Ducted Propulsors in Open Water
First steps towards their rational evaluation

Michael Schmiechen, Berlin, March 16, 2007.

Abstract

Torque and thrust at the rotor and thrust at stator plus duct measured at a ducted propulsor advancing in open water do not directly permit to assess the merits of a given configuration. Prerequisite for this purpose is an adequate evaluation of the observed performance in terms of the outer or jet and inner or pump efficiencies of the propulsor. Further analysis of the pumpstage permits a detailed evaluation of rotor and stator performances and may be acceptable as a first step towards a rational standard to be developed by the parties concerned.

Introduction

Based on the analysis of a paper by Jürgens and Bohm on a 'LinearJet' (1998) a written contribution had been prepared to the discussion of the recent 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 of the more recent data, 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 to provide the necessary theoretical reference for the detailed analysis of the results of CFD computations in figure 11 on page 10 of the preprint. For the purposes of illustration some plots of the results are provided in this paper. Both, this paper and the sample analysis provide references for the summary of the discussion.

The interest of the present author in the subject is twofold. 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 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, produced by the author and still to be found on his website, reproduced with small, if any, changes in Version 2002, to be found on the website of the SNAME, is no longer meeting present requirements.

Secondly, the author has been working on ducted propulsors during his whole professional career since 1961 and continues to do so. The results of this work have been presented on many occasions at various places and published in many papers, the present may be not the last one. The goal of the present paper is a sort of synthesis, showing that data plotted in the standard fashion of an open water chart may readily be supplemented by additional plots permitting the assessment of the results.

Open water chart

A ducted propulsor P is conceived as an actuator A, consisting of rotor R and stator S, in a duct D, the latter consisting of the duct proper and hub H.

Routinely measurements can be performed of torque and thrust at the rotor and of thrust at the stator and duct together at varying speeds the propulsor and rates of revolution of rotor. Thus, in terms of normalised magnitudes, the basic data are functions of the advance ratio

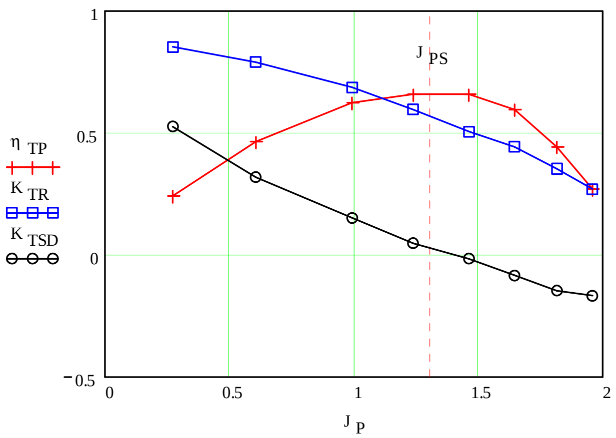
$$J_P \equiv V_P / (D_R\, n_R)$$

$$K_{QR} \equiv Q_R / (\rho\, D^5\, n^2) = k_{QR}(J_P)\,,$$

$$K_{TR} \equiv T_R / (\rho\, D^4\, n^2) = k_{TR}(J_P)\,,$$

$$K_{TSD} \equiv T_{SD} / (\rho\, D^4\, n^2) = k_{TSD}(J_P)\,.$$

These data, or any equivalent as in the case of the data analysed, do not permit to assess the merits of the configuration under investigation.



Inner efficiency

The situation is not 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 ratio

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

and the power ratio

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

as the propulsive efficiency of the propulsor depends on the propulsor loading in a known way.

The decisive criterion for the quality of a propulsor is its inner or pump efficiency, the ratio of the ideal jet power to the propulsor power

$$\eta_{JP} \equiv P_J / P_P = \eta_{TP} / \eta_{TJ}$$

obtained as the ratio of the propulsive efficiency and the outer, ideal or jet efficiency

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

This separation is particularly applicable in case of ducted propulsors with rather uniform flow in the jet, an assumption that does certainly not hold for the propulsor investigated, as figures 15 on page 12 of the preprint show. In such cases the pump efficiency includes 'losses' due to non-uniformity of the jet flow and the resulting evaluation is strictly conventional.

Naval architects do not normally use this efficiency except at the bollard condition although the present author has pointed out its advantage over and over again since his contribution to Grim's paper at Berlin in 1966 and his paper presented at the ONR Symposium at Rome in 1968.

Outer efficiency

The outer efficiency is a function

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

of the loading parameter

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

the normalised head of the propulsor. Only in case of the ideal model of an actuator disc this fundamental parameter 'happens' to be identical with the thrust loading parameter.

