Propulsive Efficiency of Submarines and Surface Warships over their Operational Speed Ranges

Gregory J. Seil, Advanced VTOL Technologies, gregory.seil@dst.defence.gov.au
Chris Gargan-Shingles, Defence Science & Technology Group, christopher.shingles@dst.defence.gov.au
Dev Ranmuthugala, Defence Science & Technology Group, dev.ranmuthugala2@dst.defence.gov.au
Martin Renilson, Pacific ESI, martin@renilson-marine.com

ABSTRACT

Surface warships and submarines are required to operate over a range of speeds, unlike merchant ships that are usually optimised for one particular cruising speed. For surface warships, the advance ratio is a function of speed due to the change in the resistance coefficient at different vessel speeds caused by wavemaking resistance and sea conditions. Surface warships are required to operate over a range of speeds, e.g. low speed cruising and high speed sprinting. Thus, their propulsors need to be efficient over a wider range of advance ratios and flow conditions, and the design process must take into account the efficiency at low and high speeds.

Deeply submerged submarines maintain a relatively constant advance ratio, and hence constant propulsion efficiency, over their operational speed range. Thus, the non-dimensionalised flow field is essentially the same and independent of speed, enabling the propulsor to be optimised for this condition.

This paper uses generic data for submarine and surface warships to show the change in propeller advance ratios with speed. It is seen that changes in a vessel's propulsive efficiency with speed are related to the resistance coefficient, which is influenced by the wave making resistance, propulsor-hull interaction and the propulsor operating point. The paper provides trends on these effects for submarines and surface warships over typical operating conditions. Unlike surface warships, the change in advance ratio for deeply submerged submarines is small over the operating speed range. Thus, the selection and optimisation of the propulsors require different strategies for surface warships and submarines.

INTRODUCTION

Surface warships and submarines are required to operate over a range of speeds, unlike merchant ships that are usually optimised for one particular cruising speed. For surface warships, the propeller advance ratio (*J*) is a function of speed due to the change in the resistance coefficient (C_T) at different speeds caused by wavemaking resistance and sea conditions. Surface warships are required to operate over a range of speeds, for example low speed cruising and high speed sprinting. Thus, their propulsors need to be efficient over a wider range of advance ratios (and thus speeds) and flow conditions, and the design process must take into account the efficiency at low and high speeds.

Deeply submerged submarines, where the influence of the free surface is negligible, maintain a relatively constant advance ratio, and hence constant propulsion efficiency, over their operational speed range. Thus, the non-dimensionalised flow field is essentially constant and independent of speed, enabling the propulsor to be optimised for this condition.

The propulsive performance of a generic frigate and a generic submarine is compared in this paper to examine differences in resistance components, propulsor-hull interaction and the variation in propulsor operating point and performance over the speed range of the vessel. Both vessels utilise conventional propellers as their propulsion device for the purposes of the comparison.

The generic frigate is based on DTMB 5415 hull form [1]. Experimental studies of a geosim of the DTMB 5415 hull form (i.e. INSEAN 2340, shown in Figure 1) were performed by Oliveri et al. [1]. Similar studies of a smaller scale geosim of the DTMB 5415 were performed by the Iowa Institute of Hydraulics Research (IIHR) at the University of Iowa. Data for this geosim (IIHR 5512) is available from that University's website [2] and has been used as the basis of the analysis presented in this report. Note: the IIHR 5512 is without appendages such as bilge keels, shafting, rudders and brackets.

The generic submarine utilised in this study is the Defence Science and Technology (DST) Group BB2 geometry, which represents a conventional diesel-electric (SSK) submarine. A model of this submarine, which has been built and tested by MARIN, is shown in Figure 2 taken from Overpelt et al. [3]. The BB2 is modelled with all its appendages.

The propulsive estimates are based on data for the Wageningen B-Series propeller given in [4]. Using the required thrust and J for each vessel, five blade propeller variants were selected using the curves provided in [4]. Full-scale vessel and propeller data for both vessels are presented in Table 1. The propeller curves used in the analysis presented in this paper have been scaled to full-scale conditions.

