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Ducted Propulsors in Open Water

Performance assessed by basic principles

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ABSTRACT

Main dimensions in terms of diameters and performance data in terms of open water charts do not permit readily to assess the merits of given ducted propulsors. Pre-requisite for this purpose are explicit 'curves' of flow cross-sections and of the equivalent ideal and the hydraulic efficiencies of the propulsors and, maybe, additional detailed evaluations of rotor and stator performances.

The sample evaluations provided, conveniently arranged in reverse order, may be acceptable as first steps towards a rational standard of presentation to be developed and agreed upon by the parties concerned.

Keywords

Performance analysis, 'ideal' efficiency, hydraulic efficiency, thrust ratios, pressure levels, flow cross-sections.

1 INTRODUCTION

Based on the analysis of a paper by Jürgens and Bohm on a 'LinearJet' (1998) provided as 'preprint' a written contribution had been prepared to the discussion of the paper by Jürgens and Heinke, presented at the annual meeting of STG at Hamburg in November 2006. Since that time the analysis of the data, finally those of the design presented in 2006, and the discussion have been continued in great depth and detail, too detailed for an update of the contribution to be included in the STG proceedings.

Accordingly the present paper has been conceived some time ago to provide the necessary theoretical reference for the detailed analysis to be found on the website of the author, based on the open water results of CFD computations in figure 11 of Jürgen's paper of 2006. For the purposes of illustration some plots of the results of the analysis are provided in this paper. The report and the doctoral thesis on a closely related project by Steden *et alii* (2010.1, 2010.2) have been received too late for an equally detailed analysis. The few results included in the present paper are based on the geometry and the model test results of the design LV4.

The interest of the present author in the subject is threefold. *Firstly*, as a member of the ITTC Presentation (!) Committee, later the ITTC Symbols and Terminology Group, from 1975 to 1996 the author feels, that for the purposes of discussion and analysis of ducted propulsors the pertinent ITTC symbols and terminology urgently need to be further developed. The first version of the newly structured ITTC List of Symbols and Terminology, Version 1993, conceived and produced by the author and still to be found on his own website, reproduced with small, if any, changes in Version 2002, to be found on the website of SNAME, is no longer meeting present requirements.

Even more than the symbols this concerns the presentation of results in standardised formats readily showing the essentials, the subject of the present exercise. Particularly in view of results of CFD codes the need for such presentations is felt to be mandatory. Results presented at the first International Conference on Numerical Ship Hydrodynamics reportedly could not be compared.

Secondly, the author has been working on ducted propulsors during his whole professional career since 1961 and continues to do so. The widely ranging results of this work have been presented on many occasions and have been published in various papers, many to be found on the website of the author. *From the very beginning of main concern have been conceptual solutions for the design and evaluation of propulsors in behind conditions, in non-uniform displacement and/or energy wakes (1994).*

This is worth noting as most ducted propulsors are still designed as 'open water' propulsors in uniform wakes and hull-propulsor interactions are treated very crudely, in fact even incorrectly according to the author's experimental results of 1961. Designers are not yet facing the problems ahead of them and thus cannot appreciate the conceptual solution proposed and successfully demonstrated. To the knowledge of the author the potential of CFD codes to account implicitly for the interactions are not yet exploited. Concerning this 'deficit' Sedow's pertinent opening address at the IUTAM Symposium in Leningrad 1971 will be quoted further down.

The 'state of the art' looks rather similar to the early applications of digital computers, *e. g.*, re-computing the tables of logarithms etc at Harvard University. And it is similar to the situation in boundary layer research before Hermann Schlichting published his 'Boundary Layer Theory'. Further it reminds the author of Goethe's remark concerning Francis Bacon's approach (Helmreich, 2007/171): 'er komme ihm so vor wie ein Herkules, der "einen Stall vom dialektischen Mist reinigt, um ihn mit Erfahrungsmist füllen zu lassen".' It requires little powers of imagination to guess why Goethe wrote (!) this immodest verdict, though only in a letter, and why it is quoted here.

Thirdly, the author has repeatedly studied performance criteria for the objective assessment of unconventional propulsors (1968, 1970). And this is again the topic of the present paper, rather a beginner's exercise in the light of the author's past research. The goal is simply to show, that the main dimensions of ducted propulsors in open water described in terms of diameters need to be supplemented by areas of flow cross-sections permitting to judge essential characteristics of the design. Further, data plotted in the standard fashion of an open water chart need to be supplemented by additional plots of equivalent ideal and hydraulic efficiencies in particular, permitting readily to assess the performance and objectively compare different configurations.

2 OPEN WATER CHART

A ducted propulsor P is conceived as an actuator, consisting of rotor R and stator S, in a duct, the latter consisting of the duct proper D and the hub H. As reference quantities the density of the water ρ and the diameters of the rotor D_R and the jet D_J will be used.

On model scale measurements can be performed of torque Q_R and thrust at the rotor T_R and of thrust at the stator and duct together T_{SD} at varying speeds of the propulsor V_P and rates of revolution of the rotor n_R. Thus, in terms of normalised magnitudes, the basic data are functions of the advance ratio (figure 1).

