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Numerical Investigation of Multi-Component Podded Propulsor Performance in Straight Flow

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ABSTRACT

The notion of high efficiency related to a low loaded propeller has been sometimes misunderstood in the context of multi-component tandem or CRP units. Individual low loaded propellers working as a part of a multi-stage propulsion unit do not lead necessarily to high efficiency since high efficiency is more related to what could be called low "propulsive" loading, than to what is usually referred to as low "propeller" loading.

In this paper, multi-component propulsors are numerically investigated in straight flow from the standpoint of efficiency and propeller interaction. Potential flow tools are used to illustrate the ability of different multi-component configurations to improve efficiency. RANS methods coupled to actuator disk models are used first to validate average loads on a CRP unit and then to analyze effective wakes in a podded propulsor with three co-axial propeller components.

Keywords

Efficiency, contra rotating propellers (CRP), multi component propellers, actuator disk, effective wake

1 INTRODUCTION

Traditionally, multicomponent propulsion units (CRP, tandem, twin arrangements …) are regarded as more efficient than equivalent single propellers for two reasons: reduction of propeller loading and cancellation of rotational losses for CRP arrangements. The former reason has been sometimes misinterpreted (Hadler et al. 1964; Larsen, 1970; Olanrewaju, 2013), leading to the inaccurate conclusion that *open water* (OW) efficiency could be always improved by splitting the total available power among several propellers, being the larger number of propellers, theoretically the better. A design with, for example, four propellers working in tandem or CRP mode would then be better than traditional two-propeller units.

In principle, such conclusion would be true for twin, triplet or quadruplet configurations where the propellers do not interact (or weakly interact) with one another, but not for multi tandem/CRP arrangements where the propellers are mounted on the same axis. High open water efficiency is more related to what could be called low "propulsive" loading, than to what is usually referred to as low "propeller" loading. In fact, the success of CRP arrangements lies mainly on the cancellation of rotational losses, not on the reduction of "propeller" loading derived from the inclusion of a second propeller.

Specifically, the "propulsive" area of co-axial multi-component units is not increased over that of conventional propellers with the same diameter. By "propulsive" area we mean the area perpendicular to the inflow directly affected by the working propulsors. For CRP or tandem arrangements it usually coincides with the disk area of the forward propeller. On the contrary, the "propeller" disk area for them is doubled when compared to a conventional propeller. In particular, the fore- and aft-propellers in multi-stage arrangements display reduced "propeller" loading, but no efficiency improvement due to unloading. This is due to a detrimental interaction effect on the individual propeller inflows: each propeller is working under a harmful effective wake caused by the action of the other propeller, which makes the benefits of such "propeller" unloading marginal or even fictitious. Low "propulsive" loading (or low "propulsor" loading) should be targeted rather than low "propeller" loading for open water efficiency improvement.

Here, we are limiting our discussion to OW efficiency. In behind conditions, the shape of the ship may influence the choice of an optimum multi-component configuration. For example, hull forms with strong flow separation areas at center-stern could be more suitable for single CRP arrangements than for twin propellers (Strom-Tejsen & Roddy, 1972), contrary to what OW considerations would suggest. The reason is that the twin units would exhibit lower values of hull efficiency than CRP arrangements. In particular, CRP units located on the center plane in the stern may contribute to the reattachment of separated flow, contrary to twin propellers located off the symmetry plane.

From a cavitation and propeller-induced vibration standpoints, the use of more than two co-axial propellers may be justified since the front propeller could be unloaded, and the rear propellers would work in the high pressure zone induced by the propeller located just in front of them.

Some authors claim that the high pressure behind the forward propeller could detrimentally affect the performance of the rear propeller (Min, et al., 2009), and therefore the rear propeller should be located as far downstream as possible. However, in our opinion, the high pressure induced by the forward propeller affects nearly equally both sides of the 'thin' blades in the rear propeller and should not have noticeable impact on performance, contrary to what may happen to rudders located in the slipstream of a propeller, where an induced pressure drag may exist. Changes in performance due to distance between propellers should be attributed mainly to the degree of development of the velocities induced by the forward propeller at the location of the rear one, rather than to an increase in the reference pressure level.

In section 2, potential flow tools are used to illustrate the ability of different multi-component propulsors to improve OW efficiency for particular design constraints. In section 3, RANS methods coupled to actuator disk models are used to analyze the interaction flow among the propellers in a multi-stage configuration. Numerical results are first validated with model test measurements for a CRP arrangement. A full scale application to a podded propeller propulsor with three co-axial propellers (Tri-CRP) is finally presented.

