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ON OPTIMUM PROPELLERS WITH A DUCT OF FINITE LENGTH. PART II.

(OVER OPTIMALE SCHROEVEN MET EEN STRAALBUIS VAN EINDIGE LENGTE. DEEL II)

by

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VOORWOORD

Het fysisch-mathematisch onderzoek op het gebied van scheepsvoortstuwers ,dat bij de Universiteit Groningen onder leiding van Professor Sparenberg wordt uitgevoerd, heeft reeds stof geleverd voor een aantal lezingen en artikelen.

Met de theoretische aanpak die in deze publikaties gehanteerd wordt, kan een aantal eigenschappen van voortstuwers verklaard worden, onder andere het feit dat een straalbuis het rendement van een schroef kan vergroten.

In het eerste rapport „Over optimale schroeven met een straalbuis van eindige lengte", gepubliceerd in de ,Journal of Ship Research' van juni 1969 bespreekt Sparenberg deze mogelijkheid om het rendement van een licht belaste schroef te vergroten door een mantel toe te passen. Aangetoond wordt dat het gunstige effect van een mantel, bij de toegepaste lineaire theorie, afkomstig is van zijn eigenschap om de tip wervels van de schroefbladen gelijkmatiger te verdelen. Ook wordt aangetoond dat de speling tussen schroefbladen en mantel, om een optimaal rendement te bereiken, zo klein mogelijk moet zijn en dat dus, bij verwaarlozing van de viscositeit, een schroef met een meedraaiende vaste ring het gunstigste is.

In dit vervolg op de genoemde publikatie wordt de invloed van de „optimale mantel" op de „optimale schroef" behandeld, geïllustreerd met numerieke resultaten van de berekeningen. (Dit „Deel II" is ook reeds verschenen in de ,Journal of Ship Research' van december 1970).

De aandacht moet er op gevestigd worden dat het effect van viscositeit en cavitatie (nog) niet in de hier toegepaste theorie is opgenomen. Natuurlijk kan men voor het werkelijke ontwerpen deze effecten niet buiten beschouwing laten, maar de lineaire theorie met de daaruit verkregen numerieke resultaten kunnen ons inzicht geven in de invloed van een aantal parameters die de werking van de schroef bepalen.

Ondertussen worden de werkzaamheden voortgezet met het verder uitwerken en toepassen van een dragende vlaktheorie om de geometrie van de schroefbladen met de meedraaiende mantel te berekenen.

Ook zal te zijner tijd voortzetting op experimenteel terrein noodzakelijk zijn.

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PREFACE

The physical-mathematical research concerning ship propulsion, carried out at the University of Groningen under the leadership of Professor Sparenberg, has already resulted in a number of papers and articles.

With the theoretical approach used in these publications a number of properties of propellers can be explained, among others the fact that a duct can increase the efficiency of a propeller.

In the first report "On optimum propellers with a duct of finite length" published in the Journal of Ship Research of June 1969, Sparenberg discusses this possibility of increasing the efficiency of lightly loaded propellers by using a shroud. The favourable effect of a shroud is, in the linear theory used, shown to come from its property to spread evenly the tip vortices of the propeller blades. It is also shown that the clearance between propeller blades and shroud, for optimum efficiency, should be as small as possible and consequently, neglecting viscosity, a propeller with a fixed rotating ring is the most favourable.

In this sequel to the publication mentioned, the influence of the "optimal shroud" on the "optimal propeller" is treated, illustrated by numerical results of the calculations. (This "Part II" has also appeared in the Journal of Ship Research of December 1970).

It must be noted that the theory used here does not (yet) include the effects of viscosity and cavitation. These, of course, cannot be omitted for actual design purposes, but the linear theory with the numerical results derived from it can give insight into the influence of a number of parameters which determine the effect of a propeller.

Meanwhile the research programme is carried on with the further development and application of a lighting-surface theory to calculate the geometry of propeller blades with rotating shroud.

Also, in due time, continuation by work in the experimental field will be necessary.

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CONTENTS

LIST OF SYMBOLS

a	ratio between angular velocity and velocity of advance, ω/V
f	relaxation factor
h	grid length in μ-direction
k	grid length in ζ-direction
m	number of blades
n	number of iterations
q	quality coefficient
u	auxiliary velocity of the "frozen" vortex sheets
F	working area of the propeller
N	total number of iterations
T	thrust of the propeller
V	velocity of advance
R_b	radius of the propeller blades
R_h	radius of the hub
R_s	radius of the shroud
ε	tolerance
η	propeller efficiency
μ, ζ, σ	helicoidal system of coordinates
ϱ	specific density of fluid
φ	solution of differential equation
ψ	$d\varphi/d\mu$
ω	angular velocity

Note: The quality coefficient q is the inverse of q used in Part I, [1].

