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Propeller Roughness and its Effects on Required Freight Rate

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ABSTRACT

The effects on Required Freight Rate (RFR) of propeller roughness causing loss of ship speed at constant power are investigated. Roughness profiles are postulated based on construction, fouling, operation and maintenance. These are utilized to determine the change in propeller efficiency and ultimately the propulsive coefficient to arrive at vessel speed. The results are then incorporated in a RFR analysis to determine the effects on vessel profitability. Examples are provided for an ocean ore carrier. The effects of all roughness factors are incorporated over a vessel life ranging from 5 to 25 years. The formulations are directly applicable to other vessels for which a lifetime roughness profile is constructed and speed/power relationships have been determined. The analysis approach provides a means for investigating different magnitudes and scenarios of causes of propeller roughness and their effects on RFR.

Keywords
Propeller Roughness, Efficiency, Speed, Fuel Consumption, Required Freight Rate, RFR

1 INTRODUCTION

The effects of propeller and hull roughness, including fouling, are known to affect the performance of a vessel, especially as measured in additional fuel consumption and less so, the number of voyages attained in a lifetime. Today there is significant attention given to hull surface cleaning, coating and propeller polishing to address these issues. Estimates of the effects of roughness vary in their complexity.

Roughness of the propeller and hull can occur due to a number of factors including hull material utilized and quality of construction, mechanical damage in operation, fouling, roughness from paints and coatings and their method of application, damage to the coating during maintenance, corrosion and pitting of the hull structure material, as well as biofouling influenced by the type of antifouling paint or coating and method of application. Herein the effects of these on the propeller will be considered. Figure 1 shows a vessel completed and ready for trials at the time its propeller roughness is at its lowest value. Figure 2 shows a vessel with severe fouling.

Knowledge of lifetime loss of speed and its effect on Required Freight Rate (RFR) gives strong and compelling support to paying more attention to the factors affecting the roughness of the ship propeller which can be experienced over its lifetime. Starting with the propeller, then the effects of fouling, operations, dry-docking intervals and approach to maintenance, it is possible to develop a lifetime roughness profile. Alternatives can be postulated and considered as to how they affect the ship operations and profitability in trade off analyses. The methods presented herein provide a means for investigating different magnitudes and scenarios of these causes of roughness rather than providing only example results.

Figure. 1 New Vessel Ready for Trials

The sections which follow this Introduction identify the mathematical formulations to assess propeller and hull roughness and its effects; resulting lost voyages; implications for RFR; application to an ocean ore carrier; and conclusions.

2 MATHEMATICAL FORMULATIONS

The resistance of the vessel is given by:

$$R = 1/2 \rho S (C_F + C_R) V_S^2 \tag{1}$$

The effective power by:

Figure 2 Vessel with Severe Fouling

$$P_E = VR = 1/2\rho S(C_F + C_R)V_S^3 \quad (2)$$

And the propulsive power is given by:

$$P = P_E/\eta_p \quad (3)$$

Where ρ = density of water, kg/m^3; S = wetted surface of hull, m^2; V_s = ship speed, knots; C_F = non-dimensional friction coefficient; C_R = non-dimensional residuary resistance coefficient; η_p = the total propulsive efficiency.

For two speeds V_{S1} and V_{S2} occurring at times t_1 and t_2 respectively, the change in required power can be represented as:

$$P_1 = V_{S1}^3(C_{F1} + C_{R1})\rho S/2\eta_p \quad (4)$$

$$P_2 = V_{S2}^3(C_{F2} + C_{R2} + \Delta C_{F12})\rho S/2(\eta_p - \Delta\eta_{p12}) \quad (5)$$

$$\Delta P = P_2 - P_1 = A_2[V_{S2}^3(C_{F2} + C_{R2} + \Delta C_{F12})] - A_1[V_{S1}^3(C_{F1} + C_{R1})] \quad (6)$$

Where $A_1 = \rho S/2\eta_p$; $A_2 = \rho S/2(\eta_p - \Delta\eta_{p12})$; η_{p1} = propulsive coefficient at time t_1; $\Delta\eta_{p12}$ = change in propulsive coefficient from time t_1 to t_2; $\Delta C_{n-1,n}$ = non-dimensional friction coefficient due to change in roughness between times t_{n-1} and t_n.

