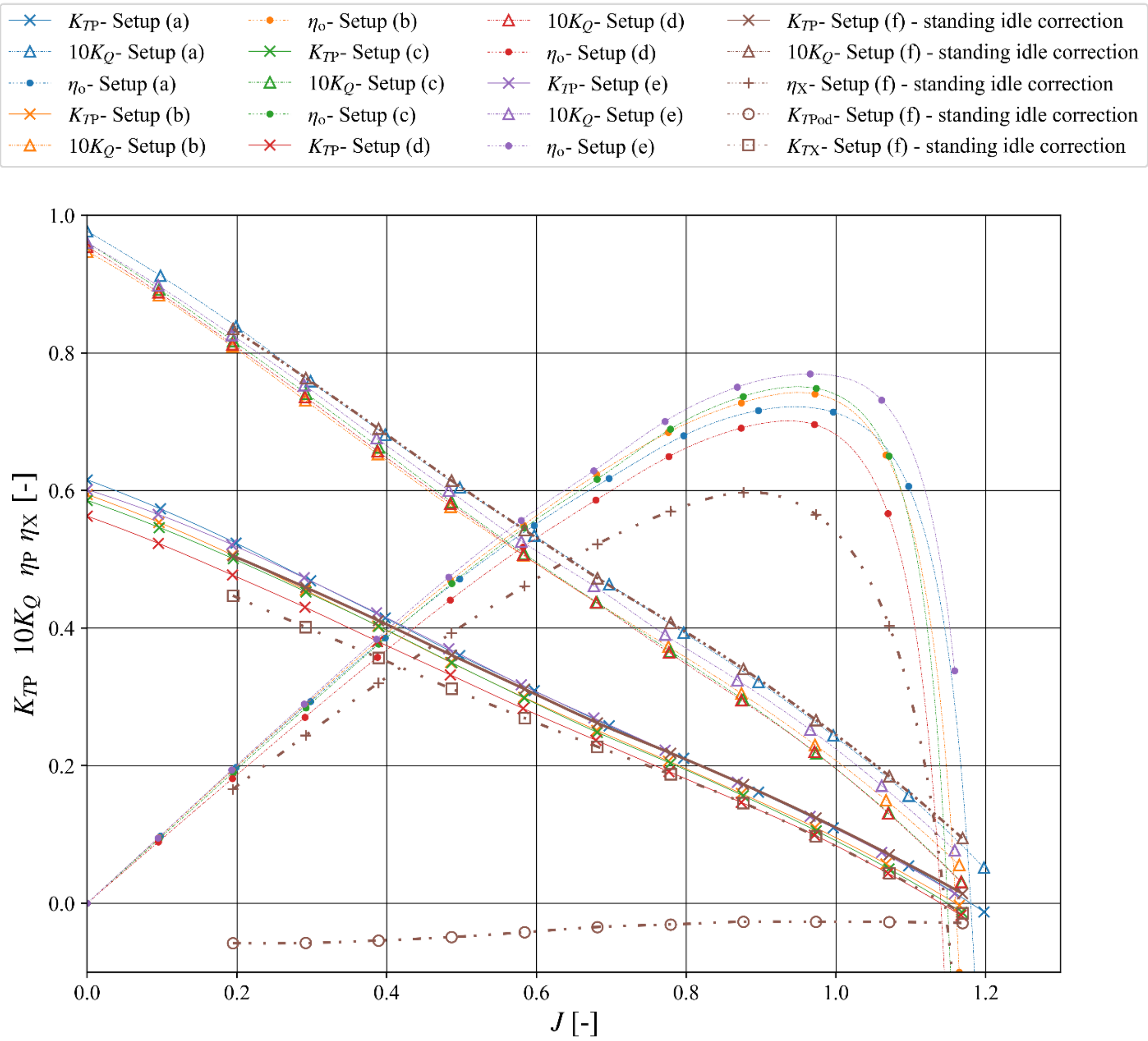

Figure 5. Podded propulsion curves of unit (f) and open water curves of alternative systems (a) – (e)

3.4 Comparison of test setups on the propeller behavior

The comparison of the different alternative setups and the pod unit model tests are conducted by the method described in chapter 2.4. The setup tests are considered analogue to a propulsion test and compared to the baseline open water test (setup (a)) by thrust identity to identify the resulting propulsion coefficients. For comparability, the results shown here are representing the propeller revolution rate for a Reynolds number of approximately $1 \cdot 10^6$.

3.4.1 Setup induced wake fraction

First, the shift in advance coefficient J is investigated by the setup-caused wake fraction as described by equation (9). Therefore, the propeller design thrust coefficient $K_T^* = 0.184$ for unaffected open water conditions were taken as baseline and all results are illustrated in respect to that.

