



# Study on proposed respectively method for marine propulsion plant system: a case study on passenger ship

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Received: 28 December 2022 / Revised: 28 July 2023 / Accepted: 1 August 2023 / Published online: 18 August 2023

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**Abstract** The improvement of ship performance and propulsive efficiency has been addressed in this article. This proposed method will enhance the operational area of marine propulsion plant and ship energy efficiency management. The main object of study is the relationship between main diesel engine–gearbox–shafting system–marine propeller. The effective power ( $N_e$ ) and revolution ( $n$ ) of main diesel engine have been established throughout the empirical equations in this research. The research results are analyzed and validated for a certain passenger ship namely Sealife Legend 02. The collected results would be discussed with the previous study of Stapersma and Woud “Matching Propulsion Engine with Propulsor” that has been published on Journal of Marine Engineering and Technology. The operational energy efficiency of marine propulsion plant system would be enlarged through this proposed method. This article is significant for the ship-operators and the ship-owners in the management of marine propulsion plant system nowadays.

**Keywords** International Maritime Organization · Marine propulsion plant · Diesel engine power · Passenger ships · Ship energy efficiency management

## 1 Introduction

The improvement of marine propulsion plant system is one of the methodologies to upgrade the ship energy efficiency management strategies. The selection of an appropriate point in marine propulsion plant system is a significant working in the ship operation activities. Additionally, the marine propulsion plant system consists of main equipment in the marine engineering such as main diesel engine, auxiliary machineries, shafting system, marine propeller and so on. Therefore, the effective management of marine propulsion plant system is an optimal method in order to enlarge the ship energy efficiency system and decrease the environmental pollution from ship operation activities.

During the operational process of vessel, there are some crucial problems which generate from mistakes of internal and external factors. These factors are difficult to control and reduce them during the ship operation activities. In where, the main reason has been found that the operational activities and management of the marine propulsion plant system. The inappropriate operation of marine propulsion plant system would cause the maritime accidents influencing on ship-operators, equipment, and engines on ships. Additionally, this one influences negatively on the ocean environment from this accident. Therefore, the management of marine propulsion plant system plays an important role in the maritime transportation industry.

Consequently, the marine propulsion plant system must comply with the initial design conditions at shipyard and the working environment at sea (Stapersma and Woud 2005). The detail of off-design condition consists of the variation of ship displacement, the increased ship resistance due to seaway, influencing the number of engines and propulsion plant system (Stapersma and Woud 2005). During the ship operation process, there are a lot of variable factors which

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are generated to impact on the ship energy efficiency as well as the marine propulsion plant system. These factors include speed loss, added resistance of ship, reduced engine power, reduced ship performance, etc. So, the international maritime organization (IMO) has issued the ship energy efficiency measures: Energy Efficiency Operational Indicator (EEOI), Energy Efficiency Design Index (EEDI), and Ship Energy Efficiency Management Plan (SEEMP) (Tran 2017). These proposed measures are the effective solutions to restrict the negative influences on marine propulsion plant system and marine engines on the vessels. These solutions have been presented through some methodologies in Fig. 1.

In reality, there are some different researches to improve the ship energy efficiency management. These studies have the private advantages to enlarge the ship operation range throughout the ship energy efficiency management. Some specific results have been indicated by some researchers. Consequently, the presentation of these previous studies has been outlined as follow. Zaccone et al. were used a 3D dynamic programming for ship voyage optimization method (Zaccone et al. 2018). Takashima and Mezaoui were used the weather routing optimization method to save the fuel oil consumption for merchant ships (Takashima and Mezaoui 2009). Moreover, the study of trim optimization method has been researched and investigated through the different trend approaching. Reichel et al., were studied the overall trim optimization for vessels (Reichel et al. 2014). The trim optimization method is one of methods to reduce the fuel oil consumption for ships through the ship dynamic ship motion during the navigation process.



**Fig. 1** The scheme of ship energy efficiency management

On another side, the waste heat recovery system is also popular for enlarging the ship operation range through the thermodynamic field. Akman and Ergin were investigated the marine waste heat recovery system under addressing the various engine operating conditions by the organic Rankine cycle (Akman and Ergin 2019). The ship speed optimization method was addressed by Kim et al., (Kim et al. 2014). Nowadays, the reduction of fuel oil consumption is applied widely by utilizing the ship speed optimization method. In particular, the slow steaming state of main diesel engine has been applied for the ships. This method is economical for the ships. However, there are some negative problems influencing on the operation and maintenance state of main diesel engine.

Moreover, the study of different methods to optimize the ship hull has been conducted by some researchers. Throughout these methodologies, the fuel oil consumption of ships will reduce during the ship operation process based on re-designing the ship hull. Yin et al., were studied the numerical and experimental method to research the hydrodynamic hull form optimization for a container ship (Yin et al. 2019).

However, there are the limited studies which investigate to the marine propulsion plant system so as to increase the ship energy efficiency management. Especially, this solution is very significant to increase the ship performance. Additionally, it will enlarge the range of ship operation between main diesel engine-shaft system-propeller. In this article, the study of marine propulsion plant system has been conducted at a certain passenger ship: Sealife Legend 02 in Halong City, Vietnam.

This article has been divided into the sections: Sect. 1, introduction; Sect. 2, the related works; Sect. 3, the proposed methodology; Sect. 4, the establishment of characteristics curve of marine propulsion plant; Sect. 5, results and discussion and Sect. 6 conclusion.

## 2 The related works

The research on marine propulsion plant system plays an important role in the field of marine engineering. The main purpose of these studies will increase the ship energy efficiency management through rising the marine propulsion plant efficiency and ship performance. The marine propulsion plant system is different at each certain vessel. Currently, there are some kinds of marine propulsion plant system including, the marine diesel engines (four-stroke diesel engine and two-stroke diesel engine), the marine steam propulsion system (steam turbine, marine main boiler, and waste heat recovery (WHR) plant). Benvenuto et al., were conducted on researching about the ship propulsion plants including, a two-stroke diesel engine, waste heat recovery system (Benvenuto et al. 2014). The

research on marine propulsion plant is very complicated as well as using a lot of different methodologies to collect the results at this topic. The overall ship propulsion plant system is a combined system between main diesel engine, propeller, and ship dynamic model on vessels. Zhao et al., were studied the marine propulsion plant system through the cycle mean value model to combine with the operation process (Zhao et al. 2015).

On the other hand, the combination between marine diesel engine, gas turbine, and steam turbine has been conducted in aim with increasing the marine propulsion system (Dzida 2011). This combination would help to increase the ship operation range. The waste heat recovery system has also been studied as an effective method to increase the ship energy efficiency (Altosole et al. 2017). The study of waste heat recovery system has brought the benefit for the marine propulsion plant of ships. It is a solution to enlarge the ship energy efficiency management as well as the operation range of ships. The transcritical Rankine cycle (TRC) has been applied to investigate the waste heat recovery system (Yang 2016). On the other hand, the combination of steam turbine and gas turbine has been researched by Dzida et al., (Dzida et al. 2009).

The alternative marine propulsion plant system has also been studied as an effective solution to increase the ship energy efficiency and the ship performance. Geertsma et al., were reviewed the hybrid power and the marine propulsion plant system for smart ships with the alternative propulsion plant (Geertsma et al. 2017). The study of clean technologies for the marine propulsion plant and the smart ships has been conducted in recent years. The purpose of these studies will bring the green technologies in the field of marine engineering. Alternatively, the use of alternative marine fuel is being conducted at some countries in the world nowadays. Litwin et al., were studied the hybrid marine propulsion like as “zero emissions” for the future ships (Litwin et al. 2019). Moreover, the alternative marine propulsion plant has been addressed through some the published papers on the international journals like as *Energy*, *Applied Energy*, *Energy Conversion and Management*, *Fuel*, *Renewable Energy*. The study of dual fuel engine propulsion plant has been conducted as well as installing the Waste Heat Recovery (WHR) system to increase the marine propulsion plant efficiency and the Selective Catalytic Reduction (SCR) to decrease the harmful gases emission (Livanos et al. 2014). In reality, there are some previous works that have been conducted by some researchers in the world approaching the different methodologies. However, the establishment of the operational characteristics curves of main propulsion plant system has not still been addressed and researched. Therefore, this paper will address the abovementioned research gap in managing the marine propulsion plant system.