In the case of constant power:

$$P_1 = P_2 \quad (7)$$

Therefore Equation (6) yields:

$$0 = A_2[V_{S2}^3(C_{F2} + C_{R2} + \Delta C_{F12})] - A_1[V_{S1}^3(C_{F1} + C_{R1})] \quad (8)$$

Or:

$$\frac{V_{S2}}{V_{S1}} = \sqrt[3]{A_1(C_{F1} + C_{R1})/A_2(C_{F2} + C_{R2} + \Delta C_{F12})} \quad (9)$$

And:

$$V_{s2} = V_{s1}\sqrt[3]{\left(\frac{\eta_{p1} - \Delta\eta_{p12}}{\eta_{p1}}\right)(C_{F1} + C_{R1})/(C_{F2} + C_{R2} + \Delta C_{F12})} \quad (10)$$

Over the life of the vessel, L, the cumulative loss in distance traveled, D, is given as:

$$L = \sum_{i=1}^{n} n\Delta t \quad (11)$$

$$D = \sum_{n=1}^{n}(V_n - V_{n-1})\Delta t \quad (12)$$

The expression for loss in distance travelled due to roughness, Equation (12), directly affects how much it will cost to deliver the cargo. It can be evaluated if the changes to effective power and propulsion efficiency, Equation (3), due to changes in hull resistance and propeller efficiency respectively, can be determined. As the frictional and residuary resistance coefficients are determined by calculation or model tests prior to the time of trial, the only remaining quantities to be determined in order to evaluate the expressions for the effective power are the change in frictional resistance coefficient of the hull and the change in propulsive efficiency due to roughness as the vessel ages. This has previously been investigated for the hull (Daidola & Esposito-Kelley 2018). If the propulsive coefficient in Equation (3) varies, then for constant propulsive power, the available effective power also varies. This latter aspect will be investigated herein.

3 PROPELLER ROUGHNESS AND ITS EFFECTS

The three principal factors affecting the propeller efficiency in service are blade surface roughness, fouling and blade damage. Damage is normally rectified at the first possible opportunity as it can have a sudden and dramatic effect on performance. On the other hand, the effects of surface roughness and fouling are constantly changing during the life of the vessel. More specifically (Stone undated) they include:

- Marine growth – primary and secondary
- Impingement attack
- Corrosion – chemical and/or electro chemical
- Cavitation erosion
- Inexpert maintenance

The effects of roughening on the propeller have been previously investigated (Kresic, Haskell, 1983) utilizing efficiency due to roughness in service are determined by finding the changes in the torque and thrust coefficients:

$$K_{T2} = K_{T1} - \Delta K_{TD} - \Delta K_{TL} \quad (13)$$

$$K_{Q2} = K_{Q1} - \Delta K_{QD} - \Delta K_{QL} \quad (14)$$

$$\eta_{0n} = \text{propeller efficiency} = \frac{J}{2\pi}[K_{Tn}/K_{Qn}] \quad (15)$$

η_{pn}= proportional to η_{0n} at time "n" for all other efficiencies constant. Where K_{Tn}, K_{Qn} = thrust and torque coefficients; ΔK_{TD}, ΔK_{QD} = change in thrust and torque coefficients due to drag; ΔK_{TL}, ΔK_{QL} = change in thrust and torque coefficients due to lift.

The expressions for changes in the torque and thrust coefficents are taken in accordance with recommendations of the ITTC-1978 Performance Committee (Oosterveld, 1978) and are dependent on changes to the lift, C_L, and drag, C_D, coefficients dependent on roughness:

$$C_D = 2\left(1 + 2\frac{t}{c}\right)\left(1.89 + 1.62\log\frac{c}{k_P}\right)^{-2.5} \quad (16)$$

$$\Delta C_L = -1.1\Delta C_D \quad (17)$$

Where t=maximum blade thickness at 0.75R, c=chord length at 0.75R and k_P=average propeller blade roughness amplitude.

The loss of open-water propeller efficiency as well as decrease of thrust coefficient and increase of torque coefficient predicted by the above formulations have been compared (Kresic & Haskell 1983) to results of model tests as shown in Figure 4.

