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Thrusters

Static and Effectiveness Performance Characteristics of Open Fixed Pitch DP/DT Thrusters

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Abstract

Existing available systematic propeller tests provide useful data base to help the designer understand the factors which influence propeller performance under various operating conditions. They also provide design diagrams, and/or charts, which will assist in selecting the most appropriate dimensions of actual propellers to a particular ship applications. Some information pertaining to stationary operation is not explicitly given by these tests. Typical examples of stationary or low speed applications includes tug boats, fishing vessels, dynamic/ tracking and heavy lift vessels. This work emphasizes the importance of parameters necessary required to assess the performance of thrusters in the stationary or low speed mode using available systematic thruster tests.

NOMENCLATURE

A_E/A_o	expanded blade area ratio
A_o	propeller disk area
C	regression coefficient
D	propeller diameter
FOB	Figure of Merit
G	gravitational acceleration
J	advance Coefficient
K_T	thrust coefficient
K_{T0}	thrust coefficient at zero advance
K'_T	thrust coefficient derivative w. r. t. advance coefficient
K_Q	torque coefficient
K_{Q0}	torque coefficient at zero advance coefficient
K'_Q	torque coefficient derivative w. r. t. advance coeff
n	rotation rate
p	pressure
P	pitch of propeller
Q	torque
Rn	Reynolds number
T	thrust
V_1	Upstream Axial velocity to the propeller
V_2	Axial velocity just before the propeller plane
V_3	Axial velocity just after the propeller plane
V_4	Axial velocity far downstream
$\dot{W}_p$	Power required at static condition
Z	number of blades

ρ mass density

Introduction

Propulsion systems used for DP/DT applications constitute practically of thrusters with augmentation device, and or an azimuthing capability. The augmentation device known as nozzles, shrouds, or ducts were originally introduced as guard to eliminate propeller noise and unfavorable effects on water bed. Later, it was employed for generating additional thrust particularly at low speeds. Situations requiring higher thrust include bollard pull, fishing, dynamic positioning and tracking. Propellers in nozzles may be fixed or controllable pitch. Extensive work was undertaken to introduce nozzles with enhanced and high efficiency performance. However, it is quite known that the ability of nozzles to produce additional thrust depends on the propeller itself. Hence, it was thought it would a better approach if more effort is exerted to understand the propeller action particularly at static and low speed modes. It was decided in this work to examine the performance of a homogenous group of fixed pitch open propellers and document the results to be used as a basis for comparison with other more sophisticated propulsion systems.

Open Propeller Performance at zero Advance Speed

Considering the control volume shown on Fig. (1), the mass flow rate through the propeller plane is:

$$\dot{m} = \rho VA = \rho V_2 A = \frac{\rho V_4 A}{2} \qquad (1)$$

where the velocity distribution along the propeller axis is as shown on Fig. (2)

The axial thrust force (or Bollard Pull) as obtained from momentum principle will be :

$$T_0 = \rho A V_2 V_4 \qquad (2)$$

Pressure difference across the propeller plane is:

$$\Delta p = \frac{T}{A} = \frac{\rho}{2} V_4^2 \qquad (3)$$

The corresponding energy and pressure variations along the propeller are depicted on Fig. (3)

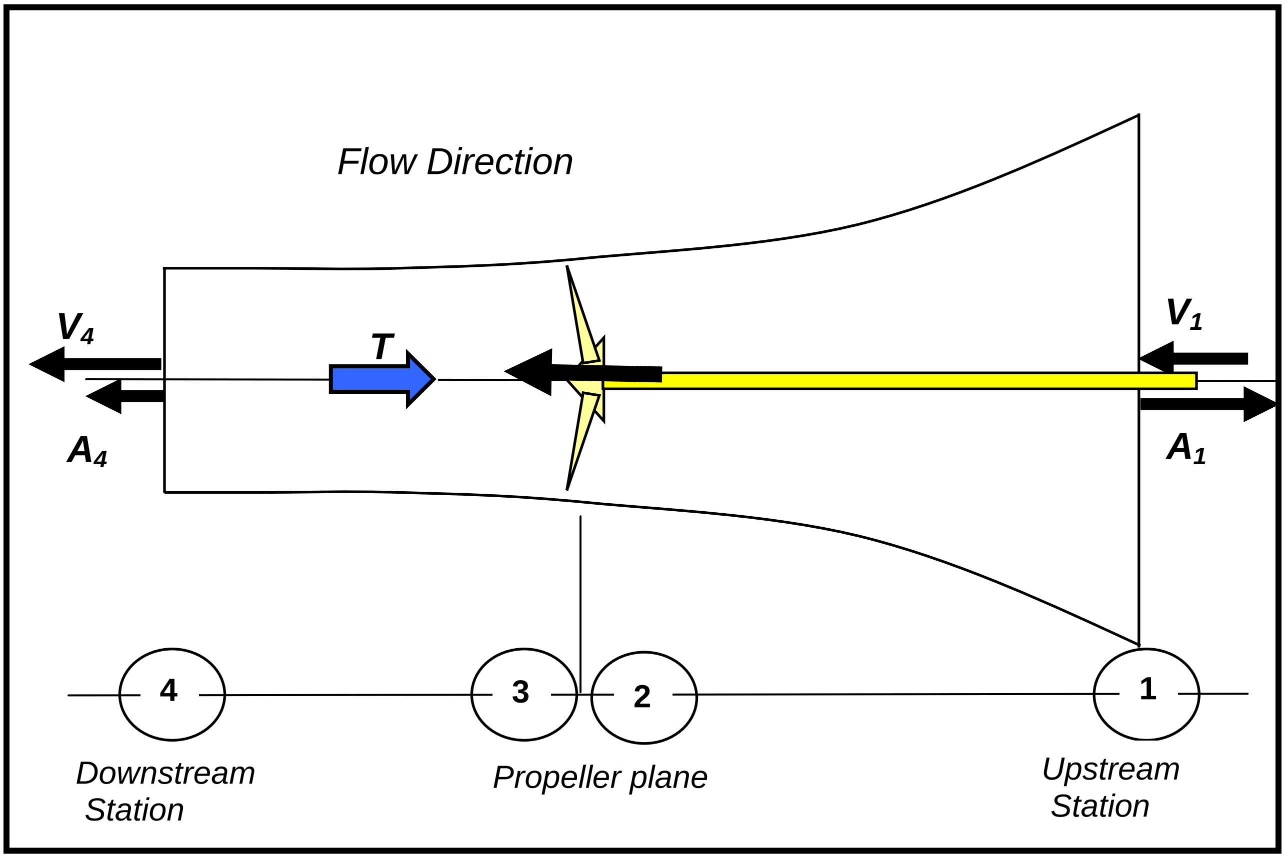

Figure (1) Control Volume enclosing propeller

The power required at static condition is given by the relation

$$\dot{W}_p = \frac{T^{1.5}}{\sqrt{2\rho A}} \qquad (4)$$

If we know the static thrust and propeller disk area, then we can calculate the required power input to the propeller. The value $\sqrt{2}$ applies to an ideal propeller, but for an actual propeller it is much smaller as will be seen later.

