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An Improved Z-Drive with Contra-Rotating Propellers for High-Speed Applications

R. Schulze [1], A. Weber [2]

[1] Potsdam Model Basin (SVA), Potsdam, Germany
[2] REINTJES GmbH, Hamelin, Germany

ABSTRACT

For high-speed planing vessels a propulsion concept improving efficiency, noise emission, and comfort was developed. The resulting FORTJES® concept from REINTJES offers remarkable improvements with respect to these aspects.

Propellers are still the most-used propulsion systems for fast ships. Theoretical considerations and tests with different arrangements of contra-rotating (CR) propellers at Z-drives for high-speed applications lead to a CR- system with one propeller in front of and one propeller behind the gear box. These scientific findings as well as mechanical and geometric boundary conditions had to be combined. Therefore all hydrodynamic active parts of this special CR-arrangement were optimized. A new asymmetric twisted strut offers the highest efficiency. An especially designed shape for the lower gear box gondola has been derived from bionic experiences and CFD calculations. Together with an exclusively designed pair of propellers these features constitute this new REINTJES concept for a high-speed drive, called FORTJES®.

KEY WORDS

CR propeller, Z-drive, push-pull arrangement, efficiency, cavitation, noise, high speed

1.0 INTRODUCTION

For high-speed planing vessels a propulsion concept improving efficiency, noise emission, and comfort was developed. The resulting FORTJES® concept from REINTJES offers remarkable improvements regarding these aspects. Propellers are still the most-used propulsion systems for fast ships. These propellers in general are combined with inclined shafts. The variation in the transversal velocity of the propeller in oblique inflow causes considerable changes in the profile angle of attack, which leads to cavitation especially if the propeller blades move downwards. To avoid such phenomena with inclined shafts, have to be applied L- or Z- drives with a lower gear box. Another aspect for avoiding difficulties with cavitation is the application of more than one propeller in a line. This originates from the idea to distribute the input power to more than one propeller, especially under restrictions in propeller diameter. The application of Z-drives with a lower gear box in combination with two propellers in line automatically leads to the idea of contra-rotating propellers. The contra-rotating arrangement of propellers at the lower gear box is practicable in three ways: Both CR-propellers can be arranged in front of or behind the lower gear box. The third possible arrangement features one propeller in front and one propeller behind the lower gear box. The hydrodynamic advantages of a Z-drive for fast ships featuring CR-propellers are the improvement in efficiency and the reduction of cavitation and noise. A higher efficiency is gained by distributing the power on two propellers. The CR-arrangement eliminates the swirl and thus gains additional efficiency. Noise and cavitation are significantly reduced by realizing propeller shafts with no inclination. This paper evaluates the hydrodynamic properties of the different arrangements of CR-propellers at Z-drives for high-speed applications. Theoretical considerations and tests with these different systems lead to a CR- system with one propeller in front and one propeller behind the gear box. These scientific findings as well as mechanical and geometric boundary conditions had to be combined. Therefore all hydrodynamic active parts of this special CR-arrangement were optimised. A new asymmetric twisted strut offers the highest efficiency. An especially designed shape of the lower gear box gondola has been derived from bionic experiences and CFD calculations. Together with an exclusively designed pair of propellers these features constitute the new REINTJES concept for a high-speed drive, called FORTJES®. For a yacht application the FORTJES®-drive was intensively tested in the model basin SVA-Potsdam. The propulsion, cavitation, and manoeuvring properties were compared to a usual twin-screw arrangement.

