Optimising technique in matching combined diesel engine or gas turbine (CODOG) propulsion system to hull and propeller of a frigate

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Synopsis

In operation of a combined diesel engine or gas turbine (CODOG) propulsion system, optimal matching of prime movers with propellers and ship hull is of great importance. Selection of an ideal propeller pitch that will be apt for different operating conditions of a marine vessel is an arduous task and requires initial assessment with a dedicated mathematical model. In this work, matching CODOG propulsion system to achieve best operation of type F90 frigate was carried out. A non-complex Java computer program (prop-matching) was developed to facilitate the matching process using dedicated simulation models in design and off-design conditions. The goal is to understand the interaction of either diesel engine or gas turbine with propeller and ship hull. The pitch of a controllable pitch propeller (CPP) was varied to the limit of optimal operation to absorb the power in either diesel engine or gas turbine mode in wide range of engine speeds and load. If a pitch other than that for the appropriate load and speed is selected, there would be an increase in fuel consumption, cavitation, vibration induced stresses in addition to stresses caused by engine load and wave motion on the vessel. The determination of the optimal operating points will lead to significant improvement in flexibility, minimum environmental impact and operating cost. Propeller characteristics were determined with hydrodynamics based on updated B-series regression polynomials which were correlated using Boundary Element Methods (BEM) and tuned with semi-empirical corrections. The analysis showed that the pitch ratio of a propeller has a dominating influence in the selection of the optimal points under operations in diesel or gas turbine mode and that the highest propeller efficiency did not occur at the optimal points. The output results for the open water propeller characteristics from this model are in good agreement with results of other authors and commercial Lindo software.

Keywords: CODOG-matching technique; prime movers; controllable pitch propeller; optimal operating point; open water propeller diagram; thrust and toque coefficients

1. Introduction

The selection of drive shaft arrangement incorporating prime movers (diesel engine or gas turbine) and propeller for a vessel is dependent on various factors such as type and size of vessel, power output of the engines, flexibility, simplicity and characteristics of the propeller. For vessels used for patrol, combat, search and rescue operations particularly in the navy and coast guard, it is desirable to provide a propulsion system which has high flexibility, low fuel consumption for long range cruising and the capability to generate high power with rapid response when needed. To satisfy these requirements, prime movers such as well matched marine diesel engines and aero-derivative gas turbines connected with gearing system to a propeller shaft as displayed in Figure 1 would be needed. A combined diesel or gas turbine engine arrangement known by the acronym "CODOG" is designed such that power is transmitted to the propeller shaft by either the diesel engine or the gas turbine. The prime mover and propeller form a single unit whose characteristics are determined by the interactions of the individual characteristics of the two units (Priyanta, 2015). Alternatively a similar system identified by the acronym ‘CODAG’ where the shaft of both the diesel and the gas turbine engines are coupled to the propeller through a gearbox is used to increase the maximum power output delivered to the shaft.

Authors’ Biography

Professor Kelvin Datonye Bob-Manuel was a Marine Engineering artificer in the Royal and Nigerian Navies and served on onboard frigates. He obtained MSc (1979) and PhD (1983) at the Universities of Southampton, and London – Queen Mary, United Kingdom respectively. He was several times Head of Marine Engineering Department from 1987 – 2009, and Dean of Students’ Affairs 2009 - 2011 at the Rivers State University, Port Harcourt, Nigeria. He was a research fellow at Queen Mary, University of London where he actively carried out research on alternative/renewable fuels for marine use since 1984. His publication on simulation model in matching waterjet propulsion system to marine diesel engine was selected as the best article in the Marine Division of the Institute of Engineers – India in 1999/2000 and was awarded a Gold Medal. . He is the first Professor of Marine Engineering in West Africa and a Fellow of the Institute of Marine Engineering, Science and Technology based in the United Kingdom and Nigerian Society of Engineers

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Matching prime movers to propellers in CODOG systems for optimal operation in service requires equilibrium between the propulsive power and the propeller torque to be maintained and hence avoid overloading of the engine throughout the range of operation of the vessel (John, 1976). For most small vessels, matching is relatively easy to develop with computer programs using Matlab, Excel spreadsheet or dedicated software (Barry, 2005). The use of initial mathematical model allows a systematic and analytical assessment of the configuration and minimises the use of experimental or hardware model tests. A computer based analysis is extremely useful because fundamental physical processes occurring in design and off-design operation provides means of design evaluation and review.

