A Newly Developed Plug-in Hybrid Electric Boat (PHEB)

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Abstract
A new type of boat, the Plug-in Hybrid Electric Boat (PHEB), was developed by electrifying a boat, and it is hoped that this will contribute to the environmental issues and reduce the use of oil. The system of the PHEB, the fuel consumption, the magnitude of vibrations and the generated noise are described in this paper. Boats which run by battery have already existed for some while. However, the smallness of energy-density in a battery, as well as the unreliability due to the evaluation of the residual battery energy, has been made it difficult to be applied for a larger ship. Accordingly, a system, which can be applied to both engine-powered and battery-powered sailing, depending on the situation, has been developed and the system was named a Plug-in Hybrid Electric Boat (PHEB). A 22 ft-length prototype boat was manufactured, and the system has proved to have both high reliability—which is the essential advantage of an internal-combustion engine—and the quietness and cleanness which are typical features of electric boats. The results of the tests are also described in this paper.

Keywords
plug-in hybrid boat, reduce the oil usage, electrification, PHEB, fuel cost

1. INTRODUCTION
The electrification of ships is important for improving the environment and for the reduction of oil use.

Table 1 Merits of using electric power

1. Electric motors do not emit gases [Little, 1994].
2. Quietness
3. Hyper slow and flexible driving in forward- and backward-movements are possible.
4. No need to use a radiator and in-water air exhaust device. No need to use an exhaust system as a part of the design.
5. Driving by connecting a high-flexible electric-wire compared with the liquid fuel pipe line for ICE is possible.
6. More options in setting up an electric motor.
7. Reduction of oil use is possible by using nuclear energy or hydrogen energy.
8. When the boat is driven at low velocity, the fuel consumption is smaller than for similar overland transportation (when a comparison is made according to weight). Thus electric hybridization can realize greater energy saving [Minami and Yamachika, 2003, 2004].

The advantages of electrification are noted in Table 1. Small-size boats running on batteries have already been developed [Duffy Boat, 2010]. However, larger-size boats which run on batteries have not yet been developed or widely used because the energy density of a battery is too small for the purpose [Minami, 2003]. The smooth control and effective sailing of ships of 10,000 tons or more have been achieved as a gas turbine-based power generation system has grown in size, as well as with the introduction of the electric motor. However, such a hybrid system is far from being called a real solution for any reduction of the use of oil.

All boats of this type use a system in which the power generator is operated by oil and an electric motor is operated by the generated electricity. A mechanical drive of the engine is not directly used; that is, it is a series-hybrid boat. The advantages of the hybrid boat are summarized as follows.

(1) The reduction gear loss due to the fast rotation of gas-turbine into a low-velocity rotation of the propeller can be eliminated.
(2) The generator can be placed separately from the driving-propeller section. This creates more flexibility in design and it can also increase the load of the boat.
(3) From the standpoint of reduction of oil use, en-

ergy is saved as the engine is used only at a high efficiency rate of rotation.

(4) A cruise ship, for example, is equipped with an extra- and large-generator because a lot of electricity for air conditioning and lights inside the ship is required. When the ship is driven by electricity, such a component generator can be used together, and it can also achieve a low cost. A more specific example of this electric system is the hybrid cruise ship of 113,000 tons, Princess Cruise, which has four 6.6 kV/14 MVA generators.

(5) With an electric motor, smooth rotation-control between the stop-position and high-velocity position is possible, and its merits are exhibited when it is used in, for example, a pleasure ship or an ice breaker boat.

(6) Natural gas, bio-based fuel or other types of fuel can be also used. Naturally, it is possible to generate electricity by driving a turbine with the heat of nuclear energy. In this sense, a nuclear aircraft carrier or nuclear-power submarine belongs to the series-hybrid type of ship.

(7) Although such a hybrid ship which uses no electric battery improves when comparison is made with a boat run only on engines, it is still a means of transportation which emits noise and gases. A recently-manufactured fishing boat of this type emits less noise, but such a small-size cruise ship which still emits engine noise and a gas-smell damages passenger's pleasure of enjoying the beauty of a landscape.

(8) A propeller-driving system (POD system) which has 360-degree rotation can be installed and this can improve operability.

