CHOICE OF AN OPTIMUM DUCTED PROPELLER.

Ing. A.P. de Zwaan

Reportno. 778

11 June 1991

Delft University of Technology
Ship Hydromechanics Laboratory
Mekelweg 2
2628 CD Delft
The Netherlands
Phone 015 - 78 68 82

INDEX.

Introduction.

In the last years there is an increasing demand for better manoeuvrability and dynamic positioning of special ships and floating constructions such as supply vessels , fishing vessels, drilling rigs and other ships exploring the sea.
Ducted propellers are very usefull for these applications.
Polynomials for Thrust and Torque coefficients as a function of the advance coefficient J and pitch ratio P/D are published by MARIN (former NSMB) [4],[5] and in the appendix.

With the use of these polynomials, a computer program is written in Fortran77. The program can be used in the preliminary design.
For the final design more advanced methods should be used.

Summary.

Polynomials for Thrust and Torque coefficients for eight different types of ducted propellers are used in the program. (see chapter 2.3)
Some examples for the use of ducted propellers are:

a). Less heavy loaded propellers such as for stern trawlers and supply vessels.
b). Tug boats for bollard pull and heavy loaded propellers, such as for tug boats at speed V=0.
c). Heavy loaded propellers (stern and astern) with a required bollard pull for the design.

The program can be used for:

1). Calculating an optimum propeller with diameter,thrust,bollard pull and speed as input parameters. (Optimization of propeller revolutions).
2). Calculating an optimum propeller with diameter, revolutions and engine power as input parameters. (Optimization of the diameter).

The scope of the design is maximum propeller efficiency under the given circumstances.

1. General.

1.1 Program specifications.

a). Language : Fortran 77
b). Calculation time : 2 seconds
c). Computer configuration : IBM compatible MS-dos

1.2 Aim.

Calculating an optimum ducted propeller according to K_T and K_Q polynomials designed by MARIN [4], [5].

2. Design of the program.

2.1 Applications.

Design parameters used or not used as a boundary condition:

1. Propeller revolutions rev/min : n
2. Propeller diameter m : D
3. Expanded blade area ratio : A_E/A_0
4. Pitch ratio : P/D
5. Shipspeed knots : V
6. Wake number : w
7. Relative rotative efficiency : η_r
8. Thrust N : T
9. Torque Nm : Q
10. Delivered propeller power Watt : P_D
11. Propeller type + Nozzle type : IPROP
12. Thrust curve as a function of the shipspeed in knots

Propeller revolutions n, propeller diameter D, pitch ratio P/D and the shipspeed are variables.
Only one of the parameters n, D, or V may be variable in the optimization process.
If the shipspeed V is variable, the thrust curve of the ship as a function of the speed is required as input.

The expanded bladearea ratio A_E/A_0, the wake number w, the relative rotative efficiency η_r and the propeller + nozzle type are always input data.

One of the parameters T, Q or P_D is a boundary condition for the propeller.

If propeller revolutions or diameter D has to be calculated, the thrust T is the boundary condition.
The Propeller power P_D is the boundary condition if the speed V has to be calculated.

The program can be used for two problems:

1). Calculating an optimum propeller with diameter, thrust,bollard pull and speed as input parameters. (Optimization of propeller revolutions).
2). Calculating an optimum propeller with diameter, revolutions and engine power as input parameters. (Optimization of the diameter).

2.2 Used methods.

The program uses the K_T and K_Q polynomials for ducted propellers, developed by MARIN [4],[5] and in the appendix.
The data for the propeller are calculated for the propeller behind the ship by including the relative rotative efficiency.
The calculated efficiency is $\eta_0 * \eta_r$, as a result of T and Q in "behind condition".

Calculating the propeller the following methods are used:

a). The iteration proces of "Newton Raphson".
b). A subroutine "NEWTON" which calculates the maximum of the efficiency function $\eta = G(P/D,J)$ and Bendemann coefficient $\eta_B = P(P/D,0)$.
c). External penalty functions in the efficiency equation for minimal values of the pitch ratio or the propeller power P_D.
d). The thrustcurve expressed in a "Theilheimer polynomial" [1].

