Design and Evaluation of Ducted Propellers as Pumps

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Synopsis

By way of reconstruction of the basic concepts of the theory of propulsion it is shown how methods for design and evaluation of ducted propellers, water jet propulsors in general, can be derived without explicit reference to hull-duct-propeller interactions. By treating propulsors consistently as pumps all interactions between hull and propulsor, consisting of a duct and an actuator, i. e. a pump stage, the latter consisting of a rotor and, maybe, a stator, are accounted for implicitly, different from all other design and evaluation methods.

The underlying model permitting the solution without explicit reference to hull-propulsor interactions is the model of the equivalent propulsor in the energy wake alone, in plausible terms: the equivalent propeller "far behind the ship", if there were no diffusive decay of the wake. This model is not a physically realizable propeller, but an extremely powerful conceptual tool, which has been used by Horn in Germany for the study of hull-propeller interactions. In Russia the same model is being used, surprisingly with different results. This paper presented at the historical meeting of the Centennial of the Krylov Ship Research Institute is intended to continue the discussion and hopefully clarify some of the issues.

1 Introduction

Design or selection and evaluation of ducted propellers are usually based on the conceptual model of the open water condition, although this model is quite inadequate for the problems at hand. It accounts neither for the vorticity in the wake of the hull ahead of the propulsor nor, even more importantly, for the fact, that the interactions between duct and pump stage in the behind condition are totally different from the open condition.

The above mentioned problems can be solved, if instead of the conceptual model of the open water propeller the conceptual model of the equivalent propeller in the energy wake alone is introduced, which accounts for all interactions implicitly. Although this concept is based on the well-known principles of hydromechanics, the balances of mass, momentum, and energy, naval architects are not ready to accept it yet. The reason is that they traditionally are treating interactions as if hull and propeller could be investigated separately, which may have been true for some configurations long ago, but is no longer true for most wake-adapted propulsor designs today.

In a project at VWS, the Berlin Model Basin, two ducted propellers for a body of revolution have been designed, produced under numerical control, and investigated under service conditions on the basis of methods developed earlier. Methods for the evaluation of the propulsive performance of ships based on propulsion tests under service conditions alone have been developed by the present author since twenty five years (1968, 1970). The corresponding design procedures have only been developed over the last ten years (1983/1993).

The goal of the project was the detailed development of the design procedure proposed earlier down to the numerically controlled production of the blades and of the evaluation procedure. In future the procedures developed will have to be integrated into expert systems for propeller design in order to permit wider use by designers. The results of the project have been documented in reports of the Versuchsanstalt für Wasserbau und Schiffbau (Schmiechen, Voss, Engler, 1992; Schmiechen, Goetz, 1993) and the Forschungszentrum des Deutschen Schiffbaus. Although the performance of the propellers was acceptable, the measurements in the large circulating tunnel of VWS produced values still different from the design values. The main reason for these differences may be attributed to the rather elementary and inadequate method of blade design, which has been used and which in future will be replaced by CFD methods. In this short summary only the basic concepts and some results can be outlined.

In order to avoid confusion the whole propulsive system will be called propulsor and its components will be referred to as duct and actuator or pump stage, the latter "ideally" consisting of rotor and stator.

2 Basic concepts

2.1 Ideal propulsors

An ideal propulsor is completely specified by its speed of advance V_P , its flow rate Q , and its "head" e , i. e. the increase of the total energy density of the flow. Normalizing the "head" with the dynamic head results in the loading coefficient

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

and consequently the propeller efficiency, the ideal or jet efficiency

$$\eta_{JP} = 2 / (1 + (1 + c_T)^{1/2}) .$$

This relation is independent of the "design" of the ideal propulsor. Evidently the loading coefficient is identical with the thrust loading coefficient of the equivalent actuator disc, the usual conceptual model of non-ducted propellers. Due to the ill-defined flow conditions at the edge of the actuator disc a much more reasonable model of an ideal propulsor, at least in the present context, is a ducted actuator disc with vanishing thrust at the duct (1978, 1979).

