

## Computerized method for propeller design of optimum diameter and rpm

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**ABSTRACT:** The process of marine propeller design, using theoretical or experimental charts of methodical series, consumes time and effort. This work proposes a computerized design process for optimization of propeller diameter and number of revolutions for better characteristics and higher performance. In this process, for known propeller rpm, thrust, and blade area ratio, another expression of propeller thrust coefficient is developed such that the unknown diameter is eliminated. Hence, a new developed curve of thrust coefficient can be plotted on any arbitrary propeller performance curves such as SSPA or Wageningen B-Series charts of propeller performance.

Using Newton's divided difference method of interpolation, the required optimum propeller diameter can be determined. A similar process has been applied to determine the optimum propeller number of revolutions of known propeller diameter.

Flow charts and computer programs have been developed to represent the proposed procedure. Applications have been performed on the design of three different propellers of the existing ships. Complete agreement is achieved between results of the present work and the real ships propeller diameters.

### NOMENCLATURE

$\left(\frac{A_E}{A_o}\right)$	blade area ratio,	$K_Q$	diameter,
$A_P$	projected area,	$K_T$	torque coefficient of open propeller,
$C_{ijkl}$	Wageningen series coefficient of Rn	$P_o$	thrust coefficient of open propeller,
effect,		$P_v$	static pressure at propeller CL, psi
$C_Q$	torque coefficient,	$R_n$	water-vapor pressure, psi
$C_T$	thrust coefficient,	$n$	Reynolds number,
$D$	propeller diameter,	$P/D$	propeller number of revolutions per second,
$i, j, k, l$	integers,	$Q$	propeller pitch/diameter ratio
$J$	advance ratio,	$T$	propeller torque,
$K_d$	thrust coefficient with eliminated number of revolutions,	$t$	propeller thrust,
$K_n$	thrust coefficient with eliminated	$V_a$	thrust deduction factor,
		$V_s$	propeller advance speed,
			service ship speed,

w	ship's wake fraction,
Z	number of blades,
$\eta$	propeller efficiency,
$\rho$	water density.

## 1. INTRODUCTION

To perform a successful propeller design, a naval architect is faced with some important requirements, such as:

- 1- High efficiency,
- 2- Sufficient thrust
- 3- Proper strength,
- 4- No cavitation erosion,
- 5- Acceptable low vibration and habitable noise excitation.

Generally, the most efficient propeller is that having the largest possible diameter and lowest rpm. Usually there are two ways to develop a successful propeller design, namely, the theoretical and experimental methods. There are many modern theoretical methods, such as lifting line and lifting surface theories, Breslin, et al (1994), Kerwin, (1981), Bahgat, (1966), Morgan, (1979, Andersen, et al (1979), Gaafary, (1987 and 1995), and Carlton, (1994). Also, there are many experimental propeller series test results, such as the NSMB Wageningen A- and B-Series, Troost, (1951), SSPA-Series, Lindgren, (1961), and many others. The Wageningen B-Series is still up to now applicable, and it is very efficient method of conventional propeller design, but the area ratios are limited, and a designer usually interpolates between charts, which makes it a difficult process. Oosterveld, et al (1975) has developed a mathematical polynomial to represent the propeller performance curves of B-Series propeller type. This useful and simple polynomial form is expressed by its multi-terms of arbitrary propeller's number of blades, blade area ratio, pitch/diameter ratio, advance ratio and Reynolds number.

Either theoretical or experimental method is applied the main task of propeller design is the optimization process of propeller particulars, to achieve the highest possible efficiency, Bertram, (2000), and

Turnock, et al (2006). It is the main target of this paper to develop a direct computerized design procedure for optimization of propeller diameter and rpm that guarantees the highest possible propeller performance. In this process, for known propeller rpm, thrust, and blade area ratio, another expression of propeller thrust coefficient is developed such that the unknown diameter is eliminated. Hence, a new developed curve of thrust coefficient is plotted on Oosterveld's form of Wageningen B-Series charts of propeller performance, (1975). Using Newton's divided difference method of interpolation, Carnahan, et al (1976), the required optimum propeller diameter has been determined from the advance ratio of the highest propeller efficiency. A similar process can be applied to determine the optimum propeller number of revolutions when the propeller diameter is known. Also, this proposed procedure is valid to apply when the propeller torque is known, instead of the propeller thrust, hence, the optimum diameter and rpm can be determined.