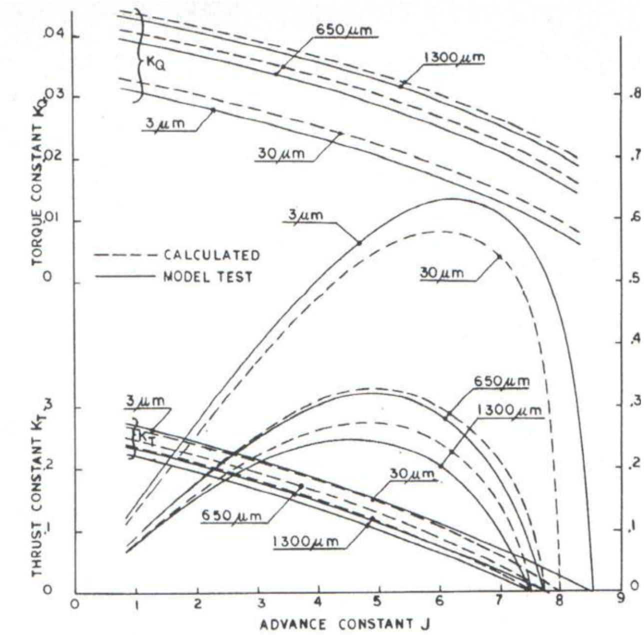

Figure 4 Propeller Performance Changes due to Roughness

The only unknown for a specific propeller in the formulations above is the average propeller roughness amplitude k_P which represents the surface roughness and fouling. The surface roughness of a new propeller in trial condition is taken as 30µm per the ITTC 1978 recommendation and which is higher than the ISO standards of less than 10µm (Stone undated) but accounts for handling in the shipyard. In service this surface roughness can increase at the rate of 20µm per year on average. During drydocking the propeller receives the treatment consisting of a high pressure seawater wash, hand scraping, hand polishing by wire brush machine and a coat of grease to protect from hull painting; removing all effects of fouling and a correction in surface roughness of 10µm. At each fourth drydocking every 10 years, the propeller is polished and restored to a roughness of 40µm. Fouling is taken as causing an equivalent roughening of 10µm per year approximately as used in other studies.

Classification societies generally require vessels to be dry-docked twice in a 5 year period. Accordingly it is assumed the dry-docking period will be every 2 ½ years. Figure 5 provides the corresponding blade roughness time-history over a 25 year life. If the restoration is not accomplished every 10 years then the roughness profile would be as depicted in Figure 6.

Since propeller fouling has been known to be significant and the 10µm pales when compared to the approximate 180µm per year for the hull once the effectiveness of the antifouling paint is exhausted (Daidola & Esposito-Kelley 2018) a case has been considered where the fouling is 100µm per year. The roughness-time history is shown in Figure 7 without any restoration at 10 year intervals. Finally, Figure 8 depicts the case where restoration is accomplished at every drydocking.

With knowledge of propeller roughness over the vessel life, the changes in propeller efficiency can be determined as shown in Figure 4.

