A Study on Fuel Saving Effect in Hybrid Propulsion System for Tugboat

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Abstract

Tugboat's market has strong interest in saving FOC (Fuel Oil Consumption). In order to provide alternative solution, authors have which consists of several mathematical models studied a hybrid propulsion system without battery for tugboats to save fuel consumption. The FOC model has also been developed to evaluate the hybrid propulsion system. It can calculate SFC (Specific Fuel Consumption) of a propulsion system by setting up rated output power and estimating efficiency of each apparatus constituting propulsion system. The characteristics of SFC in conventional and hybrid system are clarified by simulating on the FOC model. In addition to this, both systems' amounts of the fuel consumption are simulated by inputting the demanded propulsion power data which was measured in real tugboat. By comparing these simulation results which include conventional and proposed hybrid system, the fuel saving effect of the hybrid propulsion system is clarified and evaluated.

Keywords: Tugboat, Hybrid propulsion system, Fuel oil consumption simulation

1 Introduction

Harbor tugboat has two middle speed and high power engines to push and pull large vessels comparing to general cargo vessel of similar size. Fig.1 shows a sample of real data which was measured a trend of a demanded output power while the tugboat is operated in one working cycle. This data is classified to analyse the tugboat's operation into three situations.

Transit situation shows the time that tugboat navigates between its base port and the working spot.

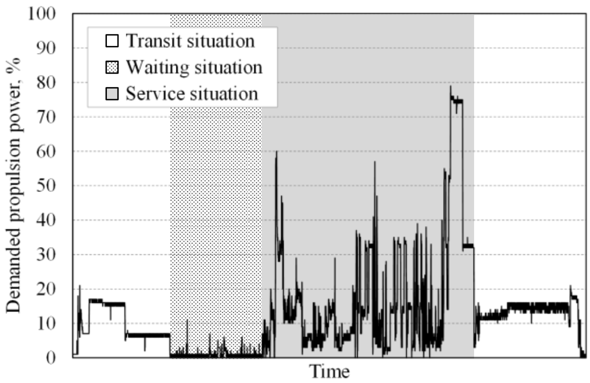


Fig. 1 Sample of measured propulsion power

In this situation, the required propulsion power is low and constant because it is not necessary to go fast in harbor. Waiting situation means that the tugboat is waiting until service starts. Thus, the main engines are almost idling. Necessary power is extremely low since the propulsion power is used only to keep tugboat's position. In Service situation, the tugboat works to push or pull the large vessel under pilot order. In this situation, it is clear that the demanded propulsion power fluctuates frequently and changes largely from low to high depending on its working condition.

To clarify the characteristics of tugboat's operation, the data shown in Fig.1 is resolved the demanded propulsion power and its integrated time which means the frequency in use. Fig.2 illustrates the resolved data of demanded propulsion power in each situation.

As is clear from Fig.2, a wide range of propulsion power is required in service situation. On the other hand, in transit and waiting situation, a demanded propulsion power is not high but low power less than 20%. In other words, the duration time that tugboat's main engines are operated at low loaded condition is long in both situations.

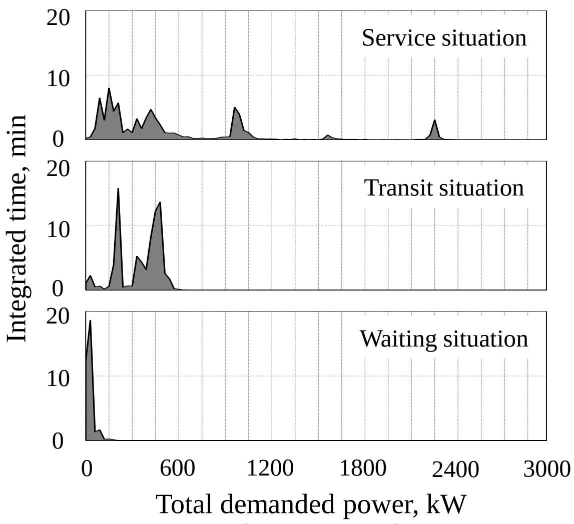


Fig. 2 Integrated time in each situation

Generally, the thermal efficiency of engine for ship is low in low loaded condition. Tugboat's engine tends to be operated in low load and low efficiency for a long time. For this reason, it is effective to improve the thermal efficiency in low loaded condition. By focusing on this characteristic, several hybrid tugboats which have a large capacity rechargeable battery has been already developed [(1) - (3)]. It is reported that an efficiency of propulsion system is improved by using the battery as one power source and an energy buffer when the demanded power is low. However, a building cost becomes high as a rechargeable battery is expensive. For this reason, authors have studied a hybrid propulsion system without using battery [(4) - (6)].