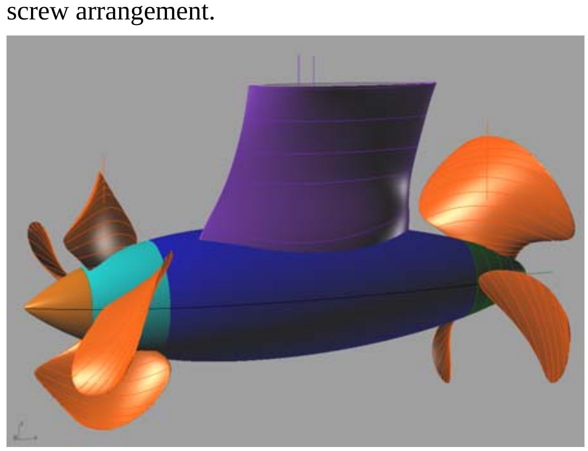

Fig. 1. FORTJES®-drive concept

2.0 TWIN PROPELLER PRE-DESIGN

For a highly-loaded propulsion system it is common practice to distribute the power (thrust) to more than one propeller (dependence of ideal efficiency of thrust loading coefficient). If the outer diameter of the propulsion system is restricted this becomes of special importance. Different propulsions systems are compared in Fig. 2, showing the dependency of the thrust loading coefficient.

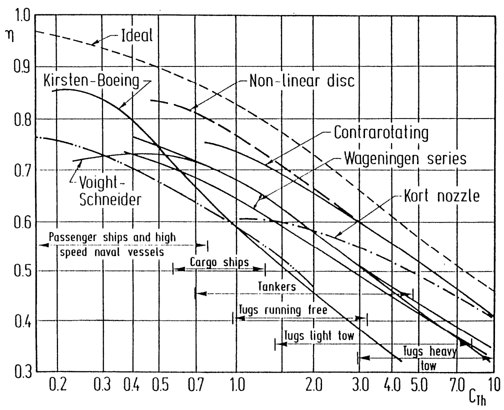

Fig. 2. Efficiency of different propulsor types (Breslin, Anderson)

For the distribution of the power or thrust on more than one propeller (or propulsion system) there are essentially the following possibilities:

1. Multiple propellers on one shaft line (in most cases two propellers on one shaft line (twin propeller))
2. Single propellers on more than one shafts (e.g. usual twin screw ships)
3. Combinations of case 1 and 2

For case 1 both propellers on one shaft line can rotate in one direction or can be contra-rotating. Furthermore, it is also possible to vary the distance between the propellers.

The achievable efficiency depends not only on the thrust loading coefficient. Other losses represented in Fig. 3 have also be taken into account. The losses originated from the swirl in the propeller jet (Fig. 3, differences between curve (1) and (2)) can be reduced for twin propellers for one rotating direction by guide fins (e.g., Schottel twin propellers). In the case of a contra-rotating twin propeller arrangement (FORTJES®, REINTJES), the losses by swirl in the propeller jet can be eliminated, which is the main advantage of contra-rotating propellers.

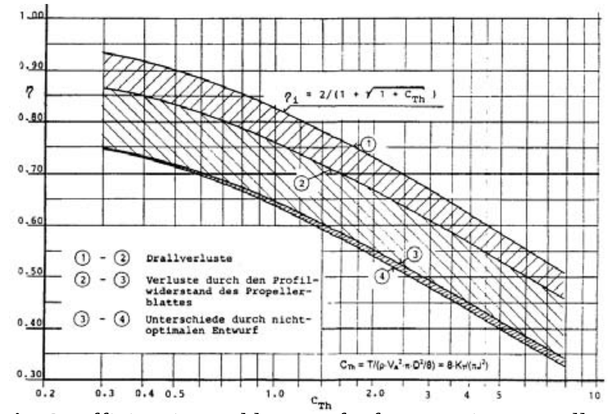

Fig. 3. Efficiencies and losses of a free-running propeller in dependence of the thrust loading (van Manen)

There are the following possibilities to arrange contra-rotating pairs of propellers at a lower gear box:

1. Both propellers in front of the gear box (pull-pull)
2. Both propellers behind the gear box (push-push)
3. One propeller in front of and one propeller behind (pull-push)

The pull-push arrangement has the essential mechanical advantage, that the hollow shaft is dispensable.