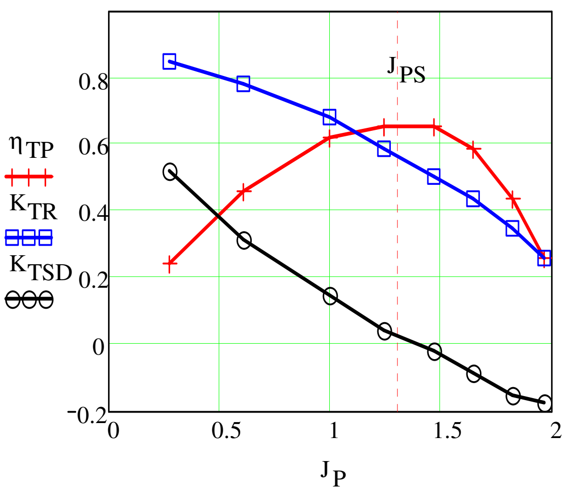

Figure 1: Open water chart of Jürgen's propulsor

These data, or any equivalent, computed model and full scale as in the case of the data analysed, do not permit directly to assess the merits of the configuration under investigation.

The situation is *not 'really'* improved by introducing the propulsive efficiency

$$\eta_{TP} \equiv T_P\, V_P / P_P = K_{TP}\, J_P / K_{PP}\,,$$

with the total thrust

$$T_P = T_R + T_{SD}$$

and the power

$$P_P \equiv 2\,\pi\, n_R\, Q_R$$

and the corresponding thrust ratio

$$K_{TP} \equiv K_{TR} + K_{TSD}$$

and power ratio

$$K_{PP} \equiv 2\,\pi\, K_{QP}\,,$$

respectively.

At the service condition the thrust at stator and duct together is nearly vanishing. For optimum designs the thrust at the duct alone should indeed be zero at the service condition. As has been pointed out over and over again, contrary to professional superstition the purposes of ducts are not to 'produce' thrust, but to produce, together with the stators, uniform jets as far as possible.

3 HYDRAULIC EFFICIENCY

The criterion for the quality of any propulsor in open water is its hydraulic efficiency, the ratio of the minimal power necessary to produce the given thrust at the given speed and the actual power required by the propulsor

$$\eta_{JP} \equiv P_J / P_P\,.$$

The minimal power P_J is the power of the ideal equivalent propulsor with the 'ideal' efficiency

$$\eta_{TJ} \equiv T_P\, V_P / P_J\,.$$

The hydraulic efficiency may thus be obtained as the ratio of the propulsive efficiency and the 'ideal efficiency'

$$\eta_{JP} = \eta_{TP} / \eta_{TJ}\,,$$

This efficiency includes not only frictional losses at the duct, rotor stator and hub, but also losses due to any nonuniformity of the flow behind the stator, if any, and is thus adequately called 'hydraulic efficiency'. The names 'pump efficiency' or 'inner efficiency' are meaningful only in special cases, which are not of interest in the present context, aiming at a general procedure for assessing and comparing performances of ducted propulsors in open water.

The separation of the propulsive efficiency into its components is of fundamental interest in judging a propulsor design in the context of a ship or vehicle design. A low value of the ideal efficiency is to be blamed on the naval architect, providing too little space for the propulsor, while a low value of the hydraulic efficiency is to be blamed on the 'pump' designer.

Naval architects known to the author do not use the hydraulic efficiency as performance criterion, different from pump designers, except at the bollard condition, although the advantage of the concept has been pointed out repeatedly (Schmiechen, 1966, 1968).

In order to identify values of the hydraulic efficiency values of the power or the efficiency of the ideal equivalent propulsor have to be determined, a problem to be discussed next.

4 'IDEAL EFFICIENCY'

The 'ideal efficiency' of *any* propulsor is the function

$$\eta_{TJ} = 2 / (1 + (1 + c_E)^{1/2})$$

of the energy loading parameter (Energie-Belastungsgrad)

$$c_E \equiv \Delta e / (\rho V_P^2 / 2)$$

$$= Q \Delta e / (Q \rho V_P^2 / 2) ,$$

the 'head' Δe and the flow rate Q of the propulsor.

In terms of the parameter of the vorticity generated (!), the normalised speed excess

$$\tau \equiv (V_J - V_P) / V_P$$

and the relationship

$$c_E = 2 \tau + \tau^2$$

the 'ideal efficiency' may also be expressed in the simple format

$$\eta_{TJ} = 1 / (1 + \tau / 2) .$$

The advantage of this exposition is that it is independent of the type of propulsor considered, that it is clearly distinguishing the ideal jet produced from any ideal propulsor that may be conceived to produce that jet.

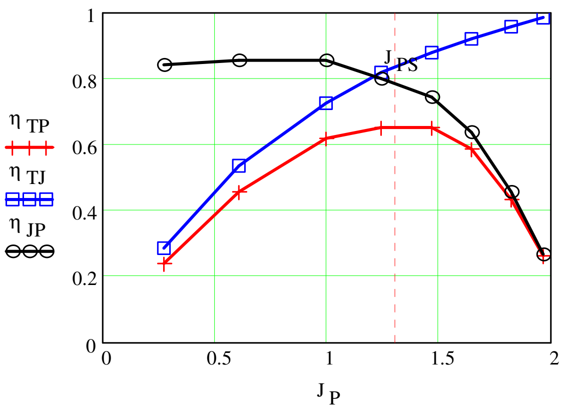

Figure 2: Ideal and hydraulic efficiencies of Jürgen's design

Only in case of the usually only model, an ideal actuator disc with area A_A , the fundamental energy loading parameter 'happens' to be equal to the thrust loading parameter