Based on the jet diameter the thrust ratio permits to identify the normalised speed excess or vortex parameter

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

from the equation

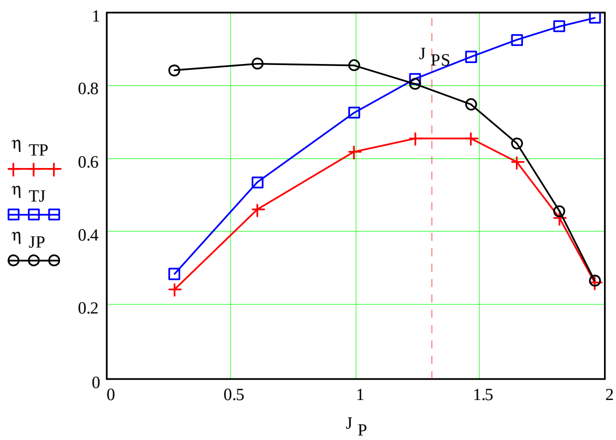
$$\tau + \tau^2 = K_{TP} / J_P{}^2 \, D_R{}^2 / (\pi \, D_J{}^2 / 4)\,.$$

and subsequently the load parameter

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

and thus the jet efficiency

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



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

$$K_{TA\,n} = r_J \, K_{TP}$$

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

$$r_A = r_J\, a$$

with

$$a = (D_R^{\,2} - D_H^{\,2}) / D_J^{\,2} .$$

Distribution of thrust: actual

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

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

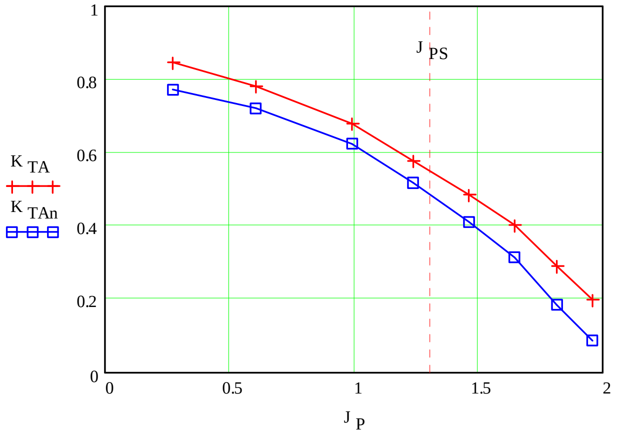
taking into account the advance ratio of the rotor

$$J_R = J_P\, (1 - \tau) / a$$

and the efficiency of the actuator, assumed to be

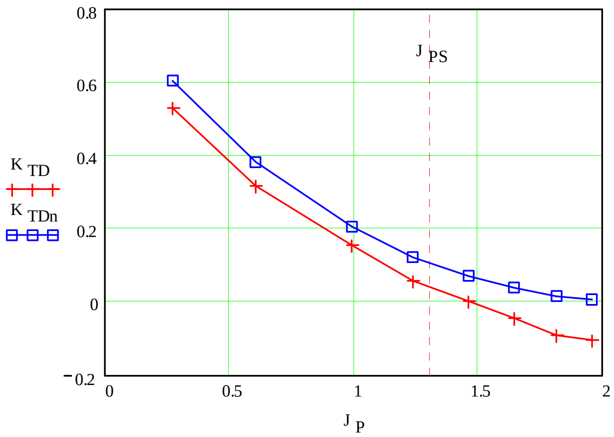
$$\eta_{AP} = 1 - x_A\, (1 - \eta_{JP}) ,$$

the unknown ratio x_A crudely guessed to be 50 %.



Accordingly the actual duct thrust ratio is

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



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

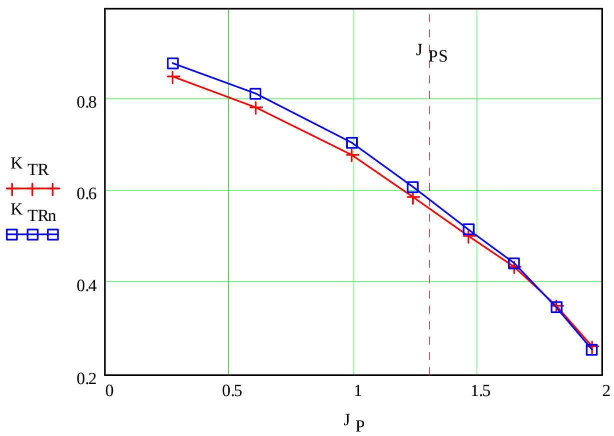
$$K_{TR\,n} = \eta_{RP} K_{PP} / J_R\ .$$

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

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

$$\Delta K_{TR} = K_{TR} - K_{TR\,n}$$

is nothing but the interaction between rotor and stator, caused by the pressure reduction due to tangential velocity field between the two.