By contrast, a plug-in hybrid, which has begun to be used widely for electric vehicles, is a system whereby battery power charged from a commercial power line is used within a certain range of travel, while an internal-combustion engine is used beyond the range.

If this system is applied to a boat, the boat can operate—as a boat run on a battery—for a certain limit of distance and also it can operate—as a boat run on an internal-combustion engine—outside of that limit. This system makes it possible for the boat to travel for a long distance while still using the advantages of electric boats, which include quietness and lack of gas emissions. A boat of this type, whereby the boat runs on both an internal-combustion engine and a battery, we have named a Plug-in Hybrid Electric Boat (PHEB). This system can provide reliability—a most important point for ships. By converting a boat which is already operating on an internal-combustion engine into a boat with this system, such a boat will manage energy-saving along with reliability. The PHEB-system can promote the spread of electric boats.

The PHEB-system uses commercial power line and this is an advantage from the viewpoint of environmental improvement and reduction of oil use. As for overland means of traffic, it has been long since that the railroad was electrified, but in contrast, cars, airplanes and other means of traffic have not yet been widely electrified. This is mainly so because the capacity of a battery is, unlike oil, not properly sufficient for carrying energy.

In this paper, the PHEB-system and its expected characteristics are described first, and then the reasons why the development were made will be described. Design-elements will also be described as they will be necessary when Plug-in Hybrid Electric Boats are actually manufactured. Based on expectations, a prototype boat was manufactured. The boat was made open to the public in Nakanoshima region of Osaka River, Osaka, in Japan, as a part of a pilot program in the autumn 2009. Fuel consumption for this boat was compared between when it was run on a diesel engine and on an electric motor. Quantitative analysis was also conducted on the effects of CO_2-reduction. The experimental results are examined and refereed for future use.

A 22-foot-long prototype boat using both a diesel engine and an electric motor was manufactured in order to show the possibility of realizing the PHEV system and to find any problems. The system from engine to electric motor was designed to operate manually. Since a single propeller is used in this system, the differences in fuel consumption, vibration and noise are compared equally between the boat running on a diesel engine and running on an electric motor.

The plug-in system is described first, and then the fuel consumption and CO_2-emission will be described based on the results.

A block diagram of the PHEB is shown in Figure 1. A photograph of the boat is shown in Figure 2.

Figure 3 shows the energy flow of the PHEB in operation. The electric motor is operated on a battery. Figure 4 shows the energy flow when the boat is run on an engine. Figure 5 shows the energy flow when the battery is charged on an external commercial power-line.

2. A PLUG-IN HYBRID BOAT

The name "Plug-in Hybrid Electric Boat (PHEB)" has been applied by us for the first time in the world. As described in the introduction, a conventional hybrid boat running on oil has just such merits of the reduction of oil use. If only a battery is used to run the boat for the higher velocity or the long distances, a huge