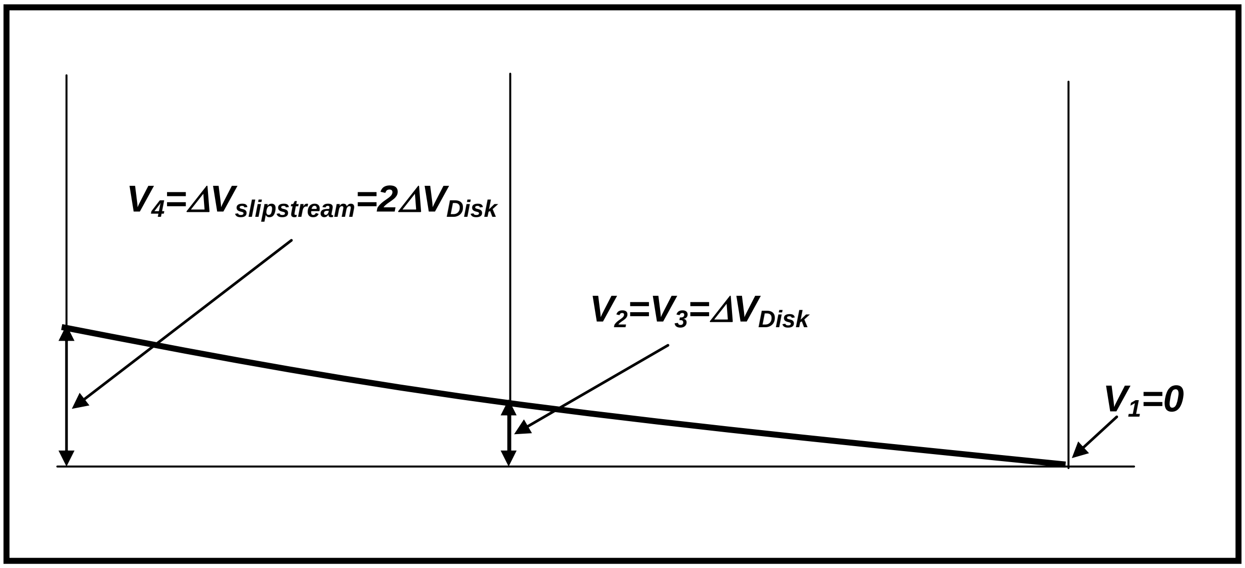

Figure (2) Axial Velocity Variation through propeller at zero advance speed

The thruster "Efficiency" or effectiveness at static condition can be derived from equation (4) to yield

$$FOM = \frac{(K_{T0})^{1.5}}{\pi^{1.5} K_{Q0}} \qquad (5)$$

K_{T0}, and K_{Q0} are thrust, and torque coefficients at static conditions defined as:

$$K_{T0} = \frac{T_0}{\rho n^2 D^4} \qquad (6)$$

$$K_{Q0} = \frac{Q_0}{\rho n^2 D^5} \qquad (7)$$

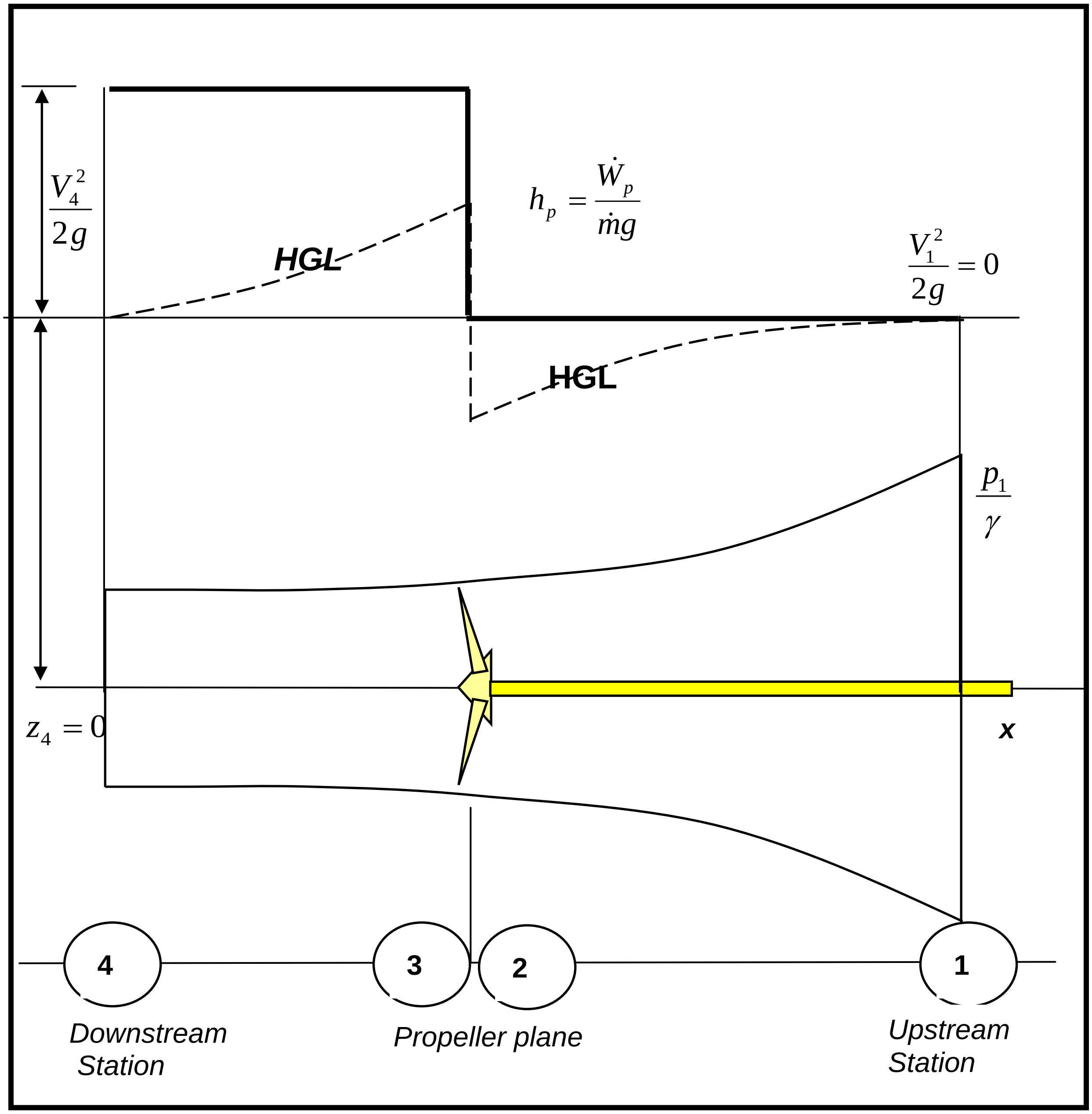

Figure (3) Energy and pressure variation along propeller Axis

Similar parameter to that given in equation (5) has been widely used in aeronautical applications (e. g. helicopter rotors and VTOL aircraft). It is termed the static merit coefficient or figure of merit. Ref. (1)

Thrust and torque coefficients are obtained from open water tests on model propellers in water tunnels and presented in graph form. They are usually functions of number of blades, pitch diameter ratio, Reynolds number, cavitation number, and advance coefficient.

In addition to the figure of merit derived earlier, a number of other criteria is usually devised to assess the performance of thrusters at zero or low speeds. These are : thrust and torque coefficients at zero speed as given in equations (6) and (7) , and their derivatives with respect to advance coefficients at zero advance. These derivatives are defined as:

$$K'_T = \left.\frac{dK_T}{dJ}\right|_{J=0} \qquad (8)$$

$$K'_Q = \left.\frac{dK_Q}{dJ}\right|_{J=0} \qquad (9)$$

where J is the advance coefficient defined as:

$$J = \frac{V}{nD} \qquad (10)$$

These parameters can be picked up using performance open water data or graphs resulting from model testing.