Available methods for propeller performance modelling are numerous and the current knowledge on simulation is wide and complex in some cases (Dalheim, 2015). Boundary Element Methods (BEM) and other three-dimensional approaches have been developed and further improved upon for the purpose of accurate prediction of propeller characteristics in various conditions The continuous development of computational capability has also resulted in the introduction of Computational Fluid Dynamics (CFD), Blade Element Momentum theory, Lifting line or Surface and Panel Methods to the field of propeller design.

According to Salvatore et al (2011) computational models based on the BEM have been extensively applied during the last decade to the analysis of marine propellers in open water and in behind-wake conditions under non-cavitating or cavitating flow regimes. Hence in this work hydrodynamics based on updated B-series regression polynomials (Oosterveld, 1975) which were correlated with BEM proposed by Salvatore et al (2011) and Reynolds number 2.0 x 10^6 were used to determine propeller performance to match prime movers and hull of a frigate. Laplace equation for the perturbation velocity potential was solved using boundary integral formulation whereas the momentum equation took the form of the Bernoulli equation to evaluate pressure and incoming velocity to the propeller disk. The torque (Q) and thrust (T) values obtained by integration of normal and tangential stress over the surface of the propeller blades as proposed by the author were used to correlate equations (8) and (9) respectively.

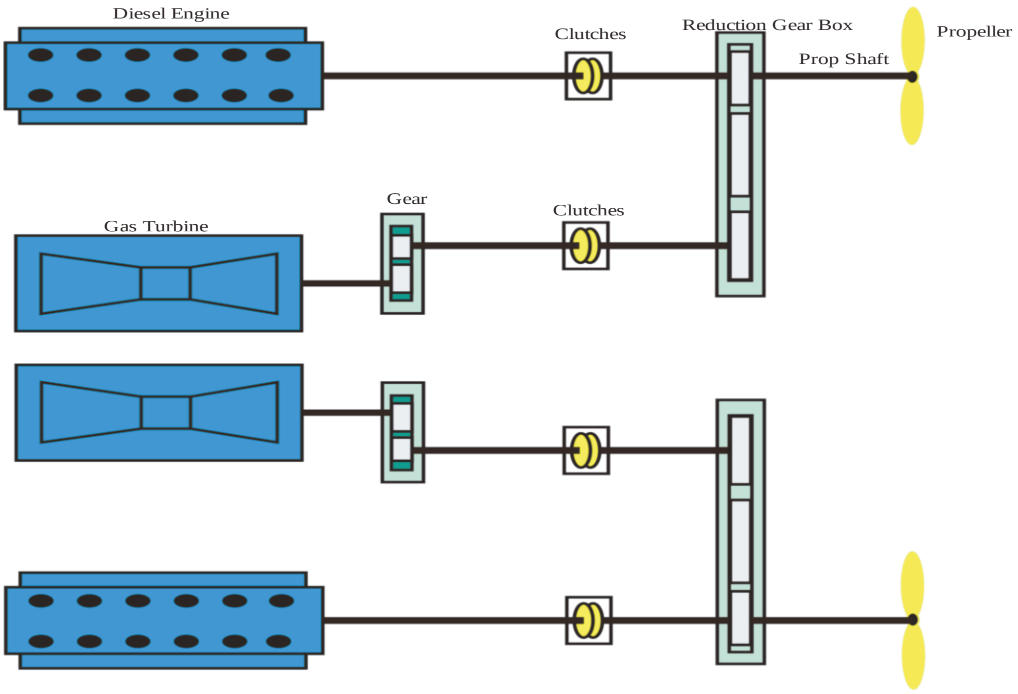


Figure 1: Prime movers and propellers layout in a CODOG configuration

A frigate with CPP is considered in this work because the propeller can develop more thrust, higher propulsive efficiency and better manoeuvrability than fixed pitch propeller (FPP) since the pitch can be varied to suit all operational conditions (Schulten & Johannes, 2005; Zarbock, 2009). CPP provides means of giving astern thrust without reversing shaft rotation and reduces consequential loses in power and speed when operating in off-design conditions such as cruising in stormy weather or hull surface fouling, etc. (Schanz,1967). Other advantages of the CPP includes short response time while maintaining full power output with constant operation of the engine at its nominal speed which will result to low fuel consumption, reduced maintenance cost and clutch disc wear, etc. (Mason-Marine, 2018).

To optimise the matching of a CODOG system with CPP, vessel type, transmission efficiency, fuel economy, reduction in exhaust emission and noise levels, and passengers/crew comfort have to be taken into consideration. For fast ferries and coastal patrol boats, initial investment, operational economy and the environmental pollution impact on coastal communities are crucial factors considered while ships lifetime is given less attention (Grunditz, 2015).