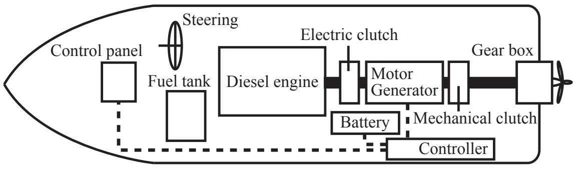


Fig. 1 A block diagram of the PHEB system

Fig. 2 A photograph of the prototype PHEB

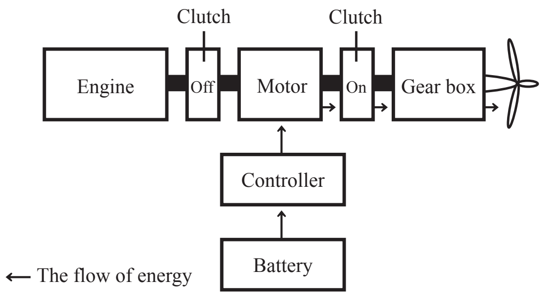


Fig. 3 The Energy flow when the boat is run on a battery

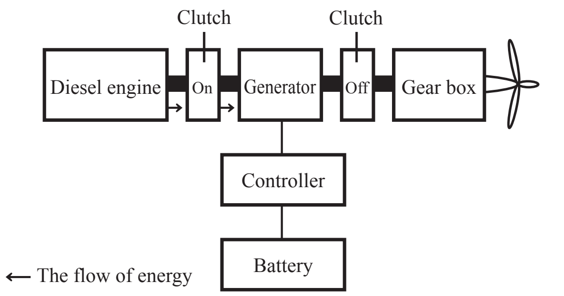


Fig. 4 The Energy flow when the boat is run on an engine

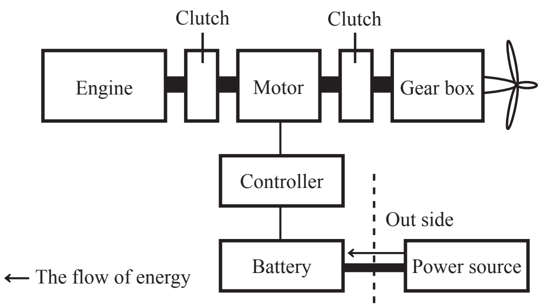


Fig. 5 The Energy flow when the battery is charged on an external commercial power line

quantity of batteries will be needed. In contrast, with the PHEB the operation mode can be selected as required, such as running it on the engine or running it only on the battery by stopping the engine. The PHEB also contributes to the quietness and energy saving while providing reliability. When long-distance travel is required, this is also possible.

In this study, a prototype boat based on the system was manufactured on the assumption that the targeted types of boats for this system are small-size pleasure boats and fishing boats. More specifically, the PHEB system used in this study was realized by installing an electric motor between the engine and propeller via the clutch and the propeller-shaft.

The PHEB runs mainly on a battery of which the energy source is charged from an external commercial power line, but the PHEB can also run on a diesel engine if this is required. Since the performance and ability of a battery performance has been insufficient, this PHEB system is considered the only way to realize any practical use of an electric boat. The other advantage of PHEV is that this sutemu can be manufactured by remodeling an existing boat. If a high performance is achieved, the PHEB will be widely used and this will contribute to an increase of demand for electric power.

A hybrid boat runs on diesel power generation at a velocity of 10-20 knots. The target size and velocity for development of a PHEB is a cruising boat of 6-20 m in length, which runs about at 5 knots on lakes or rivers (The necessary energy for a boat is proportional to the cube of the velocity, and thus the battery is not suitable for high velocity). The category of boat

Table 2 Reasons for developing PHEB

1. Within the limits of battery capacity, the PHEB runs on electricity charged from a commercial power supply, and thus it is useful for reduction of oil use.
2. As an electric ship, the PHEB can run without polluting water, making less noise and less emitting gases [Gillmer and Johnson, 1982].
3. Operation by electric power makes it possible to be run by means of various kinds of energy sources.
4. The merits of an electric boat can be added to existing boats by remodeling.
5. The effects of reducing CO2-emission between when a boat runs only on an electric motor and when the same boat runs on diesel can be experimentally shown just by switching the modes.
6. A PHEB still can operate on an engine even when it has run out of charged energy, and this is an advantage in practicability and safety.
7. Electric power companies can promote more electric power demands than shore power consumptions by anchored ships.

aimed in this study belongs among small-sized boats in Japan, to which a license is given according to an inspection conducted by the JCI (Japan Craft Inspection Organization). Compared with larger-size boats, the amount of regulation is low. This helps in the promotion of PHEB use for the future. The merits of the PHEB are listed in Table 2.

2.1 The PHEB system

A PHEB was set up and designed for evaluation. The results are described here. This prototype PHEB was built by replacing the propeller-shaft, which connects the engine inside the boat and the propeller, with a clutch and electric motor. This system can be applied as a method for remodeling various kinds of boats—cruising boats, fishing boats and small-sized pleasure boats—easily to PHEB. The shape of the diesel-operated boat used in this study is shown in Figure 6. The full length of the boat is 22 ft (approximately 6.5 m). Figures 7(a), (b) and (c) show structural photographs of the engine and propeller-shaft before it was remodeled. Figure 8 shows photographs of the PHEB drive-part after the propeller-shaft was replaced with an electric motor.