2.3 Used propeller series.

Propeller type	Nozzle
Ka 3-65	19a
Ka 4-55	19a
Ka 4-70	19a
Ka 5-75	19a
Ka 4-70	22
Ka 4-70	24
Ka 4-70	37
Ka 5-100	33

2.4 Formulas.

The function to be maximized is the propeller efficiency:

$$\eta = \frac{K_T(x,J)}{K_Q(x,J)} * \frac{J}{2\pi}$$

with

a). $(\frac{P}{D})_{min} \leq x \leq (\frac{P}{D})_{max}$
b). $T - \rho n^2 D^4 K_T(x,J) = 0$ (if thrust T is input parameter)
c). $P_D - 2\pi\rho n^3 D^5 K_Q(x,J) \geq 0$ (if P_D is input parameter)
d). $Q - \rho n^2 D^5 K_Q(x,J) \geq 0$ (if torque Q is input parameter)

If the shipspeed has to be calculated, one restriction will be added:

e). $T(V_a) - \rho n^2 D^4 K_T(x,J) = 0$,

with $T(V_a)$ is the thrustcurve as a function of the advance speed.

The function to be maximized becomes:

$$\eta = G(x,J) = \frac{K_T(x,J)}{K_Q(x,J)} * \frac{J}{2\pi} - \sum_{i=1}^{2} \frac{g_i^4}{r_i} - \frac{g_3^2}{r_3}$$

with

a). x is the pitch ratio P/D as free variable.
b). $J = f(V_a,n,D) = V_a/(n * D)$ the advance coefficient.
c). g_i an external penalty function.
d). $r_i = 10^{-k}$ for k is the number of iterations.

The penalty function g_3 will only be used if the ship speed has to be calculated (propeller power is input parameter).

The object function $G(x,J)$ has three inequality constraints g_1, g_2 and g_3:

1). $g_1 = (\frac{P}{D})_{max} - x \geq 0$

2). $g_2 = x - (\frac{P}{D})_{min} \geq 0$

3). $g_3 = \frac{P_D}{2\pi\rho n^3 D^5} - K_Q(x,J) \geq 0$

or

$$g_3 = \frac{Q}{\rho n^2 D^5} - K_Q(x,J) \geq 0$$

with

$(\frac{P}{D})_{max}$ = 1.4 for propeller series Ka 3-64, Ka 4-70 and Ka 5-75 with nozzle 19a

$(\frac{P}{D})_{max}$ = 1.6 for propeller series Ka 4-55 with nozzle 19a and Ka-70 in combination with nozzles 22,24 and 37

$(\frac{P}{D})_{min}$ = 1.0 for propeller serie Kd 5-100 with nozzle 33.

$(\frac{P}{D})_{min}$ = 0.6

$$f(J) = T(J.n.D) - \rho n^2 D^4 K_T(x,J) = 0$$

$$h(J) = \frac{P_D}{2\pi\rho n^3 D^5} - \frac{K_Q(x,J)}{\eta_r} \geq 0$$

or

$$h(J) = \frac{Q}{\rho n^2 D^5} - \frac{K_Q(x,J)}{\eta_r} \geq 0$$

The advance coefficient will be calculated with the method of "Newton Raphson":

$$J_n = J_{n-1} - \frac{f(J_{n-1})}{\frac{d}{dJ} f(J_{n-1})}$$

2.5 The optimization proces.

The program can be used for two problems:

1). Calculating a propeller (P/D unknown) with Thrust and shipspeed as input.
Revolutions or diameter unknown.

2). Calculating a propeller with Propeller power P_D, revolutions and diameter as input.
Shipspeed and P/D has to be calculated.
The thrustcurve as a function of the advance speed as extra input required.

2.5.1 Propeller revolutions or diameter unknown.

The pitch ratio and the advance coefficient are calculated iterative with:

a). The efficiency equation:

$\eta = G(x,J)$ see chapter 2.4

b). The thrust equation:

$$f(J) = F(x,J) = T - \rho n^2 D^4 K_T(x,J) = 0$$

From the requirement of maximum efficiency follows:

$\frac{d\eta}{dx}$ is minimal, which means:

$$\frac{d\eta}{dx} = \frac{d}{dx}G(x,J) = \frac{\partial G}{\partial x} + \frac{\partial G}{\partial J} * \frac{dJ}{dx} = 0$$

x is calculated in subroutine "NEWTON".