### 3 The materials and methodologies

#### 3.1 The empirical theory for establishing the characteristic curve

During the operation process of ships, the specific parameters of marine diesel engine are not stable. These parameters are the uncertain factors depending on the operational characteristics and the navigation environmental conditions. In reality, the operational characteristic curves of ship are the variable equations based on changing the engine speed. That data will be changed when the ship speed changes in case of the fixed pitch propeller.

Determining some criteria such as economy criteria, efficiency criteria, longevity criteria, and some other criteria will depend on the operation conditions and the safety purpose. The operators should know about the status of engine during its operation and maintenance. A certain operation characteristics between engine–marine propeller is a database group to collect the specific parameter under the certain environment condition. Typically, the name of the operation state is determined through the specific case of ship including, the heavy, the normal, and the light operation condition. The speed state represents the operation of the engine at a constant speed. The load state of ship is also represented through the operation of engine at the fixed load (mean effective pressure  $P_e$  or effective torque of engine  $M_e$ ).

There is no load state that the diesel engine operates without a load (output) or  $P_e = 0$ . The minimum speed state means that the engine will work at minimum constant speed ( $n_{min}$ ). In order to determine the efficiency of engine at the different working conditions, the specification of the engine at an initial state is compared with the nominal specification.

##### 3.1.1 The characteristics of diesel engine

In order to determine the performance of an engine, the characteristic curve of engine is also addressed the fundamental theory. Depending on that, the operator can check the specification of the engine and determine appropriately the efficiency of diesel engine.

The characteristic curves of engine will express the relationship between the main specifications of engine corresponding to a certain operation condition of vessel. The characteristics of marine diesel engine can be divided into two groups:

##### Speed characteristic group

The speed characteristic curves will indicate the relationship between the main specifications of engine and its speed or the ship speed at a certain operation condition.

The speed characteristics can be separated into three groups:

- The engine output characteristics
- The propeller characteristics
- And the boundary characteristics

#### Load characteristics group

The load characteristic curves will identify the relationship between the main specifications of engine and its load ( $P_e$ ,  $M_e$ ) at a certain operation condition.

Altogether, there are four characteristic curves which will be considered:

- Engine output characteristics
- Propeller characteristics
- Boundary characteristics
- Load characteristics

### 3.1.2 The characteristics of marine diesel engine

**3.1.2.1 Speed characteristics** The speed characteristic curves will describe the relationship between the main engine of engine and its speed or the ship speed at a certain operation condition.

The speed characteristics will be presented through the functional equations:

$$N_e = f(n) \quad (1)$$

Or  $N_e = f(V)$ .

Where  $N_e$ : effective power of the engine (HP),  $n$ : speed of the engine (rpm),  $V$ : velocity of the ship (knots).

There are two main types of speed characteristics including, the engine output characteristics and the propeller characteristics.

#### a. Engine output characteristics

The output characteristic curve of engine illustrates the relationship between the main specifications of engine ( $N_e$ ,  $P_e$ ,  $M_e$ , etc) and its speed ( $n$ ) when keeping the constant fuel rack position of the fuel injection pump, or it means the amount of fuel supplied into the combustion chambers of engine at each cycle is fixed.

It can be showed through the functional equations:

$$N_e = f(n), d_w = \text{constant}.$$

$$M_e = f(n), d_w = \text{constant}.$$

Where  $d_w$ : the amount of injected fuel is supplied into the combustion chamber of engine at each cycle.

To establish the engine output characteristics, the effective efficiency of engine is kept at the fixed position during the ship operation ( $\eta_e = \text{constant}$ ).

The effective power of engine is calculated through the functional equation:

$$N_e = G \cdot Q_H \cdot \eta_o / 632.2 \quad (2)$$

where  $G$ : the amount of fuel fed to diesel engine in a hour, kg/h.

$$G = 60 \cdot z \cdot d_w$$

$n$ : the ship speed of engine, rpm;  $z$ : the stroke coefficient of main engine (two-stroke engine  $z = 1$ , and four-stroke engine  $z = 1/2$ );  $Q_H$ : the low calorific value of the fuel oil, kCal/kg.

To replace  $G$  into the above Eq. (2), then  $N_e$  will be rewritten in Eq. (3):

$$N_e = \frac{60 \cdot z \cdot Q_H \cdot \eta_e}{632.2} \cdot n \cdot d_w \quad (3)$$

With a particular engine uses a certain kind of fuel (heavy fuel oil or diesel oil), the above equation will be expressed as follow:

A constant coefficient:

$$C_1 = 60 \cdot z \cdot Q_H / 632.2 \quad (4)$$

Hence:

$$N_e = C_1 \cdot n \cdot d_w \cdot \eta_e$$

From Eq. (4), the engine output is proportional with its speed. The amount of fuel will be pumped into the combustion chamber of engine at each cycle is constant ( $d_w = \text{constant}$ ). The output characteristics of engine will be presented in Fig. 2.

The effective power of engine  $N_e$  will be presented in Eq. (5):

$$N_e = M_e \cdot n / 716.2 \quad (5)$$

From that, we can calculate:

$$M_e = 716.2 \cdot N_e / n \quad (6)$$

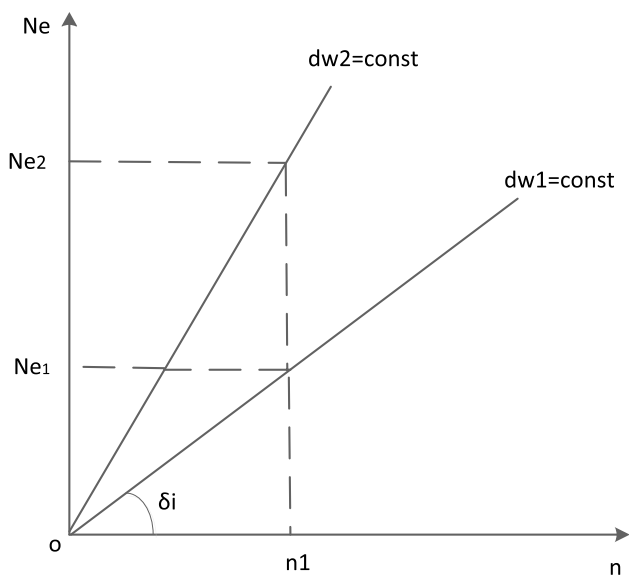
Replace  $N_e$  from formular (5), it is clear that:

$$M_e = C_2 \cdot d_w \quad (7)$$

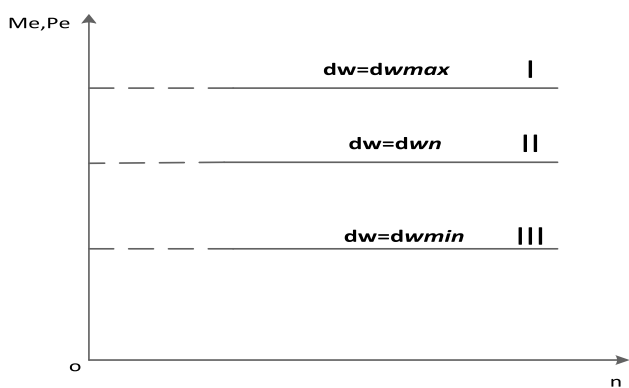
$C_2 = \text{Constant}$ .

When  $d_w$  is kept constantly then the effective moment  $M_e$  is also constant. It is the same with the effective mean pressure  $P_e$ .

The output characteristic curves of engine are also presented in Fig. 3. Then, the presentation of engine output characteristics will be described through  $P_e$ ,  $M_e$  with  $n$  in case of  $d_w$  is constant.