Independently of the propulsor "design" the jet power

$$P_J = Q \Delta e$$

produces a total thrust

$$T = \rho Q (V_S - V_P) ,$$

where

$$V_S = V_P (1 + c_T)^{1/2}$$

denotes the flow velocity far behind the propulsor.

The ideal propulsor introduced, without the usual and unnessecary reference to the actuator disc (1978), does not serve as an approximation for real propellers, but, as has been explained in many papers of the present author at great detail, as an axiomatic model for the coherent definition of quantities which cannot be measured directly.

2.2 Thrust at the duct

If the area of the actuator is A_P the thrust of the actuator is

$$T_P = A_P \Delta e$$

and consequently the thrust at the duct

$$T_D = T - T_P ,$$

independent of the shape of the duct. In practice one has of course to pay attention that the flow does not separate at the duct.

Ideal propulsors can be realized as far as possible by ducted propellers with actuators, i. e. pump stages consisting of rotor and stator. It has to be noted, that in this case the thrust to be measured at the rotor is not identical with the thrust of the pump stage as a whole. Further one has of course to account for the internal pump efficiency when determining the power requirements.

If the area of the pump equals that of the jet, i. e. if the velocity in the pump equals the jet velocity the relative thrust at the duct depends on the loading coefficient. The usual "conclusion" is that a duct produces extra thrust, up to 100 % at bollard condition. Evidently this gain is only apparent. There is no perpetuum mobile, not even in hydrodynamics!

For the following the limiting case of vanishing thrust at the duct is much more interesting. The thrust at the duct vanishes if the area of the actuator is

$$A_P = \eta_{TJ} \, Q \, / \, V_P \, .$$

Only formally the ideal propulsor reduces to the usual actuator disc without duct. The duct does in fact retain its function, permitting optimum head distribution, the circulation not dropping off towards the tips. And this is evidently one advantage of ducts and not the apparent gain in thrust.

The distribution of thrust between actuator and duct is more or less arbitrary and a matter of various aspects, it does not affect the energy balance "at all". In practice this is of course not quite true in view of the pump efficiency depending on the flow conditions in detail.

2.3 Wake concept

Theoretically ideal propulsors can be investigated in uniform, parallel wake fields consisting of displacement wake w_D and energy wake w_E components. Comparison of the thrust T_E of the equivalent propeller in the energy wake alone, i. e. "far behind the hull", and the thrust of the propeller in the total wake provides the thrust deduction fraction as a function of the loading coefficient and the displacement influence ratio

$$\chi = w_D \, / \, (\, 1 - w_D - w_E \,) \, .$$

But this line of thought (1968/1980) cannot be followed here. In view of the length of ducts the concept of open water condition is quite inappropriate, in case of partial ducts in tunnels and in case of jet propulsors it is completely obsolete. For fundamental considerations only the concept of uniform wake without the assumption of parallel flow may be maintained.

In this case the condition of self propulsion may be formulated as momentum balance

$$m \, a + R_E = T_E + F$$

with the effective resistance R_E and the effective thrust T_E , the interpretation of both quantities in terms of measurements has yet to be defined. The inertial resistance has been kept in view of the fact that it may contribute substantially to the momentum balance in case of large masses even at extremely small values of the acceleration.

In general an external towing force F cannot be distinguished from the resistance, but it may be useful to keep track of it separately if possible, e. g. if it is known from measurements.

While for non-ducted propellers the global thrust deduction fraction according to the definition

$$R_E = T \, (\, 1 - t \,)$$

for steady open water conditions without extra external forces can be saved by conventions even in cases, where it is physically not meaningful, this is neither possible for ducted propellers nor jet propulsors.