2 POTENTIAL FLOW ANALYSIS

2.1 Study case

A preliminary viability study was made for various multi-component configurations. The design constraints were: delivered power, 2090 kW; inflow, 7.7 m/s; power per shaft in co-axial arrangements should not exceed 60% of the total power; maximum number of propellers, four. The configurations included individual propellers working in CRP or tandem mode relative to the other propellers in the unit. An additional constraint was that the rotational speed should be the same in magnitude, but not necessarily in direction for all propellers.

Several arrangements and distribution of loads between the propellers were analyzed with potential flow tools.

2.2 Theoretical approach

The potential flow method used as design tool is the vortex-lattice lifting line model described in Sanchez-Caja et al. (2014). The assumptions that the lifting-line theory adopts are similar to those presented in Kerwin et al. (1986), but the multi-component propeller interaction and optimization is made iteratively. The inflows to each propeller are calculated from the circumferentially averaged velocities induced by the other propellers.

2.3 Parametric Study

A parametric study was made on various multi-component solutions with the design constraints mentioned in section 2.1. First, optimum values of RPM for the conventional CRP and multi-CRP concepts were studied for several reference diameters with the restriction that the working RPM should be the same for all propellers inside the multi-component units. Expanded area ratios were selected according to Keller's criterion with about 5% margin. The calculations revealed that a power split of 60%-40% was optimum for the CRP unit of the study. A Tri-CRP configuration with three propellers mounted on the same axis and the middle propeller rotating opposite to the other two was optimized. As shown in Figure 1, the CRP concept was slightly more efficient than the Tri-CRP one for all diameters, for a power split between the propellers of 40%-40%-20%. As the load of the rear propeller is shifted to the forward one (50%-40%-10% power split), the efficiency of the Tri-CRP approaches that of the conventional CRP.

In a second stage, focusing on the 2.5 m diameter case, a set of Tri-CRP calculations were made trying to get 60% of the power in the front propeller. This means that the two rear propellers should work in tandem mode being fixed to the same shaft. The splits between the tandem propellers were 20%-20% and 30%-10%. The latter configuration yielded a slightly better efficiency than the former, but both configurations yielded slightly less efficiency than the CRP one.

Then, a Quatro-CRP configuration with four co-axial CRP propellers was studied with a power split of 36%-24%-24%-16%. After optimizing the RPM the efficiency of the Quatro-CRP was still somewhat lower than the original CRP.

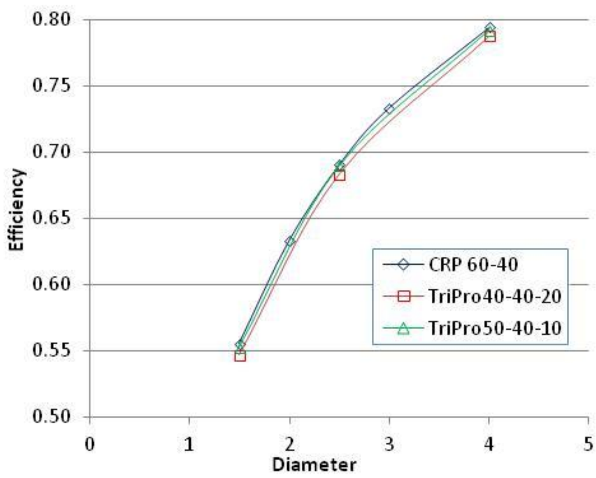

Figure 1: Optimum efficiency versus maximum diameter for different propulsion concepts for selected percentages of power between the propellers (fore-aft or fore-mid-aft propellers).

The explanation of these findings is that efficiency can be improved either by cancelling rotational losses, or by reducing the thrust density per "propulsive" area, or by minimizing frictional losses. Concerning the first alternative, the rotational losses cannot be cancelled in principle by a Tri-CRP unit to a greater extent than they would be by a conventional CRP arrangement.

Concerning the second, what is most important for improving efficiency at a given speed is not thrust density per propeller disk area, but thrust density per propulsive area. The propulsive area is the same for units with two or three propellers mounted on the same axis and is equal to the area swept by the unit largest propeller. Therefore, no significant benefit can be obtained from units with 3 or more co-axial propellers. Concerning the third reason, the rear propellers work at larger effective inflows and therefore under larger frictional forces. Increasing the number of rear propellers and their loading would penalize somewhat efficiency.