$$c_E = c_{TA} \equiv T_P / (A_A \rho V_P^2 / 2) ,$$

with the thrust

$$T_P = A_A \Delta e = A_A \Delta p .$$

In case of an ideal ducted propulsor the area of the actuator in the duct may be any and thus it is *not* useful as a reference, but has to be replaced by the area of the jet produced by the propulsor

$$A_J = \pi D_J^2 / 4 .$$

In this case the vorticity parameter is obtained from the equation

$$2\tau (1 + \tau) = c_{TJ} \equiv T_P / (A_J \rho V_P^2 / 2)$$

$$= 2 K_{TP} / J_P^2 D_R^2 / A_J .$$

Accordingly values of the ideal efficiency

$$\eta_{TJ} = 4 / (3 + (1 + 2 c_{TJ})^{1/2})$$

and subsequently of the hydraulic efficiency have been computed using the outlet area of the duct as reference. *To denote the two different thrust loading parameters by the same symbol is grossly misleading.*

The jet area, though being an adequate reference, is not readily available, but may be more or (usually) less smaller or larger than the outlet area of the duct, depending on the shape of the duct and its outlet. Unless detailed data are available the outlet area may be considered as a *conventional*, well defined reference and the efficiencies should in future be denoted accordingly.

The results (figure 2) show that despite the frictional losses at the stator and the duct high values of the hydraulic efficiency, in the same range as those of open model propellers, are achieved due to the nearly uniform load distribution and the nearly complete absence of swirl in the jet. The quite high ideal efficiency indicates that the energy loading parameter of the design analysed is rather small, 1.0 at the service condition.

Figure 3 shows a comparison of the propulsors of Jürgens and Steden *et alii* in a 'universal' chart proposed earlier by the author. The two efficiencies introduced are plotted versus each other, the hydraulic efficiency versus the ideal efficiency, the latter as a 'universal' measure of 'advance' and as 'inverse' measure of the energy loading parameter.

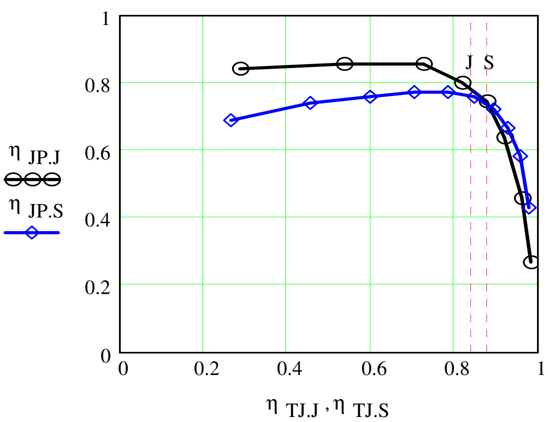

Figure 3: Jürgen's and Steden's designs compared

For ready reference figure 4 shows a comparison of the propulsive efficiencies of both propulsors with those of the open propeller B 4.60.

The purpose of these plots is not to discuss the differences of the two designs available for analysis, but to demonstrate the advantage of the presentation proposed for scrutinising and comparing competitive designs.

5 WHEN TO USE DUCTS?

According to a simple estimate by Horn in the 1950s the value 1.0 of the energy loading parameter is the lower limit for ducts to be applied, and if any, they should include stators. In the literature other criteria are to be found based on different rationales.

A very elaborate analysis has been published by Dickmann based on the state of art in pump design, 'of course' in terms of dimensionless pump parameters and their optimal relationship, the Cordier 'line' (1955).

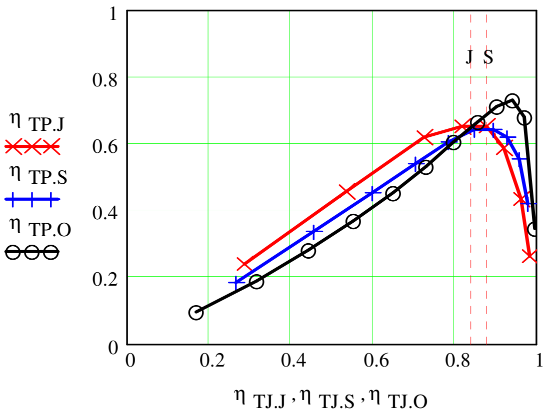

Figure 4: Propulsive efficiencies compared

As for the Jürgens propulsor no competing design of an open propeller is available in figure 5 only the essentials are shown in 'universal' plots for the propellers B 4.60 open, *i. e.* without duct, and KC 4.60 in duct 19A, respectively, both with pitch diameter ratio 1.2. It is noted that both propulsors are not optimum designs according to present day standards.