The advance coefficient J follows from the equation in 2.5.1 under b).
and also

$$\frac{dJ}{dx} = -\frac{(\partial F/\partial x)}{(\partial F/\partial J)} \text{ for } x = x_n \text{ and } J = J_n$$

The iteration proces will be stopped if:

$|J_n - J_{n-1}| \leq 10^{-6}$ and $|x_n - x_{n-1}| \leq 10^{-6}$

with n is the number of iterations.

2.5.2 Ship speed unknown.

The diameter D ,propeller revolutions and power are now the input parameters.
With the efficiency equation, the power and thrust equation as an inequality constraint: the pitch ratio x and advance coefficient J are calculated iterative.

The equations in the iteration proces are:

a). The efficiency equation:

$\eta = G(x,J)$ see chapter 2.4

b). The thrust equation:

$$f(J)=F(x,J)=T(V_a) - n^2D^4K_T(x,J) = 0$$

c). The power equation:

$$P_D - 2\pi\rho n^3D^5K_Q(x,J) \geq 0$$

According to the requirement of maximum efficiency $\frac{d\eta}{dx}$ is minimal, which means:

$$\frac{d\eta}{dx} = \frac{d}{dx}G(x,J) = \frac{\partial G}{\partial x}+\frac{\partial G}{\partial J} * \frac{dJ}{dx} = 0$$

x is calculated in subroutine "NEWTON".

The advance coefficient J follows from the equation in 2.5.2 under b).

and also

$$\frac{dJ}{dx} = -\frac{\partial F/\partial x}{\partial F/\partial J} \text{ for } x = x_n \text{ and } J = J_n$$

The iteration proces will be stopped if

$$|x_n - x_{n-1}| \leq 10^{-6} \text{ and } |j_n - j_{n-1}| \leq 10^{-6}$$

with n is the number of iterations.

2.6 Bollard pull as additional condition.

If the bollard is an additional condition, the free-sailing propeller must fulfil this extra condition. At speed $V = 0$ the propeller must deliver a demanded Thrust (pulling power).

The design proces is as follows:

a). Design a propeller for free sailing conditions, see chapter 2.5
b). Design a propeller for bollard pull conditions, see chapter 2.6.1.

The largest value of this two a). or b). defines the propeller.

2.6.1 Optimization for bollard pull.

The function to be maximized is the so called Bendemann coefficient η_B :

$$\eta_B = \frac{K_T^{1.5}(x,J)}{\pi^{1.5}K_Q(x,J)} \quad \text{with the restriction}$$

a). $(\frac{P}{D})_{min} \leq x \leq (\frac{P}{D})_{max}$

The advance speed coefficient $J = 0$.

The function to be maximized becomes:

$$\eta_B = P(x) = \frac{k_T^{1.5}(x,0)}{\pi^{1.5}K_Q(x,0)} - \sum_{i=1}^{2} \frac{g_i}{r_i}$$

with

a). x is the pitch ratio as free variable.
b). g_i an external penalty function.
c). $r_i = 10^{-k}$ for k is the number of iterations.

The external penalty functions g1 and g2 in the obobject function $P(x)$ are two inequality constraints:

1). $g_1 = (\frac{P}{D})_{max} - x \geq 0$

2). $g_2 = x - (\frac{P}{D})_{min} \geq 0$

For the values $(P/D)_{min}$ and $(P/D)_{max}$ see chapter 2.4

From the requirement of maximum efficiency follows:

$$\frac{d\eta_B}{dx} = \frac{d}{dx}P(x) = 0$$

x is calculated in subroutine "NEWTON".

The iteration proces will be stopped if

$$|x_n - x_{n-1}| \leq 10^{-6}$$

with n is the number of iterations.