Stator thrust ratios

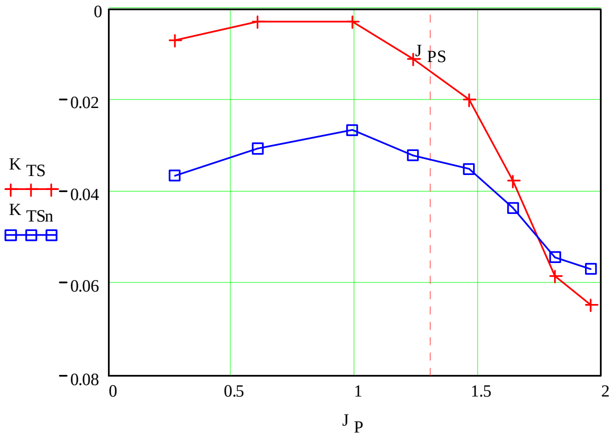
The nominal and the actual stator thrust ratios are now obtained by the simple equations

$$K_{TS\,n} = K_{TA} - K_{TRn}$$

and

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

respectively.



Pressure levels

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

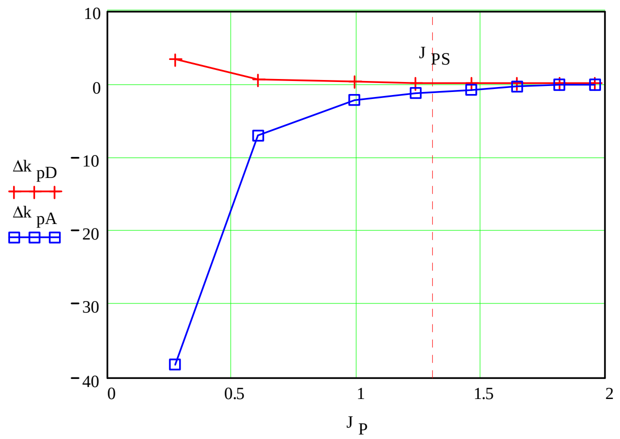
$$k_{pA} = 1 - (J_R / J_P)^2$$

is of particular interest. It is lower than the ideal pressure level due to the rotor area being smaller than the exit area.

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

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

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



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

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

Conclusions

This completes the evaluation of the open water performance of a ducted propulsor according to simple principles based on the momentum theory and the Bernoulli equation including energy input and energy losses. Even the values called 'actual' are still 'nominal' or rather 'conventional', if the flow in the jet is far from uniform. But they already provide very detailed insights into the operation and performance of the propulsor and its components.

The advantage of ducted propulsors with stators is that they permit to approach ideal propulsors. This gain may be more than balanced by the frictional losses in stator and duct unless the ducts are kept extremely short. In the case analysed the outflow is far from ideal due to the 'incredible' hub as shown in figure 15 on page 12 of the preprint. Thus the analysis provides in fact only conventional values.

As the name 'LinearJet' suggests and as has been observed earlier the design investigated very closely resembles the ideal 'tube' propulsor discussed by Föttinger in 1918. The main disadvantage of this type of propulsor is the low pressure level ahead of the actuator, a problem that can be easily avoided by increasing the area of the rotor.

This measure together with the adequate design of the stator on 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. At the early stages of the design the equation of continuity, more or rather less advanced potential theory, is perfectly sufficient (Schmiechen, 1978, 1983).

Outlook

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 found out experimentally in 1961 and has been repeatedly stated 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 recently been confirmed by observations at the SVA Potsdam.

This observation has lead the author to develop a method for the design of ducted propulsors in the behind condition. In that case it is of advantage to forget about the naïve conception of propulsors as thrust producers, but consider them as pumps proper and treat all the energetically neutral interactions implicitly as the pump designers do. All his work on this subject is documented on the website of the author.

While the design procedure poses no serious problems the evaluation of hull adapted propulsors based on integral values has not yet been developed to satisfaction. This task can be tackled now following the example of 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).

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The above papers by the author are to be found under 'What's new in propulsion?' and under 'Recent papers on propulsion' on the website of the author, a complete list of papers is to be found under 'Bibliography on propulsion'.

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