Finally, a twin-CRP configuration was studied to check the effect of decreasing the loading per propulsive area. The two CRP units were considered as mounted on different parallel axes, side by side (not one in front of the other as before in the Quatro-CRP configuration). Due to the cancellation of rotational losses and reduction of load per propulsive area, an improvement of 11.5% for a front propeller diameter of 2.5 m in efficiency is reached.

A summary of the efficiencies obtained by the lifting line method with different propulsor configurations is shown in Fig. 2 for a reference diameter of 2.5 m..

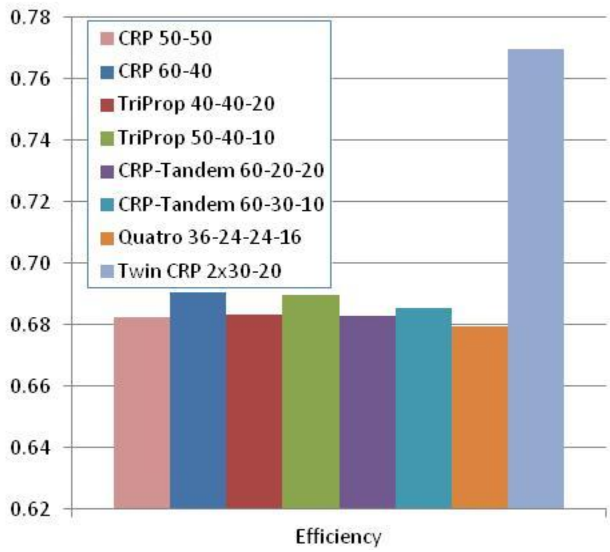

Figure 2: Summary of open water efficiencies for different propulsor configurations for a fixed diameter and delivered power. The label numbers mean power split between propellers.

Generally, from the standpoint of cavitation and within certain limits, the lower the loading of the forward propeller is, the better its performance would be. Therefore, the ranking of the propulsor configurations would be from best to worst: twin-CRP, Quatro-CRP, Tri-CRP 40-40-20, CRP 50-50 and so on.

3 RANS ANALYSIS

3.1 Theoretical approach

The flow simulation in FINFLO is based on the solution of the RANS equations by either the artificial compressibility or the pressure correction method. A detailed description of the numerical method including discretization of the governing equations, solution algorithm, boundary conditions, etc. can be found in Sánchez-Caja et al. (1999) and Miettinen & Siikonen (2015). The approach to the estimation of the effective wake is explained in Sánchez-Caja et al. (2014). It is based on a correction factor scheme for the cancellation of the numerical errors derived from coupling a potential flow method with a RANS method.

The procedure can be summarized as follows. The geometries of the various propellers integrating the multi-component unit are first analyzed by lifting line (LL) theory with lifting surface correction factors subject to an initial inflow. Then, the calculated propeller forces are expressed in terms of body forces and included in the RANS computation via an actuator disk interface. The RANS solution provided a new inflow at the location of the propellers after subtracting the LL circumferentially-averaged induced velocities from the total velocities of the bulk flow. The procedure is repeated for each RANS iteration. The LL problem has fast convergence, and does not contribute to increase noticeably the total CPU time. A correction factor scheme is used to minimize the viscous-potential flow coupling errors inherent to hybrid numerical methods. The approach allows accurately capturing the interaction flow among the various propellers in a multi-stage unit. The SST k-omega turbulence model was used in the simulations.

3.2 Validation in model scale

Computations are made in this section for a pushing CRP pod arrangement and the results are compared to model scale tests. Figure 3 shows the shape of the thruster where the propellers are mounted, and the location of the propellers in the form of actuator disks. The pressure contours are visible. The propellers induce a pressure increase behind the disks, which reduces pod drag.

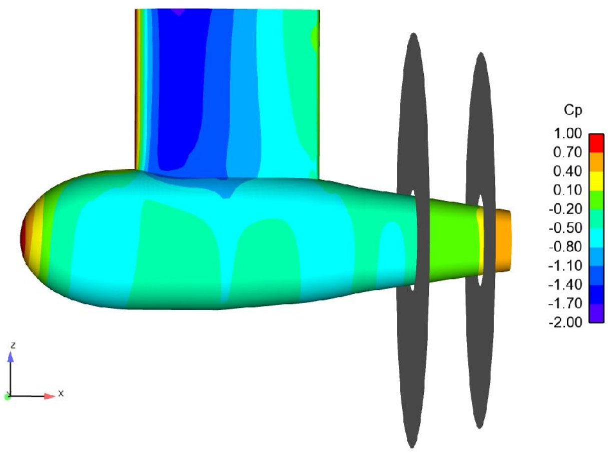

Figure 3: CRP unit modeled with actuator disks. Pressure distributions on housing. The pressure grows behind the disks.