In this work, the principal particulars of Nigerian Navy (NN) frigate, NNS Thunder having principal particulars shown in Table 1 (formerly USCGC Chase, Hamilton Class high Endurance Cutter of the United States Coast Guard) using CODOG propulsion system was used as a case study to determine the best technique in matching prime movers and CPP. (NNS Thunder (F90) – Wikipedia (2017))

2. Optimisation of matching power of prime movers to propeller thrust and torque

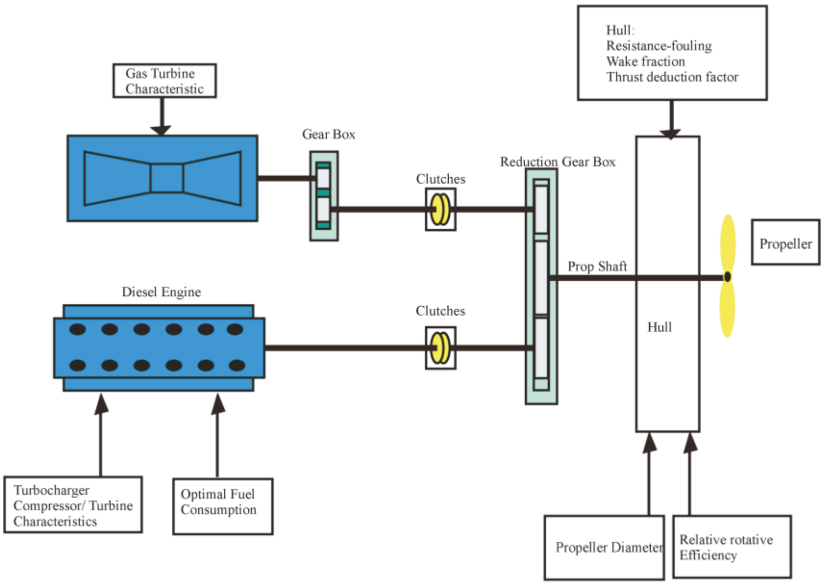


Figure 2: CODOG system's prime movers & propeller operating mode

Analysis and optimisation of the thrust and torque produced by a propeller with prime movers and ship hull in an operating mode - Figure 2 is complex hence a finite dimensional analysis model is normally developed from the laws of physics (Lee, et al 2010; Stalinski, 1983) and according to Pivano (2008) the thrust and torque depend on the propeller geometrical parameters. In a paper of Priyanta (2015), he proffered that the matching is an application of the principle of conservation of energy i.e. power produced by the engine is equal to the power absorbed by the propeller with reasonable unavoidable losses.

The characteristics of propellers are best described by open water diagram i.e. without the influence of the ship hull (Stapersma & Woud, 2005). Neglecting the effect of waves, ocean current and assuming a well submerged propeller, its efficiency relationship with thrust power (P_T) and propeller power (Po) is given as:

$$\eta_o = \frac{P_T}{P_o} \tag{1}$$

Propeller characteristics can be described graphically in several ways. Most appropriate are plots of torque (K_Q) and thrust (K_T) coefficients plotted as functions of the advance coefficient (J) which are derived from the open water diagram, hence

Equation (1) can also be expressed as:

$$\eta_o = \frac{1}{2\pi}.\frac{T.V_A}{Q.n_P} = \frac{K_T.\rho.n_P^2.D.^4V_A}{2\pi.K_Q.\rho.n_P^2.D^5.n_p} = \frac{1}{2\pi}.\frac{K_T.J}{K_Q} \qquad (2)$$

Where:

Q is torque in open water condition
D - propeller diameter
V_A - advance Velocity
n_p - rotational speed of the propeller
ρ - density of water

The thrust and torque coefficients are expressed as functions of propeller parameters and expressed as:

$$K_T = F_T(J, {}^P/_D, {}^{A_E}/_{A_O}, Z, R_e, {}^t/_c) = \frac{T}{\rho.n^2D^4} \qquad (3)$$

and

$$K_Q = F_Q(J, {}^P/_D, {}^{A_E}/_{A_O}, Z, R_e, {}^t/_c) = \frac{Q}{\rho.n^2D^5} \qquad (4)$$

Where:

${}^P/_D$ is pitch diameter ratio
${}^{A_E}/_{A_o}$ - blade or expanded area ratio
A_E - propeller expanded area
A_O - propeller disk area
Z - number of blades
R_e - Reynolds number of a characteristic radius (0.75R).
${}^t/_c$ - ratio of the maximum propeller blade thickness to the length of the cord at a characteristics radius (0.75R).