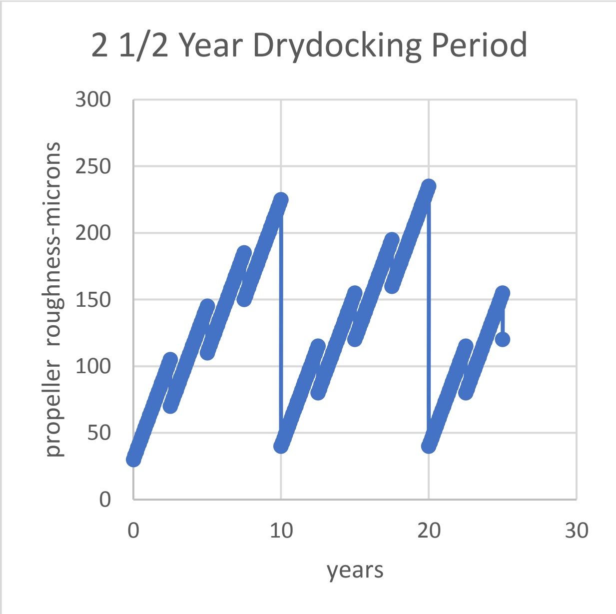

Figure 5 Propeller Roughness - 10µm fouling per year and 10 year restoration

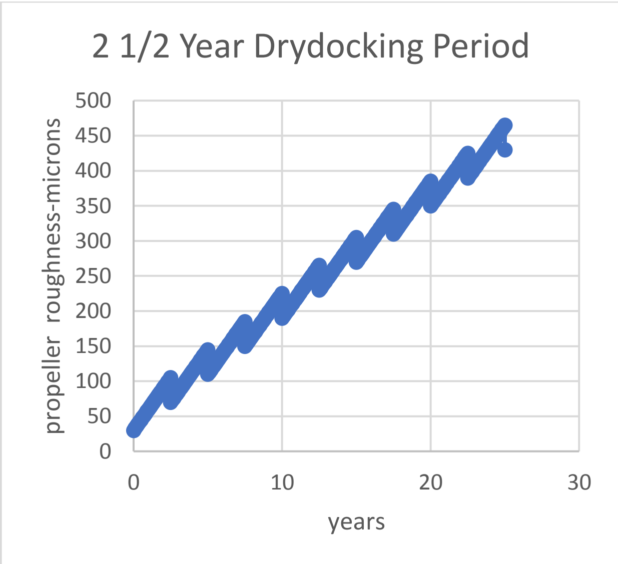

Figure 6 Propeller Roughness - 10µm fouling per year and no restoration

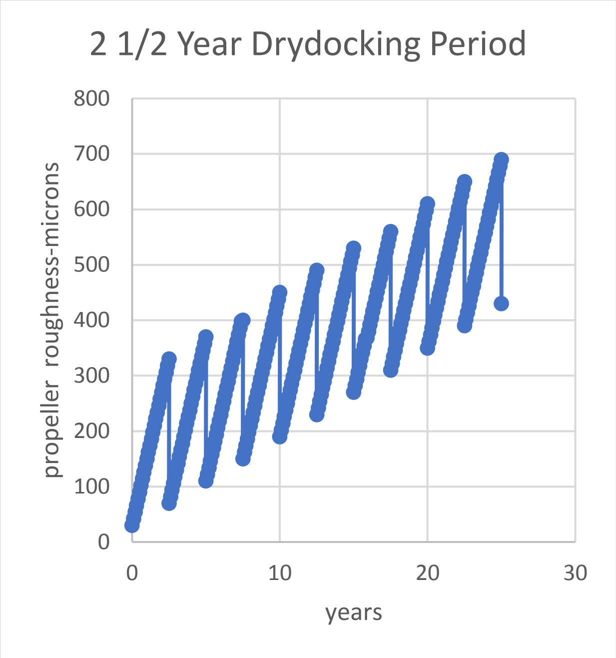

Figure 7 Propeller Roughness - 100µm fouling per year and no restoration

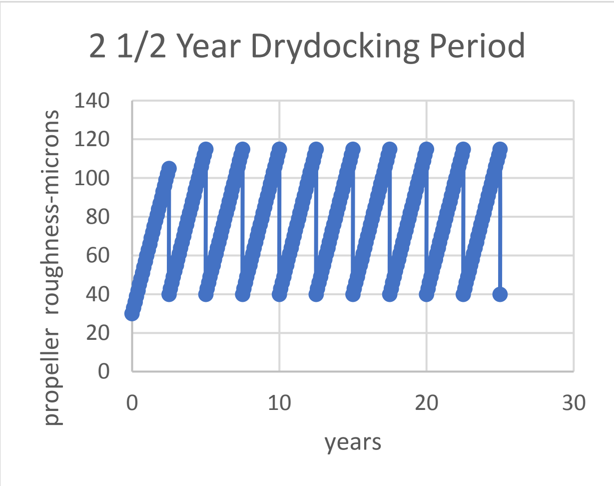

Figure 8 Propeller Roughness - 10µm fouling per year and 2 1/2 year restoration

4 APPLICATION

The application considered herein is for an ocean ore carrier with principal characteristics given in Table 1. The RFR for this vessel with hull roughening only has been previously studied in the past (Daidola et al 2018).

The vessel is intended to carry iron ore over a distance of 19300 km (12,000 miles) and return in ballast. Fuel oil for the round trip is taken aboard at the cargo discharge point. Capital costs are based on an owner's stipulated after-tax interest rate of return of 3 percent, a 48 percent corporate profit tax, a life of 25 years with a scrap value of 20 percent of original vessel cost, an all equity investment and inflation of 2 percent per year. Nominal sea speeds are taken as predicted for the trial condition at 80 percent of the maximum installed power (which is 10 percent over normal power) to allow for fouling and weather. The results for RFR are given in Table 2.

Table 1 Principal Characteristics of Ore Carrier

Length between perpendiculars…..	223 m
Limiting operating draft…………	10.4 m
Design draft………………………	11.4 m
Block coefficient at design draft…	0.80
Beam-draft ratio at design draft…...	2.5
Displacement at design draft……...	60,040 MT
Displacement at operating draft…..	54,350 MT
Machinery…………………………	Single screw, diesel
SHP………………………………..	To be optimized
Sea speed………………………….	To be optimized

Equations (10) and (15) for constant power are applied to determine the reduction in speed over the vessel's life due to propeller roughening only (ΔC_{F12} = 0) and its impact on RFR. Tables 3-6 provide the average roughness over time for the various propeller roughness profiles exhibited in Figures 5-8 respectively, as well as the resulting changes in propeller efficiency as exhibited in Figure 4 and the resulting propulsive coefficient, η_P. Application of Equation (10) results in the loss of speed over time depicted in Figs. 9-12. These new speeds, taken as operating speeds in line 10 of Table 2, result in the changes in the RFR depicted in Figs. 13-16.