RESISTANCE OVER SPEED RANGE

A vessel operating on the surface has three primary components of resistance:

1) Viscous resistance: these include skin friction and pressure drag arising from the development of the boundary layer around the hull. Hull roughness increases the frictional resistance.
2) Wavemaking resistance: this is associated with pressure changes on the hull due to interactions with the free surface and flow separation (such as off the transom). This results in wavemaking, sinkage and trim changes.
3) Air resistance – this is the basic aerodynamic drag of the hull and superstructure above the water.

For a submarine operating deeply submerged, there is no wavemaking (due to no interaction with a free surface) or air resistance.

The resistance coefficient (C_T) can be calculated as,

$$C_T = \frac{R_T}{\frac{1}{2}\rho S_W V^2}$$
(1)

where R_T is the resistance of the vessel, ρ is the density of the fluid, V is the speed of the vessel and S_W is its wetted surface area.

For the surface ship, neglecting air resistance, the resistance curve of the IIHR 5512 scaled to full-scale is calculated from the model-scale data of [2] using,

$$C_{TS} = C_{FS} + C_R + \Delta C_F$$
(2)

where C_{TS} is the total resistance coefficient at full-scale, C_{FS} is the frictional resistance coefficient at full-scale, C_R is the residuary resistance coefficient and ΔC_F is the roughness allowance accounting for the fact that the hull is not hydraulically smooth.

The residuary resistance coefficient is generally constant for the model and full scale. The frictional resistance coefficient is calculated using the ITTC 1957 correlation line [5],

$$C_{FS} = \frac{0.075}{(\log_{10} Re - 2.0)^2}\ ,\ \ Re = \frac{\rho V L_{WL}}{\mu}$$
(3)

where Re is the Reynolds number, L_{WL} is the length of the vessel and μ is the dynamic viscosity of the fluid.

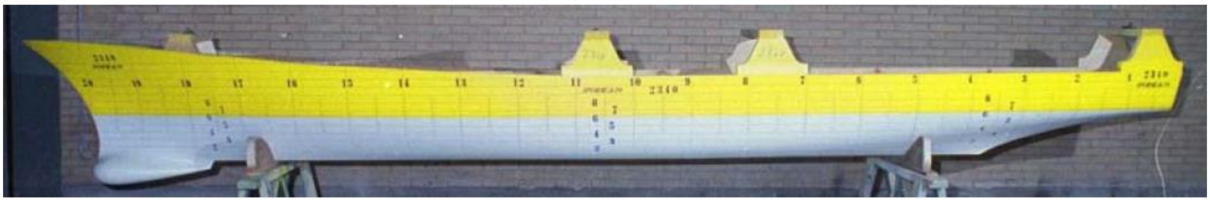


Figure 1: Geometry of INSEAN 2340, photo taken from [2]. Both the INSEAN 2340 and the IIHR 5512 are geosims of DTMB 5415. Scale ratio (λ) of INSEAN 2340 is 24.824 and for the IIHR 5512 is 46.6.

Figure 2: Free running model of BB2. Photo taken from [3].

As there is no wavemaking resistance for a deeply submerged submarine, the wavemaking resistance coefficient, $C_W = 0$. Thus the resistance of the deeply submerged submarine BB2 can be calculated as,

$$C_{TS} = (1 + k)C_{FS} + C_R + \Delta C_F \quad (4)$$

where $(1 + k)$ is a whole-of-boat form factor which includes the effect of both friction and pressure (form) drag. For the BB2 geometry, a form factor of 1.2 is used based on CFD results and C_{FS} is given by equation (3). The residuary resistance coefficient (C_R), which includes other effects such as induced drag, is relatively small and can be neglected in this case.

The full-scale resistance coefficient curves for the IIHR 5512 in calm water and the BB2 deeply submerged are shown in Figure 3 and Figure 4 respectively. For this study, $\Delta C_F = 0.0004$, in accordance with the information provided in Renilson [6].