Interaction of propeller and ship hull

For a given ship, maximum propeller diameter is influenced by the ship resistance and draught. The thrust coefficient is rewritten for the ship as:

$$K_{Tship} = \frac{T}{\rho n^2 D^4} = \frac{R_T}{\rho n^2 D^4 (1-t)} \qquad (5)$$

and advanced ratio obtained as:

$$J = \frac{V_A}{nD} = \frac{(1-w)v_s}{nD} \qquad (6)$$

Brake power of diesel engine is expressed as:

$$P = 2\pi nQ \qquad (7)$$

Where Q = Torque

$= K_Q \times \rho \times n^2 \times D^5$ (K_Q derived from open water diagram) (8)

n = engine speed

Similarly the thrust is obtained as:

$T = K_T \times \rho \times n^2 \times D^4$ (K_T derived from open water diagram) (9)

The relationship between the effective towing power and the thrust is the hull efficiency which is expressed as:

$$\eta_H = \frac{P_E}{(K_{p.}P_T)} = \frac{1-t}{1-w} \qquad (10)$$

Where t = thrust deduction and t = wake fraction

A propeller produces thrust at an advance velocity and the thrust deduction allows part of the produced thrust to overcome the pure towing resistance while the remaining part overcomes resistance due to propeller influence on the hull. The wake fraction allows for the difference between ship speed, V_s and advance velocity, V_A experienced by the propeller as a result of boundary layer in the wake of the hull (Stapersma & Woud, 2005). According to Kuiken (2008), higher wake fraction increases the risk of propeller cavitation hence it is necessary to design the stern in such a way that optimum wake fraction is achieved to avoid cavitation.

The determination of effective towing power, P_E of a ship is normally made from model tests. Actual engine test bed measurements show that power and engine speed are a "directly" proportional in most cases, whereas a theoretical relationship of power (P) and engine or shaft speed (n) for propeller law is defined as:

$$P \propto n^3 \tag{11}$$

and for large high-speed ships such as container vessels and frigate, the propeller law can be expressed as:

$$P \propto V^4 \tag{12}$$

The various mathematical relationships from equation (1) to (11) were used to analyse the optimal matching points using the computer program developed with Java programming language.

2.2. Cavitation constraint

Cavitation is a phenomenon observed in highly loaded propellers, manifesting itself beyond a certain number of its revolutions by noise, vibration and erosion of the blades and can affect its performance. Hence it is necessary to take cavitation into consideration in propeller design process or operational mode. Generally the appearance of cavitaion on propellers depends on the type and shape of blade profile and the thrust loading of the blades (Salvatore, 2011). The determination of the onset of cavitation is very complex, therefore sophisticated computer program including the use of computational fluid dynamics (CFD) are appropriate. Such application is beyond the scope of this investigation. According to Gaafary et al (2010) a simple way to avoid cavitation is to increase blade area ratio to an optimum point. He expressed the minimum blade area ratio required to avoid cavitation as:

$$\left[\frac{A_E}{A_O}\right]_{\min} = \frac{(1.3+0.3Z)T}{(P_o-P_V)D^2} + \mathrm{K} \tag{12}$$

Where $\left[\frac{A_E}{A_O}\right]_{\min}$ is the minimum expanded area ratio (EAR). The coefficient K is equal to 0.1 for twin–screw ship and equal to 0.2 for single-screw ships. However an increase in EAR reduces efficiency a little, but reduces cavitation a lot. Using BEM theory to attain an optimum propeller efficiency and reduced cavitation with EAR of 0.75 can gave optimum matching and propeller efficiency (Salvatore, 2011). The occurrence of cavitation and its intensity depends on the angle of incidence of water inflow and on the load of the propeller. The efficiency of the section as a lifting device is measured by the ratio, lift/drag (L/D) .This ratio is at its maximum at small angle of incidence and therefore for such sections the angle of incidence should be kept low. The ultimate goal is to design a propeller with the best efficiency at the lowest cavitation sensitivity.