Table 3 Propeller Roughness - 10µm fouling per year and 10 year restoration

Years	0	5	10	15	20	25
k_P , µm	30	89	128	118	133	126
$\Delta\eta_0$, %	0	-9.7	-13.8	-12.8	-14.1	-13.6
η_P - $\Delta\eta_P$, %	0.753	0.68	0.649	0.657	0.647	0.650

Table 4 Propeller Roughness - 10µm fouling per year and no restoration

Years	0	5	10	15	20	25
k_P , µm	30	89	128	168	208	248
$\Delta\eta_0$, %	0	-9.7	-13.8	-17.6	-21.	- 24.3
η_P - $\Delta\eta_P$, %	0.753	0.68	0.649	0.621	0.595	0.57

Table 2 Ore Carrier Required Freight Rate versus Horsepower and Speed – Foreign Costs

	Description	Value					
1	SHP/1000 - British	5	10	15	20	25	30
2	DWT/Displacement - LT	0.764	0.761	0.758	0.755	0.753	0.751
3	Design DWT LT 1000s	45.2	45	44.8	44.6	44.5	44.4
3a.	Design displacement - LT 1000s	59.16	59.13	59.10	59.07	59.10	59.12
4	Oper. DWT - LT 1000s	39.6	39.4	39.2	39	38.9	38.8
	Investment (costs in $1000s)						
5	Line 8						
6	Line 8						
7	Line 8						
8	Capital Cost	35528	36482	37430	38370	39366	40357
	Schedule						
9	Design Speed - knots	11.2	14.1	15.6	16.6	17.3	17.8
10	Oper. Speed - knots	11.3	14.2	15.7	16.7	17.4	17.9
11	Sea days/RT	88.7	70.4	63.7	59.8	57.4	55.8
12	Port days/RT	3.7	3.7	3.6	3.6	3.6	3.5
13	Total days/RT	92.4	74.1	67.3	63.4	61.0	59.3
14	RT/year	3.68	4.59	5.06	5.36	5.57	5.73
	Weights - LT						
15	Fuel LT/day	16.6	33.2	49.8	66.4	83.0	99.6
16	Fuel DWT	847	1345	1824	2285	2741	3196
17	Misc. DWT	232	242	252	262	272	282
18	Cargo/RT	38521	37813	37124	36453	35887	35322
	Fuel - LT						
19	Fuel LT/day	17	33	50	66	83	100
20	Sea fuel/RT	1472	2339	3171	3974	4766	5559
21	Port fuel/RT	16.65	16.65	16.2	16.2	16.2	15.75
22	Productive fuel/RT	1489	2356	3188	3990	4783	5575
23	Productive fuel LT/year	5482	10806	16114	21391	26656	31969
24	Idle fuel /year	293	293	293	293	293	293
25	Total fuel/year	5775	11099	16407	21684	26949	32262
	Port and Canal Costs (in $1000s)						
26	Port costs/RT	5.7	5.7	5.7	5.7	5.7	5.7
27	Bunker costs/RT	2	2	2	2	2	2
28	Total/RT	7.7	7.7	7.7	7.7	7.7	7.7
	Annual Costs and Summary (costs in $1000)						
29	Port and Canal	28	35	39	41	43	44
30	Crew wages	844	675	675	675	675	675
31	OH and misc.	244	195	195	195	195	195
32	Maint. and Repair	582	582	582	582	582	582
33	Stores and supplies	214	214	214	214	214	214
34	Subsistence	79	63	63	63	63	63
35	Insurance	218	218	218	218	218	218
36	Sub total	2210	1983	1987	1989	1991	1992
37	F.O.	2515	4834	7147	9445	11739	14053
38	Annual oper. costs	4725	6818	9134	11434	13730	16045
39	Annual cost cap. recov.	1904	1955	2006	2057	2110	2163
40	Average annual cost	6629	8773	11140	13491	15840	18208
41	Cargo/yr (1000 LT)	141.8	173.4	187.7	195.4	200.0	202.6
42	RFR - $/LT	46.75	50.58	59.36	69.03	79.19	89.89
	Ship Day Rate - $	19497	25803	32764	39679	46587	53553
	Ship Day Rate w/o CRF - $	13897	20051	26864	33630	40381	47191

Table 5 Propeller Roughness - 100μm fouling per year and no restoration

Years	0	5	10	15	20	25
k_P , μm	30	203	242	282	321	361
$\Delta\eta_0$, %	0	-20.7	-24.1	-26.6	-29.7	-32.2
$\eta_P - \Delta\eta_P$, %	0.753	0.597	0.571	0.553	0.53	0.51