Flow charts and computer programs have been developed to represent both of the Oosterveld's mathematical polynomial of Wageningen series and the proposed procedure. Applications have been performed on three different propellers of existing ships, where complete agreement has been achieved for propeller particulars deduced by the proposed method and those of the real ship.

## 2. FORMULATION OF THE METHOD

This work presents a proposed procedure for propeller design, where it deals with charts of propeller performance curves of ( $K_T$ ,  $K_Q$ , and  $\eta$ ) versus ( $J$ ). These curves are based on theoretical or experimental results of methodical series of marine propellers. Aside from the well known useful charts of  $B_p - \delta$ , of propeller series of B-type of NSMB, Troost, (1951) and Lewis, (1989), the present work introduces some kind of substitute of these design charts. The main target of this work is to develop a simple computerized procedure of propeller design that achieves optimum propeller diameter and number of revolutions. This is to develop the proper theory, then computerize that method, apply the

computer program on existing ships of the same propeller type, and finally, compare the results. This might be a direct verification of this computerized method.

### 2.1 Optimum Propeller Diameter

Consider a specific systematic series of conventional marine propellers with available performance curves, such as those of Troost, (1951), and Lindgren, (1961), the optimum propeller diameter can be accomplished by eliminating the diameter between the relations defining thrust coefficient, ( $K_T$ ) and advance ratio, ( $J$ ). To reach there a naval architect need to know the following propeller particulars:

1. propeller rpm,
2. speed of advance,
3. blade area ratio,
4. required propeller thrust, and
5. propeller number of blades.

These particulars can be determined according to the following:

- To avoid the harm of cavitation, the lower propeller rpm, the less chance of cavitation occurrence could be,
- Knowing the ship's wake, ( $w$ ) at ship service speed, the speed of advance is:  
 $V_a = V_s (1 - w)$
- As the blade area ratio increases, there will be less chance of cavitation occurrence, and less propeller efficiency. However, to avoid cavitation or reduce it, an expression of projected blade area has been developed by NSMB, as in Lewis, (1989). When this expression is plotted, it gives a line just above the upper limit of Burrill's cavitation diagram for merchant ships, Lewis, (1989), this expression is,

$$(A_P)^2 = \frac{T^2}{1360(P_o - P_v)^{1.5} V_a} ; \text{sq ft}$$

where, according to Burrill,

$$A_E = \frac{A_P}{1.067 - 0.229 \left(\frac{P}{D}\right)}$$

Using this equation one can get the blade area ratio, ( $\frac{A_E}{A_o}$ ), where,

$$(A_o = \frac{\pi}{4} D^2).$$

- The propeller thrust can be determined on basis of accurate determination of the total ship resistance,  $R_T$ , and the thrust deduction factor, ( $t$ ), as:
- $T = \frac{R_T}{(1-t)}$
- For the number of propeller blades, ( $Z$ ), as it increases, the propeller efficiency and performance will increase.

Now, we might return to our main track of finding the optimum propeller diameter, where

$$K_T = \frac{T}{\rho n^2 D^4} \quad (1)$$

but

$$J = \frac{V_a}{n D} \quad (2)$$

Introduce a new variable,  $K_n$  as developed by Breslin, et al (1994),

$$K_n = \frac{n^2 T}{\rho V_a^4} \quad (3)$$

Manipulating equations (1, 2, and 3) together to get:

$$K_T = K_n J^4 \quad (4)$$

This relation of equation (4) can be graphed on a specific Wageningen B-Series chart of marine propellers performance curves of ( $K_T$ ,  $K_Q$ , and  $\eta$ ) versus ( $J$ ), of specific number of blades, and blade area ratio, as shown and depicted on Figure (1). A possible manual solution can be secured as follows,

1. Determine each intersection of ( $K_T$ ) of (4), with those ( $K_T$ ) curves which are dependent on varying ( $P/D$ ) ratio,
2. Determine the different values of ( $\eta$ ) for each intersection, and then draw a curve connecting them,
3. Consider the point at which the curve of ( $\eta$ ) osculates the envelope of maximum efficiency curves,
4. The optimum diameter is secured at a specific manually interpolated ( $P/D$ ) ratio

that corresponds to the point where the two curves of ( $\eta$ ) osculate each other,

5. The advance ratio at this osculation point determines the optimum diameter,

$$D_{Optimum} = \frac{V_a}{n \cdot J} \quad (5)$$

Until now, this procedure is performed manually for propeller design according to one of the available methodical series charts of propeller performance curves.