2.3. Matching procedure

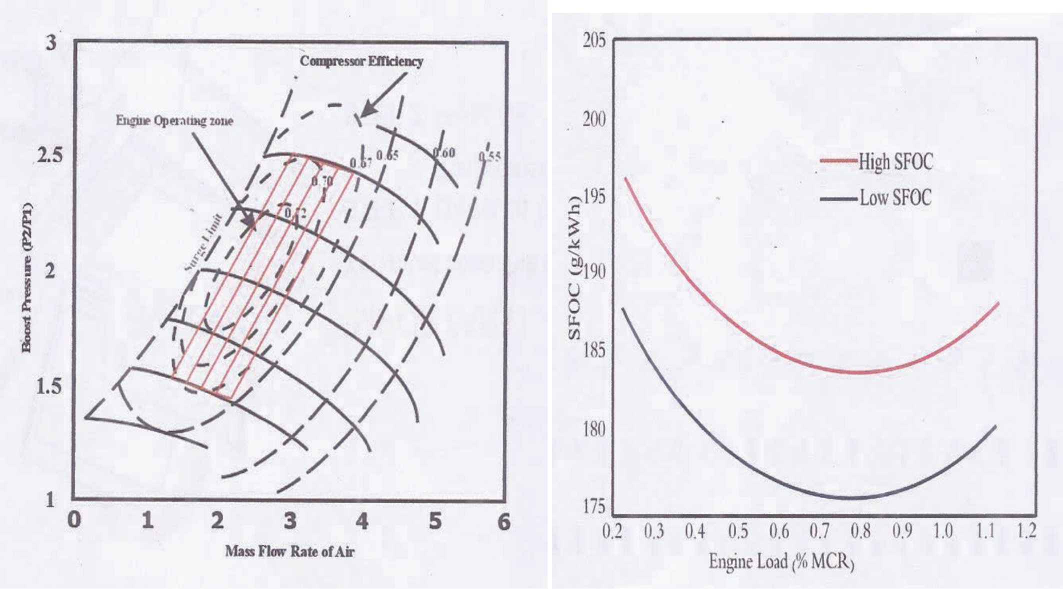
Table 1: Principal particulars of the case study vessel, Source: NNS Thunder (F90) Frigate, Wikipedia (2017)

Particulars	**Parameters**
Displacement	3250 tonnes
Length overall	115.2m
Beam	13.1m
Breath on waterline	12.5m
Draught	4.6 m
Propeller Diameter D	4.0m
No. of Propellers	2
No. Propeller blades	4

Parameters	**Gas turbine**	**Diesel engine**
Vessel speed (knots)	28	17
Rated power (kW)	13410	2700@900 rpm
Propeller speed (rpm)	235	149
Gear ratio	15	6
Gear Efficiency	0.98	0.975

STEP 1

The parameters that influence the performance of a compressor are the mass flow rate, efficiency and temperature rise for a particular engine power and speed (Williams & Leslie, 2012). The first step, therefore in the matching procedure is to plot the values of mass flow rate of air through the engine vs the boost pressure ratios on a given turbocharger compressor characteristics map i.e. ($\frac{m\sqrt{T_{01}}}{P_{01}}$ vs $\frac{P_{02}}{P_{01}}$) with lines of constant speed $\frac{N}{\sqrt{T_{01}}}$ and efficiency η_{is}. Engine running zone is then superimposed on high efficiency portion of the map. This is to create an operating envelope within the turbocharger limits and determine the operating zone of the engine as shown in Figure 3 (a); but the choice of compressor should allow for operation away from the surge and choke limits. The engine's specific fuel oil consumption (SFOC) varies with the engine load and is minimum (i.e. maximum thermal efficiency) at certain load range; typically for diesel engines it is in the range of 70 to 90% of Maximum Continuous Rating (MCR) as displayed in Figure 3 (b). It is necessary to ensure that the engine operating area also falls at the low fuel consumption zone. Therefore, the power will be matched at optimum setting of corresponding engine speed.



(a) (b)

Figure 3: (a) Superimposition of best engine running lines on high efficiency zone of compressor map: propeller law. (b) Specific fuel oil consumption (SFOC) profile with % maximum continuous rating (MCR)

STEP 2

2.4. Determination of operating points at rated power and speed

The diesel engine and gas turbine propeller load curves are plotted in power vs. engine/propeller speed; and the propeller characteristic curves are superimposed on this plot as shown in Figure 4. Since the case study vessel is a frigate, no Engine Margin was allowed, i.e. (EM = 1) (Bob-Manuel, 2017). Hence the operating points occurred at the MCR for both the diesel and the gas turbine. The points of intersection at (1) and (2) on the Figure shows the design and off-design operating points respectively for diesel engine while points (3) and (4) display the design and off- design operating points respectively for gas turbine. The propeller pitch setting for the two operating conditions are also determined.