**Fig. 2** The engine output characteristics when  $d_w = \text{const}$ .  $\delta i$ : the angle between  $N_e$  and  $n$  demonstrates the quantity of injected fuel oil into the chamber of engine or  $P_e, M_e$  when  $d_w$  are changeable



**Fig. 3** The demonstration of  $P_e, M_e$  and  $n$  when  $d_w = \text{constant}$

I:  $P_e, M_e$  get the minimum values when  $d_w = d_{w \min}$  it means the fuel oil will be supplied into the chamber of engine at the minimum level.

II:  $P_e, M_e$  get the nominal values when  $d_w = d_{wn}$ , so the fuel oil will be supplied into the chamber of engine at the nominal level.

III:  $P_e, M_e$  get the maximum values when  $d_w = d_{w \max}$  it means the fuel oil will be supplied into the chamber of engine at the maximum level.

In fact, the efficiency  $\eta_e$  is not constant in operation condition of engine ( $n_{\min}, n_{\max}$ ), therefore the output characteristics of engine are nonlinear. They are showed in Fig. 4 and these curves will be divided into the different kinds.

1. The maximum output characteristics ( $N_{e \max}$ ) will present the ability of engine at the maximum power with the nominal speed or the maximum speed.

2. The nominal engine output characteristics ( $N_{en}$ ) will present the ability of engine at the maximum constant power with the nominal speed.

3. The operational output characteristics ( $N_{ek}$ ) of engine will be presented at the variable operation conditions of ship like as the smooth ocean operation. In where, the main engine operates in the good technical condition along with the hull and propeller are cleaned.

Normally the output power of main engine is about:  
 $N_e = (0.85/0.95) \cdot N_{ek}$

4. The partial load characteristics ( $N_{ek'}$ ), ( $N_{ek'} < N_{ek}$ ) will be used during the operational process of engine at heavy working condition or during maneuvering of ship.

*b. Propeller characteristics*

The propeller characteristics will present the relationship between the main specification of engine driving the propeller. Additionally, the amount of fuel will be injected into combustion chamber of engine is not constant. However, the total generated power of engine will be transmitted to the propeller.

The moment and power of engine are estimated through the functional equations:

$$N_e = N_s = C \cdot n^x \tag{8}$$

$$M_e = C' \cdot n^{x-1}$$

where:  $x$ : exponential coefficient, it depends on the profile of the hull (hull's shape) and the propulsion arrangement,  $x = 2.5/3.2$ ;  $x = 2.5$ : with high speed vessels (sliding vessels, passenger vessels);  $x = 3.0/3.2$ : with cargo vessels, merchant ships;  $C, C'$ : coefficients, depending on the dimension and construction of the hull and propeller and also their technical condition.

Moreover, they are influenced dramatically by the ship operation condition including, sea conditions, working water zone, flow, cargo loaded and so on...

The numerous experiments will be conducted to collect the empirical equations. It could be found that mostly cargo vessels with the coefficient  $x$  are equal to 3 with sailing speed around 10–16 knots. These empirical equations will be presented in Eqs. (9) and (10).

$$M_e = C' \cdot n^2 \tag{9}$$

$$N_e = C \cdot n^3 \tag{10}$$

In reality, the operation condition of ship will change including, the variable wave, wind, flow of sea current, the depth, the water gravity and the other factors. In where,

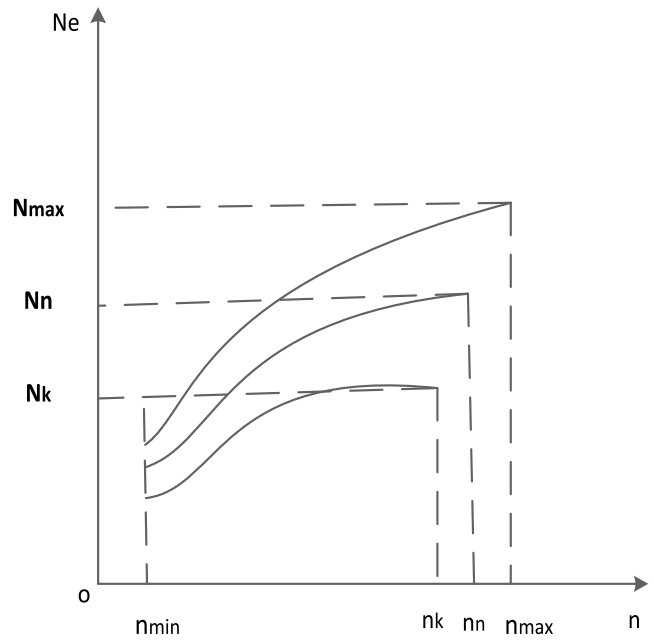
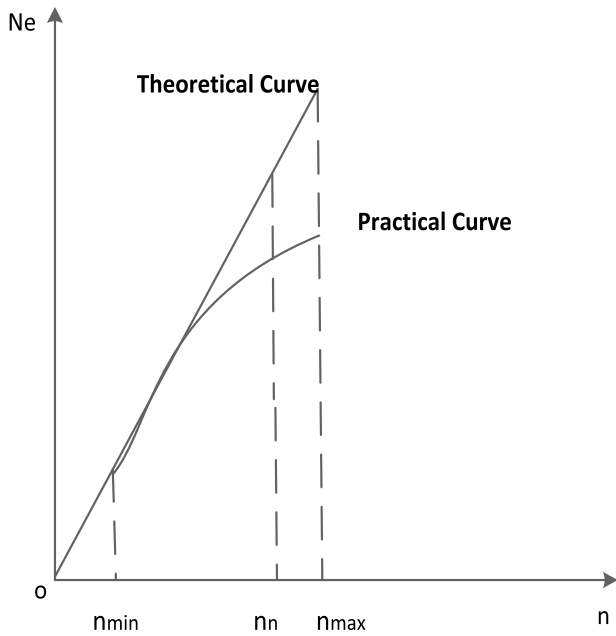


Fig. 4 The engine output characteristics

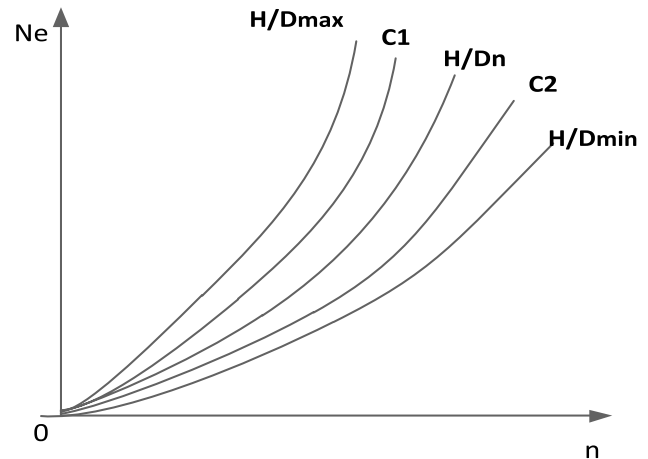
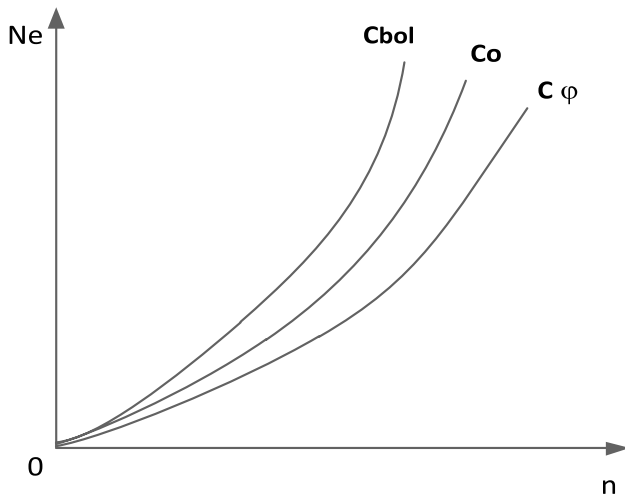