2.1 Estimation of optimal thrust distribution for two propellers

The following considerations based on the momentum theory and are valid for twin propellers on one shaft line (independent of direction of rotation). Because the first propeller accelerates the water, the second propeller has another thrust loading coefficient. From this follows, that in terms of ideal efficiency the best thrust distribution for both propeller is not 1:1. For a total thrust of T_1+T_2 and the first propeller diameter of D_1 Fig. 4 shows the ideal efficiency in dependence of the distribution parameter α. The maximum ideal efficiency is reached for α = 0.47. For gondola applications the hub diameter is in general an important variable. The diagram in Fig. 4 considers this circumstance by taking two different hub diameters into account (D_H/D_1=0.406 and D_H/D_1=0.435 mm).

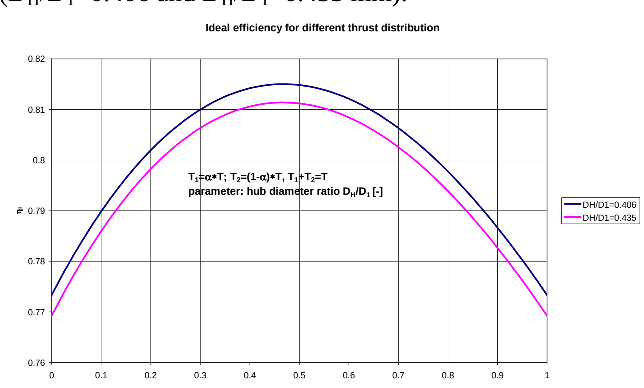

Fig. 4. Ideal efficiency in dependence of the thrust distribution between both propellers for two hub diameters

Due to the contraction of the jet caused by the acceleration of the first propeller, an optimal diameter of the second propeller can be derived. This is represented in Fig. 5 for different hub diameters in dependency of the distribution parameter α.

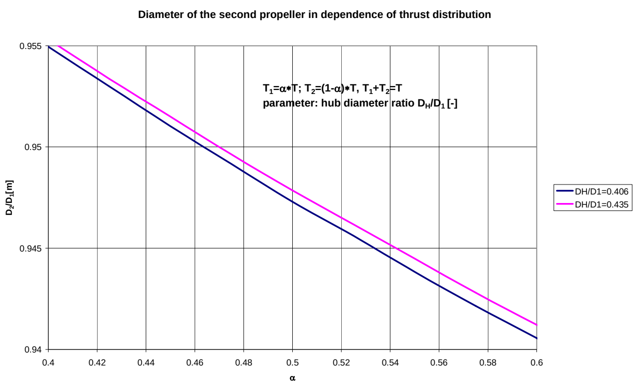

Fig. 5. Diameter of the second propeller in dependence of the thrust distribution and the hub diameter

2.2 Interaction of propellers with gondola

The shape of the gondola of the lower gear box has an essential influence on the hydrodynamic parameters of a twin propeller arrangement. This has been studied extensively by Schulze (2001).

In dependency of the length and the gondola diameter a set of four real parameters (G_D, w_D, R_D, w_R) to describe the following formulas were introduced.

$$K_{T(gondola)}(J) = G_D * K_{T(open\ water)}(J*(1-w_D))$$
$$K_{Q(gondola)}(J) = R_D * G_D * K_{Q(open\ water)}(J*(1-w_D)*(1-w_R))$$

Based on experiments with systematically-modified gondola diameters and lengths, the parameters (G_D, w_D, R_D, w_R) were derived in such a way that the minimum of the following function f was determined for this set of measurements:

$$f(G_D, w_D, R_D, w_R) = \int (K_{T(gondola)}(J) - G_D * K_{T(open\ water)}(J*(1-w_D)))^2 + (K_{Q(gondola)}(J) - R_D * G_D * K_{Q(open\ water)}(J*(1-w_D)*(1-w_R)))^2\, dJ$$

where the integral was to be determined over the interval (J_{min}, J_{max}). The minimum problem has a unique solution. The dependencies of the gondola geometry on these parameters is summarised in Figures 6 and 7.