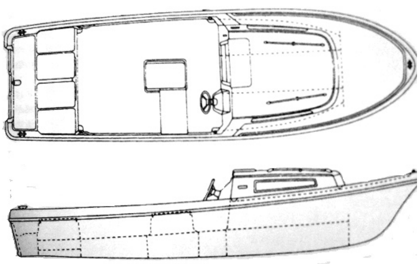
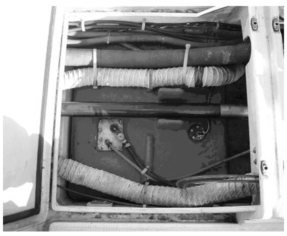


Fig. 6 Shape of the 22 ft diesel-operated boat used in this study

(a)

(b)



(c)

Fig. 7 (a) The engine before it was remodeled. (b) and (c) Structure of the propeller-shaft.

Fig. 8 Photographs of the PHEB drive-part after the propeller-shaft was replaced with an electric motor.

Figure 9 shows a catalogue characteristics of the rotating velocity and output of the Yamaha diesel engine D200KH used in this study.

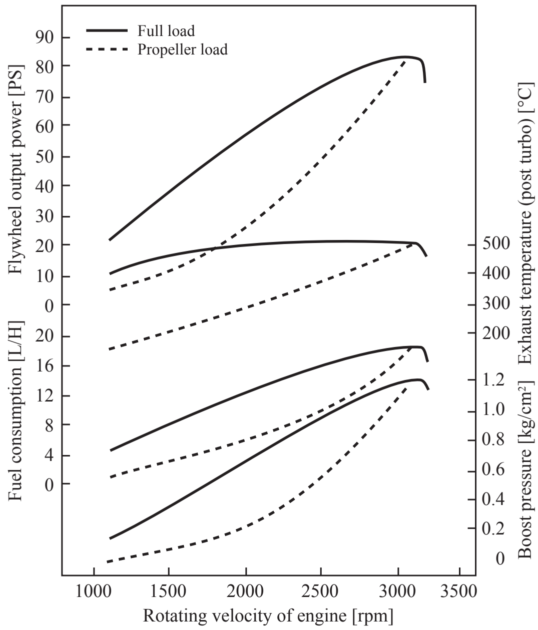


Fig. 9 The characteristics of the rotating velocity and the output of the diesel engine D200KH used in this study

2.2 Evaluation of the installed motor-capacity

Based on the engine characteristics described earlier, the capacity of the electric motor in response to the capacity of the boat (engine capacity) is examined here. The selection of a battery rating for an electric boat is examined first. The specifications of the electric motor used for the prototype boat are shown in

Table 3 Specifications of the electric motor used

DC shunt-motor Maximum drive-voltage 108 V (Used at working voltage 96 V and maximum current 250 A) Rated output 14 kW/5,300 rpm (Maximum output 19 kW) field current = 12 A（n < 3,300 rpm） (field current = 6 A（n > 3,300 rpm）)

Table 3. A shunt-motor was selected in this evaluation since the alternation of excitation current can change the functions as a motor or a power generator.

Figure 10 shows the motor-shaft output in response to the applied voltage of the motor used in this study. It shows that an output power of approximately 15 kW is achieved at a field current of 12 A and applied voltage of 80 V. Figure 11 shows the relation between the rotating velocity and battery voltage at a field current of 12 A. It shows that if the shaft is driven by such as, for example, an engine and it achieves more than 2,700 rpm rotating velocity, a battery of terminal voltage 80 V can be fully charged. Figure 12 shows the relation between the engine-rotating velocity and the power-generation voltage. The dots show the results of actual measurements of the terminal voltage which are achieved as a generator by rotating the engine. The