Fig. 5 The characteristics of marine propeller through ( $N_e$  and  $n$ ) coordination when  $d_w =$  changes at the different operation condition.  $C_{bol}$ : the propeller characteristics under bollard condition ( $V=0$ ).  $C_o$ : the propeller characteristics under standard condition.  $C_\phi$ : the propeller characteristics under easier conditions (ballast condition/light ship)

Fig. 6 The propeller characteristics of propulsion plant with an engine driving the controllable pitch propeller.  $C_o$ : the propeller characteristics with nominal pitch ratio  $(H/D)_n$  under nominal condition.  $C_1$ : the propeller characteristics with lower pitch ratio  $\{(H/D)_1 < (H/D)_n\}$   $[(H/D)_1 < (H/D)_n]$  under the same condition.  $C_2$ : the propeller characteristics with high pitch ratio  $\{(H/D)_2 < (H/D)_n\}$   $[(H/D)_2 < (H/D)_n]$  under the same condition.  $(H/D)_{max}$ : the propeller characteristics with maximum pitch ratio.  $(H/D)_{min}$ : the propeller characteristics with minimum pitch ratio

the characteristics of marine propeller will be presented in Fig. 5.

The graphical construction of the propeller also changes according to its characteristics. Therefore, a controllable-pitch propeller (CPP), the pitch ratio  $(H/D)$  will change when the propeller characteristics will be changed during the operation condition of ship (Fig. 6).

### 3.1.3 Load characteristics

The load characteristics will present the relationship between the main specifications of engine and its load (likes  $N_e, M_e$  or  $P_e$ ) while ship speed is constant ( $n = \text{constant}$ ).

$$N_e = (P_e \cdot S \cdot F \cdot n \cdot i \cdot z \cdot 10^4) / 60.75 \tag{11}$$

For particular engine, the above equation is showed in Eq. (12):

$$N_e = K \cdot P_e \cdot n \tag{12}$$

where:  $K$  is constant, it presents for the engine type and the engine particular data.

The indicated power is calculated through Eq. (13):

$$N_i = N_e + N_m \tag{13}$$

where:  $N_i$ : the indicated power;  $N_m$ : Mechanical losses for the moving parts of main engine due to the friction.  $N_m = A \cdot n^\beta$ ,  $N_m$ , is constant coefficient when the engine speed is kept constant and coefficient is calculate  $A = N_m/n^\beta$ ;  $\beta = 1.0/1.3$  with low speed marine diesel engine;  $\beta = 1.5/2.0$  with high speed marine diesel engine (Fig. 7).

The load characteristic curve is usually used for the engine driving the electric generators, the cargo pumps, and the air-compressors. Then, the main engine is responsible for transmitting the power through the marine propulsion plant. Consequently, the engine speed of the load characteristics is equal to the nominal speed ( $n_o = n_n$ ). In fact, this one can be a little differences in order to adjust the changes during the operation condition of ship. This task is conducted by the governor. The position of fuel rack is controlled proportionally according to the variable environment condition during the ship operation process.

Normally, the governor will be operated at a fixed position through the desired speed of the operator. This one is explained that engine speed will be set up at a fixed position

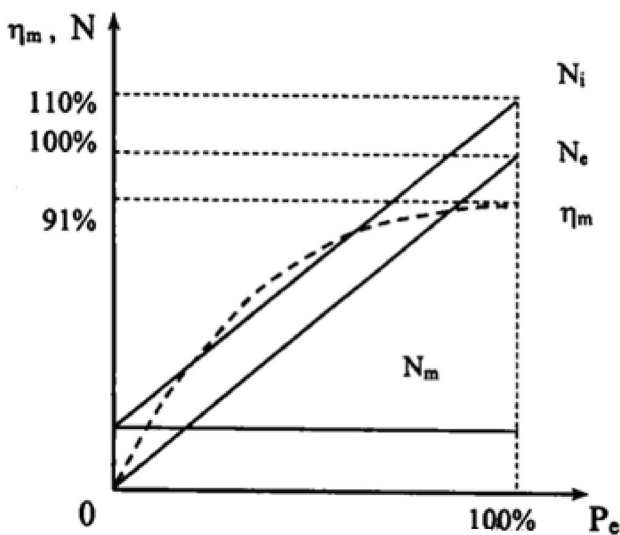


Fig. 7 The relationship between  $N_i$ ,  $N_e$ ,  $N_m$  and  $P_e$  while the engine speed is kept constant by the governor

corresponding to ship speed under the normal operation condition.

For the electrical transmission propulsion plants, the governor is a multi-state governor. There is a system that allows the speed of engine will change depending on the variable loads of the diesel generators. The operational process of ship in this case will be presented in Fig. 8. In particularly, the engine works at level of 40% load then the characteristic curve will move from  $n_1$  to  $n_2$ . From then, the fuel consumption of engine will decrease ( $g_e$ , decreases,  $g_{e3} < g_{e2}$ ). Therefore, the fuel oil consumption will be saved when the economical characteristics will move down near ( $g_{e\min}$ ). The amount of fuel will decrease from 6 to 10% if the load characteristics will move near to the economical curve.

### 3.2 Basic connection of the main engine and the controllable pitch propeller

The generated power of main engine can be transmitted to the propeller through the direct mode (direct transmission) and the indirect mode (indirect transmission).

#### 3.2.1 Direct transmission mode

The Fig. 9 presents the propulsion arrangement of marine propulsion plant which the diesel engine directly drives a propeller.

This mode is often applied for the low-speed marine diesel engines such as manufacture of Sulzer, MAN, Burmeister and Wain, Fiat and etc. The engine is arranged at the ending position connects directly the propeller via the shaft system. The generated power of engine will be transmitted totally to the propeller. Additionally, the engine speed is equal to the

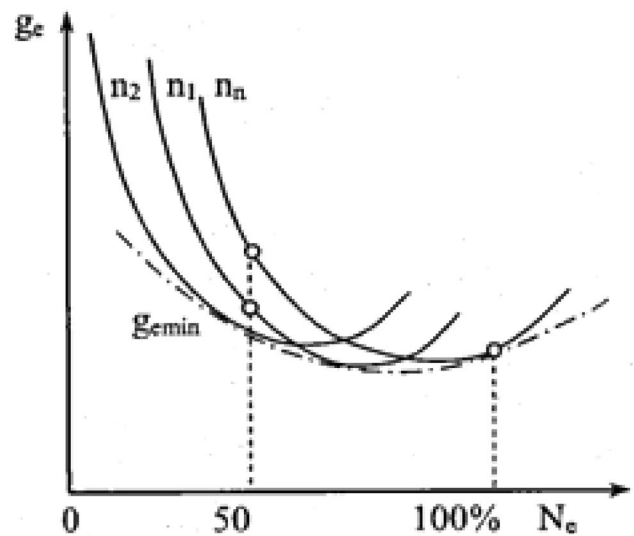
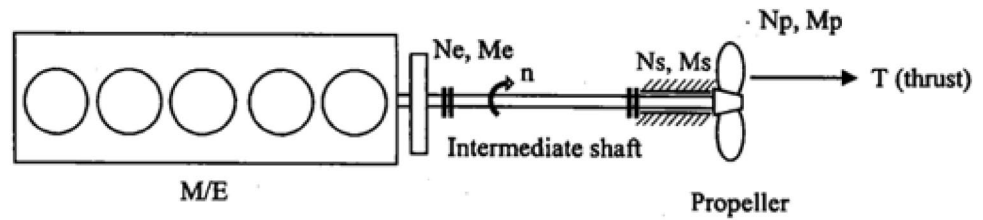


Fig. 8 The demonstration of the minimum  $SPFC_{g_{e\min}} = f(N_e)$

**Fig. 9** Direct transmission mode



speed of propeller. Therefore, there is no loss during transmission of this mode.