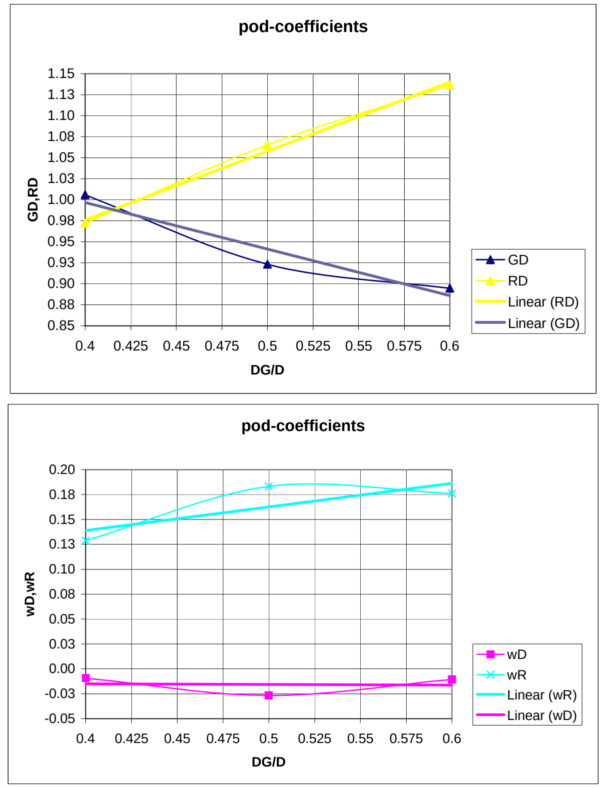

Fig. 6. Gondola-coefficients in dependency on the diameter ratio (Gondola diameter DG, propeller diameter D)

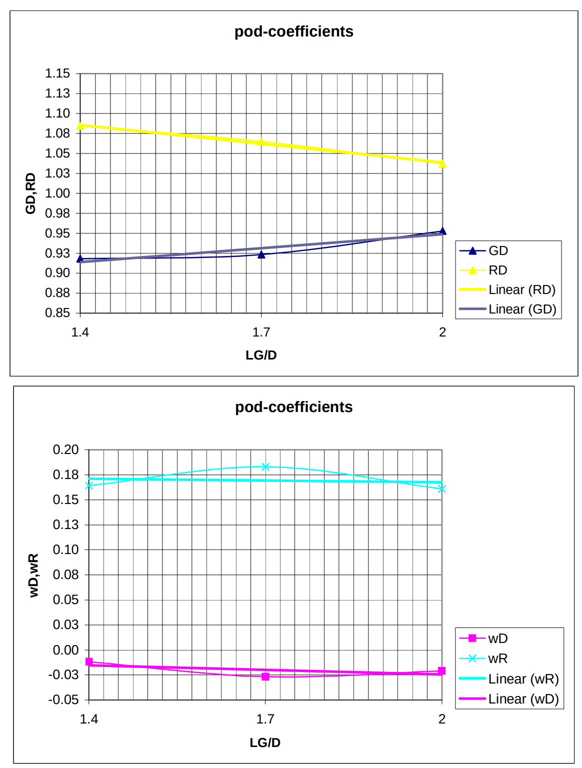

Fig. 7. Gondola-coefficients in dependency on the length ratio (Gondola length LG, propeller diameter D)

3.0 FINAL HYDRODYNAMIC DESIGN OF FORTJES® Z-DRIVE

All hydrodynamic active parts of the FORTJES® were optimized by REINTJES in cooperation with the Potsdam model basin. The basic configuration of a CR propeller arrangement with propellers at a lower gear box was tested in the Hamburg model basin, with a pre-design for strut, gondola and an initial design for propellers.

3.1 Propeller arrangement at gear box (push-push, pull-pull or push-pull)

In a first step different possibilities fort the arrangement of propellers were tested in the model basins. The open water tests were carried out in the towing tank of the SVA Potsdam (280 x 9 x 4.5 m). The differences in efficiencies between the three types of arrangements (push-push, pull-pull and push-pull) are not so significant. The push-pull arrangement was preferred, because in this case the CR propellers at the gondola (gear box) works without a hollow shaft.