3 Evaluation

3.1 Energy fluxes

The problem outlined can be solved, if apart of the mass flow only energy fluxes are used for the definition of the quantities in question. The advantage of these quantities is that they remain unchanged at changes of the pressure level and that they consequently can be used for the construction of the equivalent propeller in the energy wake.

The advance speed of the equivalent propeller is

$$V_E = (\, 2 \, E_E \, / \, (\, \rho \, Q \,))^{1/2}$$

with the energy flux at the propeller inlet

$$E_E = Q\ e_E\ .$$

This simple relation holds of course only in case of uniform energy density

$$e_E = (\ \rho\ V^2/2 + p +\ g\ z\ )_E$$

in the inflow. In general it has to be replaced with the integral over the flow rate, and may be used for the definition of an average energy wake

$$V_E = V_H\ (\ 1 - w_E\ )\ .$$

More important is the definition of the energy flux

$$E_J = Q\ e_J$$

at the exit of the propulsor and the corresponding energy velocity

$$V_J = (\ 2\ E_J / (\ \rho\ Q\ ))^{1/2}\ ,$$

which is evidently the jet velocity of the equivalent propeller.

3.2 Thrust of duct

With the fluxes defined so far the momentum fluxes

$$M_i = \rho\ Q\ V_i = (\ 2\ \rho\ Q\ E_i\ )^{1/2}$$

ahead and behind the equivalent propulsor and the effective thrust of this propulsor may be defined

$$T_E = M_J - M_E = \rho\ Q\ (\ V_J - V_E\ )\ .$$

In the steady case with no additional towing forces the momentum balance reduces to

$$R_E = T_E\ .$$

The values of the so defined and measured resistance are in general different from the values of the towing resistance of the hull alone, provided the latter may be determined in a meaningful way. In resistance tests for jet propelled vehicles e. g. the inlets and/or outlets of jet propulsors may have to be closed in order to provide reasonable flow conditions. The values of the towing resistance obtained in this way are certainly not useful for purposes of evaluation. For rather slender hulls propelled by non-ducted propellers on the other hand the values of the effective resistance and the towing resistance proved to be surprisingly close to each other.

Evidently the thrust of the actuator and at the duct are equally irrelevant for the evaluation, as they may assume rather accidental values which do not affect the propulsive performance. In case of a rather slender seagoing vessel the actuator thrust was nearly equal to the effective thrust

$$T_P = T_E\ ,$$

independent of the duct shape (1963). This condition may be considered as rather typical, as the outflow of the duct does neither contract nor expand substantially.

For the same condition the thrust at the duct, taking values depending on shape of the duct, equals the suction at the hull, in formal terms

$$T_D = T -\ T\ (\ 1 - t\ ) = t\ T\ ,$$

if the thrust deduction is introduced.

This at first sight surprising fact has a simple, plausible reason, which is to be found in the mechanism of the thrust and suction generation, which is exactly the same for both, namely the pressure reduction in the duct inlet, which depends on the velocity increase in the duct inlet, which in turn depends on the opening of the duct inlet. This very simple model based on experimental evidence, not published at its discovery (1963), was actually the starting point of the rational theory of hull-propeller interaction (1969/1980), which has been developed in many directions since then.

In other terms: The thrust at the duct and suction are acting in a short circuit without affecting the propulsive performance. The consequence of this finding is that a duct with larger thrust is not necessarily an advantage, as it implies higher flow velocities and consequently larger frictional losses as well as the need for stronger support of the duct as compared with a duct with less thrust.

3.3 Factors of merit

For the evaluation of propulsors various factors of merit may be defined (1970/1980). The jet efficiency has already been introduced. Much more interesting is the outer or configuration efficiency

$$_{TEJ} = T_E \, V_H \, / \, (E_J - E_E) = 2 \, V_H \, / \, (V_J + V_E) \, ,$$

which may be interpreted as the product of hull efficiency and jet efficiency. For the evaluation of real propulsors the inner or pump hydraulic efficiency

$$\eta_{JP} = P_J \, / \, P_P$$

has to be accounted for as well, which may be interpreted as ratio of the propeller efficiency and the jet efficiency.