In reality, there is a little power loss during the transmission process. Then, the power, the torque and the speed of engine are higher than the position at marine propeller.

$$M_p = M_s \cdot \eta_p = M_e \cdot n_{tr} \cdot n_p \tag{14}$$

$$N_p = N_s \cdot \eta_p = N_e \cdot n_{tr} \cdot n_p \tag{15}$$

where:  $M_p, N_p$ : the propeller moment and thrust power of propeller.  $M_s, N_s$ : the moment and power absorbed by the propeller.  $M_e, N_e$ : the moment and power produced by the main engine.  $n_{tr} = n_{sh}$ : transmission efficiency of the shaft system;  $n_{tr} = 0.96/0.99$ .  $\eta_p$ : propeller efficiency;  $\eta_p = 0.65/0.7$  and the maximum value is achieved as propeller speed around  $n_s = 90/120$  rpm.

### 3.2.2 Indirect transmission mode

In the indirect transmission mode, there are some additional devices including, the clutch, the gear-box, or the long shaft system with some intermediate shaft joints. This mode has been presented in Fig. 10 below.

This mode is usually used for the medium-speed marine diesel engine driving propellers. The engine will be arranged at the middle of ship. Then, the power transmission of engine and propeller will have a transmission ratio (i). This transmission ratio (i) will be presented in Eq. (16).

$$n_s = i \cdot n \tag{16}$$

where:  $i$ : the transmission ratio of the gear box and  $i$  always less than one with the marine propulsion plant.

During the ship operation, there are losses of energy at the gear box position, clutch, and intermediate shafts. Therefore, the received power at the marine propeller is illustrated through the Eqs. (17) and (18).

$$M_p = M_s \cdot \eta_p = (1/i) \cdot M_e \cdot \eta_{sh} \cdot \eta_{cl} \cdot \eta_{gb} \cdot \eta_p \tag{17}$$

$$N_p = N_s \cdot \eta_p = N_e \cdot \eta_{sh} \cdot \eta_{cl} \cdot \eta_{gb} \cdot \eta_p \tag{18}$$

where:  $\eta_{cl}$ : the efficiency of the clutch,  $\eta_{cl} = 0.97/0.98$ .  $\eta_{gb}$ : the efficiency of the gear box,  $\eta_{gb} = 0.94/0.96$ .

## 4 The establishment of characteristics curve of marine propulsion plant

### 4.1 The fundamental theory and empirical equations

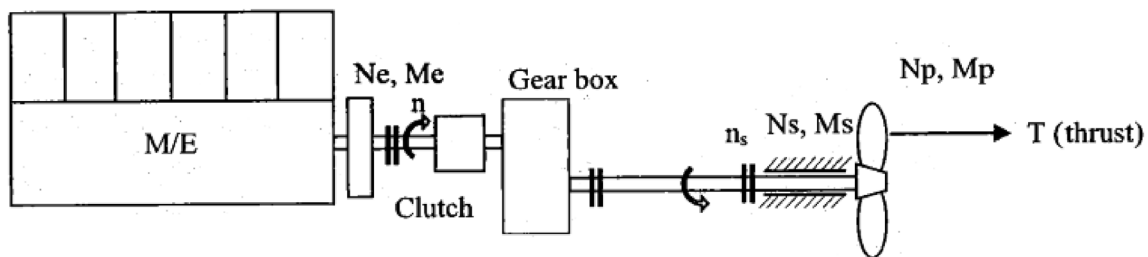
The power of main engine will be presented through the ship speed in Eq. (19).

$$N_e = C \cdot n^x \tag{19}$$

where:  $C$ , coefficient, it depends not only the operational condition but also the pitch ratio ( $H/D$ );  $x$ , coefficient, it doesn't depend on the pitch ratio ( $H/D$ ).

Under a certain operation condition of ship, the Eq. (19) will be presented through the parallel straight lines with the variable values of pitch ratio ( $H/D$ ) on the logarithmic coordinates.

By choosing  $C_1$  is coefficient then  $C$  will be presented at the operational condition of the propeller with the pitch ratio ( $H/D$ ). The Eq. (19) will be expressed into Eq. (20) below.



**Fig. 10** Indirect transmission propulsion plant



$$N_e = C_1 \cdot (C/C_1) \tag{20}$$

At the value of  $(H/D)_1$  the specific parameters of operation process will be presented as follow:

$$\begin{cases} N'_1, n'_1, V'_1 \\ N''_1, n''_1, V''_1 \end{cases}$$

The exponential coefficient  $x$  is also calculated:

$$x = \log \frac{N'_1/n'_1}{N''_1/n''_1} \tag{21}$$

$$C_1 = \frac{N'_1}{N''_1} = \frac{n'_1}{n''_1} \tag{22}$$

Based on the experienced working at some kinds of ship, the relationship between  $C/C_1$  and the pitch ratio  $(H/D)$  will be presented in Eq. (23).

$$\log \frac{C}{C_1} = m \cdot \left(\frac{H}{D}\right)_1 + K \tag{23}$$

where:  $m, K$  are the empirical coefficients, they depend on the propeller.

Representing the equations through the logarithmic axis coordinate in case of the pitch ratio  $(H/D)=\text{constant}$  and the same working condition  $(C=C_2)$ :

$$\log \frac{C_1}{C_1} = m \cdot \left(\frac{H}{D}\right)_1 + K \tag{24}$$

Because  $\log 1 = 0$  so:

$$\log \frac{C_1}{C_1} = m \cdot \left(\frac{H}{D}\right)_1 + K = 0 \rightarrow K = -m \cdot \left(\frac{H}{D}\right)_1 \tag{25}$$

When the pitch ratio  $\left(\frac{H}{D}\right)_2 = \text{Constant}$  and the same operation conditions  $C = C_2$ :

$$\log \frac{C_2}{C_1} = m \cdot \left(\frac{H}{D}\right)_2 + K \tag{26}$$

Replace  $K$  into the Eq. (26):

$$\log \frac{C_2}{C_1} = m \cdot \left(\frac{H}{D}\right)_2 + K \rightarrow \log \frac{C_2}{C_1} = m \cdot \left(\frac{H}{D}\right)_2 - m \cdot \left(\frac{H}{D}\right)_1 \tag{27}$$

So that:

$$m = \frac{\log \frac{C_2}{C_1}}{\left(\left(\frac{H}{D}\right)_2 - \left(\frac{H}{D}\right)_1\right)} \tag{28}$$

In case of the different types of ship, the relationship between ship speed  $(V)$  and engine speed  $(n)$  is represented through the Eq. (29).

$$V = \alpha + \beta \cdot n \tag{29}$$

where:  $\alpha$ : coefficient, depends on working conditions,  $\alpha=0$  under normal condition (calm sea),  $\alpha < 0$  under heavier condition,  $\alpha > 0$  under easier condition;  $\beta$ : angular coefficient, it depends on the pitch ratio  $(H/D)$ .

When the pitch ratio  $\left(\frac{H}{D}\right)_1 = \text{Constant}$  and the same operation condition, the Eq. (29) will be written as follow.

$$V = \alpha + \beta_1(\beta/\beta_1) \cdot n \tag{30}$$

From the specific experimental values, then the Eq. (3) will be expressed as follow:

$$\begin{aligned} \alpha &= V'_1 - \beta_1 n'_1 = 4.5 - 0.003333 \times 900 \\ &= 1.50V''_1 - \beta_1 n''_1(\beta/\beta_1) \\ \log \frac{\beta_2}{\beta_1} &= z \left[ \log \left(\frac{H}{D}\right)_2 - \log \left(\frac{H}{D}\right)_1 \right] \\ z &= \frac{\log \left(\frac{\beta_2}{\beta_1}\right)}{\log \left(\frac{H}{D}\right)_2 - \log \left(\frac{H}{D}\right)_1} \\ &= \frac{\log \frac{0.003796}{0.003333}}{\log 0.5 - \log 0.615} = -0.491142(H/D)_2 \\ \beta_2 &= \frac{V_2 - \alpha}{n_2} = \frac{5.6 - 1.5}{1080} = 0.003796 \\ x &= \frac{\log \frac{N'_1}{N''_1}}{\log \frac{n'_1}{n''_1}} = \frac{\log \frac{260}{455}}{\log \frac{900}{1200}} = 1.945258 \\ m &= \frac{\log \frac{C_2}{C_1}}{\left[\log(H/D)_2 - \log(H/D)_1\right]} \\ z &= \frac{\log \frac{\beta_2}{\beta_1}}{\left[\log(H/D)_2 - \log(H/D)_1\right]} \\ \beta_1 &= \frac{V'_1 - V''_1}{n'_1 - n''_1} = \frac{4.5 - 5.5}{900 - 1200} = 0.00333 \end{aligned} \tag{31}$$

In the same operation condition,  $\alpha$  is constant at the fixed pitch ratio  $\left(\frac{H}{D}\right) = \left(\frac{H}{D}\right)_1$ , coefficient  $\beta = \beta_1 = \text{Constant}$ .