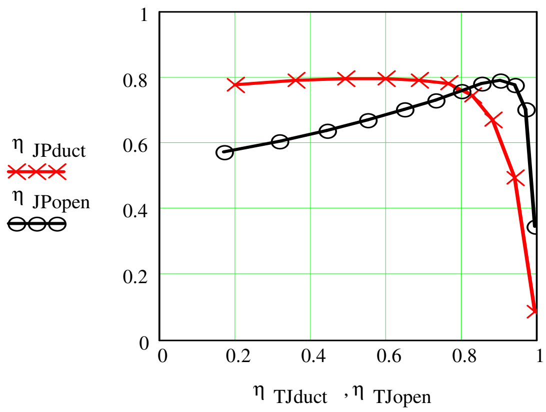

Figure 5: Open propeller B 4.60 versus ducted propeller KC 4.60 in duct 19A, P/D 1.2

Thus a criterion for the application of ducts (though without stator) is

$$\eta_{TJ} < 0.8$$

in terms of the ideal efficiency, corresponding to

$$c_E > 1.25$$

in terms of the energy loading parameter and this is close (enough) to Horn's criterion, which is thus felt to be substantiated in a very fundamental and intellectually satisfactory fashion.

As stated by the authors the propulsors under investigation have both not been designed for conditions typically met at vessels navigating shallow waters, but to compete with lightly loaded open propellers for high speeds.

Thus the hydraulic superiority of ducted propulsors is not exploited, but as figures 3 and 4 show both designs shift Horn's criterion to considerably higher values of the ideal efficiency and correspondingly lower values of the energy loading, in case of Steden's design

$$\eta_{TJ} < 0.88$$

corresponding to

$$c_E > 0.62 ,$$

only half the conservative value stated before.

6 DISTRIBUTION OF THRUST : NOMINAL

If an ideal propulsor with an actuator of the same area as the jet is being considered the distribution of the thrust between actuator

$$K_{TAn} = r_J K_{TP}$$

and the duct

$$K_{TDn} = (1 - r_J) K_{TP}$$

is determined by the theoretical function

$$r_J = (1 + \tau/2)/(1 + \tau) .$$

The notation indicates that under real conditions these magnitudes are nominal magnitudes based on the specific energy between inlet and outlet, the jet flow assumed to be uniform.

If the area of the actuator is different from that of the jet the thrust distribution is obtained according to the same laws provided the ratio r_J is replaced by the ratio

$$r_A = a_J r_J$$

with the ratio

$$a_J = (D_R^2 - D_H^2)/D_J^2 .$$

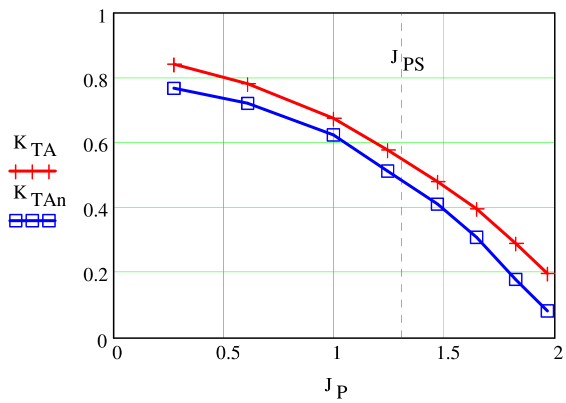

Figure 6: Actuator thrust ratios of Jürgen's design

In the design analysed the ratio of areas is very nearly

$$a_J = a_J = 1 ,$$

to be discussed under '11 Design considerations'. In case of Steden's design the entry area is larger than that of the inflow thus increasing the pressure in front of the rotor and reducing the cavitation susceptibility.

As the derivation clearly shows and has been repeatedly stated the distribution of thrust and thus the cavitation susceptibly do in principle not depend on the meridial profile of the duct, but solely on the area of actuator relative to the area of the jet.

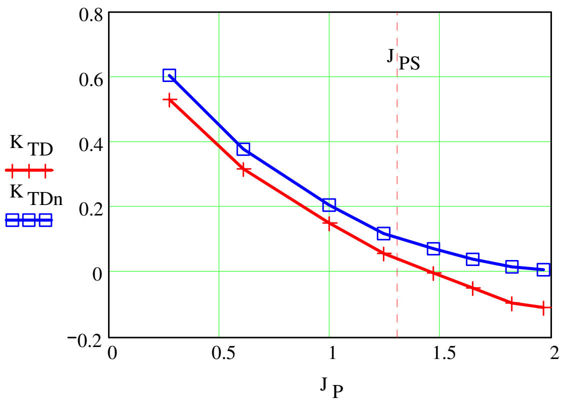

Figure 7: Duct thrust ratios of Jürgen's design

Although Dickmann and Weissinger (1955) already treated ducted propulsors as pumps they did not explicitly note these fundamental facts (Schmiechen, 2003), which still contradict the 'instinctive beliefs' (Russell, 1912) of naval architects known to the author.

7 DISTRIBUTION OF THRUST : ACTUAL

The actual actuator thrust ratio can be determined from the power ratio

$$K_{TA} = \eta_{AP} K_{PP} / J_R$$

taking into account the advance ratio of the rotor

$$J_R = J_P (1 + \tau) / a_J$$

and the efficiency of the actuator, assumed to be

$$\eta_{AP} = 1 - x_A (1 - \eta_{JP}) ,$$

the unknown ratio x_A crudely guessed to be 50 %.

Accordingly the actual duct thrust ratio is

$$K_{TD} = K_{TP} - K_{TA} .$$

8 ROTOR THRUST RATIOS

In addition the nominal thrust ratio at the rotor may be determined from the power input into the fluid at the rotor according to the equation

$$K_{TRn} = \eta_{RP} K_{PP} / J_R .$$

with the efficiency of the rotor η_{RP} assumed as for the actuator, the unknown ratio x_R crudely guessed to be .25.