It is the target of this paper to perform this procedure using a newly developed computer program. During the development of the program, some special steps are made to treat the differences between applying the method numerically and manually.

*Differences when the procedure is applied numerically rather than manually:*

1. Not to find intersections between  $K_T$ -curve of (4), with ( $K_T$ ) curves of varying (P/D) ratio, but to determine numerically, by Newton's interpolation, the (P/D) ratio of  $K_T$ -curve at every value of (J) with equal small steps,
2. At every specific value of (J) and (P/D), determine the ( $K_Q$ ) value, hence, determine the propeller efficiency for each value of (J),
3. Find the highest efficiency at every specific (J), and hence, the optimum diameter can be determined.

The applied expression of Newton's divided difference method of interpolation as given in Carnahan, et al (1976), is,

$$F(x_n, x_{n-1}, \dots, x_0) = \sum_{i=0}^n \frac{f(x_i)}{\prod_{j=0, j \neq i}^n (x_i - x_j)} \quad (6)$$

Hence, this is the formulation of the optimum diameter, now we turn to the optimum rpm formulation.

## 2.2 Optimum Propeller RPM

In a very similar fashion, a similar procedure is developed to yield the optimum propeller rpm for given:

1. propeller diameter,
2. speed of advance,
3. blade area ratio,
4. required propeller thrust, and
5. propeller number of blades.

In the same manner, these parameters can be determined as previously described.

Now, after eliminating the propeller number of revolutions, (n), between the expressions of ( $K_T$ ) and (J), one may get,

$$K_T = K_d \cdot J^2 \quad (7)$$

where,

$$K_d = \frac{\pi}{8} C_T \quad (8)$$

and

$$C_T = \frac{T}{0.5 \rho \left(\frac{\pi D^2}{4}\right) V_a^2} \quad (9)$$

To determine the optimum propeller rpm for a given diameter, one may apply a very similar procedure to that previously described. A new curve of  $K_T$ , based on equation (7), can be graphed on a specific Wageningen B-Series chart of marine propellers performance curves of ( $K_T$ ,  $K_Q$ , and  $\eta$ ) versus (J), of specific number of blades, and blade area ratio, this process is depicted on Figure (1). A possible manual solution can be secured when following the same first four steps mentioned in the case of optimum diameter, while the fifth step is given instead,

5. The advance ratio at this osculation point determines the optimum rpm,

$$RPM_{Optimum} = \frac{V_a}{D \cdot J} \quad (10)$$

The present developed computer program is applicable to determine the optimum propeller rpm, just as in the case of optimum diameter.

## 3. PROPOSED COMPUTERIZED METHOD

### 3.1 Computer Program for Wageningen B-Series

For propeller design purposes, the useful experimental test results of Wageningen methodical series of B-type propeller performance of NSMB, Troost, (1951), were plotted in charts form known

as Bp -  $\delta$  diagrams. It is true that these B-type propeller charts are still applicable and yields accurate propeller design. However, aside from Bp -  $\delta$  diagrams, it is the target of this work to apply the curves of propeller performance of ( $K_T$ ,  $K_Q$ , and  $\eta$ ) versus (J) at different (P/D) ratios. Oosterveld, et al (1975), has developed a mathematical polynomial to represent these propeller performance curves of B-Series propeller type. In the present work, a flow chart has been designed to represent the logical steps of processing numerically the Oosterveld's mathematical polynomial of Wageningen series, as shown on Figure (2). Based on that flow chart, a computer program has been designed and developed in this work. As an application of the developed computer program to determine the propeller performance values has been performed for a specific propeller of the following particulars:

- Z = 5 ,
- P/D = 0.70 ,
- $\frac{A_E}{A_o} = 0.75$  ,
- Rn =  $2 \times 10^6$

In this numerical approach, the mathematical polynomial representation of Wageningen B-Series type of propellers, developed by Oosterveld, et al (1975), is considered for applications:

$$K_T = \sum_{l=0}^3 \sum_{k=0}^6 \sum_{j=0}^3 \sum_{i=0}^3 C_{ijkl} \cdot Z^i \cdot \left(\frac{A_E}{A_o}\right)^j \cdot \left(\frac{P}{D}\right)^k \cdot J^l \dots(11)$$

The propeller performance curves of ( $K_T$ ,  $K_Q$ , and  $\eta$ ) are plotted versus (J) as shown on Figure (3).

*Important Feature I:* the propeller performance curves shown on Figure (1) of Wageningen series can be reproduced by using this developed program. Almost for any arbitrary B-type propeller, the performance curves can be developed at any intermediate blade area ratio, any number of blades, (Z), and also at any pitch/diameter ratio, (P/D).

### 3.2 Computer Program for Optimum Diameter

Considering the formulation steps of the optimum diameter introduced in 2.1, another flow chart has been designed to describe the procedure's logic and its executing steps, as shown on Figure (4). This includes representation of the mathematical polynomial of Wageningen series of propeller characteristics, calculation of ( $K_T$ ) as shown in equation (4), interpolation for (P/D) value at every step of (J) which is done according to Newton's method of interpolation.

When Newton's equation of interpolation, (6) is applied numerically to determine the required (P/D), using the "pre-" and "post-" values of ( $K_T$ ) and their corresponding (P/D) values, it yields,

$$(P/D)_{required} = PD(j) + [PD(j+1) - PD(j)] * \left\{ \frac{KT-KT(j)}{KT(j+1)-KT(j)} \right\} \quad (12)$$

At that specific (P/D), calculations of ( $K_Q$  and  $\eta$ ) are performed. Repeating this process is required at every stepped (J). Hence, a decision must be taken by choosing the highest efficiency and its corresponding advance ratio, (J), to determine the optimum diameter as in equation (5).

Based on that flow chart, a computer program has been designed and developed specially to perform this proposed procedure numerically, which will save time and effort as a contribution of this present work.

### 3.3 Computer Program for Optimum RPM

In a very similar manner, the formulation steps of the optimum rpm introduced in sub-section 2.2 are considered, and minor modifications on the flow chart of finding optimum diameter, shown on Figure (4), should be made to represent the procedure's logic and its executing steps. This includes representation of the mathematical polynomial of Wageningen series of propeller characteristics, calculation of ( $K_T$ ) as shown in equation (7), interpolation for (P/D) value at every step of (J) which is done according to Newton's method. At that specific (P/D) of equation (12), calculations of ( $K_Q$  and  $\eta$ ) are performed. Repeating this process is required at every stepped

(J). Hence, a decision must be taken by choosing the highest efficiency and its corresponding advance ratio, (J), to determine the optimum rpm, as in equation (10).

Minor modifications need to be done to the computer program of finding the optimum diameter numerically, which will save time and effort in finding optimum rpm.

*Important Feature II:* A naval architect is not obligated to use charts such as  $B_p - \delta$  which has fixed blade ratios and then interpolate between them to get the optimum propeller particulars, a process which will consume time and effort. This work provides a quick way to design a propeller with optimum diameter and rpm.

#### 4. APPLICATIONS OF THE PROPOSED METHOD

For the purpose of applying the present computerized method on some existing ships, where each set of data has been prepared as an input data to the developed computer program. In the following, there are three different examples provided herein together with the computer program output data.

##### 4.1 Optimum Propeller Diameter of SL-7 Container Ship

The SL-7 container ship has the following data:

$$V_s = 33 \text{ knots}; w = 0.125; t = 0.098$$

$$\text{EHP} = 81,028; Z = 6; P/D = 1.13$$

$$N = 134 \text{ rpm}; \left(\frac{A_E}{A_0}\right) = 0.65; D = \underline{7.0 \text{ m}}$$

Present Method Results:

$$D_{\text{optimum}} = \underline{7.2 \text{ m}} \text{ and } P/D = 1.12.$$

*Comment:* There is agreement between the diameters and P/D ratios.