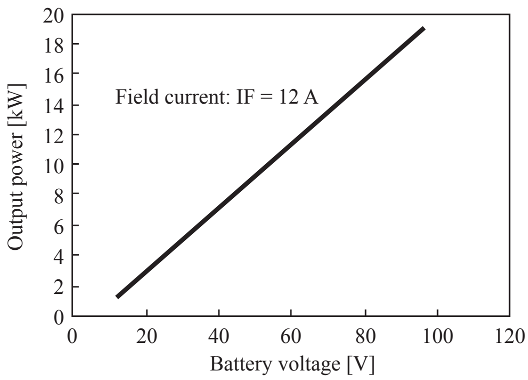


Fig. 10 Motor output–voltage characteristics

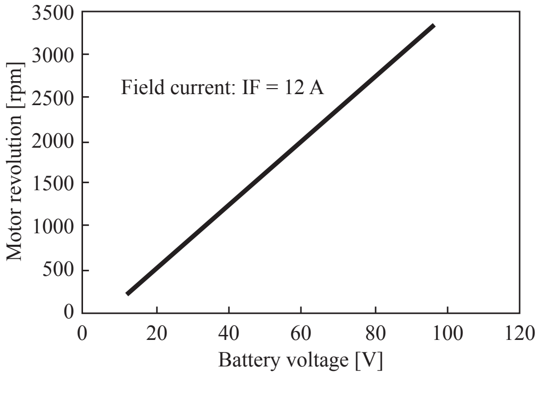


Fig. 11 Motor output- characteristics to the rotating velocity

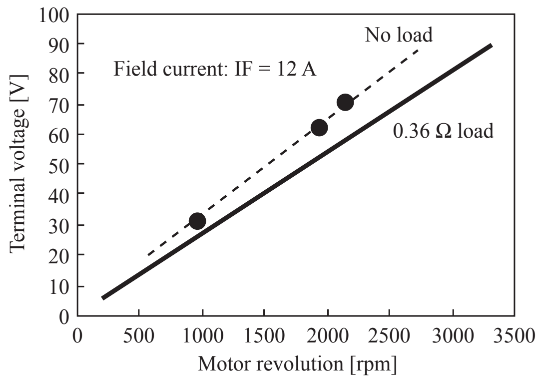


Fig.12 The characteritics of the rotation velocity [rpm] vs. the generated terminal voltage [V]. The relation between the rotating velocity of the engine and power-generation voltage.

Note: The dots shows the actual measurements achieved from the motor by rotating the engine.

results show that this system is opera table as a motor and a generator. Thus, the voltage of the battery is decided at 80 V (the rated voltage is 72 V). Furthermore, the system voltage is also set to be switched over either 80 V or 40 V, and in this way, charging is possible even when the rotating velocity of the engine is low.

A lithium-ion battery is used for the PHEB battery. A battery called a type 18650 by Sanyo Electric Co., Ltd. was used. A structure was made with 1,560 batteries—a series of 26 batteries and 60 batteries in parallel—and many series-parallel connections were structured. It has 128 AH, a rating of 72 V and 9.26 kWh of stored energy. Batteries chosen from Sanyo 18650 have characteristics of 90 Wh/kg, 200 Wh/L, output density 3,500 W/kg.

2.3 Control circuit

After selecting a driver system, electric motor and battery, a control circuit for the PHEB was designed. The PHEB is operable at the following modes. A photograph of an operation board for controlling the circuit is shown in Figure 13.

(1) Engine sailing

Fig. 13 A photograph of the operation board for switching operation modes

(2) Electric motor + battery sailing
(3) Battery charge by the engine
(4) Battery charge while sailing by the engine

3. EXPERIMENTAL CHARACTERISTICS

By applying to JCI for remodeling a boat, inspections were made as to the strength and characteristics of the boat. After passing the inspection, measurements were made on the characteristics of the PHEB. The results are described here. Meanwhile, the PHEB was opened to the public for about one month at Nakanoshima, Osaka, Japan.

3.1 Tests on fuel consumption and electricity consumption (by measuring CO_2-emission, fuel consumption, electricity consumption, and cost)

CO_2-emission, fuel consumption and electricity consumption were measured by running a PHEB on diesel and on a motor. The CO_2-emission was measured by: measuring flow velocity of the boat by GPS; then, measuring the ground velocity of the boat in a sailing position by GPS.

