Design Approach to Optimize Water Jet Performance: A Case Study of Coastal Patrol Craft, Sri Lanka Navy

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Abstract— Commercial water jet manufactures publish their water jet performance curves mostly in the form of thrust/power against boat speed. The common approach is to foresee the performance of craft with candidate water jet(s), to simply plot the developed bare hull drag curve by a Naval Architect against the published power/thrust curves in graphical mode to establish the best fit. Yet this traditional approach does not uncover information of craft performance in the entire speed range or water jet model efficiency as the best choice for a particular local application. This case study incorporates approaches to seek a reduction in the craft bare hull drag, to develop an adequate analysis that shall combine engine RPM analysis to understand the availability of full rated engine power absorbed by propulsor/water jets. Therefore, the research employs a comprehensive mathematical based methodology as compulsory, to evade performance glitches and to outline an accurate and fruitful design structure. Thus, the employment of "universal water jet coefficients" has been considered to validate the design and eliminate the flaws associated with the traditional "thrust-resistance" plotting technique. A naval project designed by the authors was used to demonstrate how the authors averted possible complications and optimized the design through a new calculation methodology.

Keywords: ***traditional approach, water jet efficiency, universal water jet coefficients***

I. INTRODUCTION

The boat propulsion system consists of a marine engine, gearbox, and a suitable propulsor and does not require any design of equipment as Original Equipment Manufacturer (OEM) is entrusted with the same. For marine engines and gearboxes, the Naval Architecture is required to confirm power transmission, power output, and RPMs meet the desired. The Naval Architecture to design hull, propeller styles may be chosen, and be suitably pitch to the engine type. Thus, equilibrium performance relations are upheld.

Figure 1 depicted below identifies the focal study elements as engine – propulsor – hull equilibrium. This necessitates propulsor performance determination with concern on boat speed, Engine/ propulsor RPM, thrust, and torque (or power). The calculated assessments mainly focus on propulsor efficiency, engine fuel consumption, and propulsor cavitation. By this means authors aptitude was to seek, how non-dimensional (same for actual boat and model) associations could use to conduct the above examination for a waterjet thrust (propulsor - hull interaction determination) and torque (engine - propulsor interaction determination).

Figure 1. Equilibrium performance schematic

Cavitation tunnel open water tests usually provide the velocity of advance, RPM, Torque, and Thrust relations of propulsor. A step forward, Propeller Theory is based on models that defines non-dimensional coefficients. With distinctive and complex propeller diagrams, which contain, i.e. J, KT and KQ curves, it is promising to estimate the propeller dimensions, and efficiency. Built around the KT/KQ nomenclature as depicted in Figure 2, it offers a successful methodology which offers the benefit of (a) work with factors rather broad 3D geometry and (b) simple to calculate yet allinclusive boat performance study. Thus, this numerically simple task leads to the successful selection of optimum parameters. Yet unfortunately, the methodology is most validated in open water propellers.

$$KT = \frac{\mathrm{T}}{\rho.n^2.\mathrm{D}^4}, \quad \mathrm{KQ} = \frac{\mathrm{Q}}{\rho.n^2.\mathrm{D}^5}, \quad \mathrm{J} = \frac{\mathrm{Va}}{\mathrm{n.D}}$$

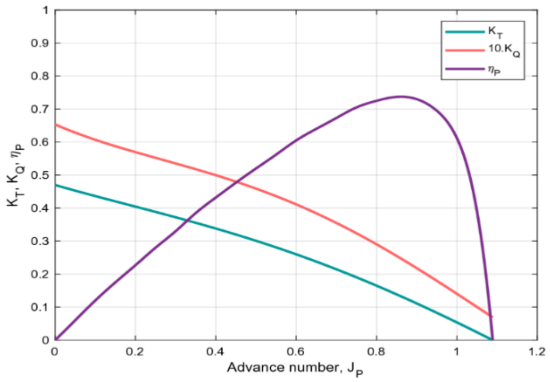

Figure 2. J, KT and KQ curves
Source: Taskar,B., Yum, K.K., Steen, S. and Pedersen, E., 2016

Predicting waterjet performance, in general, the manufacturer of waterjet provides the thrust curves for a region of defined boat speeds, the traditional approach has been the graphical mapping of boat's bare hull resistance curve on it to identify the adequacy of generated thrust to encounter the boat total resistance demand. This traditional approach does hide RPM from power and shall not allow compute and analyze important derivative performance amounts to fuel economy, boat acceleration reserves for manoeuvre/ combat operations which is of paramount importantance for naval operations.