Table 6 Propeller Roughness - 10μm fouling per year and 2 1/2 year restoration

Years	0	5	10	15	20	25
k_P , μm	30	73	75	76	76	77
$\Delta\eta_0$, %	0	-7.4	-7.7	-7.9	-7.9	-8.1
$\eta_P - \Delta\eta_P$, %	0.753	0.697	0.695	0.694	0.694	0.692

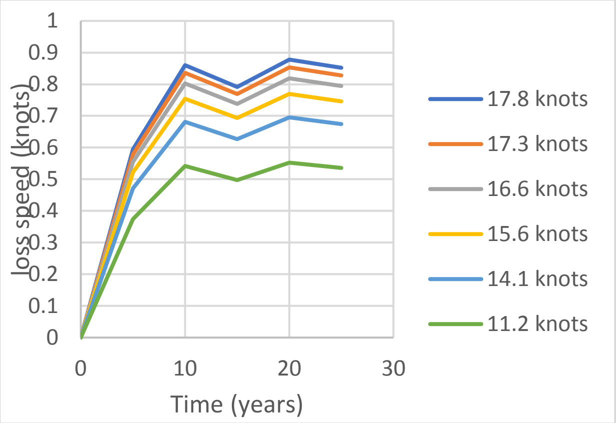

Figure 9 Loss of speed due to propeller roughness - 10µm fouling per year and 10 year restoration

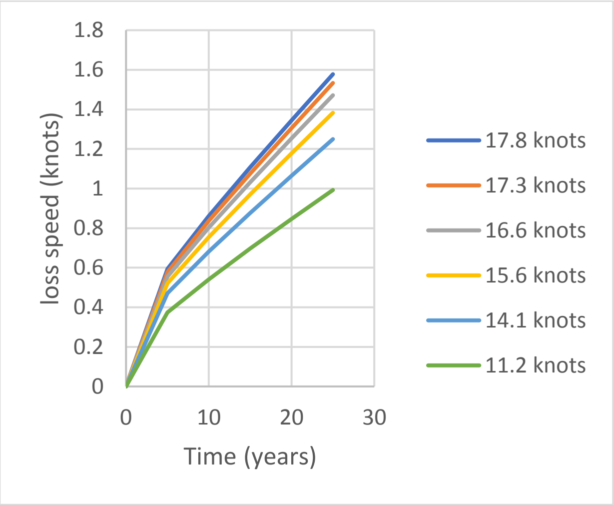

Figure 10 Loss of speed due to propeller roughness - 10µm fouling per year and no restoration

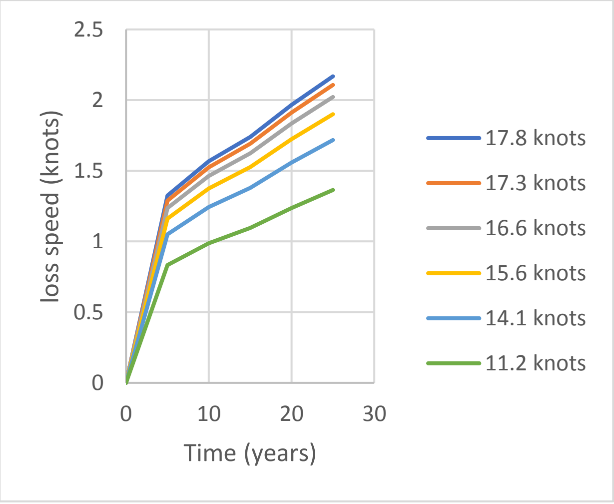

Figure 11 Loss of speed due to propeller roughness - 100µm fouling per year and no restoration

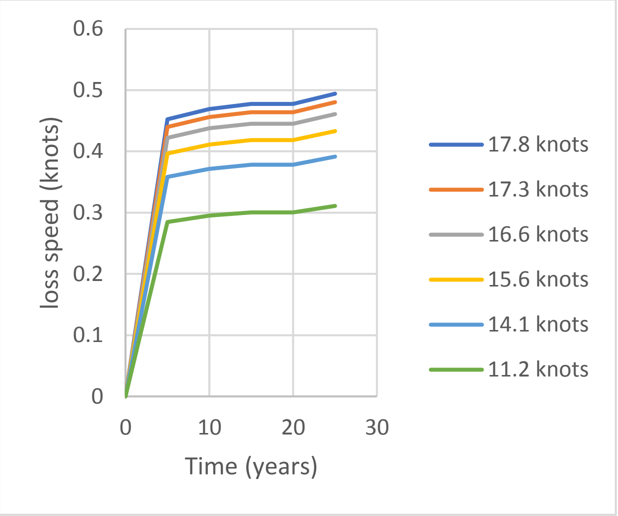

Figure 12 Loss of speed due to propeller roughness - 10µm fouling per year and 2 ½ year restoration