	Symbol	Frigate	Submarine
Waterline length (or Length)	L_{WL} or L	142 m	70.2 m
Beam	B	18.9 m	9.6 m
Draft	T	6.16 m	NA
Volume	∇	8425.4 m^3	4349.7 m^3
Wetted Area	S_W	2949.5 m^2	2143.5 m^2
Propeller Series	-	Wageningen B-Series	Wageningen B-Series
No. of Propellers	N_p	2	1
No. of Blades per Propeller	Z	5	5
Pitch-to-Diameter Ratio	P/D	1.2	0.8
Expanded Area Ratio	EAR	0.7	0.6
Propeller Diameter	D_s	4.5 m	5.0 m

Table 1: Vessel and propeller data for the IIHR 5512 frigate and the BB2 submarine at full-scale

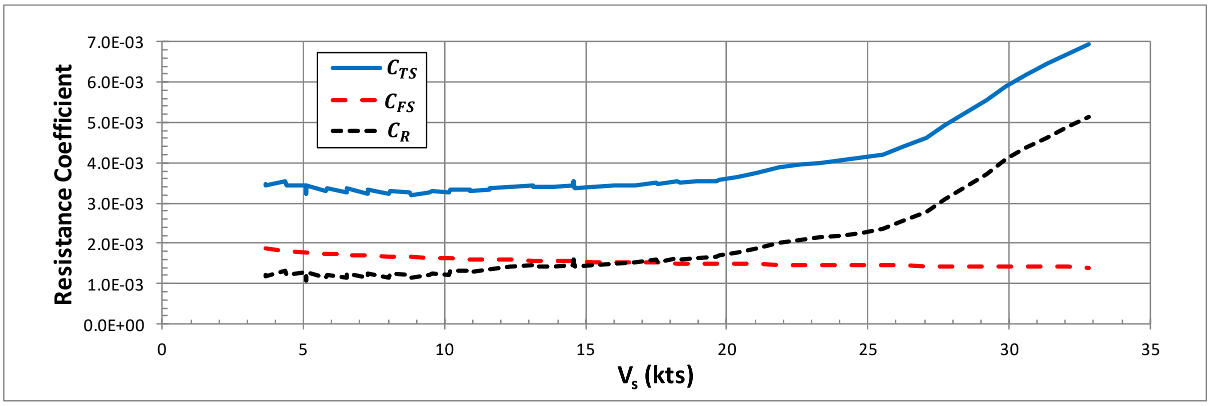


Figure 3: Calm water resistance coefficient curve for generic frigate IIHR 5512 (DTMB 5415) at full-scale

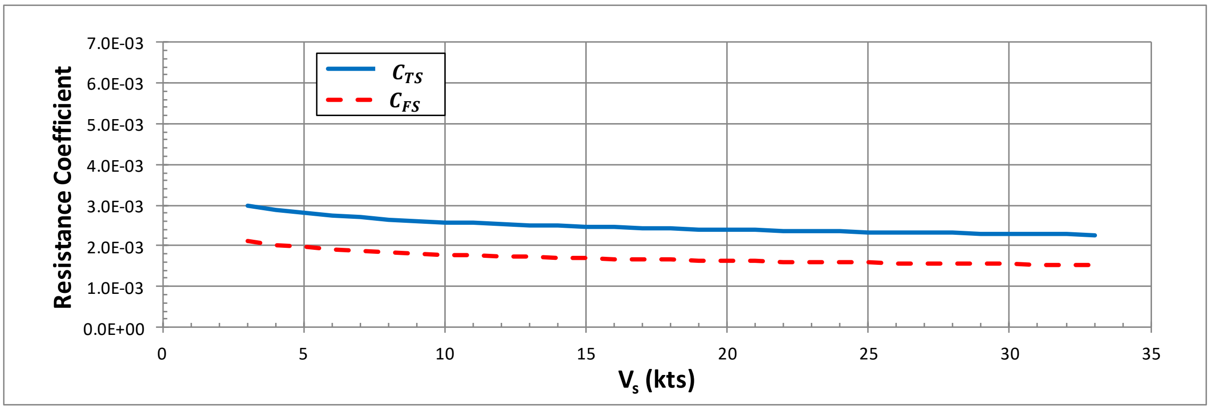


Figure 4: Resistance coefficient curve for DST Group BB2 generic submarine at full-scale

The resistance coefficient curves of both vessels show opposite trends with increasing speed. The general trend of increased C_{TS} with increased speed for the frigate, particularly for speeds greater than 20 kts, is driven by the increase in C_R. This is mainly due to the wave making resistance coefficient that increases at higher vessel speeds. The C_{TS} for the submarine on the other hand decreases slightly with increased speed due to Reynolds number dependency.