The research problem statement of the study is 'Non availability of comprehensive study approach, which uncover all parameters for military applications' thereby the scope of the study is to develop a 'Design approach to optimize the performance of waterjet driven petrol craft for Naval application'. Thereby research employs a comprehensive mathematical based methodology as compulsory, with objectives: to seek a reduction in craft bare hull drag, to promote an adequate analysis shall combine engine RPM analysis, to understand the availability of full rated engine power absorbed by propulsor /waterjets. The research significance is, the study tries to fill the gap, specially the analysis of power to RPM with a selected prime mover, fuel efficiency, boat acceleration, and treatment of sensible parameters for hull drag.

II. METHODOLOGY AND EXPERIMENTAL DESIGN

Authors scanned the international shelf to shortlist candidate waterjet models with criterions amounts to power to weight ratio, boat speed, transom detail of hull, Glass Reinforced Plastic (GRP) fabrication, and robustness for naval applications etc., as directed by Naval Headquarters.

Authors were then obligated to commence with the information/ specification data provided by all OEMs. In a detail study following were revealed;

a. Nozzle characteristics (transom angle, center of effort, diameter)
b. Impeller characteristics (diameter, pitch variations, number of blades, hub construction)
c. Physical characteristics (weight, geometry, mounting detail, steering/ reversing details)
d. Rating (maximum input power and RPM)
e. Impeller Power (absorbed shaft power) vs. RPM plots, Figure 3.
f. Thrust curves (boat speed vs. thrust/power), Figure 4.

The principal boat design parameters were: Length overall - 20 m, Beam - 5 m, Hull Material – GRP, Draught - 0.95 m, Full Load Displacement - Approx. 27 Ton, Maximum/ Cruising speed - 35/30 Knots, Hull Type - Round-bilge with hard chine, and Endurance - 350 Nm@ 35 kts.
Length, Beam and Depth were kept fixed for this project (GRP mould constraints), but the authors were attentive to see how alterations in weight, Longitudinal centre of buoyancy (LCB), Longitudinal centre of gravity (LCG), deadrise angles and trimming affected bear hull resistance. The authors' presumption on sensible parameters amounts to boat weigh, LCG and deadrise angles was found to be critical in this coastal petrol craft design. Since non availability of precise weights, parametric estimates with educated deduction arrived with the weight estimation of 27 Tons. LCG and LCB were finalized with planning characteristics (Figure 4). Large AFT/stern deadrise angle avoided

improving performance (Figure 4). Further, trim by AFT condition was promoting planning condition to swiftly transfer boat weight to hydrodynamic forces (Figure 5).

However, the authors were cognizant of the fact that an LCG too far forward or too far aft would both have adverse effects. If the LCG is too far forward, the craft would have more power to plane than the same hull shape designed with zero trim or a bit by the stern. However, if the LCG is too far aft, a dynamic instability called "porpoising" would occur, which is primarily caused by concentrating too much weight in the stern. So, you have to reach a good middle ground between keeping weight aft for good planing and keeping it far enough forward to prevent porpoising. Careful analysis was conducted by studying a similar craft and calculating the resistance against the LCG change to reach an adequate balance. The benchmark of these studies was to reach an equilibrium trim angle between 3º to 5º for the whole speed range as indicated in Figure 5.

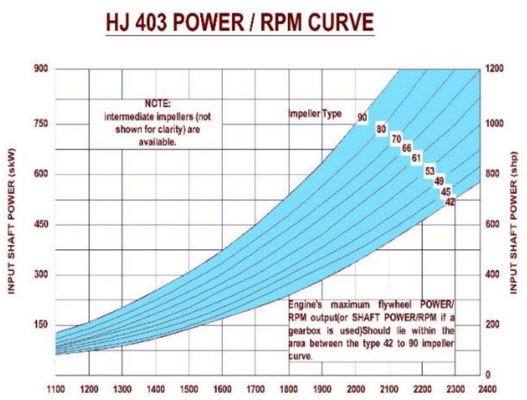

Figure 3. HJ 403 standard impeller power vs. RPM curves
Source: Ms C. W. F. Hamilton & Co. NZ (2019)

Figure 4 depicts a considerable resistance rise near 20 knots (planning of craft), with a wide flat region of the same hull resistance up to 32 knots. Naval application with extreme manoeuvres as the primary design objective, is required to operate the boat above the drag “hollow”. The authors’ initial analysis revealed boat parameter improvement is a necessity. Further, the traditional approach not allowed the visibility of acceleration reserve and efficiency of this operation. Thus, authors opted for complete system analysis with "universal waterjet coefficients" for the steady state performance with boat acceleration study, as promoted in their studies (MacPherson, 2010). Thereby, the authors evaluated possible modifications in hull form in line with performance enhancement. This numerical model provided the characteristics amounts to (a) Parametric - simple and clear define parameters, (b) Universal - applicability to all waterjets, and (c) Computational easiness - easily employed in computer codes.