As presented in Figure 6 all propellers show a similar behavior for the different model test setups, so a comparability seems feasible. The graphic indicates that the setups using a conical aft fairing tend to have a positive wake fraction, which means that these setups need to have a slower freestream inflow velocity to reach the same thrust than the open water baseline setup. Thus, the advance coefficient is shifted to the left. Most pronounced is this effect for the rotating aft fairing represented by setup (d), which can be explained by the lower thrust produced by this setup as disused in chapter 3.2. Setup (e) with the gondola shaped aft fairing tends to have almost a negligible to negative wake fraction, which indicates that the stagnation effect of the gondola and higher hub diameter compensate each other so that the propeller produces the same amount of thrust for almost the same free stream inflow velocity. The pod unit model test setup (f) approach has a negative wake fraction, which can be explained by the stagnation effect and interaction effects with the propeller slip stream of the strut and the gondola adding up. For the correction approach with the zero-speed idle measurement, the wake fraction is slightly less negative than for the approach using the forward moving idle correction, which can be explained by the smaller propeller thrust due to the forces acting on the boss cap.

3.4.2 Setup induced relative rotative efficiency

To comply with the propulsion test analogy, torque is compared by a relative rotative efficiency as described in equation (10).

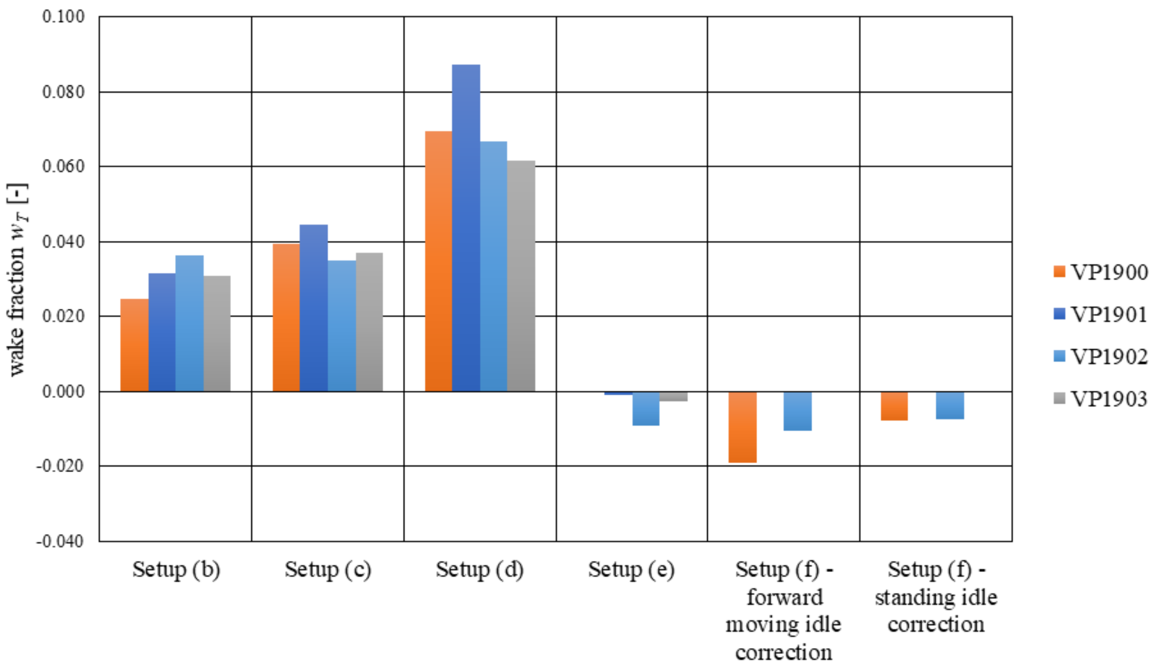

Figure 6. Alternative setup wake fraction in respect to baseline open water setup (a)