PROPELLER CURVES

The operating point of the propulsor can be characterised by its advance ratio (J),

$$J = \frac{(1-w)V_s}{nD_s} \tag{5}$$

where n is the propeller or rotor speed (in revolutions per second), D_s is the diameter of the propeller or rotor and w is the effective wake fraction. At each value of J, the performance of the propulsor is given by its thrust coefficient (K_T), torque coefficient (K_Q) and open water efficiency (η_o) defined by,

$$K_T = \frac{T}{n^2 D_s^4}\,, \quad K_Q = \frac{Q}{n^2 D_s^5}\,, \quad \eta_o = \frac{J}{2\pi}\frac{K_T}{K_Q} \tag{6}$$

where T is the thrust produced by the propeller and Q is the rotor torque. The propeller curves for the propellers used in this study and based on the Wageningen B-Series [4] are presented in Figure 5. The pitch-to-diameter ratio was chosen to provide a design advance ratio close to the peak propulsor efficiency.

PROPULSIVE PERFORMANCE

The thrust of the propulsor (T) is related to the total resistance of the vessel (R_T) by the thrust deduction fraction (t),

$$t = 1 - \frac{R_T}{T} \tag{7}$$

The propulsive efficiency (η_D) is given by,

$$\eta_D = \eta_H \eta_R \eta_o \ , \qquad \eta_H = \frac{1-t}{1-w_s}, \qquad \eta_R = \frac{K_{QT}}{K_Q} \tag{8}$$

where η_R is the relative rotative efficiency, η_H is the hull efficiency and η_O is the open water efficiency of the propeller. The relative rotative efficiency is determined in this case by the ratio of the actual torque coefficient (K_Q) to the torque coefficient determined from the propulsor curve (K_{QT}) when using the thrust identity [7]. It can be shown that the thrust coefficient can be related to the operating point of the propulsor by [7],

$$\frac{K_T}{J^2} = \frac{1}{N_p}\frac{S_W}{2D_s^2}\frac{C_{TS}}{(1-t)(1-w_s)^2} \tag{9}$$

where N_p is the number of propulsors. Calculation of the right-hand side of (9) allows the value of K_T/J^2 to be determined. Using this value in conjunction with the propulsor curves, the advance ratio (J) and the propulsor open water efficiency (η_o) can be determined. For more information on these calculations see Renilson [6] and ITTC [7].

An analysis of the self-propulsion performance of the deeply submerged submarine and the frigate was performed for their respective speed ranges. A propeller diameter of 4.5 m was chosen for the frigate and a diameter of 5.0 m for the submarine. Note that the frigate has two propellers while the submarine has a single propeller. It is assumed that that effective wake fraction (w), thrust deduction fraction (t) and relative rotative efficiency (η_R) remain constant over the speed range.

Note that no account has been made of the effect of cavitation inception on the propeller efficiency when the frigate is operating at high speed. The variations of the advance ratio (J) of the propeller operating point for the full scale IIHR 5512 frigate and the deeply submerged BB2 submarine over their respective speed ranges are marked up on the propeller open water diagrams in Figure 5. The propulsive efficiency of both vessels is compared in Figure 6. The variation of propeller speed over the speed range of each vessel is compared in Figure 7.

For both vessels, there is relatively little change in the propulsive efficiency (η_D) over the lower speed range, however, it drops offs significantly for the frigate as the speed increases. In both cases, the change in propulsive efficiency is driven by changes in the propulsor open water efficiency (η_o), since the hull efficiency (η_H) and relative rotative efficiency (η_R) remain constant. The trend in propulsive efficiency for each vessel follows the trend in their respective resistance curves.