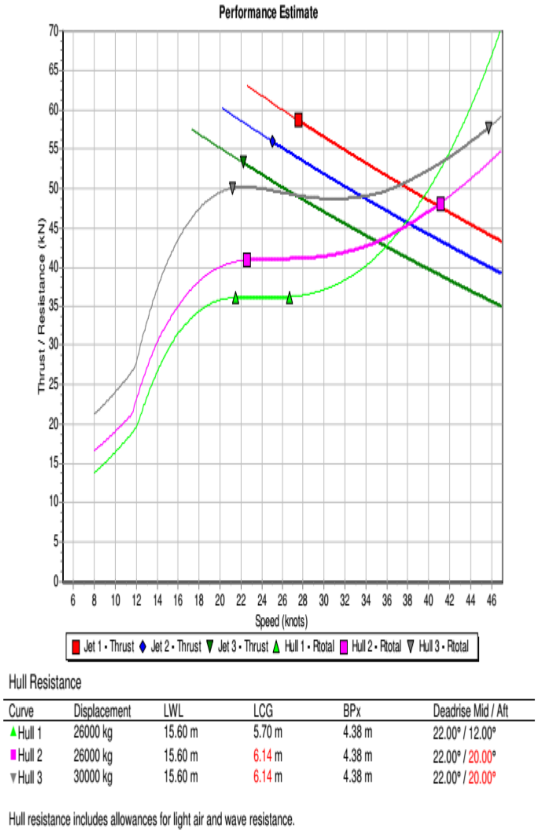

Figure 4. HJ 403 Waterjet thrust and hull drag curves
Source: Ms C. W. F. Hamilton & Co. NZ (2019)

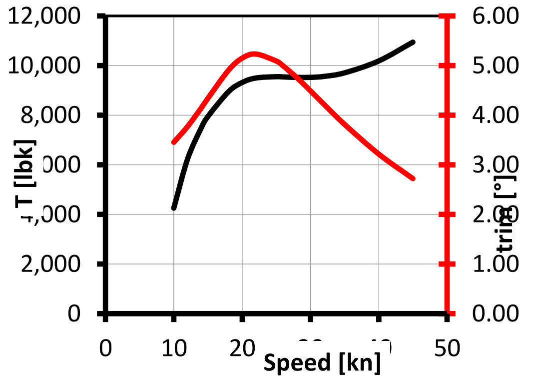

Figure 5. Boat trim conditions
Source: Calculated by authors using algorithm Developed by Dingo Tweedie

III. RESULTS AND DISCUSSION

Three coefficients were utilized by authors to transform the above mentioned commonly available waterjet information provided by respective manufacturers into non-dimensional exemplification of the traditional plots. Thus, complete physics based methodology employing "universal waterjet coefficients".

A. Speed-Thrust-Power coefficients

Figure 4 depicted the thrust curve was collapsed by authors into two coefficients, called C_P (power coefficient) and C_T and (thrust coefficient) is placed in Figure 6. Since Thrust is developed in a waterjet due to the change in the momentum of the water that accelerates through a tunnel, the Thrust could be defined as follows.

$$Thrust = \rho . V_{jet} . A_n . (V_{jet} - V_S)$$

Since the velocity of the waterjet stream can be defined in terms of ship speed using a coefficient, an equation could be developed to obtain C_T. For a given ship speed, the power of the craft is given by the following equation;

$$Power = Thrust \, . V_S$$
$$Power = \rho . V_{jet} . A_n . \left(V_{jet} - V_S\right) . V_S$$

Using the same process for C_T a coefficient for Power of the craft, Cp could be developed.

$$Cp = \frac{P}{\rho . \mathrm{An} . \mathrm{Vs}^3} \quad Ct = \frac{T}{\rho . An . Vs^2}$$

Where, P = shaft power, T = thrust, ρ = mass density of water, An = nozzle discharge area, and Vs = ship velocity, Vjet = Waterjet stream velocity.