ON OPTIMUM PROPELLERS WITH A DUCT OF FINITE LENGTH. PART II.*)

by

Drs. C. A. SLIJPER and Prof. Dr. J. A. SPARENBERG

Summary

The theory developed in the preceding report [1] has been further adapted to investigate the case of a propeller with a duct that is not rotationally symmetric, a case that actually can only be realized when the duct rotates with the screw.
To reduce the computing time a method to give a faster convergence of the iteration process is introduced.
Numerical results are given for the quality coefficient of optimum ducted propellers with systematically varying parameters. The influence of the number of blades, the advance ratio, the clearance between blade tips and shroud and the hub diameter on this quality coefficient is shown.

1 Introduction

This paper is a continuation of [1] in which the theory of the optimum ducted propeller and the underlying ideas about quality and efficiency are developed. For a number of cases we will give the quality coefficients, which are a measure for the hydrodynamic quality of the propeller. It should be noted that here the quality coefficient q equals the value q^{-1} of [1], this has the advantage that now $0 \leqslant q \leqslant 1$. When $q \approx 1$ we have a good propeller, when $q \approx 0$ the propeller is bad. Even in the case that $q \approx 0$, it is possible that the efficiency is high. This depends on the thrust which the propeller has to deliver. When the thrust tends to zero the efficiency increases and tends to one for all fixed values of q. However, when the thrust is increased the decrease of the efficiency of a propeller type with a larger value of q will be less than the decrease of the efficiency of a propeller with a smaller q. When two propellers deliver the same thrust, have the same velocity of advance and the same working area, the one with the largest value of q will have the highest efficiency.

The shroud in our case is not rotationally symmetric and can be realized only when it rotates with the screw and has suitable profiles along the relevant helicoidal lines. Its influence on the efficiency of the propeller is optimal. This means that when a shroud of our type has not much effect, certainly a conventional shroud cannot have more effect when it has the same diameter, irrespective of its length. In the case of zero clearance we have an optimum ring-propeller of which the ring is not rotationally symmetric. For ring-propellers with rotationally symmetric rings, measurements are given in [2], where also regions of applicability are discussed.

Because in the case of optimum ring-propellers concentrated free vortices are avoided, it will be possible that these propellers, from the point of view of depression of noise, will be also favourable.

Finally we stress that all our considerations neglect viscosity. For practical applications the influence of viscosity is present. It will be interesting to investigate to what extent viscosity is important and how it interacts with our results based on potential theory.

2 Numerical results and their discussion

We use in correspondence with [1] the symbols listed on page 6.

The quality coefficient q, used here, equals q^{-1} for q given by formula (36) in [1]. This quantity is defined as the ratio of the kinetic energy left behind by a suitably chosen actuator disc and the kinetic energy left behind by the propeller under consideration. The actuator disc is such that it has the same velocity of advance, thrust and working area as the propeller. From [3] it follows that

$$0 \leqslant q \leqslant 1 \tag{1}$$

The efficiency η of the propeller has the value (formula (35) [1], with q changed into q^{-1}),

$$\eta = \left(1 + \frac{T}{2\varrho q F V^2}\right)^{-1} \tag{2}$$

where ϱ is the specific density of the fluid. For $q = 1$ this formula gives the efficiency of the actuator disc.

Before giving the numerical results we will discuss the meaning of a two-sided infinitely long cylindrical hub in optimization theory. From [1] it is clear that there is no difference in the treatment of the shroud and the hub. Both for shroud and hub we demand that infinitely far behind the propeller, in the optimum case, the normal velocities on the cylinders behind

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[*] Report TW-82 of the Department of Mathematics, University of Groningen.

them are zero. This means that we can equally well interpret the hub as a shroud but now at the inner radius of the blades. Then both on shroud and "hub" we have to choose suitable profiles lying along helicoidal lines, so that the desired optimum vorticity is obtained.