In order to examine the functional dependence of these parameters on thrusters geometry; particularly pitch diameter ratio, number of blades and blade area ratio, use is made of the existing systematic data on propeller models.

Several key systematic series exist, developed for fixed pitch, controllable pitch propellers, ducted propellers, etc.

In this work, open propeller, fixed pitch type is selected for examining their suitability to static performance operation. Fixed pitch propellers are the simplest form of thrusters and the results will be used as basis for comparisons with more complicated thruster systems such as ducted propellers, controllable pitch, contra rotating or podded thrusters.

Reference here will be directed towards Wageningen B-screw series (Ref 2, 3, and 4) as it is considered the most extensive and widely used propeller series. The Wageningen series is a general purpose, fixed pitch, non-ducted propeller series which is used extensively for design and analysis purposes. The series covers a range from 2 to 7 blades, 0.30 to 1.05 blade area ratio The face pitch ratio for the series is in the range 0.6 to 1.4; See Fig. (4).

In addition to the available experimental data reported in diagrams, some detailed regression studies reported by Oosterveld and van Oossanen (Ref. 5), also reproduced in (Ref 6) for Wageningen and other Series. The regression given by the following two equations at a Reynolds number 2×10^6

$$K_T = \sum_{n=1}^{n=39} C_n (J)^{s_n} (P/D)^{t_n} (A_E/A_0)^{u_n} (Z)^{v_n} \qquad (11)$$

$$K_Q = \sum_{n=1}^{n=47} C_n (J)^{s_n} (P/D)^{t_n} (A_E/A_0)^{u_n} (Z)^{v_n} \qquad (12)$$

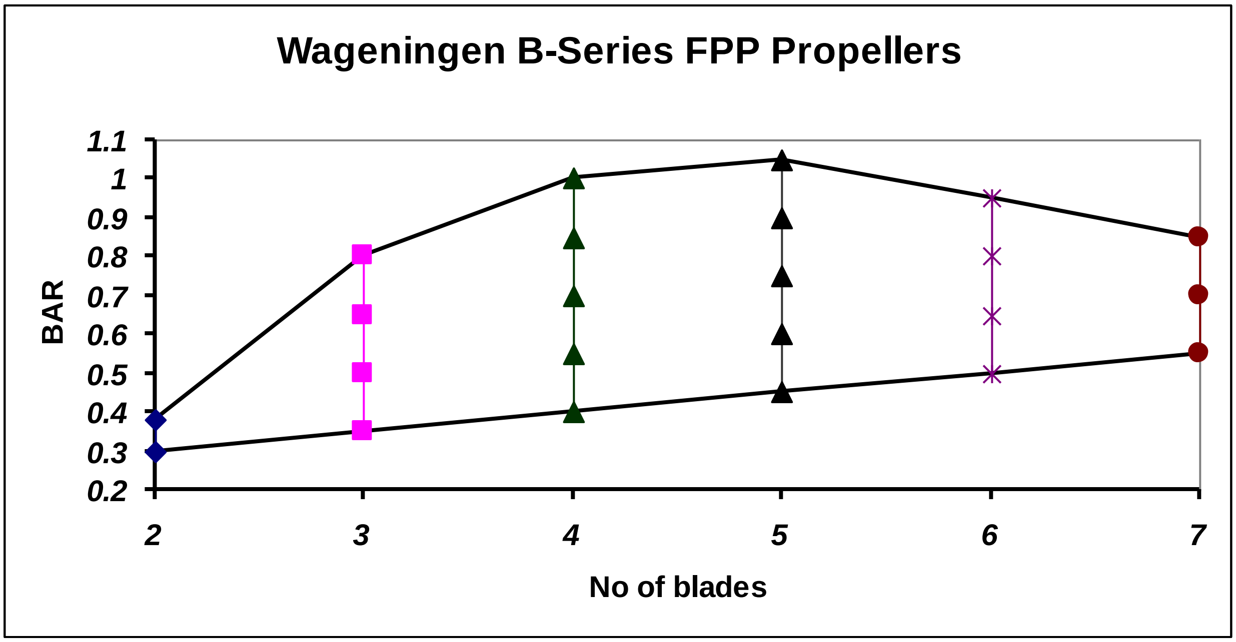

Figure (4) Wageningen B-Series Propellers

The above regression equations were used to calculate thrust, torque coefficients and their derivatives in the static mode and the associated figure of merits for the Wageningen B-Series propellers. Due to space limitations and in order to illustrate the main features of these parameters, only data pertaining to 3, 4 and 5 blades will be reported and commented upon.

Results

Figure (5) shows the static thrust coefficient as function of both P/D ratio and blade area ratio for 4 bladed B-Series thruster. In general, the thrust coefficients increase almost linearly with P/D ratio. It also, gets higher as the blade area ratio increases. The effect of blade area ratio on thrust coefficient increases at high P/D ratios.

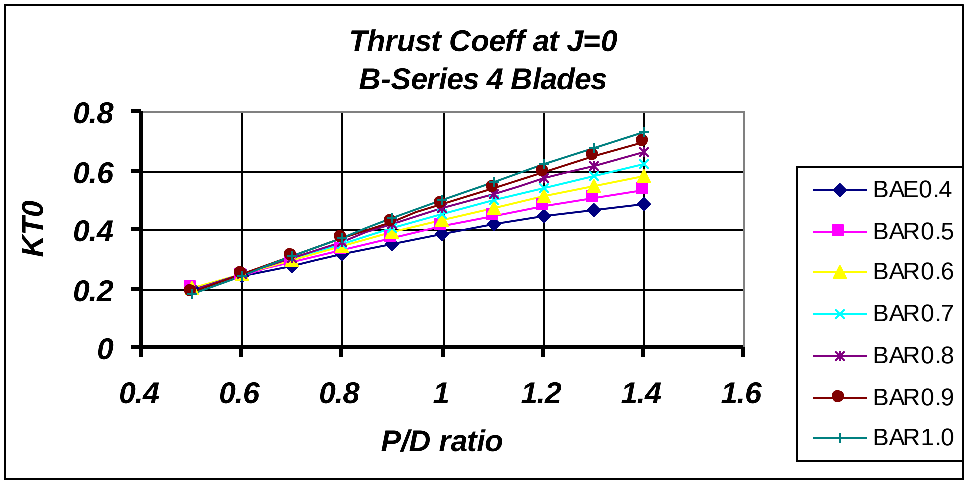

Figure (5) Thrust Coefficients at J=0 for 4 Bladed B-Series Open Propellers

Figure (6) shows the static torque coefficient as function of both P/D ratio and blade area ratio for 4 bladed B-Series thruster. The linearity trend of thrust variation with P/D is not the case with torque coefficients. However, torque coefficient increases with the increase of both P/D and blade area ratio. The effect of blade area ratio on torque coefficient is less significant at small values of P/D ratio.

The slope of the thrust and torque coefficients with respect to advance coefficient at static condition (*J*=0.0) determines the sensitivity of the thrust and torque to the current and the shaft speed. The thrust coefficient slope at J=0 increases with blade area ratio. In other words the K_T-J curve slopes more steeply down for higher blade area ratio, making the thruster more sensitive to axial current. For constant blade area ratios (up to 0.7), the thrust curve slope in absolute sense, exhibits higher value at small pitch diameter ratios. For 0.8 blade area ratio and higher, curves indicate maximum value at around P/D=1; see Fig. (7)

The torque coefficient slope at J=0 increases with both blade area ratio and pitch diameter ratio. The torque sensitivity to currents is manifested at higher pitch diameter ratio as shown on Fig. (8).