2.7 Explanation of used symbols.

Symbol	Program	Dimension	Description
A_E/A_0	AAE	-	Bladearea ratio.
D	DP	m	Propeller diameter.
g	-	m/sec^2	Acceleration due to gravity.
J	X1	-	Advance coefficient.
K_Q	KQ	-	Torque coefficient.
K_T	KT	-	Thrust coefficient.
n	NS	sec^{-1}	Propeller revolutions
P/D	PPD	-	Pitch ratio.
$(P/D)_{max}$	XMAX	-	Maximum pitch ratio.
$(P/D)_{min}$	XMIN	-	Minimum pitch ratio.
Q	IV	Nm	Torque.
η_r	RRE	-	Relative rotative efficiency.
T	IV	N	Thrust.
V	VS	knots	Shipspeed.
V_a	VA	m/sec	Advance speed.
w	PSI	-	Wake number.
z	NPB	-	Number of propeller blades.
ρ	RHO	m^2/sec	Mass density of water
η	REND(1)	-	Efficiency $\eta_0 * \eta_r$
η_B	REND(2)	-	Bendemann coefficient

3. Program application.

3.1 In and output paramaters.

i = input, o = output

A	i:	Propeller revolutions n in rev./min. A = 0 : n is a variable in the objectfunction. A $\neq$ 0 : n is a constant in the objectfunction.
B	i:	Propeller diameter D in m. D = 0 : D is a variable in the objectfunction. D $\neq$ 0 : D is a constant in the objectfunction.
D	i:	Pitch ratio P/D. D = 0 : Pitch ratio will be optimized.
V(1)	i:	Shipspeed V in knots. V(1) = 0 : The speed is a variable in the object function. V(1) $\neq$ 0 : The speed is a constant in the object function.
PSI	i:	Wake number.
RRE	i:	Relative rotative efficiency.
IKEUS	i:	Input choice of Thrust T or Propeller power P_D. IKEUS = 1 : IV(1) is thrust T of the propeller in N (V(1) $\neq$ 0). IKEUS = 2 : IV(1) is Propeller power in watt (V(1) = 0).
IV(1)	i:	Thrust T in N or propeller power P_D in watt whether IKEUS = 1 or IKEUS = 2.
IV(2)	i:	IV(2) = 0 : Don't calculated propeller for bollard pull. IV(2) = bollard pull in N : Calculate propeller for bollard pull. This condition will be compared with the free sailing condition. The program decides which one defines the design of the the propeller.
DEPS	i:	Centerline propeller shaft with respect to the waterline in m.
WAT	i:	Medium. WAT = 0 : Sweet water ρ = 1000 kg/m^3. WAT = 0 : Sea water ρ = 1025 kg/m^3.
IPROP	i:	Propeller serie + nozzle type. IPROP = 36519 : Ka 3-65 Nozzle 19a. IPROP = 45519 : Ka 4-55 Nozzle 19a. IPROP = 47019 : Ka 4-70 Nozzle 19a. IPROP = 57519 : Ka 5-75 Nozzle 19a. IPROP = 47022 : Ka 4-70 Nozzle 22. IPROP = 47024 : Ka 4-70 Nozzle 24. IPROP = 47037 : Ka 4-70 Nozzle 37. IPROP = 510033 : Ka 5-100 Nozzle 33.

In and output parameters (continued).

ITEST i:	Test variable. ITEST = 0 : No test output. ITEST = 1 : Test output.
NW i:	NW input points of the thrustcurve (V(1)=0) $6 \leq NW \leq 20$
XW(1), YW(1) ..... i: ..... XW(NW),YW(NW)	Shipspeed in knots, thrust in N. Starting point (0,0).
NS(1) o:	Propeller revolutions free sailing cond. rev./min
NS(2) o:	Propeller revolutions bollard pull cond., with constant torque. rev./min
NS(3) o:	Propeller revolutions bollard pull cond., with constant Power.
DP(1),DP(2) o:	Propeller diameter in m.
C o:	Blade area ratio A_E/A_0.
PPD(1) o:	Pitch ratio free sailing condition.
PPD(2) o:	Pitch ratio bollard pull condition.
VA(1),VA(2) o:	Advance speed in m/sec.
V(1) o:	Shipspeed in knots.
THRUST(1) o:	Thrust in N freesailing condition.
THRUST(2) o:	Thrust in N bollard pull condition, with constant torque.
THRUST(3) o:	Thrust in N bollard pull condition, with constant power.
PD(1) o:	Propeller power free sailing condition. Watt
PD(2) o:	Propeller power bollard pull condition. Watt
Q(1) o:	Torque in Nm free sailing condition.
Q(2) o:	Torque in Nm bollard pull condition.
REND(1) o:	Propeller efficiency η_0 * η_r free sailing condition.
REND(2) o:	Bendemann coefficient η_B (bollard pull).