The difference between the actual and the nominal thrust ratios at the rotor

$$\Delta K_{TR} = K_{TR} - K_{TRn}$$

is nothing but the interaction between rotor and stator, caused by the pressure reduction due to tangential velocity field between the two. The difference is small over the whole range, so that the nominal ratio will in general provide a sufficient approximation.

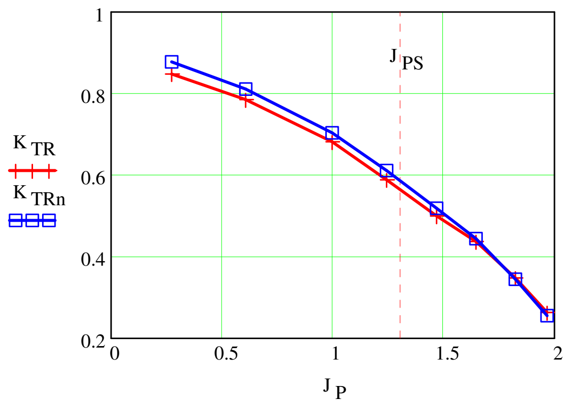

Figure 8: Rotor thrust ratios of Jürgen's design

9 STATOR THRUST RATIOS

The nominal and the actual stator thrust ratios are now obtained by the simple equations

$$K_{TSn} = K_{TA} - K_{TRn}$$

and

$$K_{TS} = K_{TA} - K_{TR} ,$$

respectively. The values being very small the differences are uncertain.

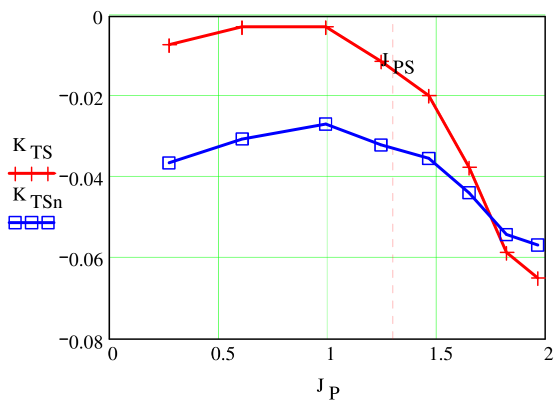

Figure 9: Stator thrust ratios of Jürgen's design

10 PRESSURE LEVELS

For the assessment of the cavitation susceptibility the pressure level ahead of the actuator, i. e. ahead of the rotor in the present design

$$k_{pA} = 1 - (J_R / J_P)^2$$

is of particular interest.

It is lower than the ideal pressure level due to the rotor area being slightly smaller than the outlet area.

The pressure level at the exit of the actuator, at the entry of the outlet duct

$$k_{pD} = k_{pA} (1 - 1 / \eta_{AP})$$

is higher than the ambient pressure due to the losses in the outlet duct.

The problem of the very low pressure level ahead of the rotor may be eased considerably by only a small increase in the area of the rotor. The rule is simply

$$k_{pA} = 1 - (1 + \tau)^2 / a_J^{\,2} .$$

To be discussed further under '11 Design considerations'.

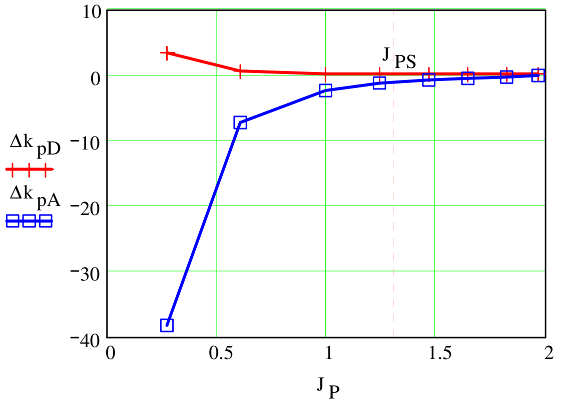

Figure 10: Pressure levels of Jürgen's design

In Steden's design the flow is retarded ahead of the propulsor, *i. e.* without losses, in order to reduce the cavitation susceptibility, and further the flow is continuously accelerated in a perfect nozzle flow as suggested by the ideal model of the author. Thus, instead of 'Linearjet' a catching name for the propulsor would have been 'Lightly Loaded Nozzle-Propeller' in contrast to Kort's heavily loaded Nozzle-Propeller (Düsen-Propeller).

11 SCALE EFFECTS

The advantage of ducted propulsors with stators is that they permit to approach ideal propulsors as has been stated over and over again 'since times unknown', more recently by Steden *et alii* with the same words. This gain may be more than balanced by losses in stators and ducts, if these are not carefully designed. Ducts have to be kept extremely short as already Kort found out.

According to CFD computations, the axial flow velocities shown in figure 15 of Jürgen's paper of 2006 (figure 12), a scale effect of 8 % in total propulsive efficiency at the service condition has been reported. Thus the full scale value of the hydraulic efficiency at the service condition may be assumed to be 0.79 x 1.08 = 0.85. In the case analysed the outflow is still far from ideal, evidently not only due to the incredible 'Ablaufhaube'. Scale effects have also been determined by Steden.