The propulsor on the frigate becomes more heavily loaded at speeds greater than 20 kts resulting in a significant reduction in the advance coefficient (J), an increase in thrust coefficient (K_T) and a drop in absolute propulsor open water efficiency (η_o) of around 5%. Note that there is a very small variation in advance coefficient and propulsor efficiency between 3.63 kts (the first data point) and 20.40 kts due to the relatively constant resistance coefficient between these speeds. It is beyond this speed that the wave making resistance effects the efficiency as the variation in *J* is of sufficient magnitude to adversely affect η_o even at the 'flatter' section of the curve, i.e. close to its peak.

For the deeply submerged submarine, the propulsive efficiency increases with increased speed as the propulsor becomes less loaded (i.e. increased J) and η_o increases. Above 10 knots, the propulsive efficiency (η_D) is almost constant as the change in J is extremely small and the propulsor efficiency (η_o) is close to the peak value on the efficiency curve, i.e. in the flatter section of the curve.

The frigate shows a linear variation in propeller speed with vessel speed (i.e. Turns Per Knot, TPK) up to 20 knots, however above this speed the variation becomes non-linear (rising above the linear trend) due to the increasing wavemaking resistance coefficient. The deeply submerged submarine shows a linear variation over its speed range due to its much smaller variation in the resistance coefficient.

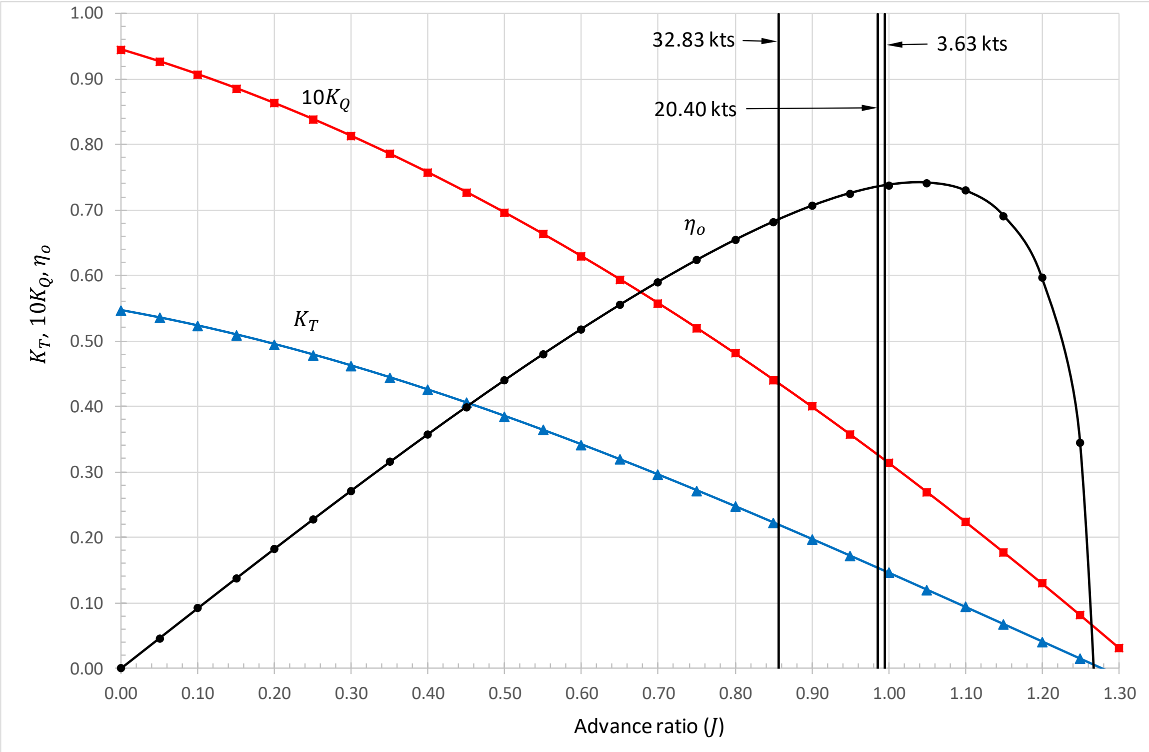
Note that the changes in the advance ratio and thrust coefficient over the speed range are much greater for the frigate than the deeply submerged submarine. Hence the operating range of advanced ratios (J) of the propeller is smaller for the deeply submerged submarine than the frigate. In other words, the propulsor on the frigate must operate over a greater range of off-design conditions, whereas the propulsor on the submarine operates over a narrow band of operating conditions. From Figure 6 it is also seen that the change in propulsive efficiency for the frigate over its speed range is much greater than the change for the deeply submerged submarine.