Water velocity (the actual velocity of a boat operated on diesel or by a motor) can be calculated by subtracting the flow velocity from the ground velocity. When the boat is run on diesel, its CO_2-emission is calculated from the fuel consumption. When it is run on a motor, the electricity consumption is calculated by the integration of multiplying the measurements of electric voltage and current, and the CO_2-emission is measured from the electricity consumption. In the study, the calculations were made with the cost for light oil at JPY100/L, and for electricity at JPY11.33/kWh. The measurements were conducted when the flow of the river was as calm as possible. The fuel consumption of the boat run on an engine was calculated by measuring light-oil consumption after 5 minutes of running.

The CO_2-emissions per hour as a function of the boat velocity are shown in Figure 14. The basic unit for CO_2 is: electricity at 0.299 kg- CO_2/kWh (according to the records of Kansai Electric Power Co., Inc. in 2008, Japan); and light oil at 2.619 kg-CO_2/L.

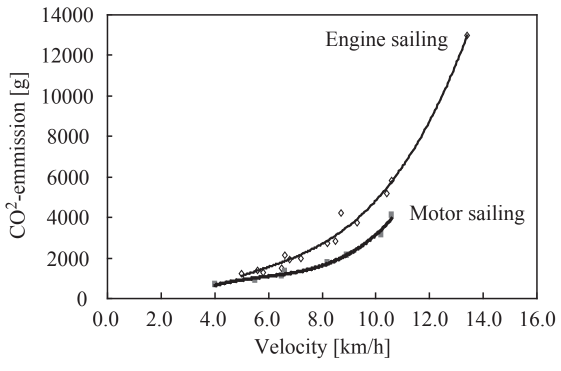


Fig. 14 CO_2-emissions per hour velocity characteristics

In relation to CO_2-emissions by motor sailing, Figure 15 shows the CO_2-emission ratio by engine sailing to the motor sailing.

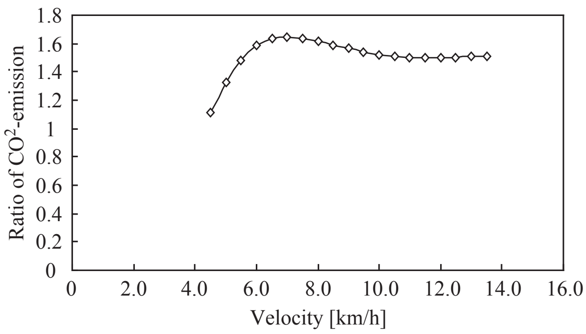


Fig. 15 CO_2-emission ratio-velocity characteristics

Characteristics of the relation between fuel costs and velocity for motor sailing are shown in Figure 16.

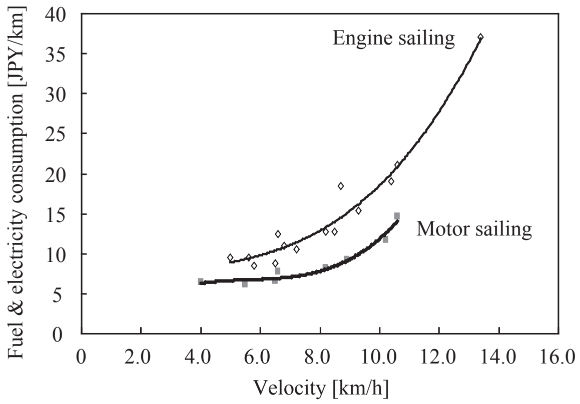


Fig. 16 Fuel and electricity consumption—velocity characteristics

In relation to the electricity consumption during the motor sailing, the ratio of electricity and fuel consumption on the y-axis and velocity on the x-axis during engine sailing are shown in Figure 17.