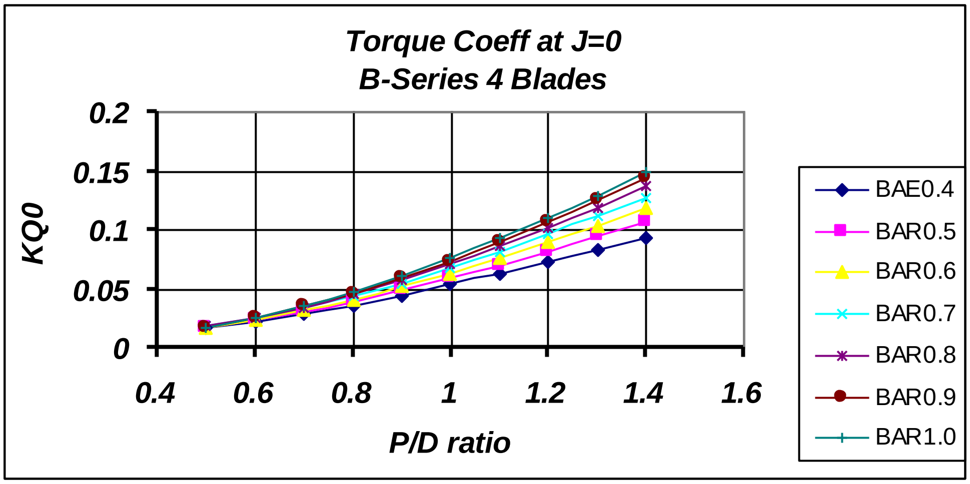

Figure (6) Torque Coefficients at J=0 for 4 Bladed B-Series Open Propellers

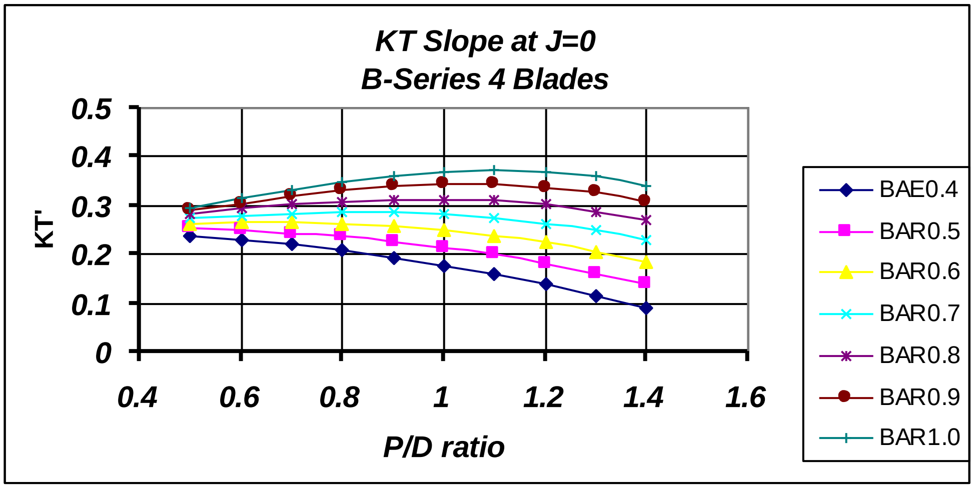

Figure (7) Thrust Curve Slopes J=0 for 4 Bladed B-Series Open Propellers

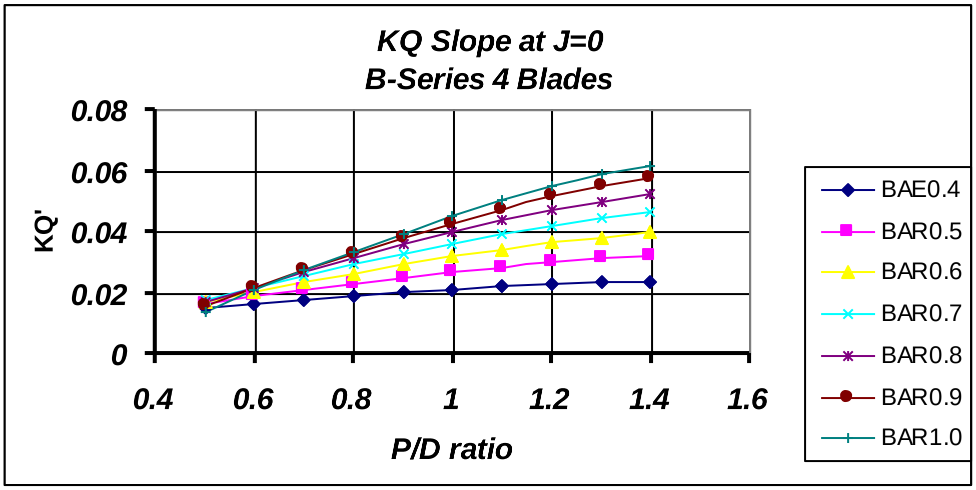

Figure (8) Torque Curve Slopes J=0 for 4Bladed B-Series Open Propellers

Figure of merit for the 4 Bladed B-Series thrusters is plotted on Fig. (9) versus P/D at a number of blade area ratios. The theoretical limit of 1.414 as per equation (4) is also displayed to illustrate the upper ceiling for this parameter. All curves falls down below this limit. The highest merit coefficient was found to be about only 0.9. This implies fair if not poor overall DP or DT performance for open propellers. The figure of merit decreases with increase of P/D ratio for the whole blade area range. Below 0.8 P/D value, higher blade area ratio has adverse effect on figure of merit while the opposite is true for P/D values higher than 0.8. An efficiency like term is defined here as :

$$Efficiency = \frac{FOM}{\sqrt{2}} \qquad (13)$$

in a way to present the thruster pulling effectiveness. The efficiency curves are shown on Fig. (10)