Large numbers for C_T and C_P indicate high thrust with low speed. Thus, the waterjet's equivalence of "bollard pull" area. Proposed waterjet manufacturer's charts and geometric data were used to calculate the coefficients as follows to identify the suitability of operation relating to Figure 6. Since the operating range of CPC (35 knots) lies in the region of small X and Y values, waterjet selection could be justified.

Nozzle area (An) = 0.126 m^2, Impeller diameter (Di) = 0.400 m, Speed (Vs) = 35 kts (18.00 m/s), Power (P) = 1,500 kW Thrust (T) = 45,000 N
CT = 1.077, and CP = 1.99

Further, coefficients were employed to determine one of the most critical parameters "jet efficiency", ηJET, which equals to C_T/C_P (and also TVs/P). Figure 7 provide the plot of ηJET vs. C_P. Thus the arrival of a clearly defined efficiency peak is a possibility. The operating region of the CPC is in at an efficiency of 0.56, almost reaching the peak efficiency as per Figure 7.

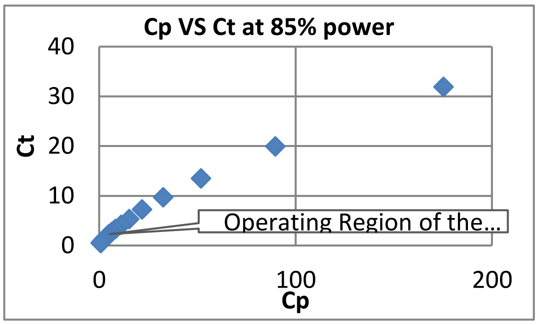

Figure 6. CT vs CP plot
Source: Calculated by authors

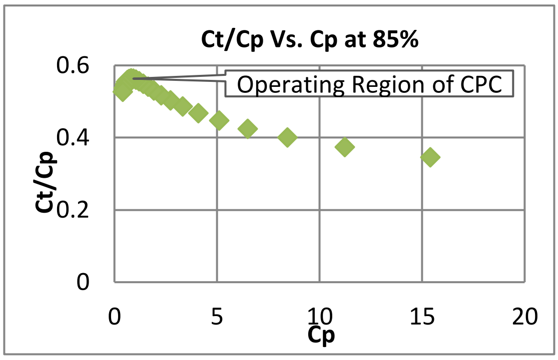

Figure 7. CP/CT (ηJET) vs CT plot
Source: Calculated by authors

One research outcome with employing "universal waterjet coefficients" was the ability to identify the operational location of maximum jet efficiency. Now it is probable to select the best performing waterjet with the greatest efficiency. A "maximum efficiency" track was plot in Figure 8. The authors design is closer to the maximum possible waterjet efficiency. Thus, the selected waterjet is with peak efficiency at a higher speed, which was the requirement. This outcome promote an adequate analysis shall combine engine RPM analysis, an objective of study.

B. Power-RPM coefficient

The authors studied the applicability to employ coefficient KQ (for a conventional propeller) to be suited for the water jet approach. Instead of torque employing power, the formula would be:

Where, P = shaft power, ρ = mass density of water, n = shaft speed, Di = impeller diameter

The torque coefficient KQ is a function of a particular standard impeller and is a fixed number for a separate impeller. Thus, KQ calculation with data from Figure 3. This approach is useful as this stage shaft power, diameter and velocity of advance are known. For impeller type 90 on the Power-RPM curve (Figure 3). Power (P) = 765 (85% Power), RPM (n) = 2150 rpm. Thus, KQ = 0.258. With the calculated KQ value, a plot is to be made in Figure 2 (with a KQ/J^3) on the optimal efficiency line to find RPM envelop. Figure 9 was developed to understand the availability of full rated engine power absorbed by propulsor /waterjets. Thus, another objective was achieved

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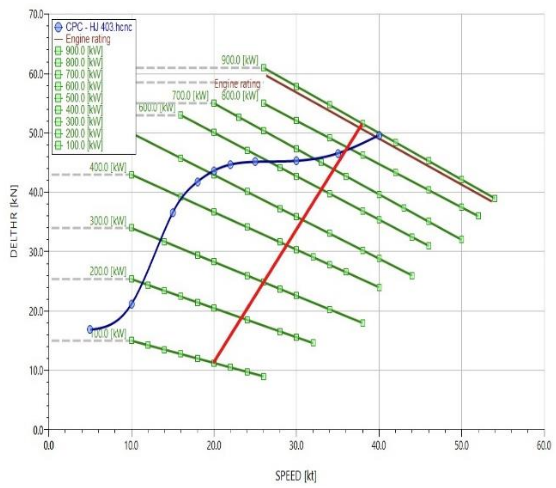