The propellers rotate at 12 rps. The flow is in the positive OX direction. The main data of the propellers are given in Table I. Grids of 0.5 and 4.5 million cells were built yielding differences in force coefficients smaller than 0.5 %, which is indicative of small numerical uncertainty.

The lifting line code with lifting surface corrections was able to simulate accurately the performance of each single propeller in open water especially for advance numbers around 0.6-0.7. Therefore, this zone was the most appropriate to check to what extent the interactions between the two propellers working in contra-rotating mode and between propellers and housing were accurately captured by the hybrid potential-viscous flow approach. Figure 4 shows a comparison of the computed and measured thruster thrust and torque non-dimensional coefficients. The global interaction is shown to be well captured. The enhanced coupling scheme was able to control numerical errors.

Table 1: Propeller main characteristics

Forward propeller		Rear propeller	
Diameter	0.246	Diameter	0.223
Pitch ratio	1.00	Pitch ratio	1.22
A_E/A_0	0.45	A_E/A_0	0.55
Blade no.	4	Blade no.	5

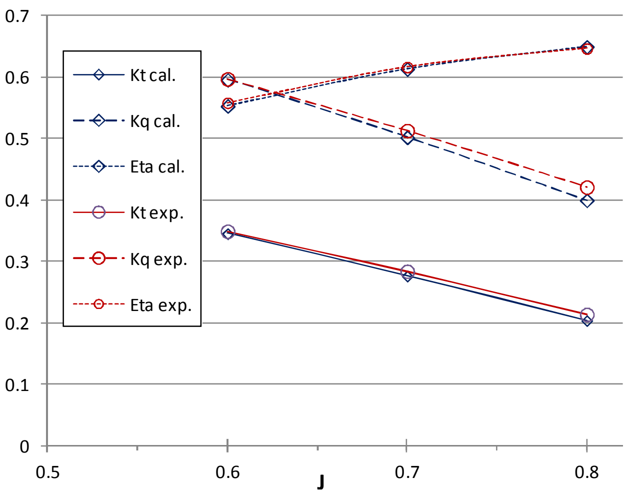

Figure 4: Comparison of numerical and measured performance coefficients for the CRP thruster at model scale.

3.3 Full scale application

Computations were made at full scale for the Tri-CRP concept with a load distribution of 40-40-20 % of the total load for the fore, middle and aft- propeller, respectively.

The RANS computations were made for a total delivered power was 2090 kW and 171 RPM. The forward propeller diameter was 2.5 m. The inflow velocity was 6 m/s. A computational grid was made consisting of 5.4 million cells. Three actuator disks were used serving as interface between a lifting line analysis tool and the RANS computational domain.

Figure 5 shows the pressure distribution on the thruster housing, which includes a strut, two fins and a pod. The location of the actuator disks is visible along the pod length.

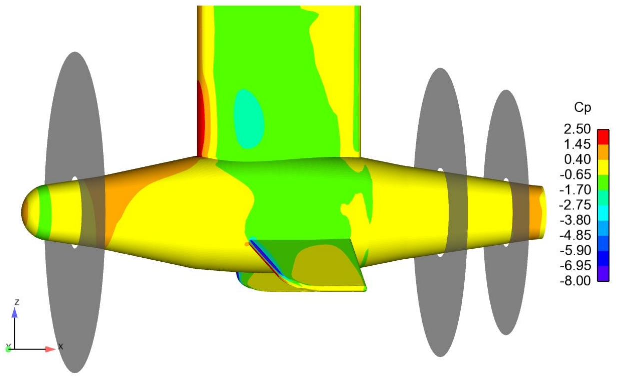

Figure 5: Tri-CRP unit modeled with three actuator disks. Pressure distributions are shown on solid boundaries.

Figure 6 illustrates the change of the circumferential component of the velocity field at various planar sections of the flow normal to the rotation axis. Sharp changes in the velocity field are observed from locations of the cutting plane in front of and behind each actuator disk. The colors on the sectional planes represent velocities and those on the housing, pressures. The first actuator disk is located between the two first images, the second between the fifth and sixth images, and the third between the sixth and seventh images. The tangential velocities are almost cancelled downstream as seen in the last image. Only some small spots are visible in yellow and blue with moderate values of circumferential velocities.