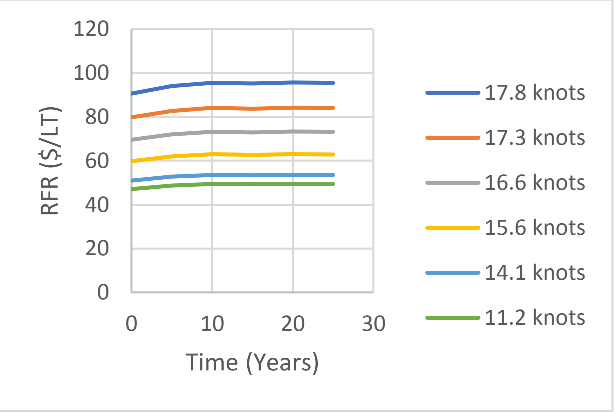

Figure 13 RFR due to propeller roughness - 10µm fouling per year and 10 year restoration

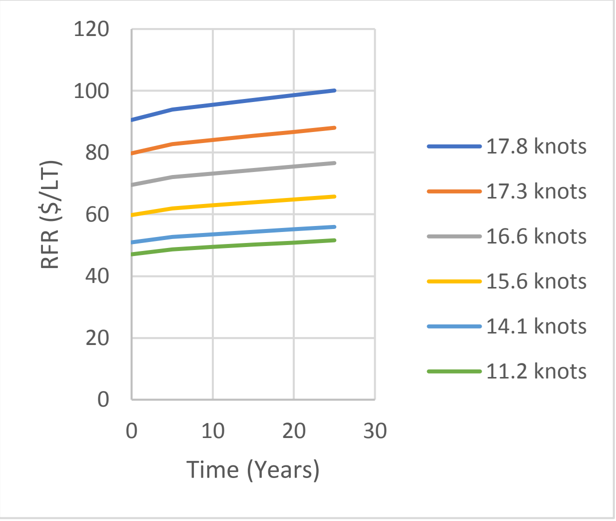

Figure 14 RFR due to propeller roughness - 10µm fouling per year and no restoration

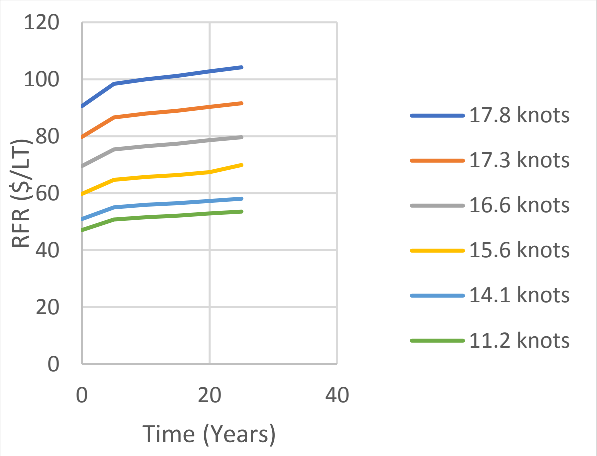

Figure 15 RFR due to propeller roughness - 100µm fouling per year and no restoration

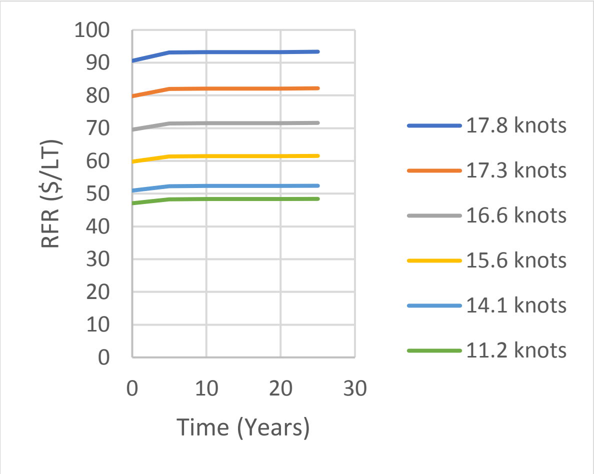

Figure 16 RFR due to propeller roughness - 10µm fouling per year and 2 ½ year restoration

5 RESULTS

The sections which follow discuss the results of the analyses presented above. They are divided into a consideration of the propeller newbuilding and maintenance regimens and their effect on roughness, the speed reduction that can be expected as a result of roughening of the propeller, and the effects of the speed reduction on RFR.

5.1 Roughening

Four scenarios of propeller roughening have been considered and the results presented in Figures 5-8. First, it is important to note that the approach postulated can be applied to any newbuilding and maintenance scenario which will then yield the roughness time history for further analysis.