The propulsion unit is shown in figure 1. The working area of such a propeller is the frontal area of the shroud, which is zero and further lies between the radii R_b and R_h. Therefore it seems natural when R_b is fixed, to take for the working area

$$F = \pi(R_b^2 - R_h^2) \tag{3}$$

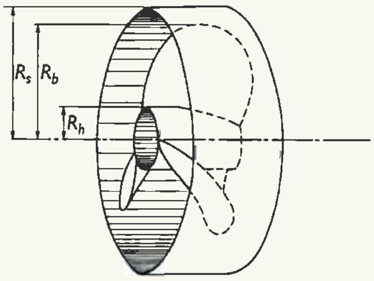

Fig. 1. The infinitely long hub interpreted as "inner" shroud.

However it is stressed that some arbitrariness remains in the definition of F. When we want to change R_h in order to investigate its influence on the value of q it is clear that we must take

$$F = \pi R_b^2 \tag{4}$$

because now vorticity can be shed within the whole cylinder with radius R_b. In other words we consider the class [3] of propellers with prescribed V, T, R_s, R_b and variable R_h with

$$0 \leqslant R_h < R_b \leqslant R_s \tag{5}$$

In the following we choose for F the value given by equation (4).

Table 1. Values of $q \cdot 10^3$. Influence of the clearance between blade tips and shroud. ($aR_h/aR_b = 0.2$)

		aR_s/aR_b						
aR_b	m	1	1.0125	1.025	1.05	1.075	1.1	∞
2	2	558	373	363	331	317	308	290
	5	581	467	448	433	427	424	416
3	2	722	561	523	493	479	471	441
	5	733	643	628	617	613	611	586
4	2	807	632	617	584	570	563	551
	5	812	713	702	693	690	689	686
5	2	856	698	685	656	644	638	631
	5	858	771	761	754	753	752	749

From table 1 it is seen that with an increase in clearance the value of q drops sharply to its value for a propeller without shroud. In the cases considered here for a $R_s/aR_b = 1.05$ the value of q for $aR_s/aR_b = \infty$ is already approximated. This means that a conventional shroud of which the clearance is 5% of the blade length will have little influence on the efficiency of the propeller, even when it would be very long. In the following we will give results for the two cases, zero clearance and infinite clearance. In the latter case the shroud has disappeared. In terms of the dimensionless quantities aR_s and aR_b these are denoted respectively by

$$\left.\begin{aligned} aR_s/aR_b &= 1 \quad \text{and} \\ aR_s/aR_b &= \infty \end{aligned}\right\} \tag{6}$$

Table 2. Values of $q \cdot 10^3$. Influence of the hub diameter.

$m = 2$

		aR_h/aR_b					
aR_b	aR_s/aR_b	0	0.1	0.2	0.3	0.4	0.5
2	1	523	539	558	563	550	516
	∞	277	285	290	282	257	217
5	1	853	862	856	826	774	699
	∞	639	647	631	609	555	479

$m = 5$

		aR_h/aR_b					
aR_b	aR_s/aR_b	0	0.1	0.2	0.3	0.4	0.5
2	1	578	579	581	575	556	518
	∞	416	417	419	412	391	351
5	1	866	867	858	827	774	699
	∞	758	759	749	719	666	591

Table 2 consists of two parts. The first refers to a screw with two blades, the second refers to a screw with five blades. We have calculated q for several values of the hub diameter. It turns out that for both cases the optimum does not occur for a hub with zero diameter; it generally occurs in the neighbourhood of $aR_h/aR_b = 0.1$ or 0.2.

From table 3 we see that by decreasing the number of blades the quality factor decreases. However, the decrease in the case of a ring-propeller, is much slower than in the case of a propeller without ring. This means that from the point of efficiency the number of blades for a ring-propeller can be taken smaller than for a conventional one.

Also in this table we see that it is certainly not necessary to determine the optimum value of aR_h/aR_b very accurately; a value of about 0.2 will be satisfactory for a good propeller. We stress however that it is difficult to interpret this result because the real hub

Table 3. Values of $q \cdot 10^3$. General survey.

aR_b	aR_h/aR_b	aR_s/aR_b	m = 1	2	3	4	5
2	0.1	1	509	539	560	572	579
		∞	190	285	345	387	417
	0.2	1	544	558	568	576	581
		∞	190	290	350	390	419
	0.3	1	558	563	568	572	575
		∞	179	282	344	384	412
3	0.1	1	691	713	726	732	736
		∞	304	438	512	558	589
	0.2	1	713	722	728	731	733
		∞	302	441	513	557	586
	0.3	1	709	712	715	717	718
		∞	283	425	498	542	570
4	0.1	1	793	806	813	816	818
		∞	402	553	626	668	692
	0.2	1	802	807	810	811	812
		∞	397	551	622	662	686
	0.3	1	784	786	787	788	788
		∞	371	527	599	639	662
5	0.1	1	855	862	864	866	867
		∞	514	647	706	738	759
	0.2	1	853	856	856	856	858
		∞	504	631	697	729	749
	0.3	1	826	826	826	827	827
		∞	472	609	667	699	719

is not infinitely long or, in other words, cannot be represented by an optimum "inner" shroud.