Bibliography.

[1] Theilheimer F. and Starkweather W.,
The fairing of ship lines on a high-speed Electronic Computer,
D.T.M.B. Report no. 1474, 1961.

[2] Wit, C. de,
Optimaliseringsmethoden en technieken in de technologie,
Collegedictaat a 165 A, 1977/1978.

[3] Weerstand en Voortstuwing,
door
Prof. Dr. Ir. J.D. van Manen,
Collegedictaat (3 parts)

[4] Oosterveld, M.W.C. en P. Oossanen,
Recent developments in marine propeller hydronamics,
Netherlands Ship Model Basin,
Int. Jubilee Meeting 40th ann. NSMB 1972,
Wageningen, 1973

[5] Oosterveld M.W.C. en P. Oossanen,
Representation of propeller characteristics suitable for preliminary ship design studies,
International Conference,
Computer applications of ship yards operation and ship design,
Tohyo, 1973.

Appendix.

Corrigated polynomials for ducted propellers.

In the publication of the polynomials for ducted propeller some mistakes where made, so the calculated curves does not match the given diagrams.
The polynomial coefficients for K_Q and K_{TN} are frequently exchanged , and some coefficients where put in the wrong column.
In some cases the failure was not due to the exchange of the coefficients.
A new regression analysis gives polynomials which fits excellent the diagrams, but differs totaly from the publicated polynomials.
On the following pages the correct coefficients for the ducted propellers are given.

The propeller - nozzle combinations are:

- Propeller Ka 4-55, nozzle 19a
  no corrections.
- Propeller Ka 3-65, nozzle 19a
  no corrections.
- Propeller Ka 4-70, nozzle 19a
  The term 0.285076 added in the K_T coefficient column.
- Propeller Ka 5-75, nozzle 19a
  The term -0.006398 must be in the K_Q - column instead of the K_T - column.
- Propeller Ka 4-70, nozzle 22
  no corrections.
- Propeller Ka 4-70, nozzle 24
  The KT - column completely changed.
- Propeller Ka 4-70, nozzle 37
  no corrections.
- Propeller Kd 5-100, nozzle 33
  The K_{TN} - column completely changed.

Accuracy.

The correlation between the corrigated polynomials and publicated diagrams are excellent.
The variations for K_T, $10K_Q$, K_{TN} and η_0 are less than 0.005.

Definitions.

$$K_T = \sum_{x,y} C_T(x,y) \left(\frac{P}{D}\right)^x J^y \text{ (total thrust)}$$

$$K_Q = \sum_{x,y} C_Q(x,y) \left(\frac{P}{D}\right)^x J^y$$

$$K_{TN} = \sum_{x,y} C_{TN}(x,y) \left(\frac{P}{D}\right)^x J^y$$

PROPELLER Ka 3-65			NOZZLE 19a	
x	y	C_T	C_{TN}	C_Q
0	0	.028100	.154000	.006260
	1	-.143910	.115560	0.0
	2	0.0	-.123761	-.017942
	3	-.383783	0.0	0.0
	4	0.0	0.0	-.008089
	5	0.0	-.741240	0.0
	6	0.0	.646894	0.0
1	0	0.0	-.542674	0.0
	1	-.429709	-.749643	0.0
	2	0.0	0.0	-.016644
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	-.162202	0.0
2	0	.671268	.972388	0.0
	1	0.0	0.0	0.0
	2	.286926	1.468570	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
3	0	-.182294	-.317644	.040041
	1	0.0	0.0	0.0
	2	0.0	-1.084980	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	-.032298	0.0
4	0	0.0	0.0	0.0
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	.199637	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	0.0
	1	0.0	0.060168	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	0.0	0.0	-.003460
	1	-.017378	0.0	-.000674
	2	0.0	0.0	.001721
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
0	7	0.0	0.0	0.0