Especially this study aims at saving FOC (Fuel Oil Consumption) by proposing hybrid propulsion system for tugboat. However it is impossible to build a real propulsion system in order to evaluate and improve the hybrid system.

Consequently authors have developed FOC model so that various propulsion systems including conventional one are evaluated to find out advantages and disadvantages. The constitution of FOC model is described in Chapter 3.

It is possible to simulate the specific fuel consumption of propulsion system by using the FOC model. Simulation result is achieved by inputting the demanded propulsion power data which was measured in real tugboat.

In this paper, the fuel saving effects of the hybrid propulsion system are clarified and evaluated by comparing these simulation results which include conventional system and proposed one.

2 Propulsion system of tugboat

2.1 Conventional propulsion system

Fig.3 shows a line diagram of conventional propulsion system which is adopted in general tugboats. It has two azimuth thrusters (ATD-1,2) which are driven mechanically by each main engine (M/E-1,2) via slip clutches (SC-1,2) and intermediate shafts. The diesel generators (D/G-1,2) supply electric power to the onboard load. In this system, both high power engines must be kept running even in low loaded or idling condition. Thus it results that fuel oil is dissipated when demanded power is low because the thermal efficiency of engine gets worse at low load condition.

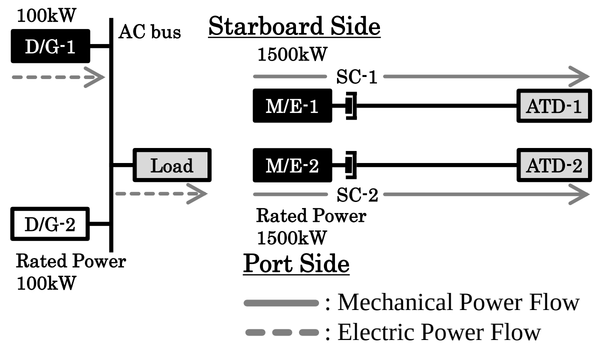


Fig. 3 Conventional propulsion system and energy flow

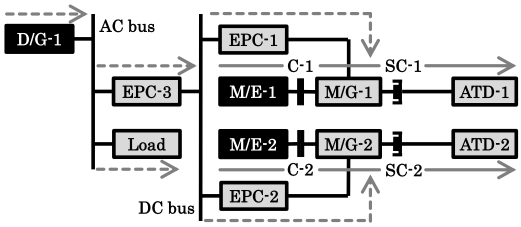
2.2 Proposed hybrid propulsion system

A hybrid propulsion system which is shown in Fig.4 has proposed to solve the problem mentioned above. A main engine system and a diesel generator system which are set independently in a conventional propulsion system are combined by using motor generators (M/G-1,2) and electric power converters (EPC-1,2,3) in the proposed one.

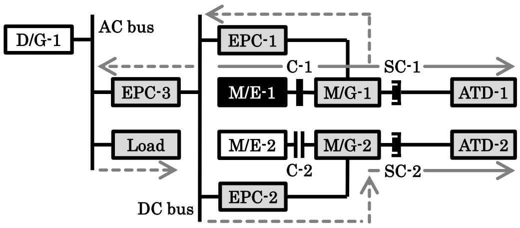
EPC-1 and EPC-2 are able to connect DC system and each M/G in bidirectional way. When they convert DC power to variable voltage variable frequency three phase electric power, each M/G can assist each M/E. M/G also can take power from the main shaft to DC system through each electric power converter like a shaft generator. When M/G acts as the shaft generator, DC power is converted to three phase AC power by using EPC-3. In this power flow, D/G can be stopped since EPC-3 works as a three phase AC power source for onboard electric apparatuses. On the other hand, D/G can supply not only the onboard electric power but driving power for M/G. Thus M/E-1 and M/E-2 can be assisted by using D/G power through each M/G (Fig.4a).