##### 4.2 Optimum Propeller Diameter of a Merchant Ship

This merchant ship has the following data:

$$V_s = 19 \text{ knots}; w = 0.25; t = 0.25$$

$$\text{EHP} = 26,606; Z = 5; P/D = 0.794$$

$$N = 105 \text{ rpm}; \left(\frac{A_E}{A_0}\right) = 0.75; D = \underline{8.2 \text{ m}}$$

Present Method Results:

$$D_{\text{optimum}} = \underline{8.26 \text{ m}} \text{ and } P/D = 0.792.$$

*Comment:* There is agreement between the diameters and P/D ratios.

##### 4.3 Optimum Propeller Diameter of 250,000 Ton Dwt Tanker

This tanker has the following data:

$$V_s = 16 \text{ knots}; w = 0.37; t = 0.22$$

$$\text{EHP} = 23,200; Z = 5; P/D = 0.74$$

$$N = 85 \text{ rpm}; \left(\frac{A_E}{A_0}\right) = 0.733; D = \underline{8.8 \text{ m}}$$

Present Method Results:

$$D_{\text{optimum}} = \underline{8.92 \text{ m}} \text{ and } P/D = 0.74.$$

*Comment:* There is agreement between the diameters and P/D ratios.

*Important Feature III:* The computer program gives accurate output results that almost agree with the real ship propeller diameters.

#### 5. ANALYSIS OF THE RESULTS

From the present work, the following remarks and comments can be drawn:

- 1- The proposed computerized method has been developed to be applied almost on any propeller performance curves, such as Wageningen B-series propellers, as shown and depicted on Figure (1).
- 2- Figure (2) shows a flow chart that has been developed in this present work, it gives the logical sequence of executing steps, in order to determine the propeller performance curves for almost any propeller methodical series.
- 3- A computer program has been developed by following the designed flow chart. As an application of the program, the performance curves of one of the Wageningen B-series propellers, as shown on Figure (3).
- 4- Figure (4) shows another flow chart that has been developed to represent the proposed computerized method that might determine the optimum propeller diameter and rpm for almost any propeller methodical series.
- 5- Applications of the present method on three different existing ship propellers, yields

almost a complete agreement of the results with those of real ships.

## 6. CONCLUSIONS

A proposed computerized method of propeller design has been developed and checked for applications on Wageningen B-series of conventional marine propellers. The following conclusions can be drawn from the present work:

- 1- For known propeller rpm, blade area ratio, ship required thrust, and number of blades, the optimum propeller diameter can be determined.
- 2- On the curve of required  $K_T$ , the Newton's divided difference method of interpolation has been applied to determine intermediate values of pitch/diameter ratios at different advance coefficients.
- 3- A computer program has been designed to represent the developed method.
- 4- Optimizing the different values of  $K_T$  and  $K_Q$  for the highest efficiency, yields the determination of optimum propeller diameter at specific (J), and (P/D).
- 5- The method could be considered as a quick alternative tool that saves time and effort that are consumed in propeller design by the available charts.
- 6- Applications of the present method on three different existing ship propellers, yields almost a complete agreement of the results with those of real ships.
- 7- The method is also applicable to determine the optimum propeller rpm.
- 8- This computerized method is also valid to be applied when the propeller torque is known instead of propeller thrust, by following the same procedure to determine the optimum propeller diameter and optimum rpm.

### Future Work:

The present method might have more development for the application on other

methodical series, such as Gawn-Burrill series, K-type propeller series of ducted propellers.