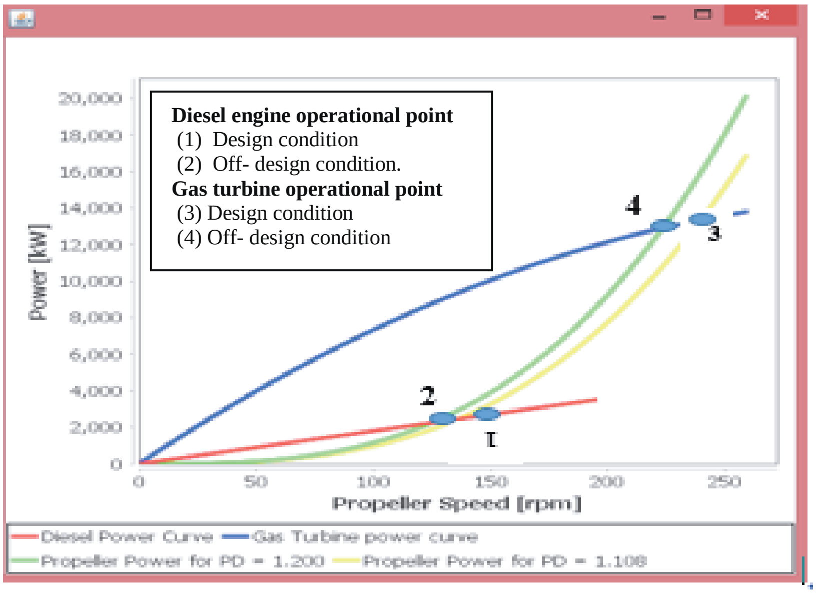
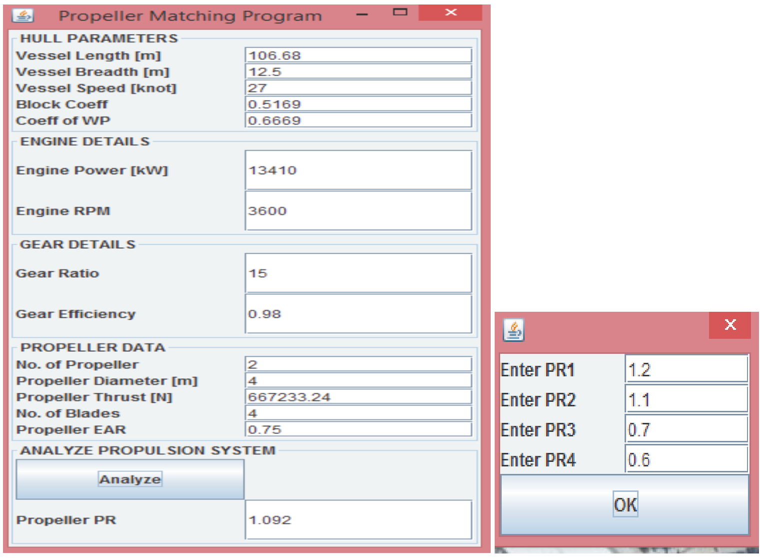


Figure 4: Diesel engine and gas turbine propeller load curves showing operational points for design and off- design condition

2.5. *Open Water Propeller Diagram at Rated Power and Speed*

On running the prop-matching program, a dialog box shown in Figure 5 (a) was set- up to enable input data of the vessel, prime movers and the propeller; and a smaller dialog box – Figure 5(b) contains a range of pitch ratios for the gas turbine operation. A plot of K_T, $10K_Q$, and η_o as functions of J was made to give the open water diagram shown in Figures 6 and 7. A set of three curves were plotted for each pitch ratio over the range 0.755 to 1.2 to determine the matching pitch. From the diagram, propeller efficiency curve, torque and thrust coefficients and advance ratios were obtained.

The K_{Tship} obtained from equation (5) was also plotted on the open water propeller diagram. The point of intersection was obtained with a line projected from this point upwards to intersect K_T, $10K_Q$, and η_o curves. Another line was projected towards the Y-axis to obtain the coefficients and the open water efficiency values and then toward the X-axis to obtain advance ratio, J. These coefficients were used in equations (8) and (9) to determine the propulsive power and thrust. The point of intersection gives the operational point of the propeller. Using the advance ratio and the appropriate wake fraction, the propeller speed can be determined.