Additionally, pure electric propulsion can be realized if the demanded propulsion power is low and all main engines are OFF.

Furthermore, if only one engine runs, both azimuth thrusters can be driven when the demanded propulsion power is low (Fig.4b).



a. Energy flow in State A



b. Energy flow in State B

Fig.4 Proposed hybrid propulsion system

3 FOC simulation

3.1 FOC model

The FOC model can calculate SFC (Specific Fuel Consumption) of a propulsion system by setting up rated output power and estimating efficiency of each apparatus constituting propulsion system.

The FOC model is consist of several efficiency estimation modules (Fig.5). The efficiency estimation modules are prepared for all apparatuses in the propulsion system and the electric system.

3.2 Efficiency estimating module

Each module estimates their efficiency which is defined as a ratio of output power to input power. The estimated efficiency data varies depending on both rated power and load factor of each apparatus.

Several efficiency data of actual apparatuses are stored in these modules. The modules can give a mathematical model of the estimated efficiency for the FOC model. For example, the module for diesel generator take account of a thermal efficiency of four cycle constant speed diesel engine, an energy conversion efficiency of alternator, and power factor of three phase AC electric system.

The electric power conversion efficiency modules estimate the efficiency of the electric power converters (EPC-1, 2 and 3). EPC-3 connects DC system and constant voltage constant frequency three phase AC system. On the other hand, EPC-1 and EPC-2 connect DC system and variable voltage variable frequency load.

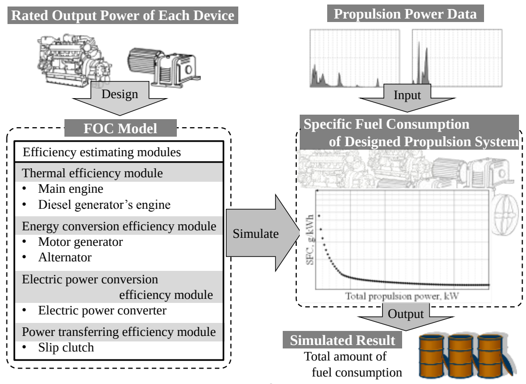


Fig. 5 Structure of FOC simulation

In consequence trend of the electric power conversion efficiency on EPC-1 and EPC-3 have little difference although their circuit configurations are same. In this sturdy, the power electronics simulation was implemented to make efficiency table of EPCs.

The power transferring efficiency module for slip clutch (SC) has to be provided. This module includes a mathematical model which is created by the relation between slip rate and the efficiency from supplier's open data about slip clutch which is used in tugboat. All modules output the mathematical model of energy transferring efficiency when their ratings are determined. The FOC model of propulsion system consists of several mathematical modules of apparatuses.

3.3 Conditions for FOC Simulation

It is necessary to design the rating of apparatus in order to calculate the SFC of propulsion system. The majority of tugboats have two main engines of around 1500kW rating and two diesel generators of around 100kW rating shown as Table 1a. It is reported that they account for 70% of total amount of tugboats which were completed during the past five years in Japan. For this reason, in this paper, total rated power of the main engines and the diesel generator is set to around 3,000kW. Table 1b indicates the ratings of each apparatus in proposed hybrid propulsion system.

Table 1 Simulation condition

a. conventional propulsion system

Item	Symbol	Rating	Number
Main Engine	M/E-1,2	1,500 kW	2 equiped
Diesel Generator	D/G-1,2	100 kW	2 equiped

b. conventional propulsion system

Item	Symbol	Rating	Number
Main Engine	M/E-1,2	1,350 kW	2 equiped
Diesel Generator	D/G-1	300 kW	1 equiped
Motor Generator	M/G-1,2	860kVA	2 equiped
Electric Power Converter	EPC-1,2	880kVA	4 blocks
	EPC-3	270kVA	2 blocks

4 Characteristics of SFC in conventional and proposed hybrid propulsion system

4.1 SFC of conventional system

Common conditions which are shown below are set to calculate SFC (specific fuel consumption) of each propulsion system.