Figure 7 illustrates the corresponding change of the axial component of the velocity field at the same planar sections. The axial velocity is shown to grow smoothly at the location of each actuator disk. Its pattern is convected downstream without noticeable rotation.

Figure 8 shows the effective wake at the locations of the front, fore-CRP and aft-CRP propellers. For the front propeller the inflow is slightly decelerated in front of the strut. The tangential wake is small and anti-symmetrical relative to the vertical OZ axis.

The axial effective wake grows steadily from the fore CRP to the after one, changing slightly the rotation direction. The tangential wake is mainly negative for the fore-CRP propeller and positive, for the aft- CRP propeller. It is induced by the propellers located upstream. On the contrary, the axial wakes are also influenced to some extent by the suction of the downstream propellers.

The tangential wake of the mid-propeller presents three zones of reduction of tangential velocities caused by three stators: the strut and the two fins. The effect of the strut is larger than that of the fins, and is visible at about the 11 o'clock position.

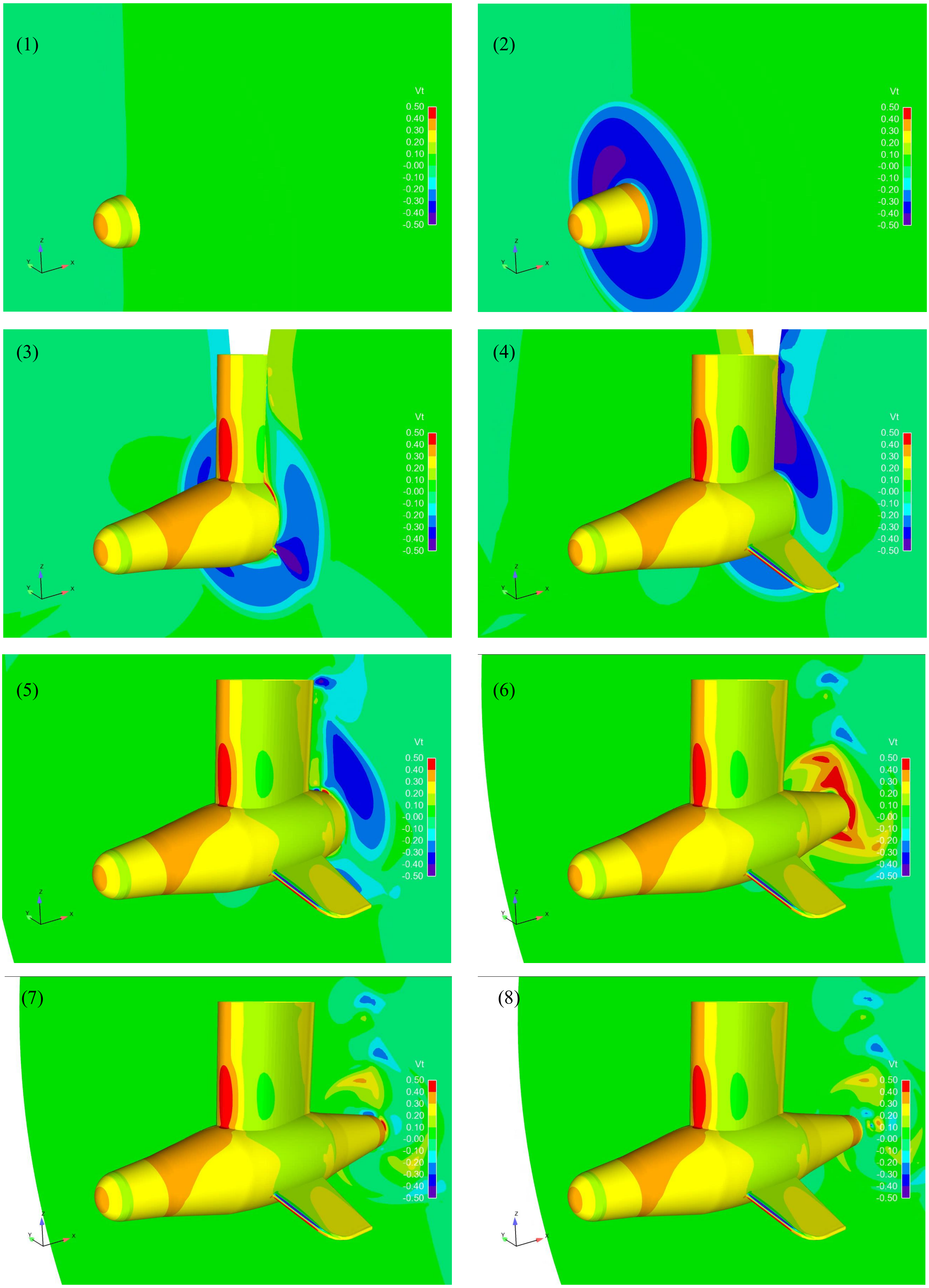

Figure 6: From left to right and from up to down, evolution of the tangential velocities on several planes along a Tri-CRP podded propulsor with propellers modeled as actuator disks. Colors on control plane are velocities, colors on solid surfaces are pressures.