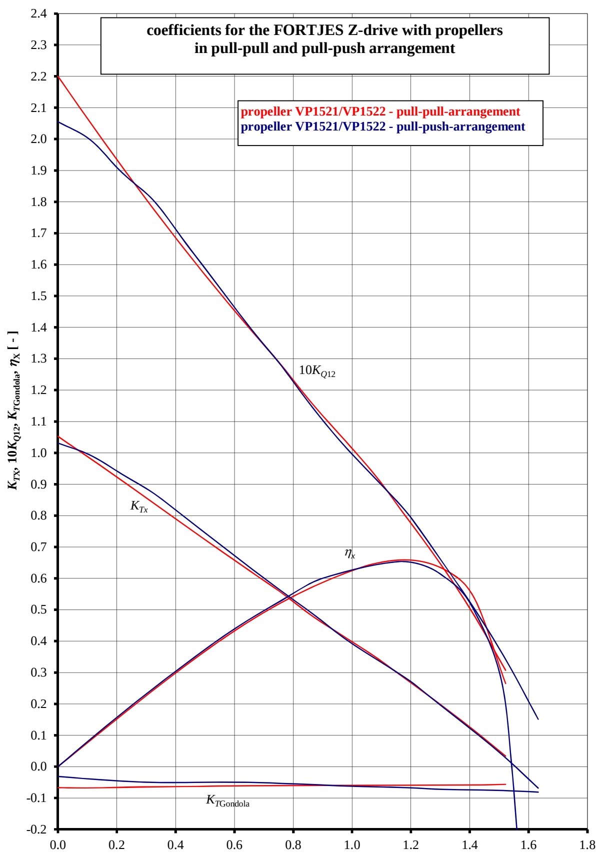

Fig. 8. Comparison of open water characteristics for the pull-pull and push-pull arrangement

3.2 Optimisation of the lower gear box (gondola) design

Referring to the results from Section 2.2 the shape of the lower gear box (gondola) has a strong influence on the hydrodynamic characteristics of the CR propeller system. The lower gear box is in general a cylindrical and symmetrical body. Hence an optimization of the gondola it is possible to use profile theoretical tools based on potential flow calculations and 2D CFD methods. For the calculation of gondola resistance the SVA Potsdam has used the open source code XFOIL 6.96 and the 2D Navier Stokes Solver Navier2D from D. Engwirda (2007) (open source code for MATLAB). The shape of the gondola must fulfill two essential requirements: At first it must be a housing for the "mechanical gear" that means it must be a good container for shaft, bearings and tooth wheels (etc.) and on the other hand the gondola must have good hydrodynamic properties, i.e., it must have especially low resistance. Under these restrictions an optimal value was found for a NACA-like family of profiles for a back position of maximal thickness of 55% and 0.25 thickness ratio for a Reynolds-number of 1E7 with the code XFOIL 6.9.

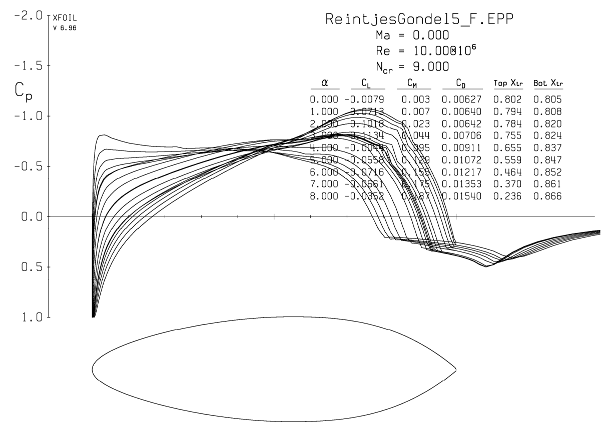

Fig. 9. Optimised NACA like – Profile with 55 % back position of maximal thickness and 0.251 thickness ratio (c_D with respect to chord length)

Then in addition, studies were carried out to simplify the hub geometry for the second propeller using CFD methods (Fig. 10).