1) Each demanded propulsion power of starboard and port side is same in SFC calculation. In actual tugboat's operation, each engine is controlled separately so that tugboat's operator can change direction of thrust force. Thus, the load factors of each engine are not same at all times.

However, the difference of load factor was not large, as long as authors observed and measured the load factor of main engine in actual tugboat over three months.

2) The onboard load is set to constant 30kW in SFC calculation. Onboard electric power changes every moment regardless of tugboat's operation. In almost case, fluctuation range of electric power is limited around several 10 kW. Consequently, it can be said that the fluctuation is negligibly small.

3) Two main engines (M/E-1,2) and one diesel generator (D/G-1) are kept running all the time in conventional propulsion system as in the Fig.3. It is described in Chapter 2.

In SFC calculation, M/E-1, M/E-2 and D/G-1 are controlled as shown in Fig.6.

Black solid line indicates M/E-1 and M/E-2's load factors and gray solid line indicates D/G-1's one in conventional system. In this time, D/G-2 is stopped because it is enough to supply electric power to onboard load. In this simulation, the friction loss on shaft bearing is not considered at all because it is negligibly small. Thus, the total propulsion power is achieved to 3000kW by outputting both main engines of 1500kW each when they are operated until their load factor reach 100%.

In these conditions, the SFC of conventional propulsion system is calculated by estimating the efficiency of main engines, diesel generator and slip clutches in the FOC model.

The calculation result is shown in Fig.7. The vertical axis indicates the SFC of propulsion system and the horizontal axis indicates the total demanded propulsion power.

When the total propulsion power is low, SFC of propulsion system gets worse comparing to high propulsion power condition. Generally the efficiency of diesel engine is low at low loaded condition. Furthermore, the energy loss increases in the slip clutch because a power transferring efficiency is extremely low when the slip clutch is slipping at low propulsion power condition. Thus, it can be understood that the SFC rises when the main engine is low loaded condition at low propulsion power condition.

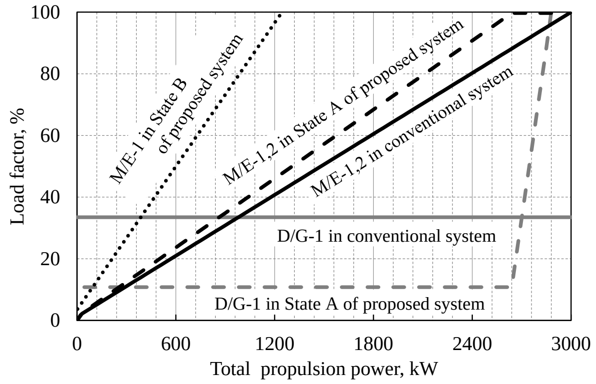


Fig. 6 Controlled pattern of each apparatus

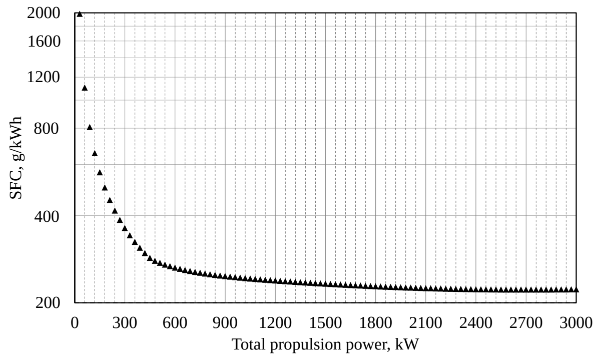


Fig. 7 Calculation result of SFC in conventional propulsion system including M/E,SC and D/G

4.2 State A in proposed hybrid system

The FOC model was also applied to the proposed hybrid propulsion system in order to find out its characteristics. In this paper, the simulated results which were calculated in two cases are discussed.