For the roughness scenarios selected, the most dramatic effect on roughness reduction is the restoration of the propeller surface to its original condition at intervals during its life. For the case of 10µm fouling per year, restoring the propeller surface at every 2 ½ year drydocking results in less than 1/3 the roughness over a 25 year life than if no restoration is undertaken. The results also show that in 25 years the severe fouling can dramatically increase the roughness, by 280% for the case considered in Figure 7 with no surface restoration, over the case with 10µm fouling and 10 year restoration.

5.2 Effects on Vessel Speed

The effects of propeller roughening on vessel speed shown in Figures 9-12 closely follow the roughening profiles. In all cases the most dramatic rate of speed reduction occurs before any corrections are applied to the roughness. In time, the effects on speed level off, except in those cases where there is no restoration of the propeller surface.

For the case of 10µm fouling per year the loss in speed at 25 years of vessel life and no restoration varies from 1 knots for a trial service speed of 11.2 knots to 1.6 knots for a trial service speed of 17.8 knots. For greater speeds a more significant reduction in speed should be expected. With propeller restoration at 10 year intervals, these speed reductions are reduced to 0.53 knots and 0.85 knots respectively, or effectively are cut in half. For restoration of the propeller surface at each drydocking, assumed at 2 ½ years in this study, the 25 year reduction becomes approximately 0.3 knots and 0.48 knots respectively; or almost half again. Clearly the benefit of propeller surface restoration and its application as often as possible has a dramatic effect on speed loss.

5.3 Effects on RFR

The RFR depicted in Figures 13-16 is directly affected by the vessel operating speed, which is reduced due to the effects of propeller roughness and the attendant reduction in vessel speed. The results show that this effect is exacerbated as vessel trial speed is increased.

In the worst case shown in Figure 15, for severe fouling and no surface restoration, the increase in RFR is 7.7% at the end of 5 years and 14% at 25 years for 11.2 knots trial service speed and 8.7% and 15.1% respectively for 17.8 knot trial speed. As with vessel speed, the effect has the greatest rate of increase with time in the early years.

When fouling is lower and propeller surface restoration occurs at every drydocking, the effects are reduced to 2.6% and 2.8% respectively for a trial service speed of 11.2 knots and 2.8% and 3.1% respectively for 17.8 knots trial speed.

6 CONCLUSIONS

6.1 Roughening

- It is possible to develop a roughness time history representing the condition of the propeller surface over its lifetime.
- Restoration of the propeller surface to as close to its original condition at each drydocking results in the greatest reduction in lifetime roughness for the cases considered.

- Especially in cases where severe fouling is present, it will benefit to more frequently clean the propeller, as with divers.

6.2 Effects on Vessel Speed

- The effect of roughening on the vessel speed follows the trend in the amount of roughness and is most significant when no propeller restoration is undertaken.
- Periodic cleaning of fouling and propeller restoration have the most dramatic effect on reducing speed loss.
- The faster the trial speed of the vessel the greater the reduction in service speed with roughening.

6.3 Effects on RFR

- The reduction of vessel speed with roughness directly impacts the RFR.
- RFR increases vary from 2.6% after 5 years for a trial service speed of 11.2 knots and propeller restoration at each drydocking to 15% after 25 years for a 17.8 knot trial speed for heavy fouling and no propeller restoration.
- With cleaning and restoration of the propeller at each drydocking, RFR increases over the 25 year life of the vessel are 2.6% at 5 years to 2.8% at 25 years for a trial speed of 11.2 knots and 2.8% to 3.1% for a trial speed of 17.8 knots.
- With cleaning and restoration at every 4th drydocking, RFR increases over the life of the ship are 3.4% to 5% and 3.7% to 5.4% respectively.
- The effects of roughness on RFR are of the same order of magnitude as the profitability of the vessel, justifying scrutiny and consideration.

REFERENCES

Benford, H., "The Practical Application of Economics to Merchant Ship Design," Marine Technology, SNAME, January 1967.

Daidola, J.C., Esposito – Kelley, D., "Hull Roughness and its Effects on Lifetime Fuel Consumption and Voyages," manuscript in preparation World Maritime Technology Conference, December 2018.

Kresic, M., and Haskell, B., "Effects of Propeller Design-Point Definition on the Performance of a Propeller/Diesel Engine System with Regard to In-Service Roughness and Weather Conditions," Trans. SNAME Vol. 91, 1983.

Oosterveld, M.W.C., Ed., Proceedings. 15th International Towing Tank Conference, Vol. I, 1978.

Stone Propeller Propulsion," Propeller Surface Roughness,", RINA, undated.

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