Figure 8. HJ 403 Waterjet thrust and hull drag curves upon parameter improvement
Source: Calculated by authors

C. The power-RPM curve

The matching of the marine engine with selected waterjet with respect to entire operation envelop is required to determine for swift operation. This study will give how good achieve the 'Hitting the Corner' criterion. Further, give a glimpse of manoeuvrability superiority of the design. Figure 10 depict the authors' predictions

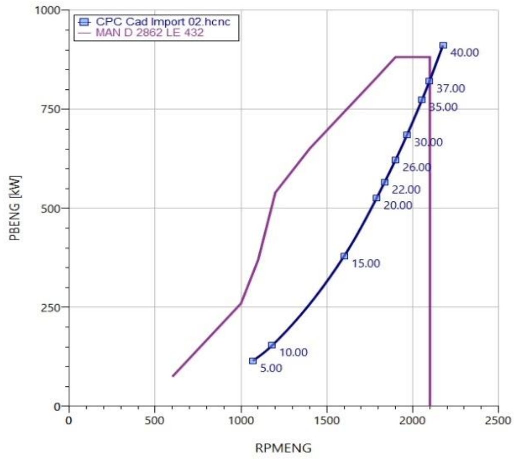

Figure 9. Power vs. RPM Curves
Source: Calculated by authors

D. Vessel acceleration

The "universal waterjet coefficients" did simplify the various powering situations with computer simulations. The boat acceleration analysis was conducted and depicted in Figure 10. The acceleration analysis with a similar waterjet model from another manufacturer was plotted to examine the variance in "time-to-speed" for both choices. The waterjet selected by the authors took approximately 20 seconds while the other unit reached the same speed in 22 seconds, to reach 30 knots. To reach the design speed of 35 knots, the selected waterjet unit took only 32 seconds, while the other unit spent 62 seconds. This information is critical since for a military patrol boat the time to reach its maximum speed is of vital importance. Hence, this approach of assessing the waterjet performance using 'universal waterjet coefficients' is justified

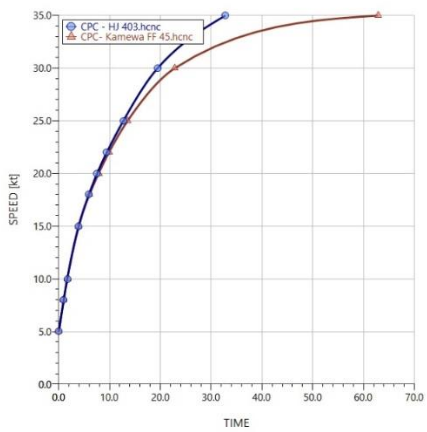

Figure 10. Vessel acceleration comparison
Source: Calculated by authors

The authors considered the cavitation regime with Figure 11 and found design areas are well clear of the cavitation region.

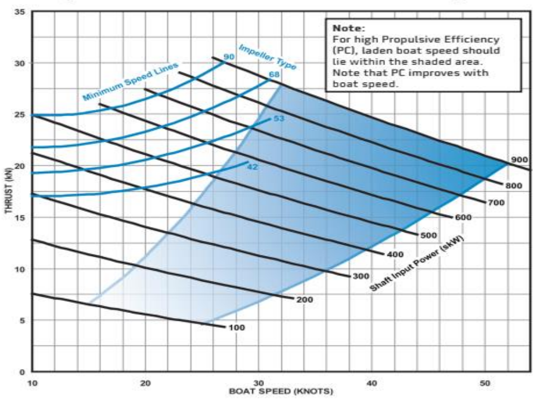

Figure 11. Cavitation study
Source: Ms C. W. F. Hamilton & Co. NZ (2019)

IV. CONCLUSION

Even though most waterjets look suitable for a particular application, waterjets are usually optimized by the manufacturer for separate applications, low speed (yet above 20 knots) and for high speeds. The appropriate selection is the duty of boat building yard Naval Architecture. The actual naval petrol craft design engineering example discussed at this juncture demonstrates why Naval Architecture shall have dependable techniques to assess waterjet performance. Traditional methods are beneficial to ensure particular waterjet will meet some performance requirements, yet the approach is usually inadequate for many virtual assessments of waterjet performance on efficiency, acceleration, entire RPM envelop operation and so forth. The authors exhibit how to employ “universal waterjet coefficients” as methodology, which guide and point the way to the accurate propulsor choice. The outcome is authors found the correct operation point/match of hull, propulsor, engine which is depicted in Figure1.

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