One case assumes a state that both main engine and a diesel generator are running as shown in Fig.4a. This state is called as State A in this paper. In State A, M/E-1, M/E-2 and D/G-1 are controlled as illustrated in the Fig.6. Black dashed line shows the each engine's load factor and gray dashed line shows the diesel generator's one. In this state, the main engine's load factor reach 100% at 2700kW in total propulsion power because its rated output power is smaller than conventional one as shown in Table 1b. Both main engines drive each azimuth thruster and the diesel generator provide electric power to the onboard load until the main engine's load factor reaches around 100%. After that, diesel generator starts to assist by providing electric power to the each motor generator through the electric power converters. The total propulsion power can be achieved around 2900kW maximum considering various energy losses on motor generators and electric power converters in State A.

4.3 State B in proposed hybrid system

Another case which is defined as a State B in this paper assumes a condition that only starboard main engine runs as shown in Fig.4b. The port side main engine and the diesel generator stop at this state. In State B, M/E-1 is controlled as illustrated in Fig.6. Black dotted line shows the engine's load factor. When required total propulsion power is zero, M/E-1 supplies only electric power to onboard load by using M/G-1 and EPC-1 and EPC-3. The total propulsion power is limited to around 1200kW because the rated power of main engine is 1350kW. A difference of these values is explained as a total of onboard electric power, electric power conversion loss of EPCs (EPC-1,2,3) and energy conversion loss of M/Gs (M/G-1,2). In these states, the SFC of the proposed hybrid system are calculated by FOC model.

4.4 SFC of proposed system

To clarify the characteristics of hybrid propulsion system from the view point of SFC, a trend of SFC ratio is provided in Fig.8. The ratio of SFC is the value that the proposed hybrid propulsion system's SFC divided by the conventional one. Thus, it can be said that the hybrid propulsion system consumes less fuel oil compared with the conventional one in a condition that the ratio of SFC is less than 100%.

Black solid line shows the SFC of conventional propulsion system. Open and closed triangle lines show the ratio of SFC in proposed hybrid system. As is clear from Fig.8, the ratio of SFC gets worse 2 ~ 5% at any power condition when the propulsion system is in State A.

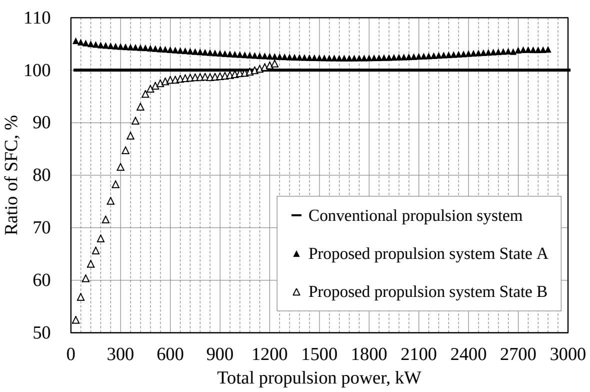


Fig. 8 Characteristic of proposed hybrid system's SFC comparison with conventional system's SFC

In proposed hybrid system, the rated output of diesel generator is set to larger than conventional one so that it can assist the main engine. The diesel generator must be kept running in low loaded condition before providing electric power to the motor generator for assisting.

Resultingly, the efficiency of diesel generator gets worse. For this reason, it is calculated that the State A' s ratio of SFC tends to rise on FOC model. In service situation which is described in Chapter 1, State A have to be selected because high output power is required depending on work situation.

On the other hand, the proposed hybrid system can improve the ratio of SFC around 40% compared to the conventional system when the propulsion system is in State B at low propulsion power condition.

In this state, one main engine drives both azimuth thrusters and supplies electric power to onboard load via motor generators and electric power converters.

As a result the load factor of main engine becomes high compared with the conventional propulsion system.

In addition to this, the efficiency of the main engine can be improved because the main engine's rating in proposed hybrid system is smaller than conventional one. Fig.9 shows an image of two diesel engine's thermal efficiency curves in a condition that their ratings are different each other. The vertical axis indicates the efficiency and the horizontal axis indicates output power. Gray solid line shows the efficiency trend of small rating engine and black solid line shows large one. In general, the thermal efficiency of large engine near MCR tends to be high than smaller engine. However, when low to middle range power is required in each engine, the efficiency of small rating engine is higher than the large one. As a result, the efficiency of proposed hybrid system's main engine is improved comparing to the conventional one when each engine outputs same power.