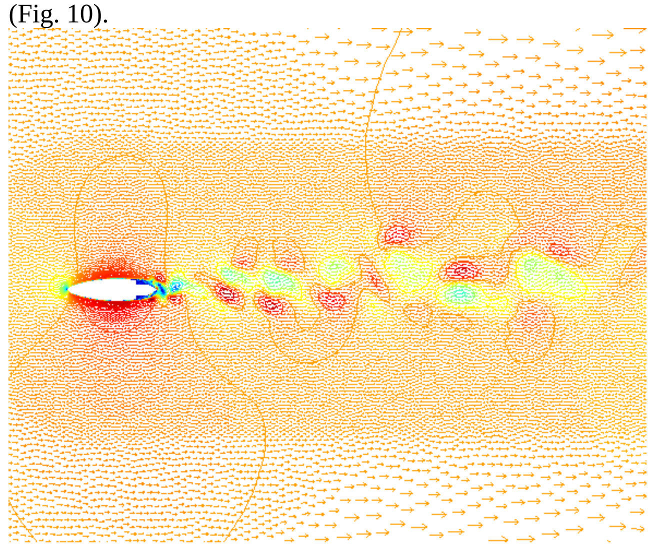

Fig. 10. Calculation of flow around the gondola with cylindrical hub for the second propeller (Reynolds-number 1E7)

The drag coefficients (with respect to the cross sectional area) were calculated to be C_{D1} = 0.0284 for a faired hub contour and C_{D2} = 0.0241 for the hub contour like Fig. 8. These values can be compared with the resistance coefficients of a penguin ($C_{D,Pinguin}$ = 0.03). Later measurements with a rotating rear propeller showed, however, lower resistance coefficients (overall efficiency) for the faired hub, i.e., the gondola and hubs (for the front and the rear propeller) have a profile as shown in Fig. 7.

3.3 Optimisation of the strut

The significant advantage of a counter-rotating propeller assembly with respect to efficiency is the swirl compensation of both propellers. With an additional body between the two propellers this swirl compensation is disturbed. Consequently, for high efficiency of the whole system the swirl of the front propeller must reach the rear propeller undisturbed. By means of potential theory method the swirl of the front propeller which interacts with the strut was determined (see Fig. 11). After the selection of suitable profile contours for the strut geometry (also in dependence of the mechanical requirements) the angle of attack for each vertical profile cut of the twisted strut was determined in such a way that the swirl is not reduced.

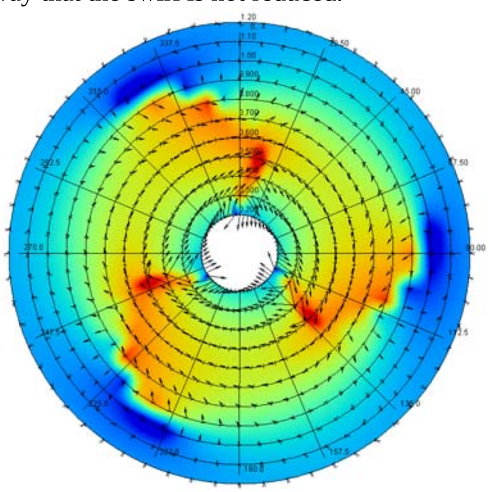

Fig. 11. Calculated flow of the front propeller with swirl (clockwise rotation)

As a result, an asymmetrical twisted strut is obtained as represented in Fig. 12.

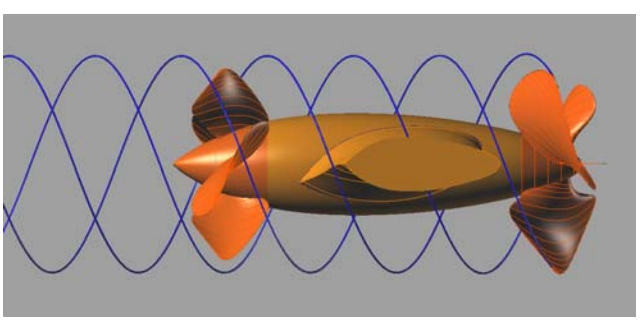

Fig. 12. Asymmetrical strut of FORTJES® with a suggested tip vortex

To check the correctness of the procedure for the strut design LDV measurements were finally carried out in the disk area of the rear propeller (Fig. 13). The results showed that the swirl of the front propeller was not reduced.