12 DESIGN CONSIDERATIONS

At the early stages of a design the preliminary procedure proposed by the author may be adapted and the equation of continuity, more or rather less advanced potential theory, is perfectly sufficient to arrive at an initial 'solution' as shown earlier (Schmiechen, 1978, 1983).

Figure 11 shows the very small relative differences between the contour of a preliminary design based on momentum theory, very few crude assumptions and the equation of continuity and the contour of Steden's design.

The purpose of this comparison is to substantiate the claim of the author, stated over and over again, that the design of the duct is 'not the problem'. All details are to be found on the website of the author in a Mathcad worksheet, including an interesting analysis in terms of specific speed and head, too 'specific' for this paper.

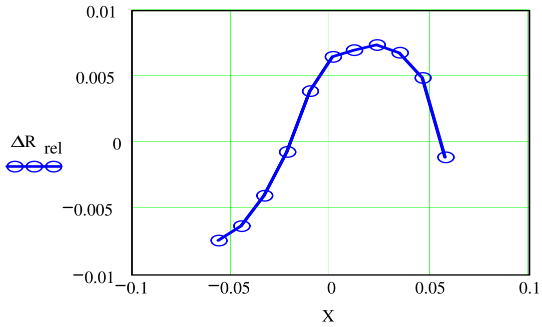

Figure 11: Relative differences of internal duct contours of a design based on the equation of continuity and Steden's design LV4

Following the design of the hub/duct system the 'only' problem is the design of the pump stages starting from ideal rotors and stators with infinite numbers of blades. In view of this 'procedure' diameter ratios, as usually provided among the main parameters of a design are of no use at all for an assessment of the design, but are grossly misleading.

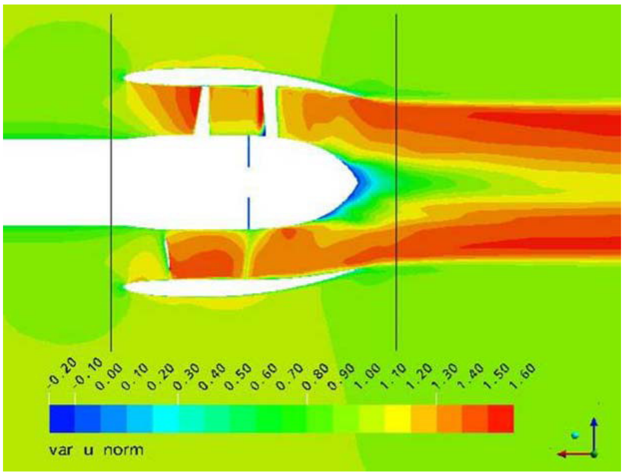

Figure 12: Computed velocities at the service condition J = 1,31 on model scale Re = 1.30*10^6 (Jürgens, 2006)

Only ratios of areas of flow cross-sections permit directly to scrutinise the design. As has been noted earlier the value 0.033 m^2 of the outlet cross-section of the design under consideration is even slightly larger than the value 0.032 m^2 of the cross-sections of rotor and stator.

As the 'original' name 'LinearJet' of the 'Voith Water Jet' suggests, and as has been observed earlier, the design investigated thus very closely resembles the ideal 'tube' propulsor (Rohr-Propeller) discussed by Föttinger in 1918 (figure 13). The main disadvantage of this type of propulsor is the high thrust of the duct and the low pressure level ahead of the actuator, causing cavitation susceptibility, a problem that can be reduced by only a slight increase in the area of the rotor. Despite the public discussion Steden's design is called 'Linearjet' (2010).

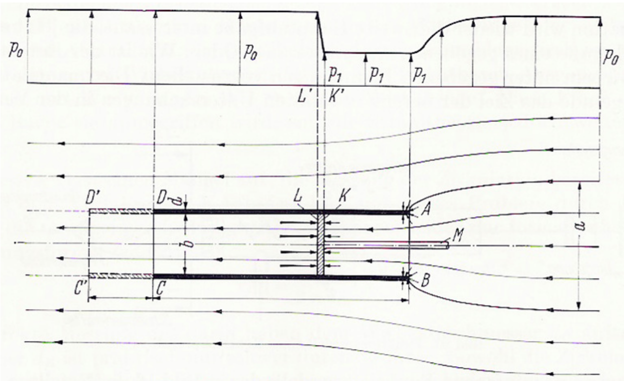

Figure 13: Föttinger's Rohr-Propeller (1918)

This measure together with the adequate design of rotor and stator *not* for axial flow and a well tapered hub in an extremely short duct will result in an optimum, nearly uniformly accelerated flow through the propulsor, small frictional losses and low cavitation susceptibility, comparable to that of open propellers, may be even better as in Steden's design.

Attempts at Wageningen long ago to reduce the cavitation susceptibility by retarding the inflow in a diffuser have been unsuccessful and have been abandoned. In view of the author's ideal propulsor model, any such attempt may be considered as somewhat 'irrational', accelerating and decelerating the flow inside the duct causing unnecessary losses.

A typical ducted propeller does not exhibit a stator. In order to permit dismounting of the rotor without dismounting the duct and stator the diameter of the rotor is slightly less than that of the outlet. Thus these ducted propellers exhibit all the 'negative' features of 'linear jets'.