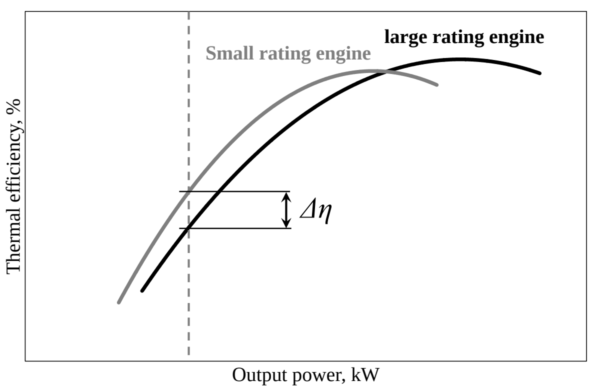


Fig. 9 Relation of output power, thermal efficiency and rating

Consequently, downsizing of the main engine's rating in proposed hybrid system contributes to improve the efficiency of hybrid propulsion system.

On the other hand, the total propulsion power is limited to 1200kW in State B. For this reason, this state can be selected in the waiting and transit situation which is not required to output high propulsion power. The duration time that tugboats are operated in these situations is long. Thus, it is expected that this state can be used effectively.

5 Result of simulation

The amount of fuel consumption in conventional and proposed hybrid system is calculated by inputting the propulsion power data as shown in Fig.2. It is also needed to select operating condition which means the number of running main engines and diesel generators in propulsion system so that FOC simulation is implemented.

In conventional system, all main engines and diesel generator have to be kept running in any situations. On the other hand, in proposed hybrid system, it is possible to reduce the number of running main engines and diesel generator depending on the situation. In this paper, the operating condition is set to Table 2 for simulating the amount of fuel consumption.

Table 2 Operated conditions of each apparatus in three situation

Device	Conventional system	Proposed system		
	Service/ Waiting/ Transit	Service	Waiting	Transit
State	-	State A	State B	State B
M/E-1	RUN	RUN	RUN	RUN
M/E-2	RUN	RUN	STOP	STOP
D/G-1	RUN	RUN	STOP	STOP
D/G-2	STOP	-	-	-

In proposed hybrid propulsion system, State A is applied in service situation because a wide range of propulsion power is required to pull and push large vessel. In transit and waiting situation, State B is selected because the high propulsion power is hardly used. FOC simulation results are shown in Table 3.

Table 3 FOC simulation result

		Total	Service	Waiting	Transit
Time	[min]	192.3	79.4	34.6	78.4
FOC of Conventional system	[kg]	393.2	209.6	34.0	149.7
FOC of Proposed system	[kg]	365.5	217.3	17.6	130.6
Increace and decrease of FOC	[kg]	-27.7	+7.7	-16.4	-19.1

The State A's ratio of SFC is worse than conventional one in all range of propulsion power in the proposed hybrid system that is described Chapter 4.

For this reason, the amount of fuel consumption in proposed hybrid system is increased a little comparing to the conventional one in service situation.

On the other hand, the proposed hybrid system State B is designed to improve the efficiency in low output. In waiting and transit situation, the duration time which tugboats are operated in low output tends to be longer than in service situation. Therefore it is expected that the fuel saving effect is high in these situations.

From these simulation results, the proposed hybrid system has a potential to save fuel oil by 27kg in total. It is considered that this proposed hybrid system is effective to save fuel consumption for the tugboat.

6 Conclusion

In this study, the characteristics of SFC in conventional and hybrid system are calculated by using the FOC model. In addition to this, the fuel saving effect of the hybrid propulsion system is evaluated by calculating amounts of the fuel consumption and comparing to the conventional one. As a result, it is clarified that this hybrid system can improve the efficiency through the FOC model when one engine and one diesel generator are stopped. Tugboats tend to be operated in low loaded condition like out of service situation. Therefore, it is expected that the proposed hybrid propulsion system can save fuel oil consumption effectively for tugboat.

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