$0.6 \leq P/D \leq 1.4$

PROPELLER Ka 4-70			NOZZLE 19a	
x	y	C_T	C_{TN}	C_Q
0	0	.030550	.076594	.006735
	1	-.148687	.075223	0.0
	2	0.0	-.061881	-.016306
	3	-.391137	-.138094	0.0
	4	0.0	0.0	-.007244
	5	0.0	-.370620	0.0
	6	0.0	.323447	0.0
1	0	0.0	-.271337	0.0
	1	-.432612	-.687921	0.0
	2	0.0	.225189	-.024012
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	-.081101	0.0
2	0	.667657	.666028	0.0
	1	0.0	0.0	0.0
	2	.285076	.734285	.005193
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
3	0	-.172529	-.202467	.046605
	1	0.0	0.0	0.0
	2	0.0	-.542490	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	-.016149	0.0
4	0	0.0	0.0	-.007366
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	.099819	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	0.0
	1	0.0	.030084	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	0.0	0.0	-.001730
	1	-.017293	0.0	-.000337
	2	0.0	-.001876	.000861
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
0	7	0.0	0.0	0.0

$0.6 \leq P/D \leq 1.4$ TUGS AND PUSHBOATS

PROPELLER Ka 5-75			NOZZLE 19a	
x	y	C_T	C_{TN}	C_Q
0	0	.033000	-.000813	.007210
	1	-.153463	.034885	0.0
	2	0.0	0.0	-.014670
	3	-.398491	-.276187	0.0
	4	0.0	0.0	-.006398
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
1	0	0.0	0.0	0.0
	1	-.435515	-.626198	0.0
	2	0.0	.450379	-.031380
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
2	0	.664045	.359718	0.0
	1	0.0	0.0	0.0
	2	.283225	0.0	.010386
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
3	0	-.162764	-.087289	.053169
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
4	0	0.0	0.0	-.014731
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	0.0
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	0.0	0.0	0.0
	1	-.017208	0.0	0.0
	2	0.0	-.003751	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
0	7	0.0	0.0	0.0

$0.6 \leq P/D \leq 1.4$

PROPELLER Ka 4-55			NOZZLE 19a	
x	y	C_T	C_{TN}	C_Q
0	0	-.375000	-.045100	-.034700
	1	-.203050	0.0	.018568
	2	.830306	0.0	0.0
	3	-2.746930	-.663741	0.0
	4	0.0	-.244626	-.195582
	5	0.0	0.0	.317452
	6	.067548	0.0	-.093739
1	0	2.030070	.244461	.158951
	1	-.392301	-.578464	-.048433
	2	-.611743	1.116820	0.0
	3	4.319840	.751953	.024157
	4	-.341290	0.0	0.0
	5	0.0	0.0	-.123376
	6	0.0	-.089165	0.0
2	0	-3.031670	0.0	-.212253
	1	0.0	-.146178	0.0
	2	0.0	-.917516	0.0
	3	-2.007860	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
3	0	2.836970	.068186	.156133
	1	0.0	.174041	0.0
	2	0.0	.102331	0.0
	3	.391304	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
4	0	-.994962	0.0	0.0
	1	0.0	0.0	.030740
	2	0.0	0.0	.073587
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	-.031826
	1	.015742	0.0	-.014568
	2	0.0	0.0	-.109363
	3	0.0	0.0	0.0
	4	0.0	0.0	.043862
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	.043782	-.008581	.007947
	1	0.0	0.0	0.0
	2	0.0	0.0	.038275
	3	0.0	0.0	0.0
	4	0.0	0.0	-.021971
	5	0.0	0.0	0.0
	6	0.0	0.0	.000700
0	7	0.0	.088319	.022850

$0.6 \le P/D \le 1.6$

PROPELLER Ka 4-70			NOZZLE 22	
x	y	C_T	C_{TN}	C_Q
0	0	.008043	.001317	.032079
	1	0.0	0.0	0.0
	2	-.208843	0.0	-.020219
	3	-.902650	0.0	-.021294
	4	0.0	-.937036	0.0
	5	.369317	0.0	0.0
	6	0.0	.682898	0.0
1	0	0.0	0.0	-.102805
	1	-.661804	-.559885	0.0
	2	.752246	0.0	0.0
	3	0.0	.951865	0.0
	4	0.0	-.376616	0.0
	5	-.159272	0.0	0.0
	6	0.0	0.0	0.0
2	0	.720632	.371000	.140281
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
3	0	-.202075	-.96038	-.026416
	1	0.0	.011043	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
4	0	0.0	0.0	0.0
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	0.0
	1	0.0	0.0	-.008516
	2	0.0	0.0	0.0
	3	0.0	-.093449	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	0.0	0.0	0.0
	1	0.0	0.0	.005229
	2	0.0	0.0	0.0
	3	0.0	.045373	0.0
	4	0.0	0.0	-.000195
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
0	7	0.0	-.244550	.001334