To keep the area of the rotor cross-section smaller than that of the outlet, as has sometimes been proposed, increases the danger of cavitation due to further reduction of the pressure ahead of the rotor and increases the hydraulic losses due to deceleration of the outflow.

A stator in front of the rotor, in the literature fashionably called pre-swirl devise, as has been used by the author in designing an optimum wake adapted propeller in order to avoid any extra struts, is not (yet) being favoured as it further reduces the pressure in front of the rotor.

Advanced design procedures, as *e. g.*, that developed by Steden, try to account for the various detrimental effects in an optimum fashion. The problem in any case is a near optimum initial design. How this is obtained is hardly ever described, neither explicitly nor implicitly (Steden, 2010/ 36-42); s. also the post scriptum. The author has proposed and successfully applied a procedure based on the dimensionless pump parameters, the specific diameter and the specific 'speed', and their optimal relationship, the Cordier line, as already used by Busmann and Dickmann.

A recent survey of design considerations is to be found in the paper by Lanni (2011) on 'Compact High Power Density Waterjet Propulsion' investigated in the Future Naval Capabilities program overseen by the Office of Naval Research.

13 CONCLUSIONS

The present analysis is not to be considered as an additional discussion of the Voith Water Jet of Jürgens and of the Linearjet of Steden, but as a sample assessment of the performance of ducted propulsors according mass, momentum and energy balances, *i. e.*, the equation of continuity the momentum theory and the Bernoulli equation, not to forget energy input and energy losses.

As the evaluation shows, even values called 'actual' are still 'nominal' or rather 'conventional', if the flow in the jet is far from uniform as in the case analysed. But they already provide very detailed insights into the operation and performances of propulsors and their components.

Although the author has explained the 'mechanism' of ideal ducted propulsors in great detail since 1978 and 1983 and in many subsequent papers and discussions (1992, 1994, 2005, 2006, 2009), in conversations he often had the impression, that the simple basic facts of hydrodynamics are no longer known and those of propulsion are still not fully understood.

In view of the omnipresent CFD codes conceptual discussions are widely considered as old fashioned and obsolete, while the author feels that teaching the fundamentals of propulsion should after all be updated and 'finally' reflect the state of research and meet the requirements of designers. In many respects the situation is close to 'The Trouble with physics' vividly described by Lee Smolin (2004).

14 EPILOGUE

As has been pointed out over and over again the design and performance of ducted propellers *in open water* is not particularly interesting. As has been observed by the author in systematic experiments in 1961, now exactly fifty years ago, and has been repeatedly stated in public since 1968 the performance of ducted propulsors *in the behind condition* is determined by the hull-duct interaction.

This observation, already reported by Busmann in 1935 (Schmiechen, 2003), has after all recently been confirmed by observations at the SVA Potsdam. Busmann has later been owner of Pleuger-Pumps, a company which produced the first podded rudder-drives as early as 1955.

The explanation of his observations has not only been the origin of the rational theory of hull-propeller interaction developed to maturity and promoted by the author, but has lead the author to develop a method for the design of optimum wake adapted ducted propulsors as pumps (Schmiechen, 1987/1993).

Different from axial, radial or mixed flow pumps designed to 'produce pressure', 'propulsor pumps' are designed to 'produce velocity'. In this case the goal is to design for continuously accelerated meridial flow in the propulsor.

In the behind condition propulsors are conveniently no longer considered naively as thrusters to overcome the resistance of given hulls and the suction of the propeller (!), but as pumps proper and all interactions are implicitly treated as in pump design. In Steden's account of the state of art the dramatic advantages of this change of paradigm have not even been mentioned.

This approach is in line with a statement L. I. Sedow in his opening address at the IUTAM Symposium in Leningrad 1971, purposely translated by Georg Weinblum for the inspiration of his German colleagues and students, though to the knowledge of the author without any 'response'. (*Translation of Weinblum's German translation: MS):*

"As everybody knows naval architects have always studied the interaction between hull and propeller. Now the problem is no longer the consideration of the interactions of separately designed compo-nents, but the design of the moving system as a unit.

While until now we used to talk about thrust and resistance of a vehicle, we shall in the very near future only talk about realising of a steadily moving system with vanishing resulting hydro-dynamic force. …"

All his work on this subject is documented on the website of the author under 'News …' and 'Bibliography on ducted propulsors', including the complete Mathcad worksheet (1990), with all details of the design procedure and including plots of the results. In view of the CFD techniques available the procedure is considered to provide 'only' the paradigm of a near optimum initial design, to be adapted in detail to the problems at hand.

While the design procedure poses no serious problems the evaluation of hull adapted propulsors based on integral values to be applied on model and full scale has not yet been developed to satisfaction.

This task may be tackled following the rational evaluation of hull/open propeller interactions, which has finally reached a state of maturity, robustness in particular, as demonstrated in the re-evaluation of a model test carried out before the METEOR tests (Schmiechen, 2005). Details are to be found on the website of the author in the section 'Ship speed trials' and in the section 'Propulsion mechanics' of his *opus magnum* (2009.2/1193-1286).

Practical limitations are that thrust measurements in the shaft line are not standardly possible, forgetting about separate measurements of the thrusts at the stator and duct and at the whole propulsor.