So that:

$$\beta_1 = \frac{V'_1 - V''_1}{n'_1 - n''_1} \tag{32}$$

From the experimental result, the relationship between ratio  $(\beta/\beta_1)$  and pitch ratio  $(H/D)$  is represented by Eq. (33).

$$\frac{\beta}{\beta_1} = d \cdot \left(\frac{H}{D}\right)' \tag{33}$$

Or

$$\log \frac{\beta}{\beta_1} = \log d + z \cdot \log \left(\frac{H}{D}\right) \tag{34}$$

Illustrate formular on the logarithmic coordinates, the relationship between  $(\beta/\beta_1)$  and  $(H/D)$  is linear.

When experiments with pitch ratio  $\left(\frac{H}{D}\right) = \left(\frac{H}{D}\right)_1$  or  $\beta = \beta_1$ :

$$\frac{\beta}{\beta_1} = d \cdot \left(\frac{H}{D}\right)_1^z \Rightarrow d = \frac{1}{\left(\frac{H}{D}\right)_1^z} \tag{35}$$

When experiments with pitch ratio  $\left(\frac{H}{D}\right) = \left(\frac{H}{D}\right)_2$  or  $\beta = \beta_2$ :

$$\frac{\beta_2}{\beta_1} = d \cdot \left(\frac{H}{D}\right)_2^z \tag{36}$$

To replace coefficient d into Eq. (36):

$$\frac{\beta_2}{\beta_1} = \frac{\left(\frac{H}{D}\right)_2^z}{\left(\frac{H}{D}\right)_1^z} \tag{37}$$

Or

$$\log \frac{\beta_2}{\beta_1} = z \left[ \log \left(\frac{H}{D}\right)_2 - \log \left(\frac{H}{D}\right)_1 \right] \tag{38}$$

Therefore

$$z = \frac{\log \left(\frac{\beta_2}{\beta_1}\right)}{\log \left(\frac{H}{D}\right)_2 - \log \left(\frac{H}{D}\right)_1} \tag{39}$$

In order to determine coefficient  $\beta_2$  along with  $(H/D) = (H/D)_2$ , there are some specific parameters of characteristic curves including  $N_2, n_2, V_2$ .

$$\beta_1 = \frac{V_2 - \alpha}{n_2}$$

where:  $\alpha$  and  $\beta$  are the coefficients.

Replacing  $\beta_1, \beta_2$  into the above equations then the coefficient z will be calculated in Eq. (39). The output power of main engine and the ship speed will be determined at the different pitch ratio  $(H/D)$ . Finally, the operation characteristics of ship will be determined through the empirical equations. Then, the marine propulsion plant system will be built through this study.

Case 1: The pitch ratio  $\left(\frac{H}{D}\right)_1$  of marine propeller will have the specific parameters of ship:

$$N'_1, n'_1, V'_1$$

$$N''_1, n''_1, V''_1$$

Case 2: The pitch ratio  $\left(\frac{H}{D}\right)_2$  of marine propeller will have the specific parameters of ship:

$$N_2, n_2, V_2$$

Besides that, the nominal parameters of M/E ( $N_n, n_n$ ) are also established through the empirical equations. From the collected results, the database of ship will be recorded for the new ships at the shipbuilding factories nowadays.

### 4.2 The establishment of characteristic curves

Step 1. Calculation of the exponential coefficient x:

$$x = \frac{\log \frac{N'_1}{N''_1}}{\log \frac{n'_1}{n''_1}}$$

Step 2. Calculation of the coefficient C at various operation conditions:

$$C_0 = \frac{N'_1}{n'^x_1} = \frac{N''_1}{n''^x_1}$$

Step 3. Calculation of the coefficient m:

$$m = \frac{\log \frac{C_2}{C_1}}{[(H/D)_2 - (H/D)_1]}$$

Step 4. Calculation of the coefficient k:

$$k = -m \cdot (H/D)_1$$

Step 5. Calculation of the coefficient  $\beta_1$ :

$$\beta_1 = \frac{V'_1 - V''_1}{n'_1 - n''_1}$$

Step 6. Calculation of the coefficient  $\alpha$ :

$$\alpha = V'_1 - \beta_1 n'_1$$

Step 7. Calculation of the coefficient  $\beta_2$ :

$$\beta_2 = \frac{V_2 - \alpha}{n_2}$$

Step 8. Calculation of the exponential coefficient  $z$ :

$$z = \frac{\log \frac{\beta_1}{\beta_2}}{[\log(H/D)_2 - \log(H/D)_1]}$$

Step 9. Calculation of the coefficient  $d$ :

$$d = \frac{1}{\left(\frac{H}{D}\right)_1^z}$$

Step 10. Application of pitch ratio ( $H/D$ ) into the above equations then the engine power and its speed will be calculated.

Step 11. Drawing the graph and making a conclusion.

## 5 Results and discussion

### 5.1 The target ship

The target ship is a kind of cruise ship sailing on the inland river in Quang Ninh Province, Vietnam. The main propulsion configuration system of this target ship is arranged two main engines which are located at both two sides, two auxiliary generators and one emergency generator in the engine room of ship. In this study, the cruise ship sails on the calm water condition. The specific parameters of navigation

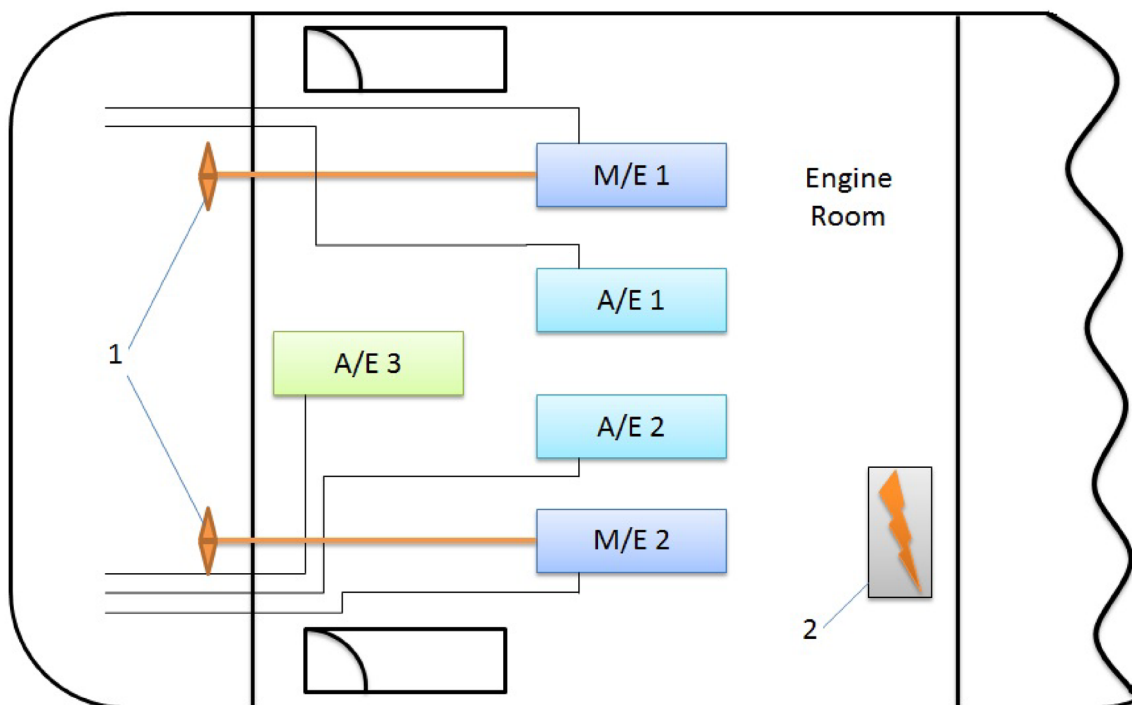
environment condition have been presented through the wind speed is 11 km/h, the wave height is 0.3 (m), the sea water temperature is 29 °C (84 °F). The marine propulsion plant of target ship in this research has been showed in Fig. 11. There are two variable pitch propellers which are driven indirectly by two main diesel engines.