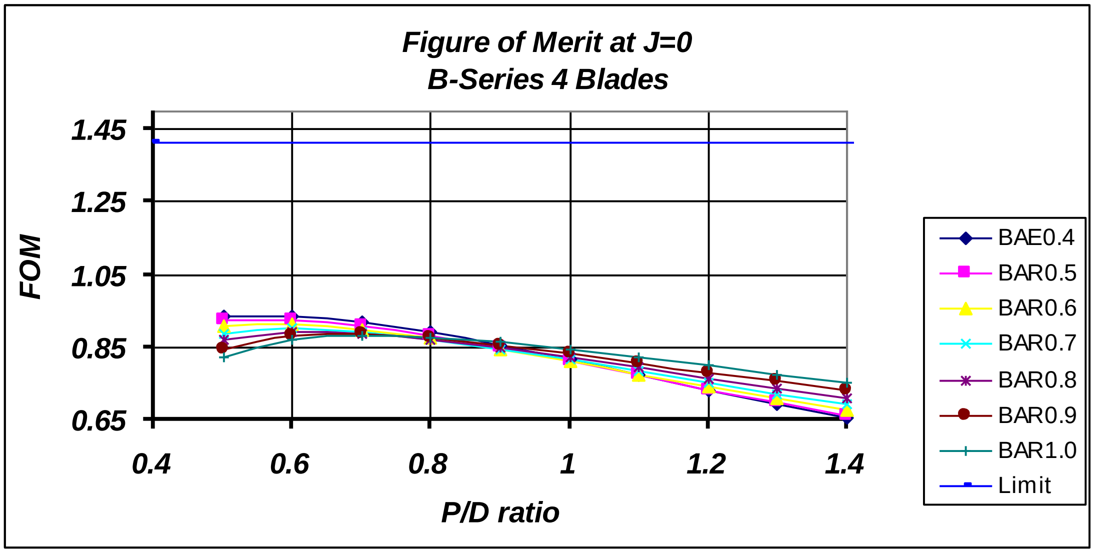

Figure (9) Figure of Merit at J=0 for 4 Bladed B-Series Open Propellers

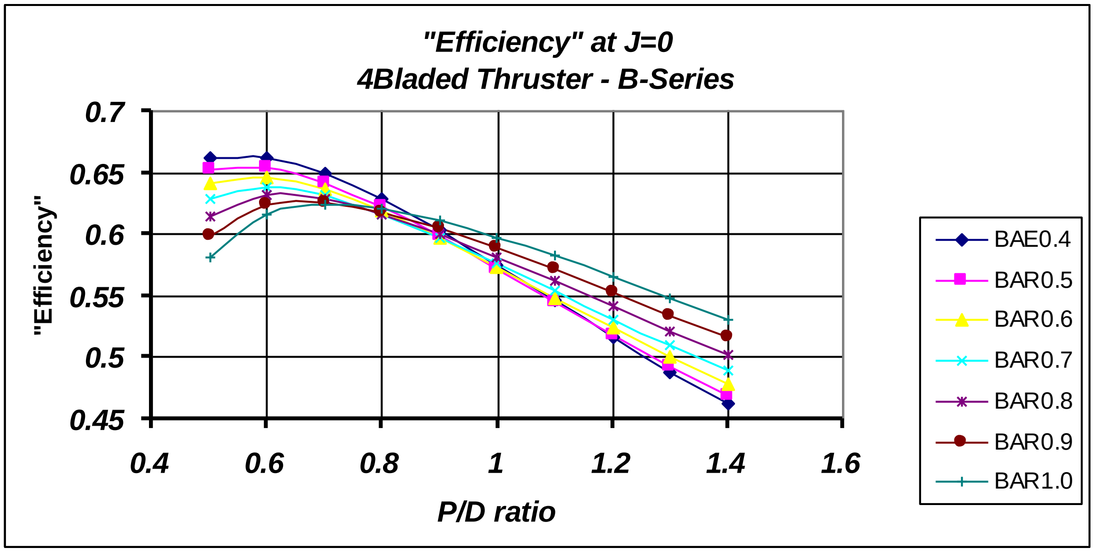

Figure (10) "Efficiency" Curves at J=0 for 4 Bladed B-Series Open Propellers

The above parameters were also plotted in an iso contour format in such a way to show the global performance and detects areas or regions of distinguishing characters.

The K_{T0} iso-contours show the region of high intensity at upper right corner where both pitch diameter ratio and blade area ratio are high. See Fig. (11).

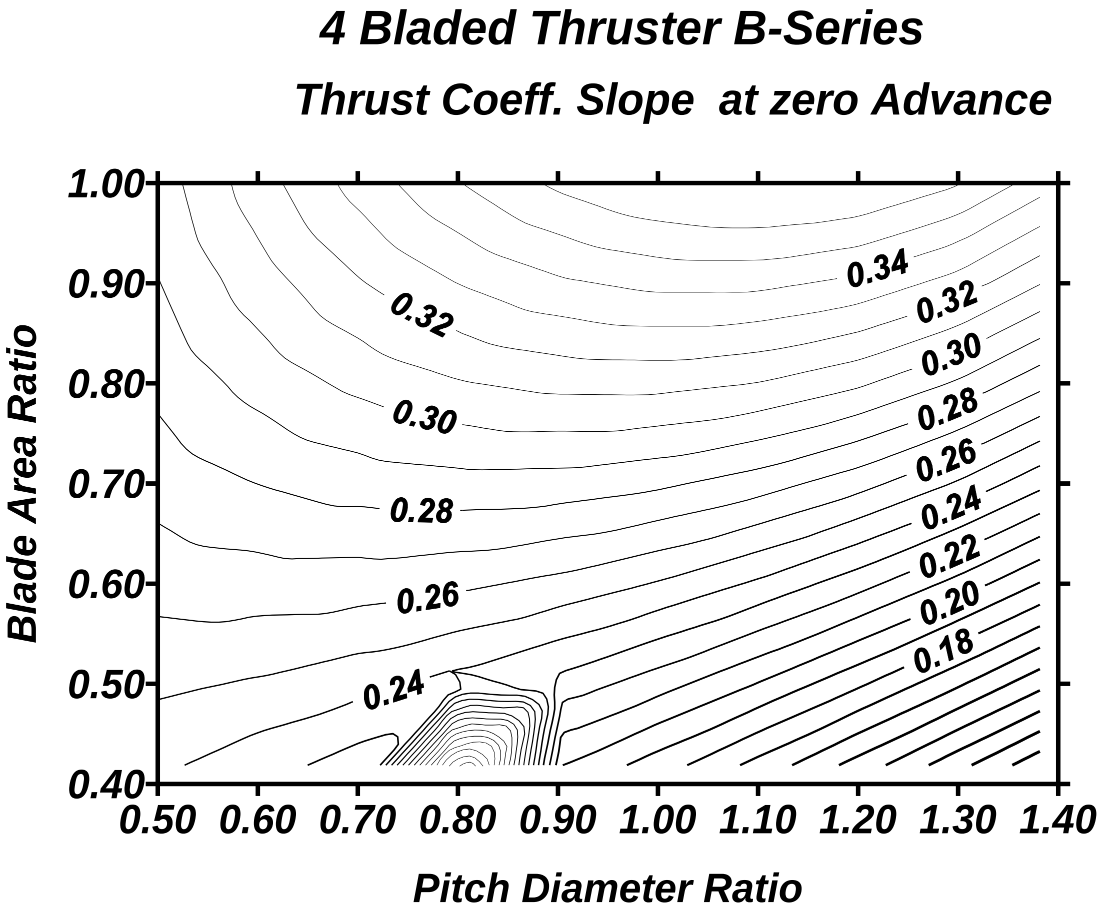

Figure (11) Static Thrust Coefficient Iso Contours for B-Series Open Propellers

Similar trend is observed for the torque coefficient indicating same region for high intensity torque, See Fig. (12)