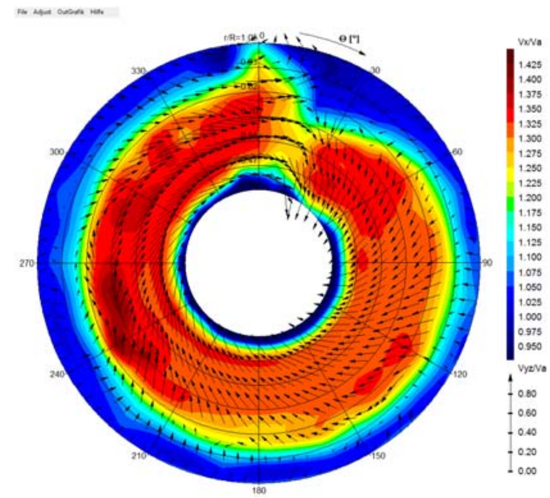

Fig. 13. LDV Measured flow in the plane of the rear propeller.

3.3 Optimisation of propellers

For the optimization of the front and rear propeller four programs (HSPopt, VORTEX, VTXopt and UNCA) were used. The program VORTEX calculates the quasi-stationary characteristics of propellers using the lifting surface method (Schulze, 1995). In cooperation with postprocessors for a graphical representation VORTEX computes the open water characteristic, the pressure distribution, the cavitation behaviour, the forces and moments, and the velocity field around the propeller. If an instationary inflow is defined, then VORTEX computes in cooperation with the postprocessor CAVIPLOT the quasi-stationary cavitation behaviour in the wake field and in cooperation with the postprocessor VTXFORCE the forces and moments acting at the blades and the propeller (body forces). The algorithms in the vortex lattice method generally lead to programs with a short computing time and sufficient accuracy. In contrast to other software VORTEX uses four parameters for a friction correction. All parameters for the friction correction are estimated by an ensemble of measurements with model propellers and have a functional representation with respect to the propeller main characteristics. This ensures a well behaved accuracy for propellers with unconventional geometry, too. The program UNCA (Szantyr, 1993) calculates the unsteady characteristics of propellers using the lifting surface method. UNCA includes a cavitation model and a tool for the estimation of tip vortex inception. The SVA has performed program interfaces between VORTEX and UNCA. The program VTXopt is based on the core of VORTEX and includes a full optimization algorithm for propeller design.

With the code HSPopt (H.-J. Heinke, R. Schulze, M. Steinwand, 2009), the pre-selection of the three-bladed front propeller for high-speed applications was carried out. After the pre-selection, the front propeller was further optimized using VTXopt to obtain the best cavitation properties and highest efficiencies.

With the methods from Section 3, the interactions of the front propeller with the gondola and strut were taken into account. After the calculation of the velocity distribution of the front propeller (Fig. 11) with VORTEX, the four-bladed rear propeller was optimized under consideration of the inflow from the front propeller using VTXopt.

The combination of a three-bladed front and a four-bladed rear propeller ensure good noise and vibration characteristics.

4.0 CONCLUSIONS

For a yacht application the FORTJES®-drive was intensively tested in the model basin SVA-Potsdam for propulsion, cavitation and manoeuvring properties in comparison to a usual twin-screw arrangement. After the tests the following advantages can be summarized as follows:

- The realization of FORTJES® as a Z-drive with two propellers makes an easy installation possible and avoids the use of inclined shafts.
- The recovering of swirl losses by the contra-rotating arrangement gives a higher efficiency than a usual twin-screw concept.
- The push-pull concept in combination with an asymmetric strut saves the advantages of the usual contra-rotating propellers.
- The distribution of the input power to a three-bladed front and a four-bladed rear propeller gives excellent cavitation, noise, and vibration properties for high-speed applications.

Future research projects are planned for improving the interaction estimations based on the methods described in Section 2.2 for gondola geometries with asymmetric struts and the definition and optimisation of contra-rotating propeller series for a variety of high-speed applications as well as the derivation of polynomial coefficients for a quick pre-selection of the propellers.

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