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Application of surface vorticity distribution in design of ducted propellers

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Abstract

The authors present an algorithm of design of ducted propellers. Three methods of flow modelling have been coupled: the lifting line model of airfoil is used in design of impeller blade, the vortex lattice model (VLM) and surface vorticity distribution are applied in calculation of influence of nozzle on flow field in propeller disk. The algorithm has been implemented in computer program. Comparison of sample projects obtained with different assumptions relating to blade geometry is presented in last section.

1 Introduction

There is e group of ships where, due to limited space and required high thrust, the loading of propeller is unusually high. There are tugs, offshore supply vessels and ample range of inland navigation vessels. In that cases the ducted propellers with accelerating nozzle exhibit evident superiority over conventional screw propellers. The task of a nozzle consists in increasing axial velocity in propeller disk. This results in decrement of impeller thrust (and loading) and, in consequence, in rise of its efficiency. The loss of impeller thrust is compensated by thrust of a nozzle which is developed owing to radial flow induced by impeller. Al high advance coefficient the thrust turns into resistance and advantages of ducted propellers with accelerating nozzle vanish.

The second, less common aim of application of ducted propellers is the reduction of blade cavitation and concurrent noise. Then application of decelerating nozzle reduces axial velocity in propeller disk thus increasing local pressure. In this case a gain in propeller efficiency does not occur.

It is evident that the influence of a nozzle on flow in propeller disk is fundamental and can not be neglected in analysis and design of ducted propellers. Just the same the disturbance in ambient flow due to impeller must be included in calculation of flow over a nozzle. All reviewed computational methods [1] developed to calculate performance of ducted propeller comply with that requirement. And so have to design methods. Most of the proposed formerly algorithms (e.g. [2]) follow the method of design of screw propeller developed originally by Morgan and based on the vortex theory. In order to include the interaction between nozzle and impeller they utilise influence coefficients determined experimentally. The range of airfoil sections possible to apply for a nozzle is then limited to the tested. Even less data are available for non-axisymmetrical nozzles.

An alternative design method consists in determination of propeller geometry on the basis of experimental data for extensively tested propeller series (e.g. Wageningen Ka-series). This method has much more constraints. Within selected series only blade area ratio and pitch of impeller blade are subject to design.

The authors developed and implemented a method that takes advantage of vortex line theory in design of impeller whereas mutual interaction of both propeller components (impeller and nozzle) is determined on computational way. No experimental data are involved. This enables to design a ducted propeller with accelerating as well as decelerating nozzle of arbitrary airfoil section.

2 Applied computational models

In order to design blade geometry the method developed originally by Morgan and extended by Koronowicz [4] has been adopted. It is based on lifting line theory with Goldstein or, alternatively, Lerbs coefficients. Some correction for lifting surface effects is included. Radial variation of inflow velocity in propeller disk is taken into account so the wake adapted propeller can be designed when velocity distribution in ship wake is known. A blade is composed of airfoil sections with NACA16 or NACA66 thickness distribution and a=0.8 or a=1.0 mean line.

Although the method is thought to determine most of geometrical parameters some restrictions may be imposed on blade geometry. This way the outline of a blade, radial distribution of blade thickness and radial distribution of pitch can be fixed in advance. This allows designer to control blade geometry in the course of design process.

Using this method the following three basic tasks can be performed:

- design of screw propeller developing specified thrust at given speed;
- design of screw propeller developing maximum thrust at given speed and delivered power;
- design of screw propeller that supplies maximum sailing speed at given

resistance curve and delivered power.

In order to determine mutual interaction of impeller and nozzle the present authors made use of a method presented [5]. Two independent flow models have been coupled: the vortex lattice model implemented before by Szantyr [6] for screw propeller and a model with surface vorticity distribution originally developed and applied for nozzles by Kulczyk and Tabaczek [7]. Involved in iterative process both models are solved separately. Only information on disturbances in ambient flow is transferred after each iteration. Successful application of that method was described in [3] and [5].

3 Algorithm of design of ducted propeller

General outline of the algorithm is shown in Fig.1. The set of data to be entered at the very beginning contains: full geometry of a nozzle, those parameters of impeller that are not subject to change in the course of design (impeller diameter, hub diameter, number of blades, properties of blade material, fixed parameters of blade geometry) and, finally, operating conditions (ship speed, impeller revolutions, velocity distribution in ship wake, resistance curve, thrust deduction factor, delivered power).

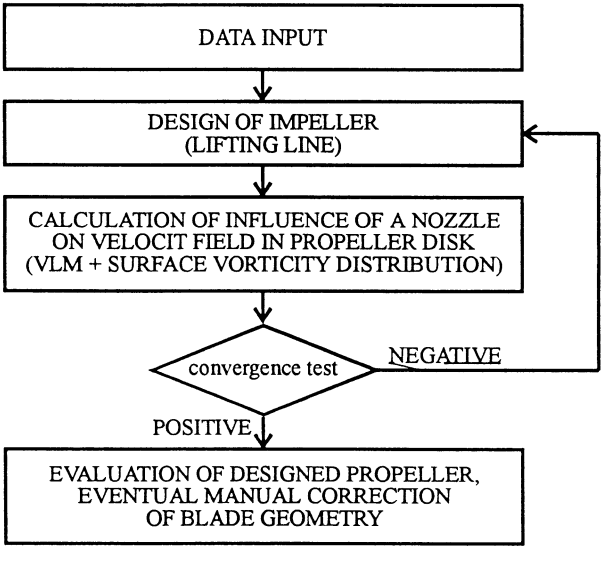


Figure 1. Flow chart of design process.