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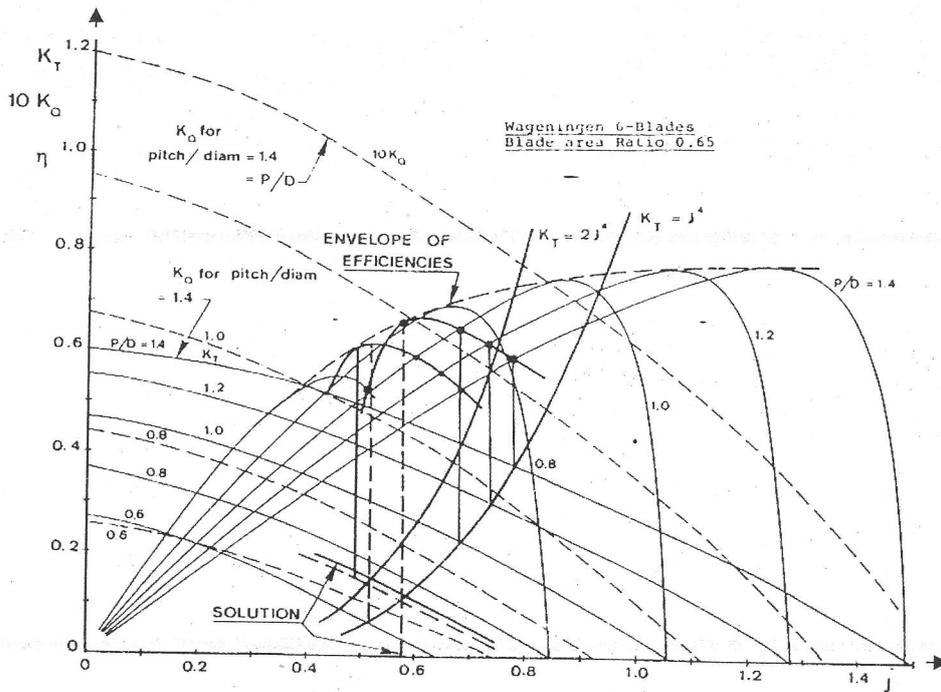


Figure (1): A scheme for the procedure of finding an optimum propeller diameter using Wageningen B-6-65 performance curves at a range of (P/D) values, Breslin, et al (1994).

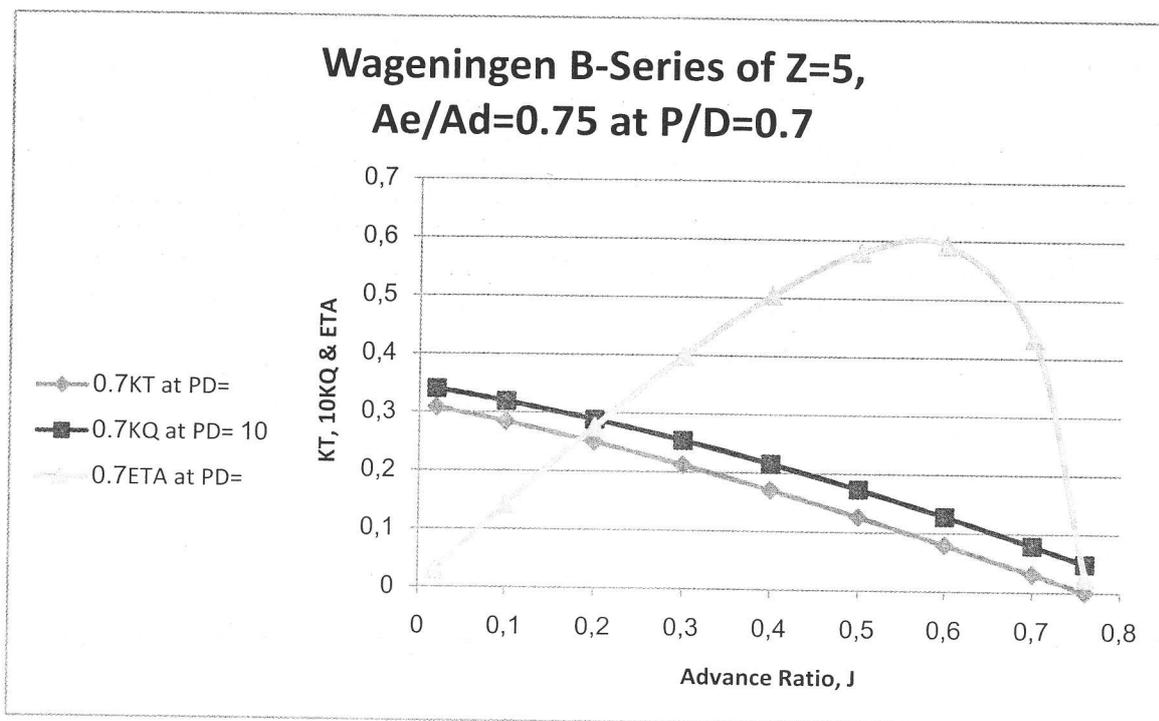


Figure (3): Present proposed method computer program output of Wageningen B-5-75 propeller performance curves.