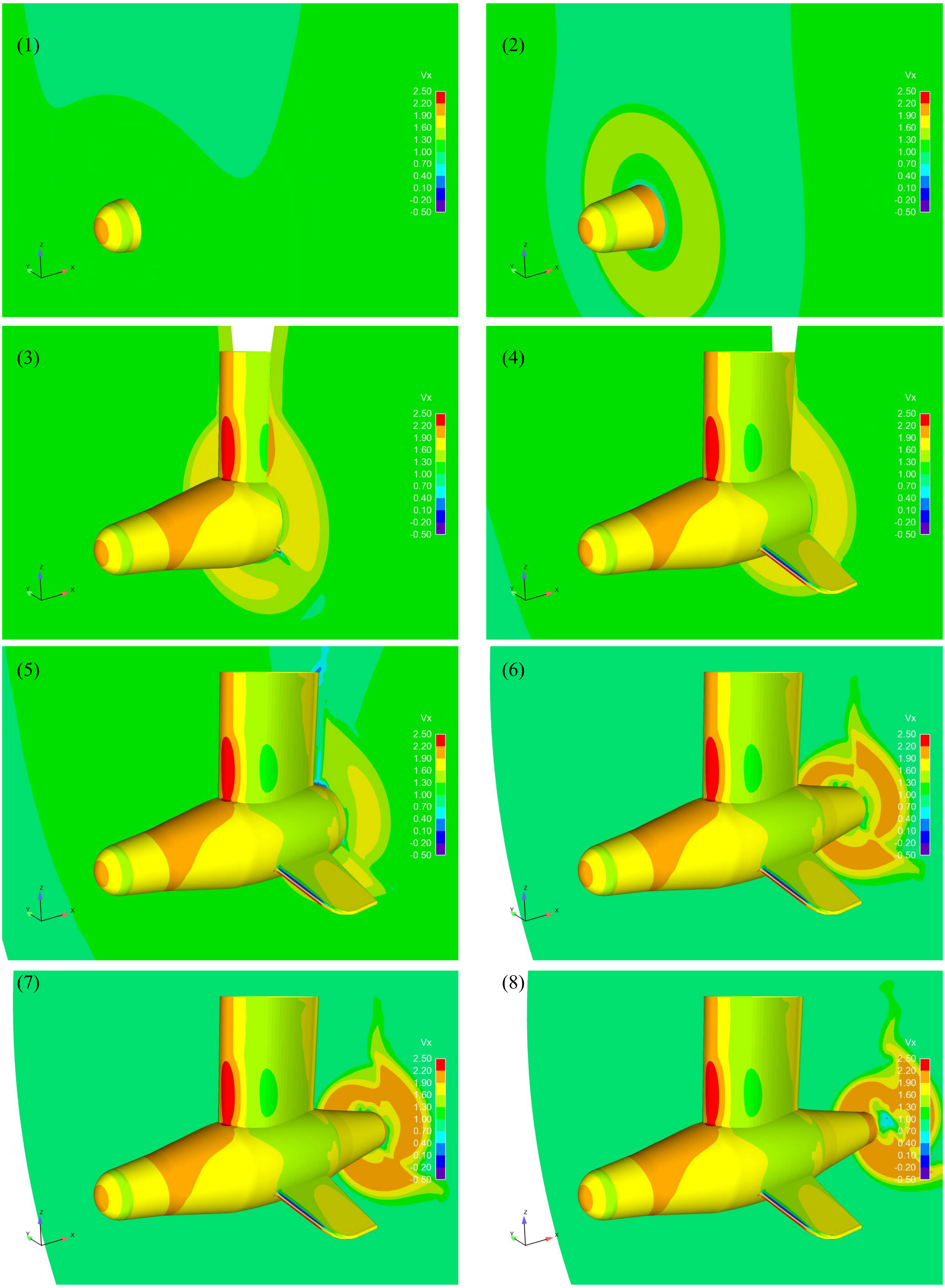

Figure 7: From left to right and from up to down, evolution of the axial velocities on several planes along a Tri-CRP podded propulsor with propellers modeled as actuator disks. Colors on control plane are velocities, colors on solid surfaces are pressures.