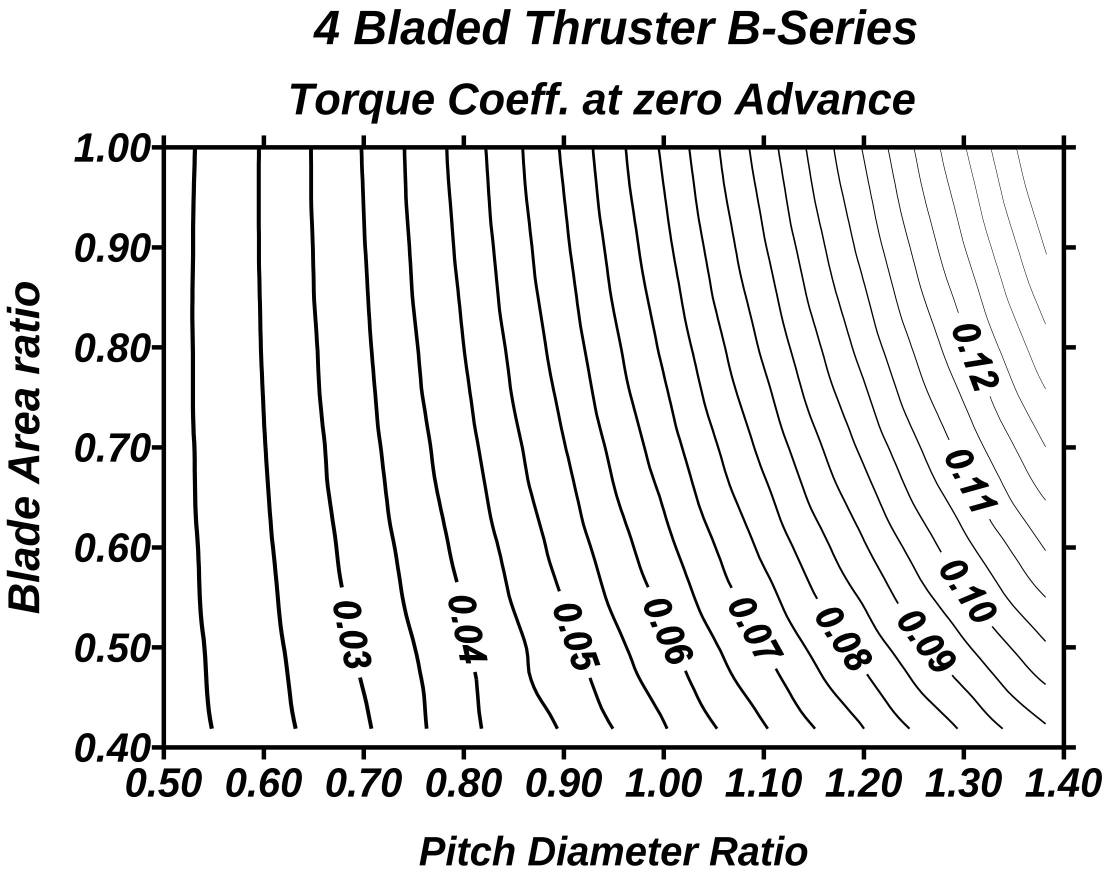

Figure (12) Static Torque Coefficient Iso Contours for B-Series Open Propellers

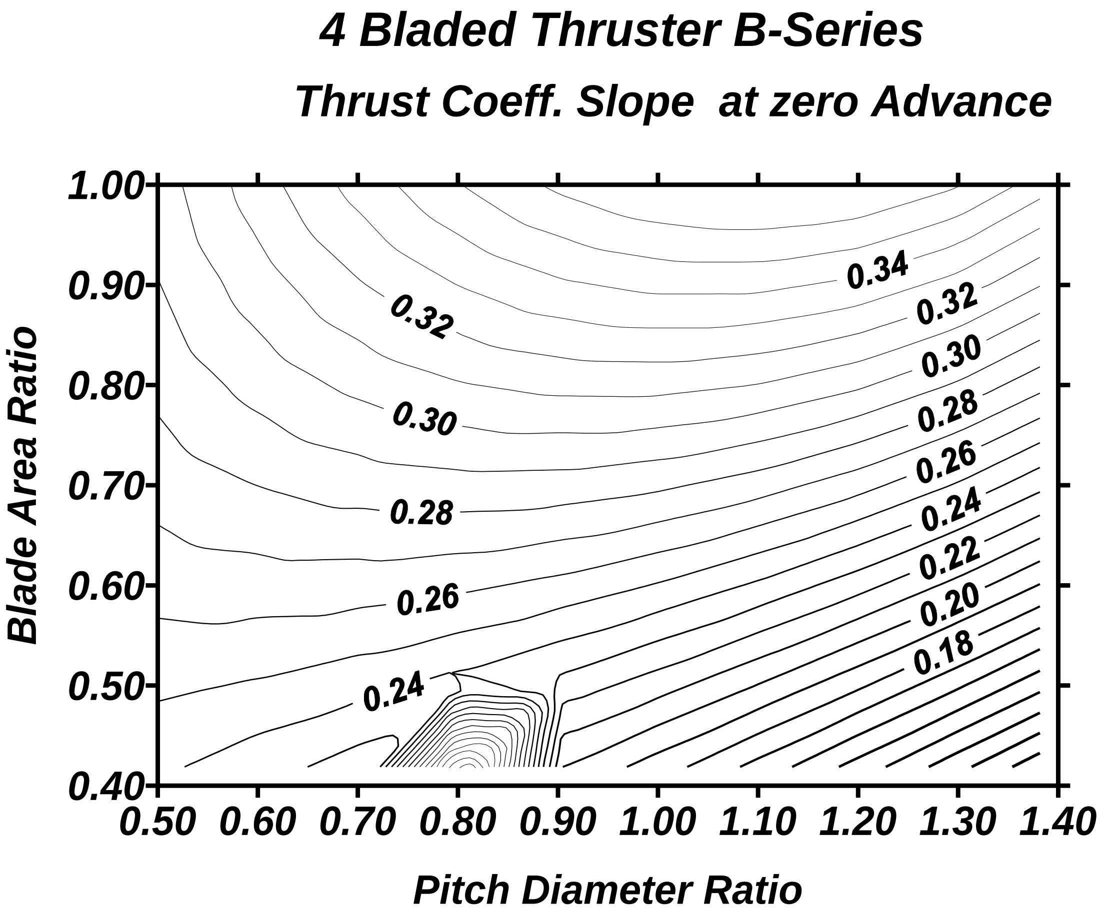

Figure (13) Thrust slope Iso Contours for B-Series Open Propellers

K_{T0} slope iso contours chart shows that for vertical lines of constant P/D ratio, the slope gets higher as the blade area ratio gets higher. The chart also shows a different pattern for horizontal lines (lines of constant blade area ratio) where some sort of maxima existing at around P/D =1

K_{Q0} slope iso contour chart shows that for both vertical lines of constant P/D ratio, and horizontal lines (lines of constant blade area ratio) the torque sensitivity to current one moves up and to the right. No regions of minimum or maximum values exists , See Fig. (14)