DISCUSSION

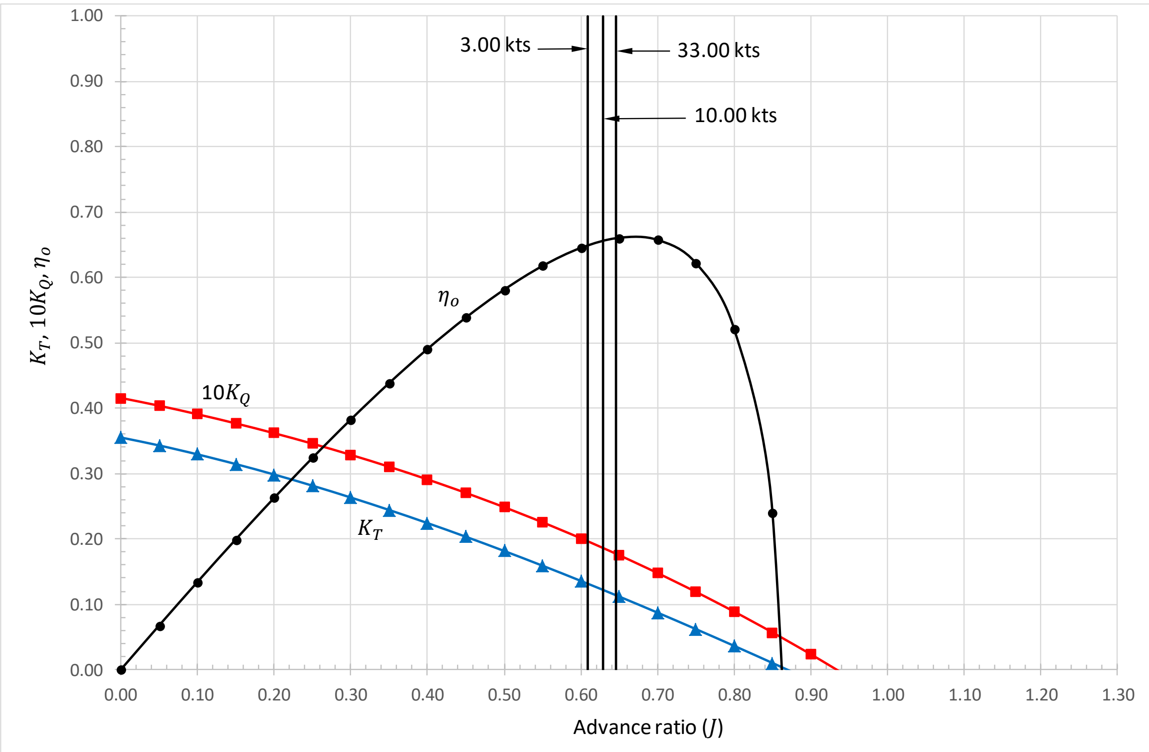
The propulsive efficiency of the frigate dropped above a vessel speed of 20 kts due to the higher propulsor loading resulting from the greater wavemaking resistance experienced by the vessel. This reduction would be even greater if the added resistance due to adverse sea conditions, propulsor cavitation, or unsteady propulsor inflow effects due to the wake generated at the aft end of the frigate hull were included. On the other hand, the propulsive efficiency of the submarine was, for all intents and purposes, insensitive to the operating condition due to the small changes in propeller efficiency over the speed range.