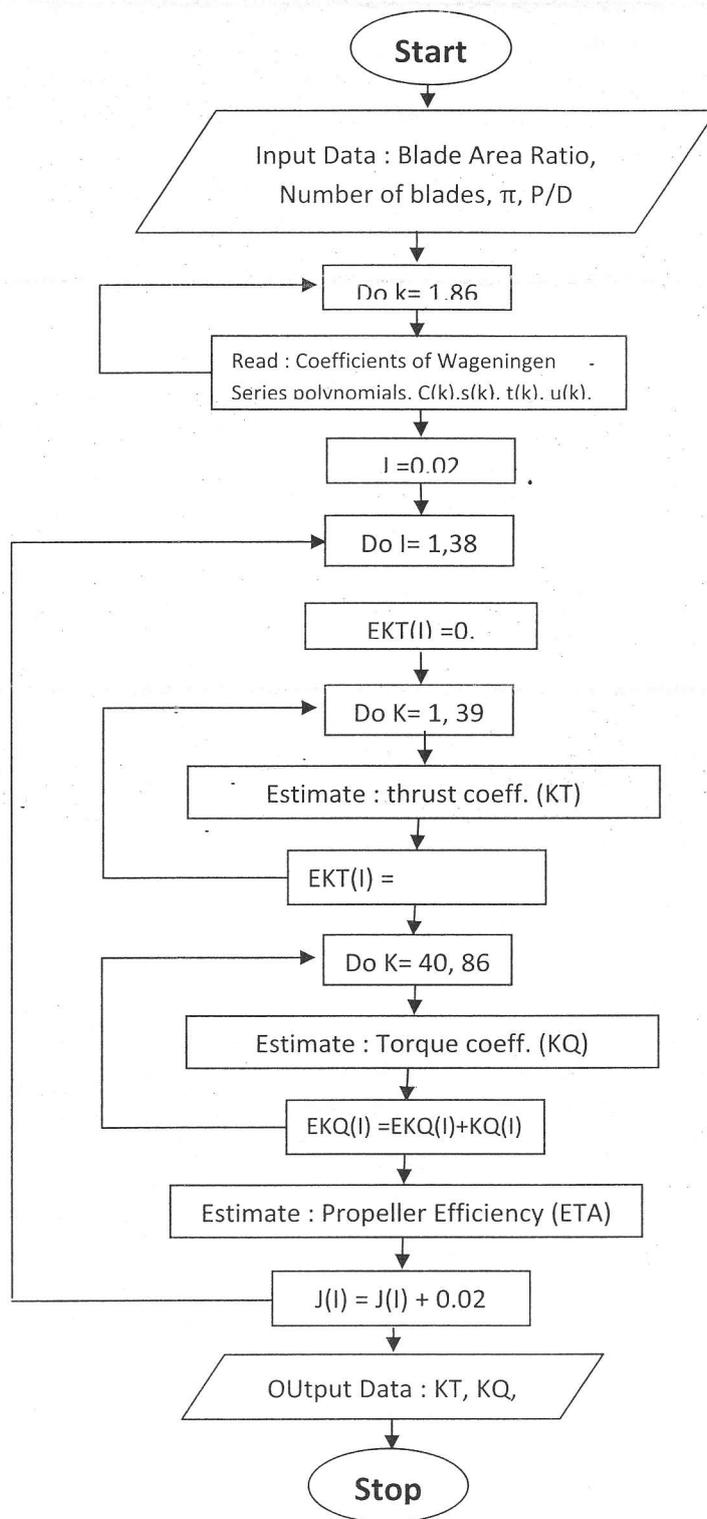


Figure (2): Flowchart to determine the propeller performance curves of Wageningen B-series.