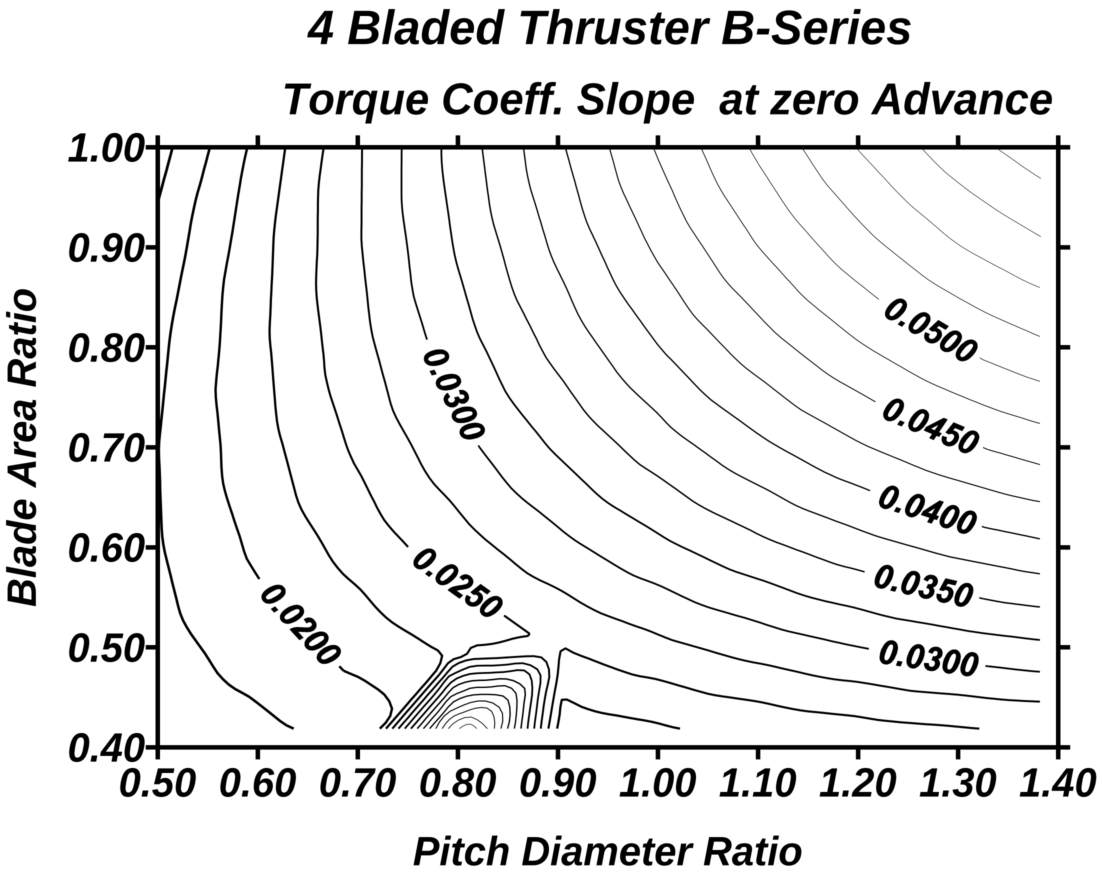

Figure (14) Torque slope Iso Contours for B-Series
Open Propellers

Two regions are displayed on the figure of merit iso-contours. The border between the two regions is the 0.9 P/D ratio vertical line. Beyond the 0.9 P/D value, the "efficiency" or figure of merit increases as the blade area ratio increases. The opposite is true for values below the 0.9 P/D ratio vertical line, where lower efficiencies are experienced as the blade area ratio increases.

The lower left corner of the diagram indicates higher "Efficiency". This is where both the P/D ratio and blade area ratio is low

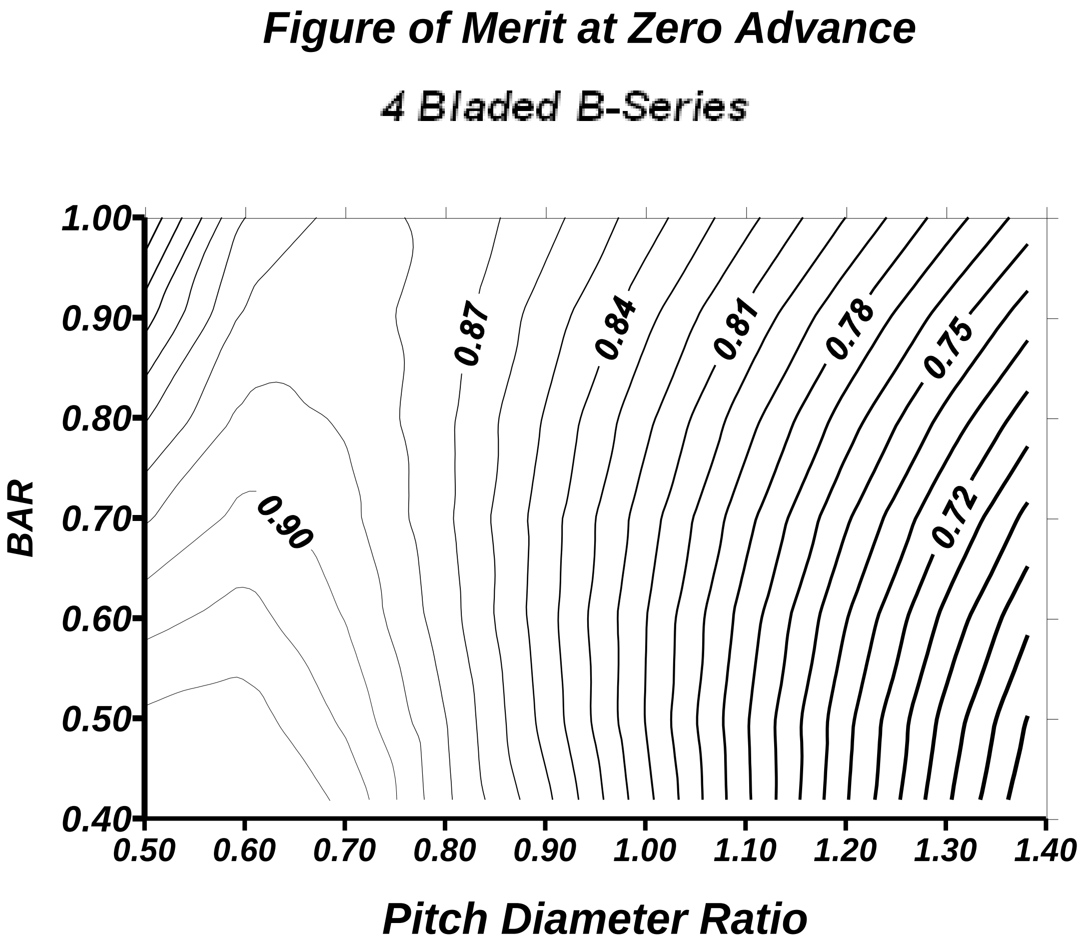

Figure (15) Figure of Merit Iso Contours for 4 Bladed B-Series Open Propellers

For the case of comparison, the "efficiency curves for the 3 and 5 blades are reported here. In Fig (16) and (17). Similar trends to the 4 bladed thrusters are observed.