If the efficiency of the propulsor is more sensitive to loading (i.e. if the vertical lines in Figure 5a and Figure 5b, denoting the operating points, moved proportionally further apart), then a greater change in propulsor efficiency (η_o) would be evident, resulting in a greater change in propulsive efficiency at off-design conditions. However, due to the greater dependency of the frigate resistance coefficient on the vessel speed (i.e. due to the wavemaking resistance), this would be particularly pronounced for the frigate and much less so for the submarine.

If the thrust and torque coefficient curves were 'flatter' (for example due to slightly different assumptions in design parameters), then a change in resistance coefficient (C_{TS}) over the speed range will result in greater spread in the advance ratio (J) about its design point, resulting in a larger change in the propulsive efficiencies. Again, the spread in the advance coefficient would be more pronounced for the frigate than for the submarine.



a) Performance curves for the full scale IIHR 5512 frigate
$t = 0.1, w = 0.03, \eta_R = 0.98$



b) Performance curves for the full scale deeply submerged BB2 submarine
$k = 0.2, t = 0.22, w = 0.32, \eta_R = 1.01$

Figure 5: Propulsive performance curves showing changes in operating point across the speed range.

In the analysis a constant value of roughness allowance was assumed. In reality this may not be the case and the roughness allowance will change as a function of speed. For the submarine, as the speed of the vessel increases, the boundary layer becomes thinner relative to the size of the vessel. This increases the resistive effect of surface coatings, protuberances, and openings on the hull, and therefore the contribution of these factors to the overall resistance coefficient will be larger at greater speeds. Hence, once these additional contributions are added, it may be expected that the resistance coefficient will increase for both the frigate and the submarine. However, due to the shape of these curves (see Figure 3 and Figure 4), the effect will be more pronounced for the frigate, thus increasing the spread of *J* as the vessel speed increases, especially at the higher end of the speed range.

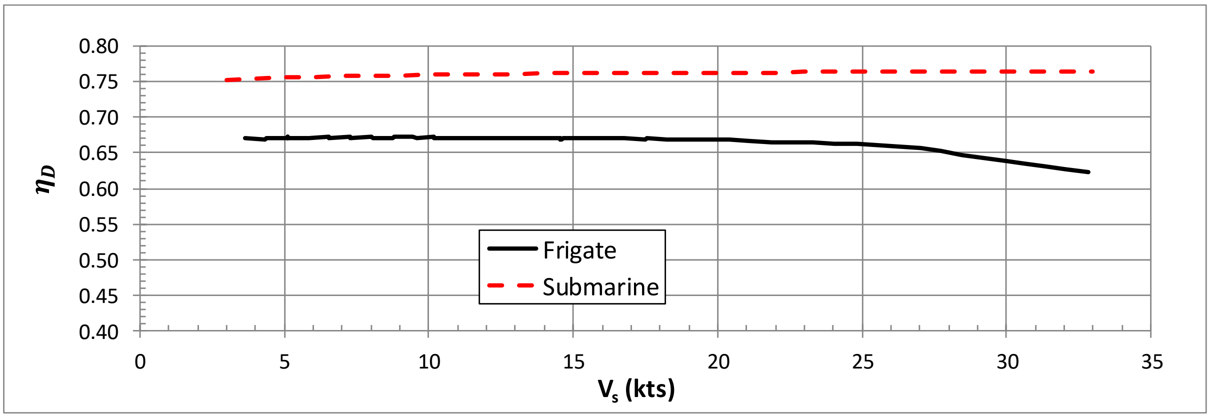


Figure 6: Propulsive efficiency over the speed range for the IIHR 5512 frigate and the deeply submerged BB2 submarine.