$0.6 \le P/D \le 1.6$ TUGS AND PUSHBOATS

PROPELLER Ka 4-70			NOZZLE 24	
x	y	C_T	C_{TN}	C_Q
0	0	-.026195	-.026195	.023557
	1	.001197	0.0	0.0
	2	0.0	0.0	-.016989
	3	-1.234240	-.838832	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	.555129	.082386
1	0	.235791	.109624	-.072021
	1	-.705042	-.681638	0.0
	2	0.0	.773230	0.0
	3	-.159436	0.0	-.037596
	4	0.0	0.0	-.034871
	5	.908131	0.0	0.0
	6	-.840424	0.0	0.0
2	0	.454377	.259217	.103364
	1	0.0	0.0	0.0
	2	1.254499	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	-.131615	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
3	0	-.110537	-.058287	-.013447
	1	0.0	0.0	0.0
	2	-.392827	0.0	0.0
	3	-.205174	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	.013180
4	0	0.0	0.0	0.0
	1	0.0	0.0	0.0
	2	0.0	0.0	-.012173
	3	0.0	0.0	.046464
	4	0.0	0.0	-.035041
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	0.0
	1	-.022669	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	-.044629	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	0.0	0.0	0.0
	1	.011161	0.0	0.0
	2	0.0	0.0	0.0
	3	.023147	.026228	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
0	7	.452712	-.239044	-.049039

$0.6 \leq P/D \leq 1.6$ TUGS AND PUSH BOATS

PROPELLER Ka4-70			NOZZLE 37	
x	y	C_T	C_{TN}	C_Q
0	0	-.162557	-.016806	.016729
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	-.077387	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	-.099544	.030559
1	0	.598107	0.0	-.048424
	1	-1.009030	-.548253	-.011118
	2	0.0	.230675	-.056199
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
2	0	.085086	.460206	.084376
	1	.425585	0.0	0.0
	2	0.0	0.0	.045637
	3	0.0	0.0	-.042003
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
3	0	0.0	-.215246	-.008652
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	-.021044	0.0	0.0
	6	0.0	0.0	0.0
4	0	0.0	.042997	0.0
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	0.0
	1	-.038383	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	0.0	0.0	0.0
	1	0.0	0.0	-.001176
	2	.014992	0.0	.002441
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
0	7	0.036998	0.051753	-.012160

$0.6 \leq P/D \leq 1.6$ TUGS AND PUSH BOATS

PROPELLER Kd 5-100			NOZZLE 33	
x	y	C_T	C_{TN}	C_Q
0	0	-.347562	.025149	-.007789
	1	-.321224	0.0	-.022424
	2	.075277	.317808	0.0
	3	0.0	-.083296	-.009087
	4	-.009560	-.070735	0.0
	5	0.0	.050083	0.0
	6	0.0	0.0	0.0
1	0	.963261	0.0	0.0
	1	-.215803	-.371072	0.0
	2	0.0	-.561715	-.010492
	3	0.0	.921327	0.0
	4	0.0	-.410495	0.0
	5	0.0	.067465	0.0
	6	0.0	0.0	0.0
2	0	0.0	.138501	.082463
	1	0.0	0.0	0.0
	2	0.0	-.315179	.026193
	3	0.0	0.0	-.009585
	4	0.0	0.0	0.0
	5	0.0	0.0	.001029
	6	0.0	0.0	0.0
3	0	0.0	0.0	0.0
	1	0.0	.235429	-.007692
	2	.013401	.077988	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	-.000094
4	0	-.016882	-.015350	-.003196
	1	0.0	-.073049	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	-.000117
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
5	0	0.0	0.0	0.0
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	0.0
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
6	0	0.0	0.0	0.0
	1	0.0	0.0	0.0
	2	0.0	0.0	0.0
	3	0.0	0.0	.000152
	4	0.0	0.0	0.0
	5	0.0	0.0	0.0
	6	0.0	0.0	0.0
0	7	0.0	-.003473	0.0

$1.0 \leq P/D \leq 1.8$ DECELERATING NOZZLE