3 The numerical method

To solve the partial differential equation (20) in [1], which reads

$$\left\{\mu\frac{\partial}{\partial\mu}\mu\frac{\partial}{\partial\mu}+(1+\mu^2)\frac{\partial^2}{\partial\zeta^2}\right\}\varphi(\zeta,\mu)=0 \tag{7}$$

we cover the region $aR_h \leqslant \mu \leqslant aR_s$, $0 \leqslant \zeta \leqslant \pi/m$ with a rectangular grid of pivotal points. The grid length in μ direction is h and in ζ direction is k. Then we replace the differential equation by finite-difference equations and solve these equations by means of iteration. We find

$$\varphi_{i,j}^{(n+1)}=\varphi_{i,j}^{(n)}+\frac{f}{2\left(i^2+\dfrac{1+i^2h^2}{k^2}\right)}$$
$$\left\{\frac{1+i^2h^2}{k^2}(\varphi_{i,j+1}^{(n)}+\varphi_{i,j-1}^{(n+1)})+\right.$$
$$+(i^2+0.5i)\varphi_{i+1,j}^{(n)}+(i^2-0.5i)\varphi_{i-1,j}^{(n+1)}-$$
$$\left.-2\left(i^2+\frac{1+i^2h^2}{k^2}\right)\varphi_{i,j}^{(n)}\right\} \tag{8}$$

where f is a relaxation factor and $\varphi_{i,j}^{(n)}$ is the value of $\varphi(jk, ih)$ after n iterations, (see figure 2).

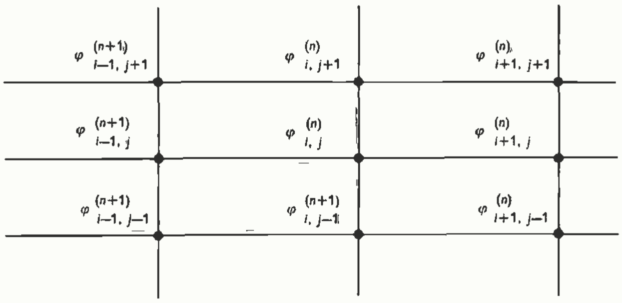

Fig. 2. Scheme of the grid points.

The iteration process is continued until

$$\max_{i,j}|\varphi_{i,j}^{(n+1)}-\varphi_{i,j}^{(n)}|<\varepsilon \tag{9}$$

where ε is a prescribed tolerance. The values of h, k and ε were determined in such a way that the quality coefficient q did not alter more than 0.5‰ when h, k and ε were divided by two.

When $f = 1$, equation (8) reduces to the normal iteration scheme for solving equation (7), however, the choice $1 < f < 2$ decreases the total number of iterations N considerably. We give the example $aR_h = 0.8$, $aR_b = 4.0$, $aR_s = 4.4$, $m = 5$, where N has been determined as a function of f for $h = k = 0.1$ and $\varepsilon = 0.00002$:

f	1.00	1.10	1.20	1.30	1.40	1.50	1.60
N	351	305	265	231	201	174	150
f	1.70	1.80	1.85	1.88	1.90	1.95	2.00
N	128	107	70	68	91	111	972

It turned out that in the case of zero clearance in spite of the optimum relaxation factor the computing time was much higher than in the case of a finite slit, even when $aR_s/aR_b = 1.05$. This is caused by the fact that the values of φ are prescribed then at only one side of the rectangle, i.e. $\zeta = \pi/m$.