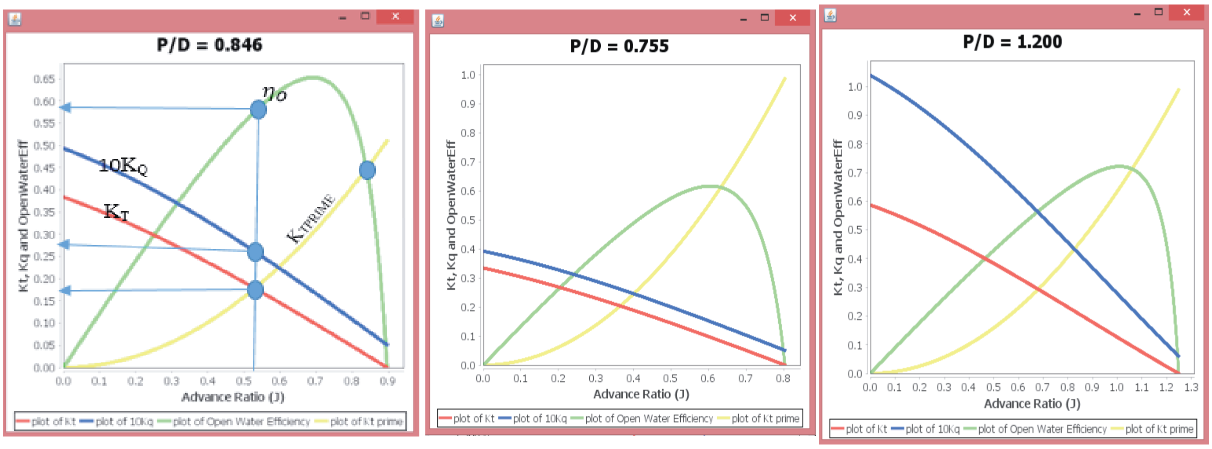


HULL PARAMETERS	
Vessel Length [m]	106.68
Vessel Breadth [m]	12.5
Vessel Speed [knot]	27
Block Coeff	0.5169
Coeff of WP	0.6669
ENGINE DETAILS	
Engine Power [kW]	13410
Engine RPM	3600
GEAR DETAILS	
Gear Ratio	15
Gear Efficiency	0.98
PROPELLER DATA	
No. of Propeller	2
Propeller Diameter [m]	4
Propeller Thrust [N]	667233.24
No. of Blades	4
Propeller EAR	0.75
ANALYZE PROPULSION SYSTEM	
Propeller PR	1.092

Enter PR1	1.2
Enter PR2	1.1
Enter PR3	0.7
Enter PR4	0.6

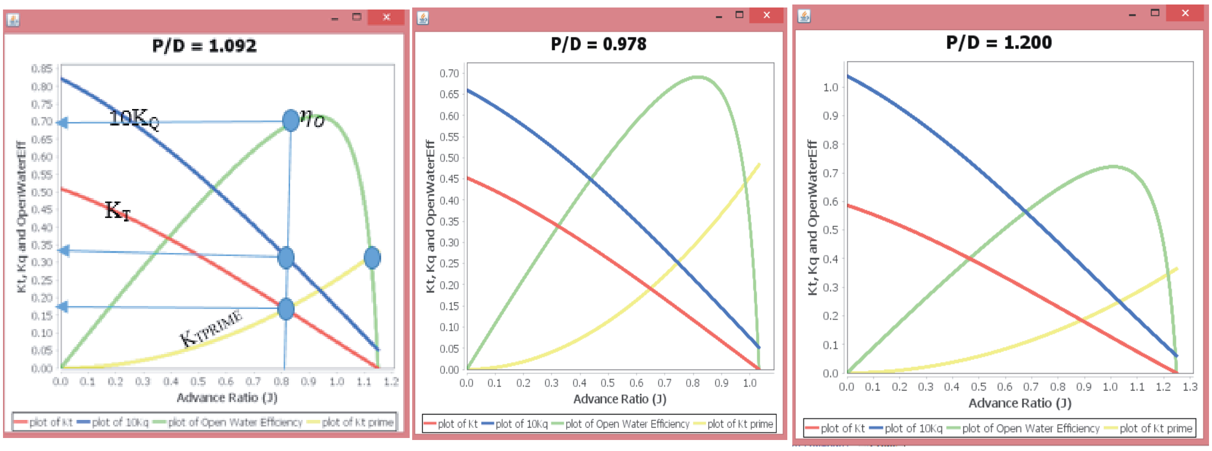
(a) **(b)**

Figure 5: (a) Propeller matching program interface (b) Pitch selection dialog box



(a) Design condition (b) Off-design condition (c) Higher efficiency

Figure 6: Open water diagrams showing design, off-design and higher efficiency conditions for diesel engine operations