Process starts with design of impeller operating in given velocity field. Influence of a nozzle is not included in this calculation. Obtained first approximation of blade geometry is next used in iterative computation of disturbance velocities induced by given nozzle in propeller disk. In subsequent

step the calculated velocities are used to modify the given velocity distribution. Now design of impeller can be repeated with better approximation of velocity field.

The latest two steps (that is impeller design, and actualisation of velocities induced by a nozzle) are repeated until blade geometry obtained from two subsequent loops are identical. In practice the convergence can be tested in more convenient way by comparison of propeller thrust calculated additionally each time after propeller flow is solved.

If finally obtained geometry of impeller is not smooth enough (e.g. can cause problems in manufacturing) some corrections can be introduced. The decision depends on designer. Enlargement of leading and trailing edge radii (in limited scale) does not affect propeller performance. Other corrections including modification of blade thickness, pitch distribution or outline of a blade may cause significant drop of propeller thrust or efficiency. In such case design process should be repeated from the beginning with modified parameters fixed at the stage of data input. Alternatively the performance of the propeller at design conditions should be calculated in order to estimate the consequences of modification.

4 Computer program and results of sample calculations

According to the introduced algorithm the present authors prepared a computer program (in more details described in [8]). The main idea of that program was to make computer to perform laborious calculations. All assumptions concerning the propeller to be designed shall be specified by designer before the program is run. Application of the program is constrained to axisymmetrical nozzles. In order to facilitate the visual evaluation and modification of blade geometry some interactive computer graphics has been included. The outline of designed blade as well as the radial distribution of blade thickness, pitch-diameter ratio and contours of blade sections are displayed on screen (see Figs 2 and 3). Results of every correction in blade geometry introduced manually to the project are visible immediately. The modified parameters are recorded automatically and can serve as data when calculations have to be repeated.

Sample calculations performed using the program comprised design of ducted propellers at the same given propeller diameter and revolutions (D=1.26m; n=6.67rps), the same given operating conditions (power of main engine P_B=132.5kW; efficiency of power transmission η_{TR}=0.95; sailing speed v=2.78m/s; wake fraction w=0.3), but with different assumptions applied to blade geometry. Two different nozzles were tested: 19A Wageningen and easy-to-manufacture DU10 nozzle developed in Institute of Fluid Flow Machinery in Gdańsk [9]. All results are collected in Table 1.

Before the principal calculations were started a ducted propeller had been designed on the basis of data for Ka4-55 propeller series in 19A Wageningen nozzle. Obtained values of geometrical parameters were subsequently used as

Table 1. Geometrical parameters and performance of designed ducted propellers

	column number	1	2	3	4	5	6	7	8	9	10
	impeller	Ka4-55	designed according to presented method								
	fixed at design:		all geom. param.	neither blade outline nor pitch distribution				only blade outline		both blade outline and pitch distribution	
	nozzle	19A	19A	19A	19A	DU10	DU10	DU10	DU10	19A	DU10
	L/D	0.5	0.5	0.3	0.7	0.3	0.5	0.3	0.5	0.5	0.5
	P/D	0.733	0.733	0.706*	0.712*	0.699*	0.704*	0.681*	0.694*	0.778	0.778
	η_0	0.384	0.380	0.453	0.419	0.482	0.443	0.463	0.412	0.386	0.397
	T [kN]	24.86	23.04	23.15	21.87	24.62	22.80	25.55	22.65	26.23	28.07
in astern conditions	w_{ef}	0.365	0.365	0.365	0.365	0.400	0.379	0.368	0.376	0.370	0.376
	T_H [kN]	24.00	22.50	21.20	20.10	20.64	20.30	23.20	22.90	26.86	25.01