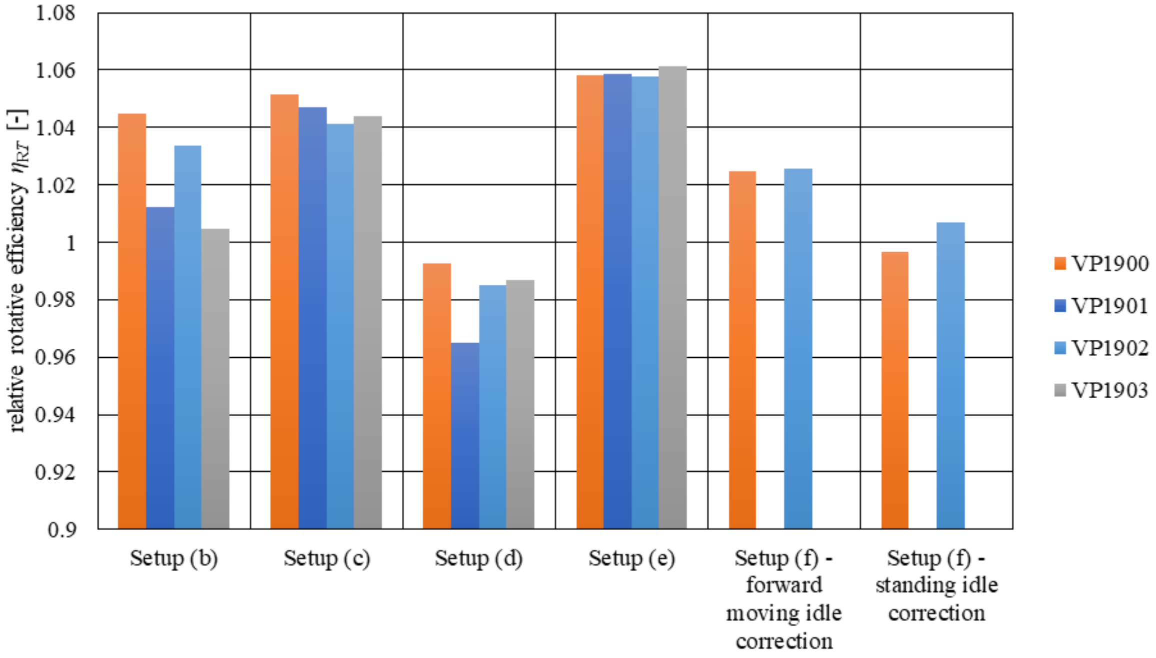

Figure 7. Alternative setup relative rotative efficiency in respect to baseline open water setup (a)

Illustrated by Figure 7, setups (b) and (c) with the increased hub diameter are leading to a slightly higher efficiency, while setup (d) tends to have a smaller efficiency than the baseline setup. This effect is also caused by the aft fairing forces included in the measurement. To reach the same thrust as in setup (a), more torque is required. The gondola shaped aft faring of setup (e) shows significantly higher efficiency. This is explicable due to the fact that with this setup the same amount of thrust as the original open water setup can be generated with less blade area because of the bigger hub diameter. Due to the bigger shift in advance coefficient, induced by the presence of the strut, for the pod unit with the forward moving idle correction the relative rotative efficiency is less than the alternative system with the gondola shaped aft fairing. Taking the boss cap forces into account, slightly more torque is needed for the same amount of thrust so that the efficiency of the pod unit with the standing idle correction levels out with the efficiency of the baseline open water setup.

4. COCLUSIONS

The extensive series of different model test setups proofed the hydrodynamic complexity of a podded propulsion system due to different parts interacting with each other. During the research, it became clear that there are two main perspectives for podded propulsion systems to look at:

On one hand, there is the propeller design perspective, focusing on the propeller and how the application on a pod unit changes the pure open water propeller characteristics (only the blades, without hub). As the results of this research topic are showing, a propeller with known pure open water curves needs to be corrected by an advance coefficient shift and a torque variation to estimate the behavior of the propeller interacting with the pod (setup (a) to setup (f)). For design and understanding purposes, open water tests with different alternative setups can be used, but all alternative systems are showing some kind of discrepancy to the final unit. If alternative setups are used, a correction needs to be applied. Regarding different approaches of alternative setups, a gondola shaped aft fairing seems to be the most promising due to its close relation to the podded setup. It has the smallest discrepancy in propeller coefficients to the podded unit. Nevertheless, due to the simplification of neglecting the strut the efficiency of this setup seems to be too optimistic and needs a correction to estimate the propeller performance with the pod unit. For the conducted model tests, the ITTC(2017) recommended alterative setup using a rotating aft fairing has shown the largest discrepancy to the final pod unit setup as well as to the initial pure open water setup (a), which are caused by the fact that the forces acting on the aft fairing are included in the measurement. This setup generally cannot be recommended.

For the second main perspective podded propulsion system model tests are used for speed and powering prediction. In this case, the model tests revealed a large difference between propeller thrust and efficiency and the total unit thrust and efficiency. Due to the additional drag of the housing, the total efficiency of the system is much lower than the single propeller efficiency. For comparison and propeller design purposes the propeller thrust and efficiency can be considered, but for powering and speed prediction, the total podded propulsion systems thrust and efficiency has to be used. Since using an alternative system for powering and speed prediction would lead to wrong propulsion coefficients it seems to be more likely to use the forces acting on the complete unit.

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