This propulsion plant has the symbol 48S-03/04 level VR-SB (Vietnam River and Coast Sea Boat). It consists of two main engines, symbol YC6TD650L-C20 with the output power is 650 HP (Horse Power), revolution 1800 rpm (Revolution per Minute), gear box JD400:  $i = 4/1$  and 02 propeller shafts which placed symmetrically through the flat along the center of ship.

The passenger ship, Sea life Legend 02, is steel—shelled ship with double bottom, installed 02 main engines driving 02 propellers. This vessel is designed with the modern design, the luxurious interior for the landscape. The specific parameters of this target ship have been presented in Table 1.

### 5.2 The establishment of characteristic curves

The establishment of characteristic curve plays an important role to making the relationship between the marine diesel engine and the propeller. This establishment has been conducted through some procedures which have been proposed in this research. The passenger ship, Sealife Legend 02 uses



**Fig. 11** The marine propulsion plant configuration system of the cruise ship—Sea life Legend 02. *M/E* main engine, *A/E* auxiliary engine. 1—propellers, 2—electrical control system box

**Table 1** The specific parameters of passenger ship

The specification parameter	Symbol	Sea life Legend 02	
Overall length	$L_{OA}$	77.68	m
Designed length	$L_D$	69.35	m
Extreme breadth	$B_{max}$	14.20	m
Designed breadth	$B_D$	13.80	m
Draught (draft)	$D$	3.80	m
Crew on board		07	Members
Staff on board		40	Members
Quantity of guest		80	People
Ship capacity		2378	$m^3$
Ship tonnage		246	Tons
Main engine	02 Yuchai main engine:	YC6TD650L-C20	
Power		$2 \times 650$	HP
Revolution		1800	rpm
Speed		16.7	km/h

**Table 2** The input specification of main engine

Name of the ship	Sealife Legend 02
Type of the main engine	Diesle engine
Nominal engine output	650 HP
Nominal engine speed	1800 rpm
Number of cylinder	6
Cylinder diameter	152 mm
Length of stroke	180 mm
Stroke coefficient	0.5
Transmission ratio	4:1

**Table 3** The experimental parameters of target ship

Number	H/D	Ne (HP)	V(knots)	n(rpm)	$n_s$ (rpm)
1'	0.615	260	4.5	900	450
1''	0.615	455	5.5	1200	600
2	0.5	585	5.6	1080	540

the indirect transmission propulsion plant system with two main diesel engines, gear boxes, two controllable-pitch propellers. The specification of main diesel engine has been provided in Table 2. Additionally, the experimental parameters of target ship have been presented in Table 3. These values will be employed to validate the proposed methodologies. Finally, the marine propulsion plant system will be established and evaluated in this study.

The steps of establishing characteristics:

Step 1. Calculation of the exponential coefficient  $x$ :

$$x = \frac{\log \frac{N'_1}{N''_1}}{\log \frac{n'_1}{n''_1}} = \frac{\log \frac{260}{455}}{\log \frac{900}{1200}} = 1.945258$$

Step 2. Calculation of the coefficients  $C$  at various operation conditions.

$$C_o = \frac{N'_1}{n_1^x} = \frac{N''_1}{n_1^{x'}} = \frac{260}{900^{1.945258}} = 0.000466$$

$$C_2 = \frac{N_2}{n_2^x} = \frac{585}{1080^{1.945258}} = 0.000735$$

Step 3. Calculation of the coefficient  $m$ :

$$m = \frac{\log \frac{C_2}{C_1}}{[(H/D)_2 - (H/D)_1]} = \frac{\log \frac{0.000735}{0.000466}}{(0.5 - 0.615)} = -1.723082$$

Step 4. Calculation of the coefficient  $k$ :

$$k = -m \cdot (H/D)_1 = -(-1.723083) \times 0.615 = 1.059696$$

Step 5. Calculation of the coefficient  $\beta_1$ :

$$\beta_1 = \frac{V'_1 - V''_1}{n'_1 - n''_1} = \frac{4.5 - 5.5}{900 - 1200} = 0.00333$$

Step 6. Calculation of the coefficient  $\alpha$ :

$$\alpha = V'_1 - \beta_1 n'_1 = 4.5 - 0.003333 \times 900 = 1.50$$

Step 7. Calculation of the coefficient  $\beta_2$ :

$$\beta_2 = \frac{V_2 - \alpha}{n_2} = \frac{5.6 - 1.5}{1080} = 0.003796$$

Step 8. Calculation of the exponential coefficient  $z$ :

$$z = \frac{\log \left( \frac{\beta_2}{\beta_1} \right)}{\log \left( \frac{H}{D} \right)_2 - \log \left( \frac{H}{D} \right)_1} = \frac{\log \frac{0.003796}{0.003333}}{\log 0.5 - \log 0.615} = -0.491142$$

Step 9. Calculation of the coefficient  $d$ :

$$d = \frac{1}{\left( \frac{H}{D} \right)_1^z} = \frac{1}{0.615^{-0.491142}} = 0.787604$$

Step 10. Choosing the values of ship speed then the characteristic curve of engine power and its speed will be established at various pitch ratios (H/D).

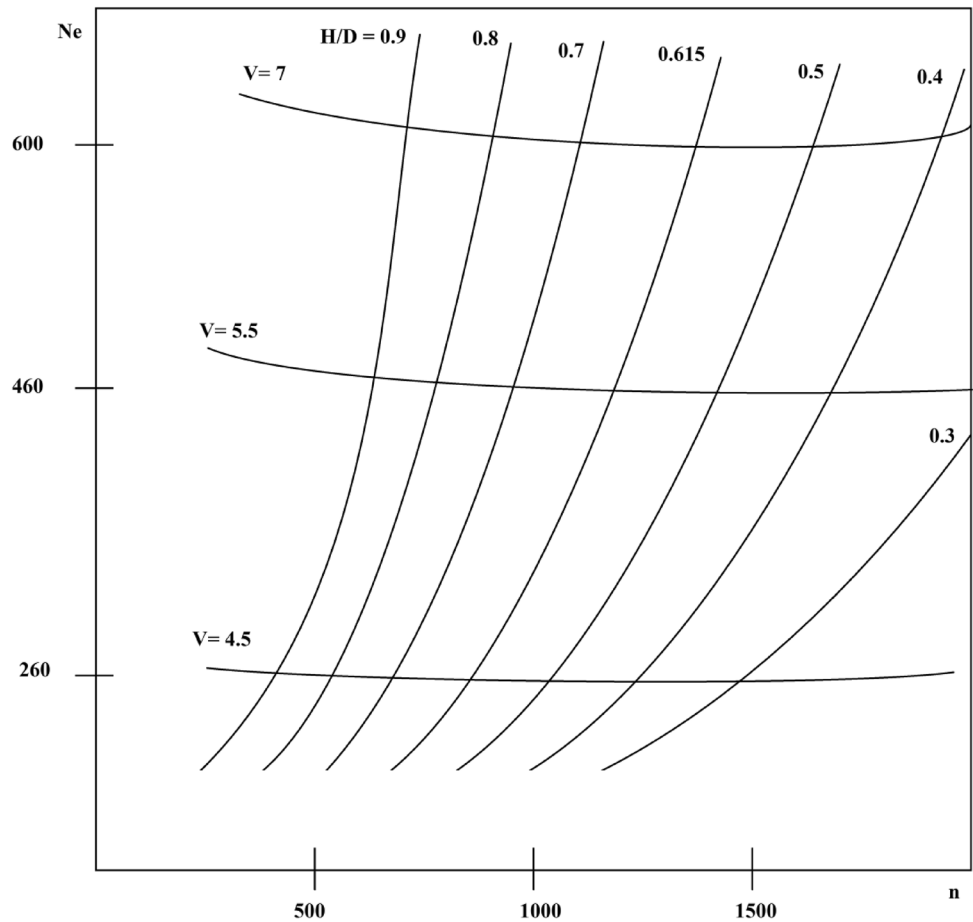
Step 11. The operational characteristic curves will be established from the collected results in Table 4.