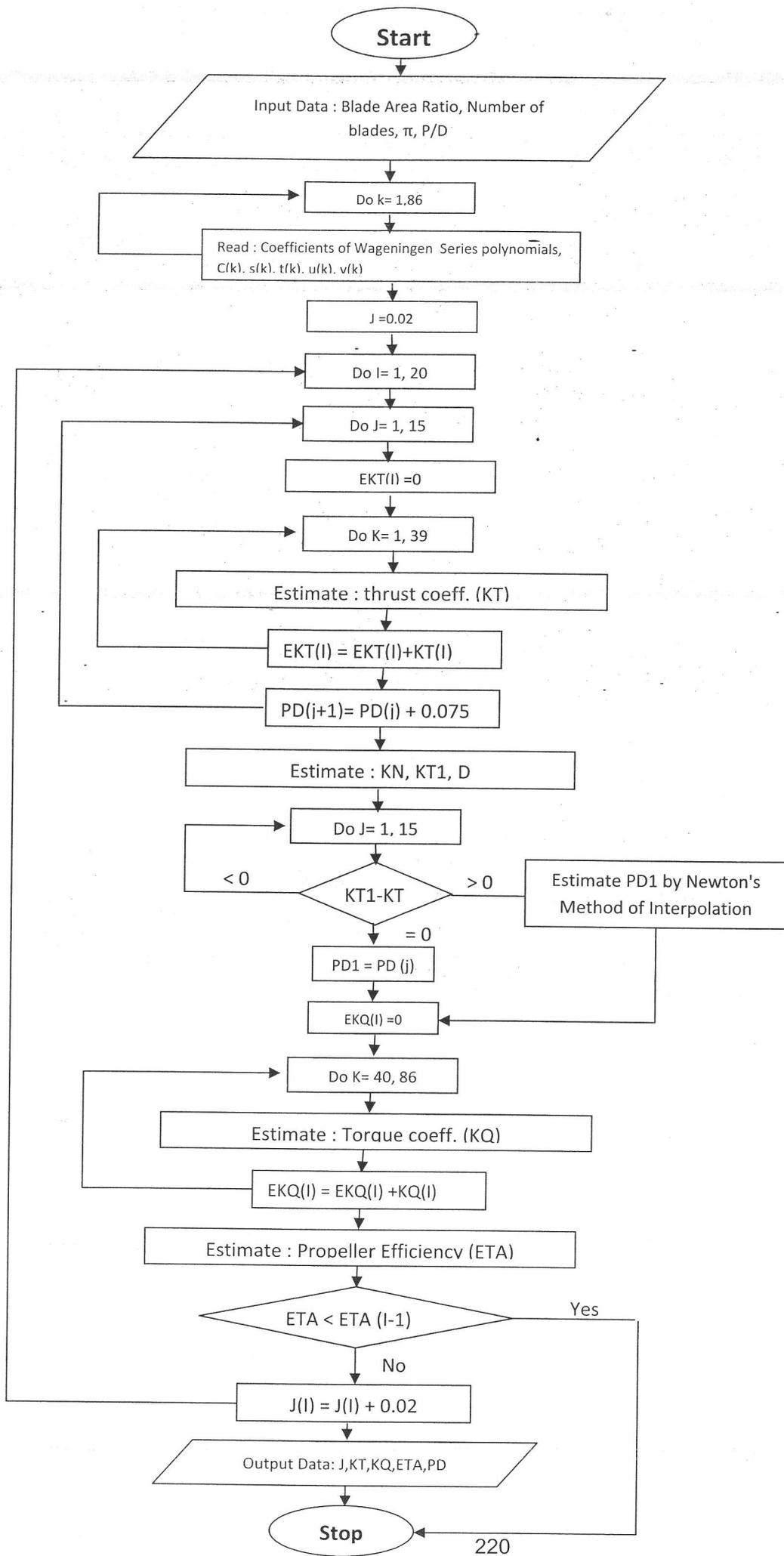


Figure (4): Flow chart of the developed proposed computerized method to determine the optimum propeller diameter and optimum RPM for one of Wageningen B-series type of propellers.