To avoid unnecessary computing time we proceed as follows. Introduce

$$\psi(\zeta,\mu)=\frac{\partial\varphi(\zeta,\mu)}{\partial\mu} \tag{10}$$

then we have

$$\frac{\partial^2\psi}{\partial\zeta^2}=\frac{\partial}{\partial\mu}\left(\frac{\partial^2\varphi}{\partial\zeta^2}\right)=\frac{\partial}{\partial\mu}\left(-\frac{\mu^2}{1+\mu^2}\frac{\partial\psi}{\partial\mu}-\frac{\mu}{1+\mu^2}\psi\right) \tag{11}$$

and we obtain by differentiation of equation (7) with respect to μ the following partial differential equation for ψ

$$(1+\mu^2)\frac{\partial^2\psi}{\partial\zeta^2} + \mu^2\frac{\partial^2\psi}{\partial\mu^2} + \frac{3\mu+\mu^3}{1+\mu^2}\frac{\partial\psi}{\partial\mu} + \frac{1-\mu^2}{1+\mu^2}\psi = 0 \quad (12)$$

Although equation (12) is more complicated than (7), the boundary conditions (figure 5 in [1]) are simplified and guarantee a much faster convergence of the iteration procedure. In fact they become

$$\frac{\partial\psi}{\partial\zeta} = \frac{u}{a}\frac{2\mu}{(1+\mu^2)^2}, \quad \zeta = 0, \quad aR_h \leqslant \mu \leqslant aR_s \quad (13)$$

and

$$\begin{array}{lll} & \zeta = \pi/m, & aR_h \leqslant \mu \leqslant aR_s \\ \psi(\zeta,\mu) = 0, & \mu = aR_h, & 0 \leqslant \zeta \leqslant \pi/m \\ & \mu = aR_s, & 0 \leqslant \zeta \leqslant \pi/m \end{array} \quad (14)$$

The successive values of $\psi_{i,j}^{(n)}$ are computed by means of

$$\begin{aligned} \psi_{i,j}^{(n+1)} = \psi_{i,j}^{(n)} + & \frac{f}{\left(2i^2 - \frac{1-i^2h^2}{1+i^2h^2} + \frac{2(1+i^2h^2)}{k^2}\right)} \\ & \left\{\frac{1+i^2h^2}{k^2}(\psi_{i,j+1}^{(n)} + \psi_{i,j-1}^{(n+1)})\right. \\ & + \left(i^2 + \frac{0.5i(3+i^2h^2)}{1+i^2h^2}\right)\psi_{i+1,j}^{(n)} + \\ & + \left(i^2 - \frac{0.5i(3+i^2h^2)}{1+i^2h^2}\right)\psi_{i-1,j}^{(n+1)} \\ & \left. - \left(2i^2 - \frac{1-i^2h^2}{1+i^2h^2} + \frac{2(1+i^2h^2)}{k^2}\right)\psi_{i,j}^{(n)}\right\} \end{aligned} \quad (15)$$

From these equations we can calculate ψ and $\partial\psi/\partial\mu$ at each grid point.

In order to find again the desired $\varphi(0,\mu)$, necessary for the computation of q (q^{-1}, formula (36) in [1]), we have to carry out some integrations along the sides of the rectangle. From equation (7) there follows

$$\left.\frac{\partial^2\varphi}{\partial\zeta^2}\right|_{\mu=aR_h} = -\frac{aR_h}{1+a^2R_h^2}\left.\left(\psi + aR_h\frac{\partial\psi}{\partial\mu}\right)\right|_{\mu=aR_h} \quad (16)$$

Integration of $\partial^2\varphi/\partial\zeta^2$ along $\mu = aR_h$ gives $\partial\varphi/\partial\zeta$ since we know

$$\frac{\partial\varphi}{\partial\zeta} = \frac{u}{a}\frac{a^2R_h^2}{1+a^2R_h^2}, \quad \mu = aR_h, \quad \zeta = 0 \quad (17)$$

Again by integration of $\partial\varphi/\partial\zeta$ we get φ since we have $\varphi(\pi/m, aR_h) = 0$.

We then know $\varphi(0, aR_h)$ and complete the procedure with an integration of ψ along $\zeta = 0$ to obtain $\varphi(0,\mu)$. The same can be done at $\mu = aR_b = aR_s$, hence we were able to check the results obtained by this method. It turned out that the accuracy obtained here was equal to the accuracy of a direct computation of φ, however, the number of iteration scould sometimes be reduced by a factor 10.

Finally the quality coefficient is computed from (36) of [1], which we rewrite as

$$q = -\frac{2m}{\pi a^2 R_b^2}\int_{aR_h}^{aR_b} \mu\varphi_1(0,\mu)\,\mathrm{d}\mu \quad (18)$$

where φ_1 is the function φ calculated in the manner above, with $u/a = 1$.

4 Acknowledgement

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