The operational characteristic curves of marine propulsion plant have been established and illustrated in Fig. 12. The case study of passenger ship has been validated in this

**Table 4** The output power and speed of engine (Ne and n) with different pitch ratio (H/D)

V (knots)	H/D	0.90	0.80	0.70	0.615	0.50	0.40	0.30	Unit
V1 = 4.5	n	461	576	720	900	1080	1296	1555	rpm
	Ne	260	260	260	260	260	260	260	HP
V2 = 5.5	n	614	768	960	1200	1440	1728	2074	rpm
	Ne	455	455	455	455	455	455	455	HP
V3 = 7.0	n	691	864	1080	1350	1620	1944	2333	rpm
	Ne	585	585	585	585	585	585	585	HP

**Fig. 12** The characteristic curves of the marine propulsion plant using the controllable pitch propeller

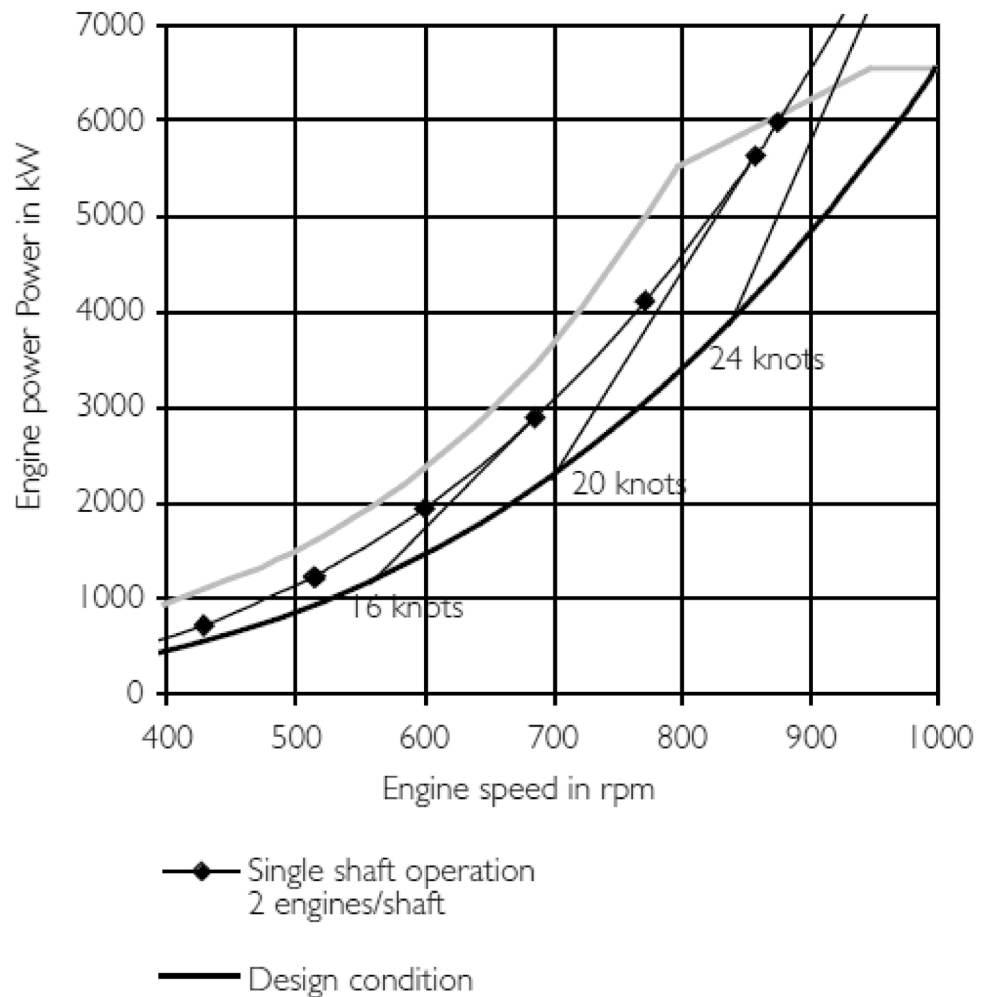


study. The changeable pitch ratio of marine propeller is an effective method to match between the main diesel engine and the propeller. The relationship between engine and propeller plays an important role in the operation process. This study is significant to support the ship-operators who can select the optimal point of ship. From the research results, the pitch ratio of propeller is  $H/D = 0.615$  corresponding to the ship speed is 5.5 knots. Then, the marine propulsion plant system will operate safely during the ship operation process.

### 5.3 Discussion

The research on marine propulsion plant plays an important role in the field of marine engineering and ocean engineering. It is necessary to match between marine diesel engine and propeller when considering the ship speed. The experimental investigation has been conducted in this research. The empirical equations have been developed and applied into the object of study. A passenger ship has been selected as a target ship in this research. The case

**Fig. 13** The operational characteristics curves of diesel engine with design load condition and single shaft load (Stapersma and Woud 2005)



study in this research is clear and the collected results have been validated through the empirical equations.

In this study, the marine propulsion plant system has been built and evaluated appropriately through the proposed methodologies. The proposed methodologies have been validated and evaluated through utilizing the passenger ship in Vietnam. Additionally, the research results have also been discussed with the previous study about matching the marine propulsion plant system in the field of marine science and ocean engineering. In the next studies, the relationship between main diesel engine-marine propeller-ship hull condition will be investigated to help the ship designers in designing the hull profile of ship.

In reality, the characteristic curves of engine will influence on the ship operation process under various conditions. Building the relationship between the engine characteristics and ship speed has also been established in Fig. 13. Therefore, the characteristic diagram between diesel engine and its speed ( $N_e-n_e$ ) is important to evaluate the ship operational process. This one relates directly the safety level of ship at the different ocean environment. Additionally, the

operational point of marine diesel engine would be determined reliably based on the collected research results from this study.

## 6 Conclusion remarks

The study of marine propulsion plant system plays a vital role in the field of marine science and ocean engineering. The enhancement of operational range between main diesel engine and propeller is very significant to improve the marine propulsion plant of vessels. A passenger ship is chosen and verified with the proposed method in this article. The determination of operational range for the marine propulsion plant has been conducted. This article is significant for ship operators in selecting the normal operation point for the passenger ships. Additionally, this research is a fundamental knowledge for the next researches in the field of marine propulsion plant system.

**Acknowledgements** The author would like to thank the valuable comments of the anonymous reviewers on this manuscript to improve the scientific quality of this paper. Besides that, the author appreciates the support from Marine Research Institute, Vietnam Maritime University, Haiphong City, Vietnam to help me complete this research.

**Funding** This paper has not received funding from any organizations.

#### Declarations

**Conflict of interest** The author declares that there is no conflict of interest.

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