(a) Design condition (b) Off-design condition (c) Higher efficiency

Figure 7: Open water diagrams showing design, off-design and higher efficiency conditions for gas turbine operation

Table 2: Simulated values from open water diagram

	P/D	**J**	**η_O**	**K_T**	**$10K_Q$**	**K_{TPrim}**
			Diesel engine			
Design	0.846	0.53	0.58	0.18	0.26	0.46
0ff Design	0.755	0.37	0.46	0.20	0.26	0.63
Higher efficiency	1.2	0.68	0.57	0.29	0.55	0.74
Commercial software Lindo-Gaafary, et al (2011)	1.08	0.78	0.62	0.18	0.36	-
Lee, et al. (2010)	-	0.58	0.61	0.22	0.33	-
			Gas Turbine			
Design	1.09	0.83	0.69	0.17	0.32	0.33
0ff Design	0.98	0.65	0.63	0.19	0.32	0.45
Higher efficiency	1.2	0.88	0.69	0.20	0.35	0.39

3. Results and Discussion

The data obtained from the propeller law curves and the open water diagrams were used in matching the propeller power developed at the design and off-design conditions to give the required speed or thrust without exceeding any limit imposed by the operational mode with the matching propeller pitch. According to Stapersma & Woud (2005), if the pitch is too low, the maximum available power will be limited by the maximum speed limit and when it is too high the maximum available power will be limited by the turbocharger limit.The pitch ratios obtained were not too low to be limited by the MCR of the engine at all operating conditions.

Also in matching prime movers to propeller, the pitch ratio of the propeller that gives the optimal matching of engine may not be the one that gives the highest possible propulsion efficiency (Bezzi, 2014; Priyanta, 2015). This was observed in Figures 6(c) and 7(c). However, propeller efficiency and/or power have to be scarified for best performance and matching points displayed in Figures 6(a) and 7(a), i.e. the prime movers deliver the required power and speed within the operational envelope in each mode.

From analysis of the six open water diagrams, Figures 6(a) and 7(a) as well as pitch ratio of 0.846 for the diesel engine and 1.092 for the gas turbine displayed in Table 2 were obtained as the optimal pitch setting for the design operational mode. The values obtained were used to confirm the rated power and speed of the prime movers.. At different pitch settings the power of the diesel engine falls at 70-90% of the MCR of the diesel engine of the case study vessel. The diagram shows that the peak open-water propeller efficiency increases with pitch and advance ratio while the pitch increases with the thrust coefficient. The increase of the thrust coefficient with open water propeller efficiency indicates that propeller performance can be enhanced by increasing the pitch angle provided the latter is smaller than the stall angle of the propeller. From Table 2, it could be observed that there is agreement with the results obtained from Lindo software and this investigation as well as that of Lee et al (2010). Salvatore et al (2011) showed from their experiment using BEM theory that at lower advance ratio the propeller is moderately loaded and was confirmed in this work and their results were also used for validation.

The off-design condition is considered as 20% increase in resistance and under this operational condition, a lower advance ratio and open water propeller efficiency were obtained. Therefore a lower pitch ratio was needed for best performance of propeller under such condition. From Figures 6(b) and 7(b) it could be observed that off-design operation gave a corresponding decrease in engine power and speed. Under this operating mode, if the fuel pump is adjusted to retain the MCR the engine will be overloaded giving rise to thermal stresses

4. Conclusion

The objective of this paper is to provide a contribution in the direction of analytical procedure in the determination of the optimal matching points in CODOG system. The developed computer model has allowed a presentation of quantitative results for F90 frigate. The results from the program clearly shows that pitch ratios of the CPP for both the gas turbine and diesel engine have dominating influence on the possibilities of obtaining an optimal matching or operating points. The open water propeller characteristics obtained with this model are in good agreement with the results of other authors and commercial Lindo software. The results also confirmed the finding of other renowned authors that the pitch ratio of a propeller that gives the optimal matching of engine is not necessarily the one that gives the highest possible propulsion efficiency.

The change in pitch that is readily accomplished in service permits the engine to run at the same speed under design and off-design operations. The CPP therefore eliminates the need for the engine margin in non naval vessel and allow it to develop full power under both trial and service conditions (trial condition refers to when the ship has clean hull, operating under calm sea state and normal draught while service condition refers to a situation the ship will encounter in operational design condition). Hence rather than operating the vessels out of the operational envelope and overload the engine, it can comfortably operate within the optimal range because CPP can adjust its pitch to suit the condition.

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