* pitch-diameter ratio at relative radius r/R=0.6

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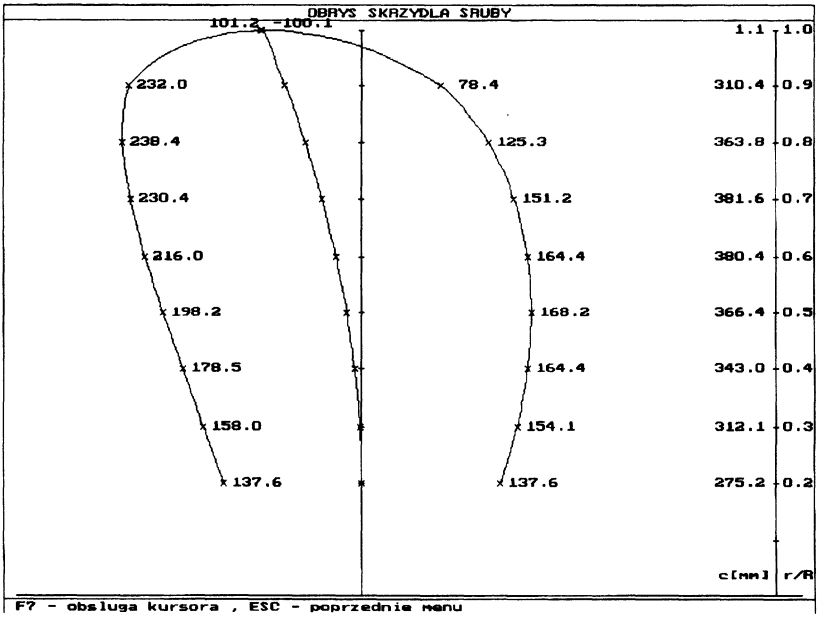


Figure 2. Outline of designed impeller blade (a sample of computer graphics).

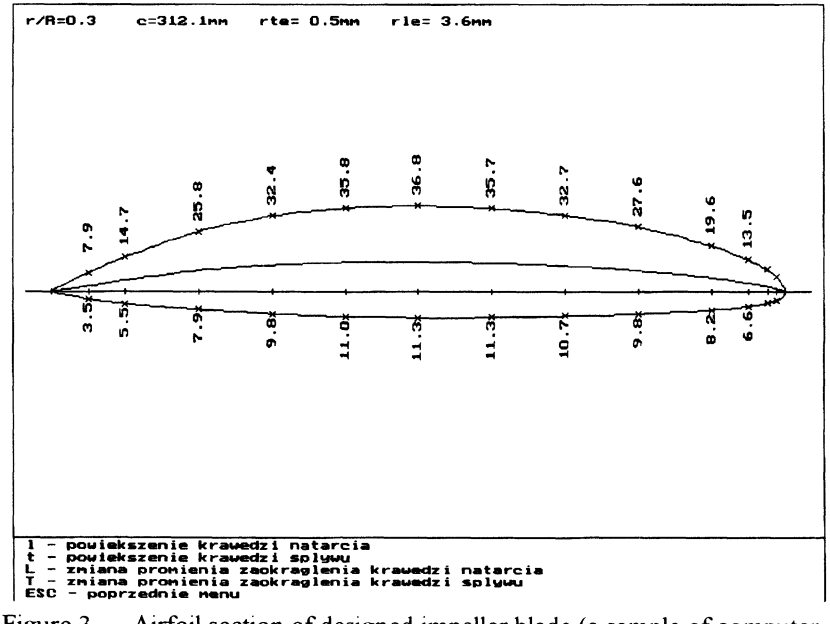


Figure 3. Airfoil section of designed impeller blade (a sample of computer graphics).

data (fixed parameters) in design performed according to the described algorithm. Predicted thrust of designed propeller differs by 7% from thrust of Ka-propeller (columns 1 and 2 in Table 1).

Next there have been performed computations with different assumptions related to blade geometry and nozzle length. Results show that length of a nozzle has significant effect on efficiency. Difference in efficiency between propellers with nozzles of different length reached up to 17% in favour of the propellers designed with short nozzles (cols 3 through 6).

Higher efficiency was predicted for propellers designed with no fixed parameters of blade geometry (compare col 5 with 7 and 6 with 8). In that case blade sections and pitch are better adapted to distribution of velocity induced by nozzle. Imposition of outline or pitch distribution each time resulted in lower efficiency. However, it was possible to design a propeller developing higher thrust at the same efficiency by enlargement of blade pitch. For instance 13 per cent increment in propeller thrust was gained at the same efficiency when pitch was enlarged by 6% and fixed (compare cols 9 and 10 with col 2).

Two last rows in Table 1 contain results obtained for the previously designed propellers put to operate in astern conditions. Propeller performance (only total thrust T_H is presented in Table 1) and effective wake fraction w_{ef} were calculated according to the method described in [3], including propeller-hull interaction. Calculated values of effective wake fraction are evidently higher than that applied in design and calculated thrust is usually lower than predicted at design conditions. The greatest relative differences in thrust are find in the cases of propellers with short nozzles (cols 3, 5 and 7). According to presented results the propellers with 19A nozzle exhibit smaller drop in total thrust when put to operate in astern conditions.

The described program has been included in computer system which is aimed to support design and analysis of screw and ducted propellers. Now open water characteristics and performance at off-design conditions of the just designed propeller can be easily calculated.

5 Concluding remarks

The presented method of design of ducted propellers does not require to introduce any experimental data regarding mutual interaction of impeller and nozzle. It assumes that an impeller can be designed for given nozzle and given operating conditions including radial variation of axial velocity in flow field. Thus so called wake adapted propeller can be designed. The prepared computer program is constrained to axisymmetrical nozzles with arbitrary airfoil sections but the method is more powerful and is able to deal with generally non-axisymmetical nozzles.

Before one starts the principal design calculations it is useful to determine initial approximation of propeller geometry and revolutions on basis of available experimental data for propeller series.

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