The advantage of both, the outer or configuration and the inner or pump efficiency, is that they are defined in terms of mass and energy fluxes only. These efficiencies tell in fact much more about the propulsor design than hull and propeller efficiencies, which depend on the propeller loading. In the extreme case of the bollard condition the value of the propeller efficiency vanishes for all propellers, while the propellers serve their purposes and can be rated adequately by their pump efficiency.

The scheme for the evaluation of propulsors based on mass and energy fluxes as proposed (1969) has been used by Masilge (1991) in an investigation of a pump jet in an inadequately modified form, the attempt being made to "obtain" the same values for the towing resistance of the hull with closed duct system and for the effective resistance.

3.4 Measurements

For ducted propellers and water jet propulsors the problem is to determine mass and energy flows from few practical wake measurements. Evidently LDV measurements in the wake are not sufficient for the determination of the energy flux. In the present project the pressure measurements have been substituted by additional computations accounting for the displacement effects. In general, for non-axisymmetric bodies this may not be possible. In any case it is not very reliable in the propeller race.

For the body of revolution under investigation a meaningful towing test was possible and the wake has been measured. The values of the resistance determined in both cases were the same. In view of the turbulent exchange in the wake the distribution of the energy velocity ahead of the propeller was estimated from the resistance as described further on.

Measurements of rotor thrust and moment are not sufficient to determine the quantities in question. For that purpose calibration tests with the pump stage similar to propeller open water tests would have been necessary. One way to circumvent this problem is to develop a rational procedure on the basis of conventions using only data from overload tests in the "vicinity" of the service conditions. Such a procedure has been developed earlier and applied in model tests (1989).

4 Design

4.1 Procedure

The procedure for preliminary propeller design, i. e. for the determination of the main dimensions has been described in previous papers (1983, 1987, 1988) and shall not be repeated here. Only the basic ideas will be recalled.

For the equivalent propeller the interactions are determined by the distribution of the energy density on the mass flow, which can be obtained, at least approximately, from the frictional resistance as has been done in the project.

Under observation of the optimum condition of uniform energy density at the exit, for any values of the effective resistance and chosen total mass flow the distribution of circulation at stator and rotor may be determined, at this stage in the invariant format as functions of the local mass flow and the frequency of revolution.

4.2 Hull flow

In the original work the actuator in the duct was modelled as a force field in order to determine the outer flow around the body and the duct (1987, 1988). The model of the force field for propellers has now been widely adopted not only for the solution of Euler equations but Navier-Stokes equations as well.

As has been found from simple considerations the computation of the whole flow field is not necessary for the present configuration. The flows at the entrance and exit of the duct are completely determined by the balances of mass and energy, contrary to most other procedures for any propulsor loading without approximation.

In the procedure the hull is still assumed to be given, e. g. optimized in some way independent of the propulsor. Usually shapes are determined without flow separation. But this is of course not necessary. Bodies have been designed and sucessfully tested with accelerated flow up to the propulsor.

4.3 Dimensions

The practical procedure of propeller design consists of few simple equations. Provided the propeller absorbs the total wake then the relation

$$V_E = 3/4\ V_H$$

holds for the mean energy velocity at the intake, V_H denoting the ship or hull speed.

From the condition of self propulsion

$$R_E = T_E = \rho\ Q\ (\ V_J - V_E\ )$$

the jet efficiency

$$V_J = V_E + V_R$$

is obtained with the velocity increase

$$V_R = R_E\ /\ (\ \rho\ Q\ )\ .$$

For the velocity at the inlet of the duct the mean velocity is arbitrarily, but not accidentally chosen to be

$$V_0 = (\ V_E + V_J\ )\ /\ 2$$

in accordance with the design crriterion of continuous acceleration of the flow.