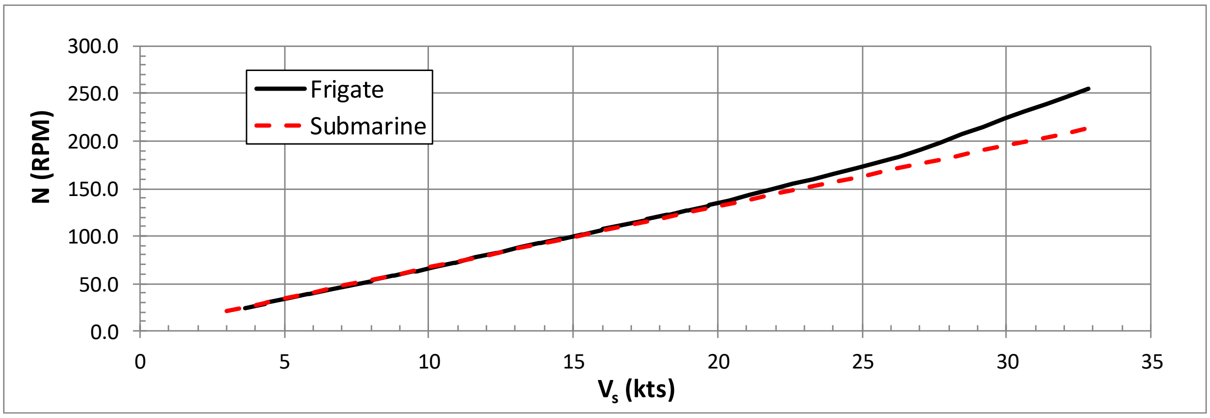


Figure 7: Variation in propeller speed over the speed range for the IIHR 5512 frigate and the deeply submerged BB2 submarine.

The above analysis for the frigate has not considered waves (sea state), dynamic sinkage and trim effects which all affect the vessel's resistance, thrust deduction fraction (t) and wake fraction (w), which in turn affects the hull efficiency (η_H) and the propulsive efficiency. This is obviously not applicable to a deeply submerged submarine.

CONCLUSIONS

From the analysis presented above, the propulsive efficiency of a deeply submerged submarine was shown to vary little over its speed range. The frigate showed a much greater variation, with an absolute variation in the propulsive efficiency of just under 5%, which can be significant.

The propulsor designed for a frigate must be able to operate successfully over a wider range of operating conditions, and hence off-design conditions, than a submarine. In other words, the frigate propulsor must represent a design compromise between low-speed cruising and high-speed sprint. However, the relatively narrow band of operating conditions of the deeply submerged submarine, allows the submarine propulsor to be optimised around a single operating point. There are other factors that will also adversely affect the efficiency of a surface vessel, such as the surface sea state conditions, dynamic sinkage and trim changes that do not apply to a deeply submerged submarine.

Thus, the selection and optimisation of the propulsors for surface warships and deeply submerged submarine require different approaches and strategies due to:

- Opposite trends in resistance coefficient as functions of speed: the resistance coefficient of a surface warship increases rapidly at high speed due to the rapid increase in the wavemaking resistance coefficient as a function of speed, whereas for a deeply submerged submarine the resistance coefficient remains relatively constant.
- The submarine propulsor operates over a significantly narrower range of advance ratios than for a surface warship.

REFERENCES

1) Oliveri, A., Pistani, F., Avanzi, A., Stern, F. and Penna, R. (2001), "Towing Tank Experiments of Resistance, Sinkage and Trim, Boundary Layer, Wake, and Free Surface Flow around a Naval Combatant Insean 2340 Model", IIHR Technical Report, No.421, September 2001.

2) https://www.iihr.uiowa.edu/shiphydro/efd-data/5512-steady/ . Accessed 29/04/2019

3) Overpelt, B., Nienhuis, B., Anderson, A. (2015), "Free Running Manoeuvring Model Tests on a Modern Generic SSK Class Submarine (BB2)", *Proc. Pacific 2015 International Maritime Conference*, Sydney, 6-8 October 2015.

4) Bernitsas, M. M., Ray, D. and Kinley (1981), "K_T, K_Q and Efficiency Curves for the Wageningen B-Series Propellers.", Report No. 237, Department of Naval Architecture and Marine Engineering College of Engineering, The University of Michigan Ann Arbor, Michigan.

5) ITTC 7.5-02-02-01 Rev. 04 – Resistance Test.

6) Renilson, M. (2018), *Submarine Hydrodynamics*, 2nd edition, Springer.

7) ITTC 7.5-02-03-01.4 Rev. 04 – 1978 ITTC Performance Prediction Method.