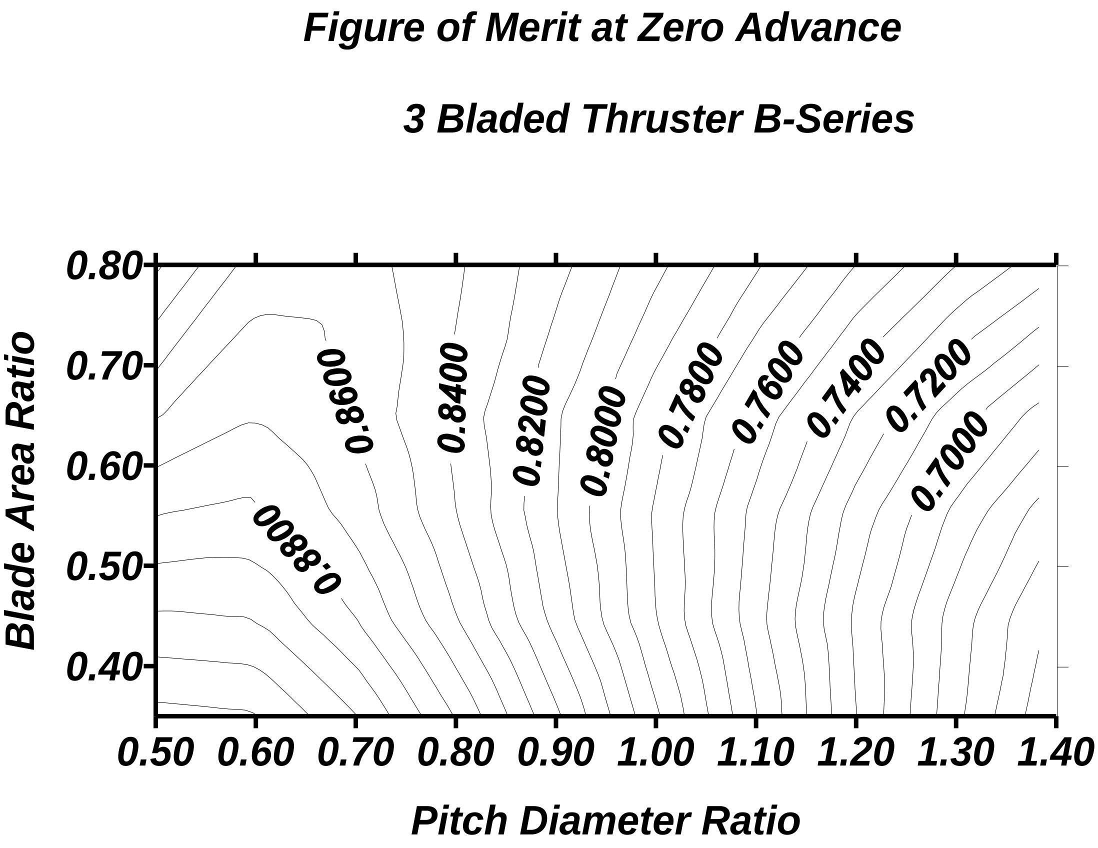

Figure (16) Figure of Merit Iso Contours for 3 Bladed B-Series Open Propellers

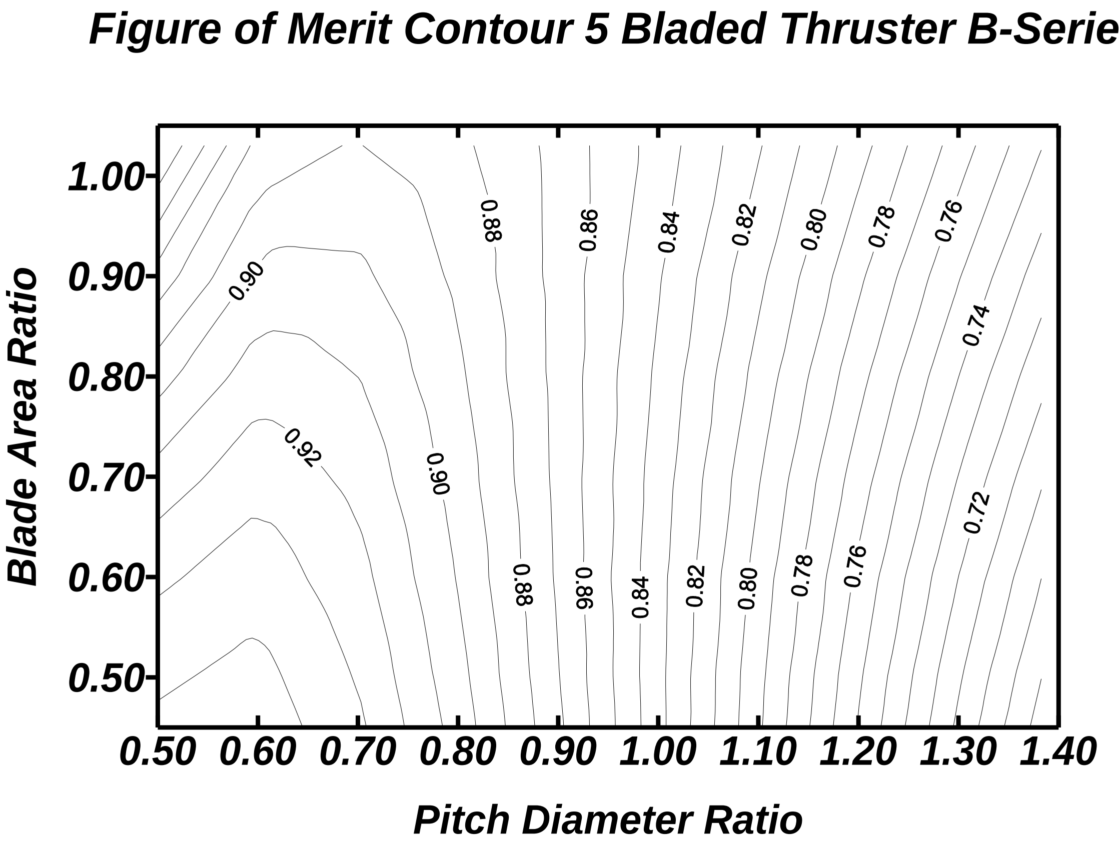

Figure of Merit Contour 5 Bladed Thruster B-Series

Figure (17) Figure of Merit Iso Contours for 5 Bladed B-Series Open Propellers

For the sake of comparison and to examine the effect of blade number on thruster effectiveness, fig. (18) was prepared where the "Efficiency" curves variation with P/D ratio for 3, 4 and 5 bladed B-type thrusters at 0.8 Blade area ratio is depicted. The graph indicate almost similar trends with a little more efficient operation for the 5 blades case over the 3 and 4 bladed case. This is in contrast to the blade number effect on sailing efficiency. The difference in effectiveness gets less significant at high P/D ratios

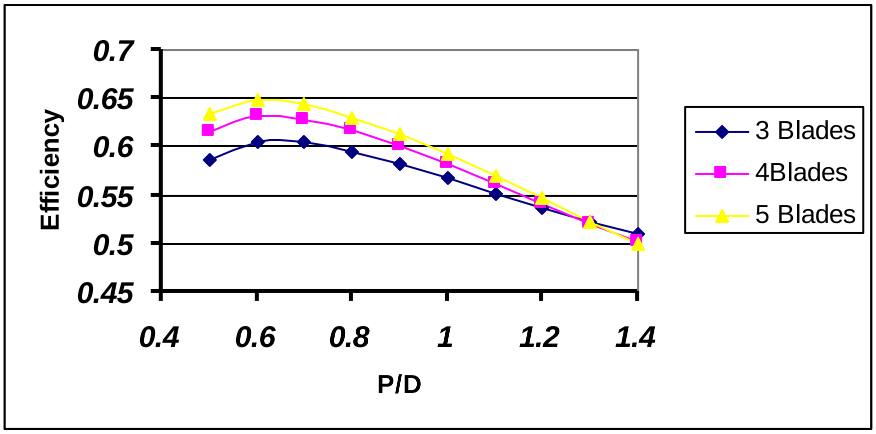

Figure (18) "Efficiency" comparison for 3, 4, and 5 Bladed B-Series Propellers at 0.8 Blade Area Ratio

Conclusions

1. Investigating the performance of open propellers at static or low speed mode is quite an important first step when considering modifications to enhance the overall performance.
2. Criteria and parameters used in this work to examine thrusters performance are quite helpful measures in quantifying or comparing the performance of different thrusters configurations
3. Existing systematic model propeller data need to be complemented with elaborated static data to assist in the selection process of efficient thrusters suitable for static or low speed applications.

4. Systematic propeller data provide a good tools for analysis particularly if regression coefficients exist
5. The reported work indicated that open propellers pulling efficiency depend on the pitch and blade area ratio selections.
6. Open thruster static performance is only efficient at low pitch diameter ratio. This could be satisfied either by low pitch or large possible diameter. Also, for open propellers with low pitch diameter ratio, low blade area ratio will further increase its effectiveness.
7. Open thrusters designed for purely dynamic positioning with low pitch diameter ratio will not equally efficient in sailing mode.
8. Methods are sought for enhancing the performance of open propellers in low speed modes.
9. The graphs produced in this work provide a good assessment to thrusters to be employed in DP/DT operations
10. Work is to be continued to examine the static mode capabilities of other systematic series.
11. Systematic propeller experimental data are needed particularly at the stationary conditions

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