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Extended in-depth discussions with Dr.-Ing. habil. Klaus Wagner during work on this paper, documented on the website of the author, resulted in elaborations on some arguments the author wrongly had considered to be well-known to and understood by any professional, while even some of the simple basic facts of hydrodynamics and propulsion are evidently no longer known as the following post scriptum shows.

The formal review of the preprint has triggered further improvements of the paper and an extended explanatory mail to the reviewer, both to be found on the website of the author.

Other contributions to the discussion are invited and very welcome. As oral and written discussions of papers presented at SMP '11 are not documented elsewhere they will be duly acknowledged and published on the website of the author as the preceding discussions.

In this connection the author suggests that the collections of papers distributed at 'symposia' are no longer called 'proceedings'.

PS: 'THEORETISCHER ABGRUND'

A particularly absurd 'account' of the fundamentals is to be found under '1.1 Theoretischer Hintergrund' in a recent research report and in the in large parts identical doctoral thesis of Steden. The pertinent paragraph is quoted here for ready reference (Steden et alii, 2010.1/6, 2010.2/8) together with notes referring to individual sentences.

"Von Dickmann und Weissinger (1955.2) wie auch von Schmiechen (1978) wird die ideale Strömung um den Propulsor betrachtet [1]. Dickmann behandelt die Theorie optimaler Düsenpropeller bei kleinen Fortschrittsgraden, die Beschleunigungsdüsen verwenden. Dabei wird ein gegenüber diesem Forschungsvorhaben grundlegend unterschiedlicher Zweck der Düse verfolgt, indem die Beschleunigungsdüse einen erheblichen Anteil des Schubes liefert [2]. Schmiechen betrachtet den Propeller als Energiezuführungsorgan, wobei sich die Schubwirkung beiläufig ergibt. [3]. Da sich aus der Beaufschlagung mit Druck in Form eines Sprunges entsprechend dem Gesetz von Bernoulli eine abrupte Geschwindigkeitserhöhung ergibt, [4], *der* [?] aufgrund der Kontinuitätsgleichung innerhalb eines Mantels physikalisch nicht möglich ist [5], verwendet er anstatt des Drucksprunges ein Propellermodell in Form eines homogenen Kraftfeldes [6]. Dieses entspricht hinsichtlich seiner axialen Ausdehnung etwa der Geometrie des Propellers [7]."

Ad 1: All ideal propulsors, including the actuator disc discussed on the foregoing page of the report, are considered to operate in ideal, infinitely extending fluids. The discussion of Dickmann's and Weissinger's paper, already treating ducted propulsors as pumps, would have deserved an extra paragraph, logically to be arranged after the discussion of the ideal models of Rankine and of the author.

Ad 2: This is not necessarily so. As has been discussed nozzles, ducts accelerating the flow, in German 'Düsen' ('Beschleunigungsdüsen' is a pleonasm, at least in hydrodynamics), are of advantage, in particular if designed for vanishing thrust at the service conditions, *e. g.*, Steden's design.

Ad 3: As in pump design *the thrust of rotor, stator and duct*, and in the behind condition all hull-propulsor interactions, *are conveniently treated implicitly and obtained as by-products, as prior assumptions, to start the design* *with, as in case of open propellers, are not available due to lack of prior data.*

Ad 4: This is by any standard the most incredible 'story' ever told about Bernoulli's equation. This 'story', which would apply in case of the actuator disc as well, is the 'result' of *the usually hopelessly inadequate exposition of the simple basic facts of propulsion, including the confusion of specific energy supplied to the flow and the pressure rise in the flow*.

Ad 5: *If energy is supplied by a singular actuator disc or an extended force field not only the pressure rises, but vorticity is generated*, ideally only a vortex-sheet at the edge, usually sketched unrealistically. Sparenberg and his students have investigated the flow resulting from the edge singularity in detail.

Ad 6: Subsequently the next argument is nonsensical as well. The extended force field has been introduced to get away from the singular actuator disc and its edge singularity hardly ever mentioned (1978/79, including the discussions with Sparenberg). *The force field introduced is not 'homogeneous', whatever that term may mean, but is a potential field, thus avoiding the production of vorticity and losses 'inside' the jet.*

The resulting ideal propeller model clearly shows how optimum propulsors are to be designed efficiently, even in the behind condition, provided the implications of the model, having been explained over and over again, are understood with only little powers of imagination. (An attempt to include the original sketch into this paper failed, but it will be shown at the presentation and will be available on the website of the author.)

As demonstrated in a Japanese research project force fields cannot standardly be realised in water. Thus in the next, 'more realistic' ideal model, force fields are replaced by ideal actuator stages, rotors and stators with infinite numbers of blades, as has been done 'since Euler's days'. In the ideal model no duct is required. If an infinitely thin duct is introduced differing from the ideal meridian local thrusts will occur, while the total net thrust *may* vanish (Schmiechen, 2007).

Ad 7: Propeller models of this type are now being used extensively as *computational tools* in CFD codes to save computing time. In the ideal propulsor model of the author force fields serve conveniently, 'though only' as *conceptual tools*.

In conclusion, it is well understood how the absurd account of the fundamentals and the state of the art originated, but it remains unexplained, how it could possibly have crept into the report and escaped the attention of the authors and those responsible for the project.

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Routes of access to work of the author prior to about 1990 are to be found on his website as well.

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