Characteristics of the cost vs. the sailing velocity are

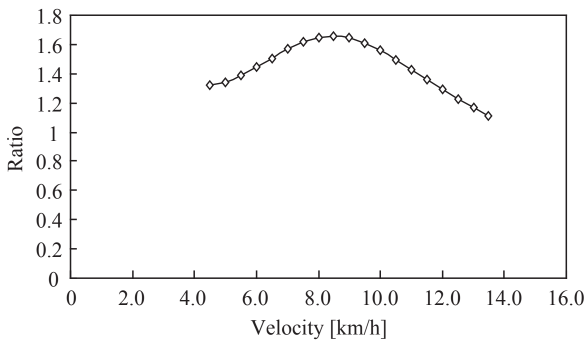


Fig. 17 The ratio of the fuel consumption to the electricity consumption—velocity characteristics

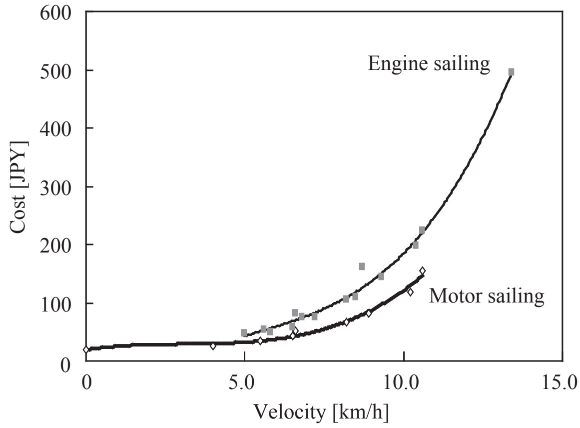


Fig. 18 The cost—velocity characteristics

shown for the engine sailing and the motor sailing in Figure 18.

The ratio of the cost of the engine sailing to the motor sailing for different velocity of the boat is shown in Figure 19.

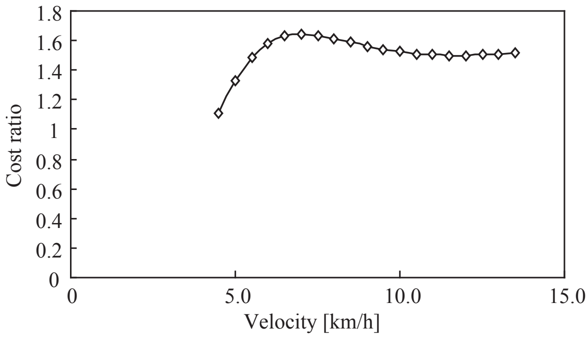


Fig. 19 Cost ratio—velocity characteristics

3.2 Results of the measured vibration and noise

The vibration and the noise of the boat during the diesel sailing were measured. As with the measurement of CO_2-emissions, the water velocity is calculated by using GPS. The vibration and the noise were measured by sensors placed at the engine seat, rear seat and pilot's seat.

The Vibration energy and the velocity characteristics during engine sailing are shown in Figure 20.

The vibration energy and characteristics to the velocity during motor sailing is shown in Figure 21. It was found that during diesel-engine sailing, the vibration energy by the enigne is approximately 100-10,000 times begger at the engine seat and rear seat than that by the electric motor.

The noise characteristics caused by the engine for different velocity is shown in Figure 22.

A characteristics of the noise and the velocity during motor sailing is shown in Figure 23. It was found that during the diesel-engine sailing, the noise energy is approximately 100-10,000 times (30-40 dB) bigger in

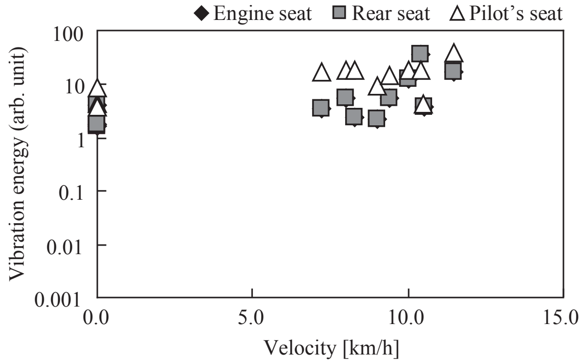


Fig. 20 The relative value of vibration energy during engine sailing for different velocity of the boat

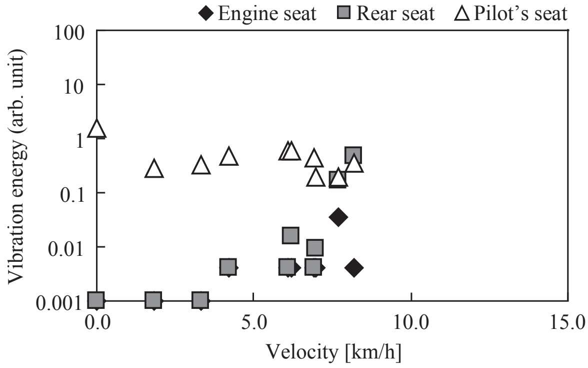


Fig. 21 The ratio of the vibration energy caused by the motor sailing for different velocity of the boat