For given effective resistance and volume flow the entrance area of the duct is

$$A_0 = Q\ /\ V_0$$

and with the velocity

$$V_6 = 0.95\ V_J$$

at the exit the corresponding area is

$$A_6 = Q\ /\ V_6\ .$$

For a selected conical body contour the inner duct contur is thus given as well.

The volume flow over the wake may be approximately determined from the frictional resistance according to the equation

$$Q_P = 4\ R_F\ /\ (\ \rho\ V_H\ )\ .$$

The propulsors have in fact been designed for a larger resistance in order to avoid the notoriously small propeller loading for self propulsion of deeply submerged bodies, but the design value

$$R_E / (2 \rho Q V_H) = R_E / (8 R_F) = 1/4$$

is still pretty small for ducted propellers.

The Cordier line linking the frequency of revolution and the diameter reduces to the equation

$$N D^2 = 2.5 Q^{1/2} (e / \rho)^{1/4} ,$$

where the "kinematic head" is

$$e / \rho = V_E V_R + V_R^2 /2.$$

4.4 Blade design etc

In order to design the blades of stator and rotor the pump has been divided into ten elementary conical pumps and standard techniques of profile selection have been used although they were felt not to be adequate for the conical flow situation. For the tests a duct supported by a five bladed stator and two rotors with three and six blades, respectively, have been designed and manufactured under numerical control.

Both propulsor configurations have been tested, the results showing no significant differences. The values obtained were still different from the design values, the differences to be attributed to the much too simple minded blade design, which will be replaced by CFD procedures in forthcoming research projects.

6 Conclusions

6.1 Review

At VWS, the Berlin Model Basin, procedures for the design and evaluation of ducted propellers have been developed earlier, which treat propulsors consistently as pumps and permit to account implicitly for all hull-propulsor interactions. According to these procedures two ducted propellers have been designed, manufactured, and tested.

Although the values measured did not quite meet the design values the results prove that the design procedure is not only practicable, but in the first attempt lead to an acceptable propulsor design, and the tests showed that the corresponding evaluation procedure leads to meaningful results.

Further it has been shown that the evaluation according to the rational method based on the model of open water conditions and the method outlined in this paper result in very similar values for the ducted propellers investigated. The reason is that both methods are based on mass and energy flows and avoid reference to energetically irrelevant global displacement effects and local pressure effects.

An evaluation on the basis of measured velocities alone is not possible. The reliable computation of the pressure values, even in the case of the axisymmetric body, is not possible in the race of the propulsor.

6.2 Outlook

While the procedure for the preliminary design of ducted propellers is very transparent, the same does not yet hold for the procedure for the design of rotor and stator blades. Consequently it will be replaced by CFD methods in the near future. For the validation of the numerical methods many detailed flow measurements will be necessary, for the evaluation of the propulsors additional pressure measurements are necessary.

In view of measurements on full scale ships the conventional methods based on integral measurements have to be further developed. At present the method based on the concept of the equivalent open water propulsor has reached a certain state of maturity. But in its present form developed basically for non-ducted propellers it is not quite adequate. One of the reasons is that the thrust at the rotor is not necessarily a measure for the "head" of the pump. So generalisations will have to be conceived. More adequate appears the evaluation of ducted propellers as water jet propulsors as outlined in this paper. But for the evaluation on the basis of measured integral values under service conditions conventions have to be developed and to be agreed upon.

7 References

The complete list of references, in particular those papers of the author documenting the development of the design and evaluation procedures, are to be found in the two reports on the project:

Schmiechen, M., A. Voss and H. Engler: Entwurf und Bewertung von Düsenpropellern mit Leitapparaten. VWS Bericht Nr. 1209/92; FDS Bericht Nr. 245/1993.

Schmiechen, M. and V. Goetz: Grundsatzversuche zu den Wechselwirkungen zwischen Schiffsrumpf und -propeller. VWS Bericht Nr. 1221/93; FDS Bericht Nr. 245/1993.