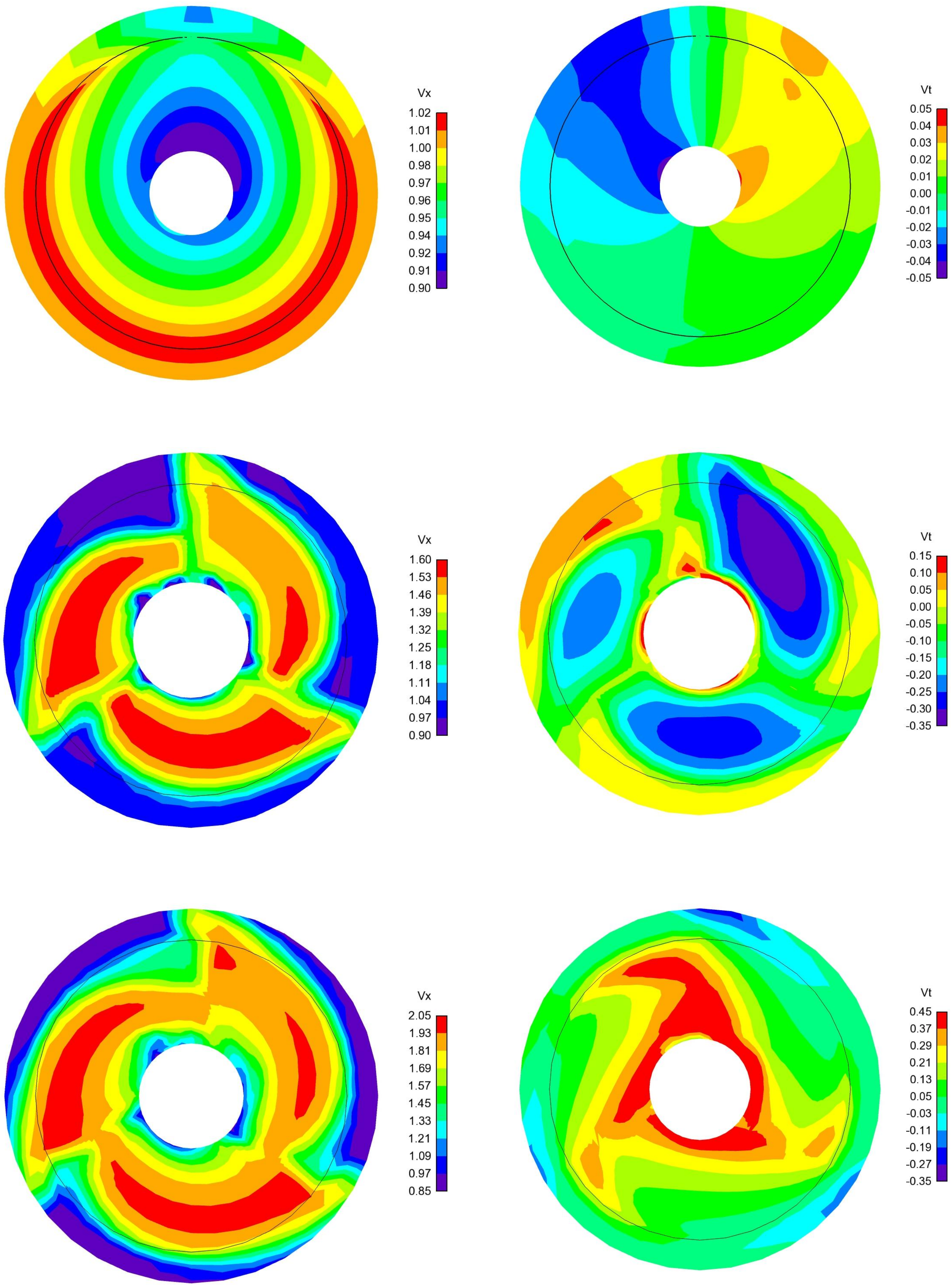

Figure 8: Axial (left) and tangential (right) effective wakes at the location of the front (up), fore-CRP (middle) and aft-CRP (down) propellers in a Tri-CRP unit. (Note the scale differences)

4 DISCUSSION

In this paper multi-component propulsors are numerically investigated in straight flow using approaches based on potential flow and hybrid potential-viscous flow theories. The aim is to provide insights into flow characteristics that may affect propeller design.