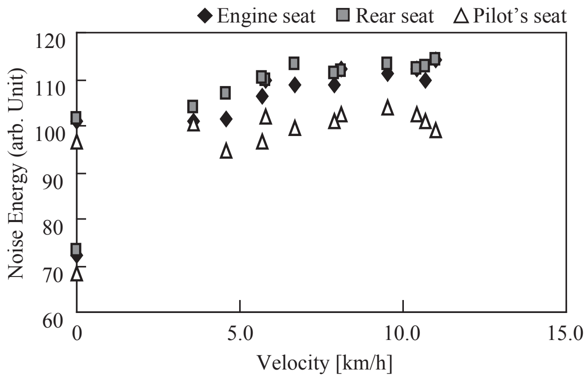


Fig. 22 The Noise energy during engine sailing—velocity characteristics

comparison to the sailing with an electric motor.

4. CONCLUSION

The results described in this paper are summarized as follows.

(1) For a small-size boat, significant characteristics of a plug-in hybrid boat are found in relation to environmental issues and reduction of oil use, and the boat with this system was named a Plug-in Hybrid Electric Boat (PHEB) by us. The possibilities for turning this system into reality for the first time

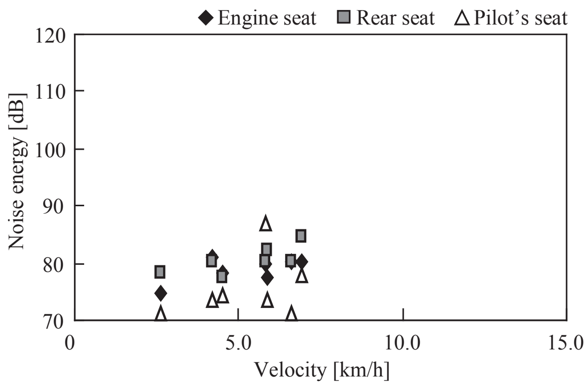


Fig. 23 Vibration energy during motor sailing—velocity characteristics

in the world were examined and a prototype boat was designed.

(2) Examining the prototype boat
PHEB for evaluation, a boat of 22 ft (6.5 m) in full length with a diesel engine was tested based on the concept.

(3) Examining the capacity of the introduced motor and batteries
The relation between the capacity of the motor and the capacity of the engine of the boat was examined. Based on the rotation velocity and the capacity of electric motors, the characteristics of the electric motor as a driving device and the desired electrical energy were examined, and a suitable DC shunt-motor was set up according to the evaluation. The type of battery used in this study was a lithium-ion battery of 9.6 kWh.

(4) Inspection by JCI
A sampling of technical opportunities for the prototype PHEB was conducted. The strength and safety of the boat which are required for operating a PHEB were inspected by JCI and passed the criteria.

(5) Control system
As a method for controlling the engine and motor, a system whereby 4 driving modes using the engine and the motor were possible was designed and manufactured.

(6) Examining fuel consumption and electricity consumption
A comparative evaluation of economic efficiency and quietness was conducted. The prototype PHEB was actually operated, and the fuel consumption, the electric power consumption, the vibration and the quietness were measured and compared. It was found that the electric-motor sailing generates only about one-1,000-10,000th of vibration energy in comparison to the diesel-engine sailing. It was also found that the motor sailing generated only about one-1,000-10,000th of noise energy comparing to the diesel-engine sailing.

(7) It has become clear that the PHEB is quiet and friendly to the air environment while offering safety and reliability, which are essential for boat sailing, and that a PHEB has good fuel-efficiency and can contribute to lowering CO_2-emissions.

(8) According to the results of the questionnaire survey conducted at the pilot program in Nakanoshima, many members of the public have given good evaluations of the boat.

Acknowledgement

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