First, potential flow tools are used to illustrate the ability of different multi-component propulsors to improve efficiency. From an *efficiency* standpoint, it is shown that there is no need to increase the number of propellers over two in co-axial arrangements. Moreover, efficiencies are found very similar for different number and combinations of co-axial propellers with equal "propulsive" area.

Such findings can be explained first in a potential flow context by momentum considerations relating the change in axial momentum from upstream to downstream infinity planes. It is known within potential theory that the distribution of induced velocities at the Trefftz plane located downstream at infinity will determine the total thrust and efficiency, independently of the number of intermediate stages used to develop such velocities. As the axial induced velocities cannot be completely suppressed for a given target thrust, the only way to increase efficiency is to optimize their spatial distribution via LL variational approach and to suppress tangential velocities at the Trefftz plane. The latter can be done with only two contra-rotating propellers, being of no significant benefit the use of more propellers.

On the other hand, if frictional drag is introduced into the problem, in a multi-component co-axial unit, the more downstream a propeller component is located, the larger its effective inflow would be, and consequently the larger the frictional forces acting on it would be. Therefore, from the efficiency standpoint, the minimum number of propeller is the best; and two are needed at least to cancel rotational losses. Nevertheless, as shown in section 2, an appropriate distribution of expanded area among the propellers of a multi-component unit would result in small efficiency differences among the different concepts.

Special applications where cavitation is the main concern may make it attractive to use multi-component propulsors with more than two propellers. An appropriate distribution of loading among the propellers and a careful selection of propeller expanded area ratios would be required to keep efficiency at the level of conventional CRP arrangements with improved cavitation performance.

A simple, robust and accurate hybrid RANS-potential flow approach has been used for the flow analysis of a full scale Tri-CRP concept. Validation of the method with model tests made on a CRP unit has been provided. The approach is capable of accurately capturing the flow interaction among the propellers in a multi-component unit, by minimizing numerical errors derived from coupling potential and viscous flow methods. The actuator disk simulates the working propeller and yields body forces dependent on the magnitude and direction of the inflow. In our opinion, methods for the prediction of effective wakes based on body forces should avoid sophistications that complicate the numerical approach to an extent similar to that of modeling the actual propeller blades.

The current numerical approach can be used with other potential flow methods for the representation of the individual propellers, like lifting surface or panel methods. The success of the approach would depend on the ability of the selected method to predict efficiency for each single propeller component in open water since numerical coupling errors are already accounted for within the numerical scheme. In fact, lifting line theory with lifting surface correction factors seems a fast and accurate practical choice for propeller modeling. More elaborated potential flow methods with larger CPU time consumption would require coupling loops outside the RANS solution iteration step to keep the computation time within reasonable limits.

A practical approach for the preliminary estimation of unsteady loads in propeller design would be using RANS-lifting line coupling for the evaluation of the effective wakes, and then making the final analysis of propeller forces and cavitation by an unsteady lifting surface or panel method on the converged effective wake.

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DISCUSSION

Question from Hannu Jukola

In your study you claim that in a multi-component propulsor the reduced propeller loading does not increase the overall efficiency. However, according to our investigations contra-rotating propellers increase the efficiency more than what would be possible if only the rotational losses can be recovered. Can there be other factors than just the axial losses, like lower blade area or reduced frictional losses?

Author's closure

In the paper we have shown from *potential flow* considerations that the propulsor open water efficiency of a multi-component co-axial unit cannot grow over the efficiency increase due to the cancelation of rotational losses. If we consider now *viscous losses* due to friction, usually a CRP unit has larger wetted blade area than a single propeller for the same maximum diameter and loading. This can be easily seen by applying for example Keller criterion for the selection of the expanded area ratio to a single propeller and comparing that area to the one obtained by the sum of the two propellers of the CRP unit. If the wetted area is larger for the CRP unit, the frictional losses will be larger in principle (especially considering that the rear propeller is subject to a larger inflow). Then, assuming that we are comparing a single and a CRP unit for a given maximum diameter, the reason for a larger improvement in efficiency may be that the single propeller is not working at its own optimum conditions but at the optimum conditions of the CRP. For example, the comparison might have been made at equal RPMs (note that optimum RPMs differ from single to CRP units). Another reason may be that the expanded area ratio is not properly chosen for the single unit (either it is excessively low, resulting in an overpitched propeller with large detaching and/or cavitating flow; or excessively large, resulting in significant frictional losses).