Usefulness of a Plug-in Hybrid System for Small Fishing and Cruising Boats

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Abstract

In this paper, it is pointed out that the battery contained in the plug-in hybrid boat, PHEB, has a high potential for the real electrification of a small boat for providing outstanding performances. The purpose of this paper is to encourage the spread of such a useful PHEB system for small cruising, fishing and working boats. The PHEB system is equipped an internal combustion engine, electric motor, battery, and an electric charger for shore power receiving system. For the practical use of PHEB, it is also suggested to equip electric generators. According to experience, the PHEB works very well with silence, low pollution, and low CO_2 emission during the electric mode together with the ICE's usefulness represented by the robustness of the fuel infrastructure and high energy density. Three PHEB's were produced and introduced to show the usefulness for boating.

Keywords

plug-in hybrid system, electric motor, fishing boat, cruising boats, CO_2 emission

1. THE ADVANTAGES OF A BATTERY DRIVEN HYBRID BOAT AND USEFULNESS OF PHEB SYSTEM

1.1 The advantages of a hybrid boat

The pure battery boat can be used only for low velocity applications because of the very low battery energy density [Minami and Yamachika, 2003; 2004; Minami, 2003]. Also, there is a severe safety issue for the reliable use of an electric boat. The use of ICE together with an electric motor is the best solution for the professional application of a boat. This is called a hybrid boat. Electric motor driven boats with ICE can be categorized in to 7 different styles as shown in Table 1.

Table 1: The different electric driven boats

Name of boat	The Flow of energy	Mostly used
Pure electric boat	Grid → Battery → Propeller	Small boat
Series hybrid ship (Battery-less hybrid ship)	Foci fuel → Generator → Electric motor → Propeller	Large scale sightseeing ship Ice breaker ship
Solar boat	Solar cell → Battery → Electric motor → Propeller Grid → Battery → Electric motor → Propeller	Small boat
Fuel cell boat	Hydrogen → Fuel cell → Electric motor → Propeller Hydrogen→ Fuel Cell → Battery → Electric motor → Propeller	Fuel cell boat
Parallel hybrid boat	Foci fuel → Engine → Propeller Foci fuel → Generator → Electric motor → Propeller	No example
Series parallel hybrid boat	Foci fuel → Engine → Propeller Foci fuel → Generator → Battery → Electric motor → Propeller	Submarine
Plug-in hybrid boat (PHEB)	Grid → Battery → Electric motor → Propeller Renewable energy electric power → Battery → Electric motor → Propeller Foci fuel → Engine → Propeller Foci fuel → Generator → Battery → Electric motor → Propeller	Author

The PHEB is specified as the use of three power sources of the grid, the internal ICE generator and the ICE direct propeller driving. In this case, the hybrid boat is a battery-less series hybrid boat. Such a so-called hybrid boat has additional advantages as shown here.

1.2 The usefulness of PHEB

In addition to the advantages of the hybrid boat (series hybrid boat), the PHEB (Plug-in hybrid boat) has the following advantages.

- PHEB can be a pure electric boat, so that it has the advantages of quietness of an electric ship, no exhaust gases and no vibration.
- It has safety and robustness because it can be an engine boat. Even without a charging station, there are oil stations in ports all over the world.
- Existing boats can be remodelled, and the system can be converted into PHEB at low cost. The performances of the existing diesel engine can be retained.
- Available as an excellent electric boat at the right place.
- It is possible to clearly compare the differences of performances, such as CO_2 reduction, noise, gas emission etc. between the ICE system and the electric system using the same boat only by changing the function.
- Using power-line system power as much as possible, it can also contribute to the reduction of oil consumption.
- This PHEB system makes it possible to reduce the use of foci fuels without reducing the boat performance. The electric power can be obtained from different energy sources.
- Electric driving system makes it possible to control the ultra-low velocity movement.
- It is also possible to improve the fishing environment through the advantages of no exhaust gas emission during idle stop operation with PHEB. The environment of the sea area where many fishing boats gather usually suffers from diesel engines.
- During fishing, as an electric boat, it is possible to stop idling. The idle stop function shows great effect for the environment of fishing, especially when the Ippon-zuri fishing method (a way of fishing where a fishing line and a hook is used) is performed.
- The Plug-in hybrid boat contains very high electric battery energy compared with an ordinary ICE boat. By using part of the electric energy, electric power can be stably supplied to all the electronic equipment required for the boat. It can realize a high-technology boat that can demonstrate effective reduction and high efficiency of fishing.

2. EXAMPLES OF PRODUCED PHEB

2.1 22 ft Proto-type Small PHEB, PHEB-1

A plug-in hybrid boat (length of 22 ft) driven by an electric motor and a diesel engine [Minami et al., 2010]. This proto-type boat is named "Plug-in hybrid electric boat-1" or PHEB-1.

The PHEB-1 system was produced based on past feasibility studies and experimental research [Minami and Yamachika, 2003; Minami, 2003]. This system shows

Figure 2: A photograph of the demonstration of PHEB-1 on Biwako-lake in Japan

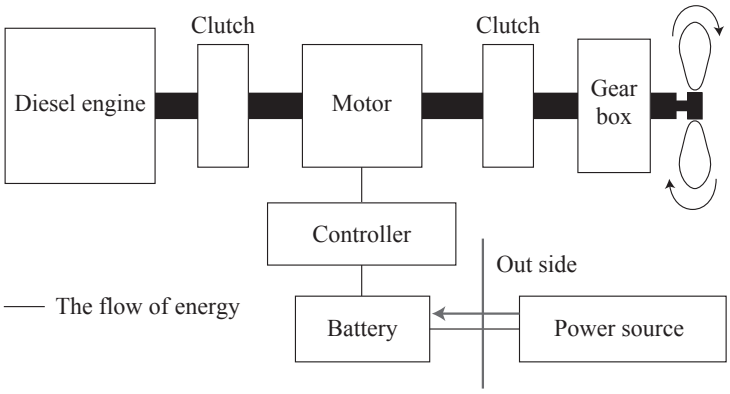


Figure 1: A block diagram of PHEB-1

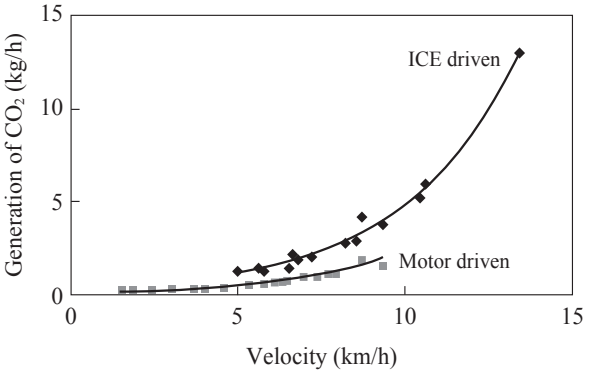
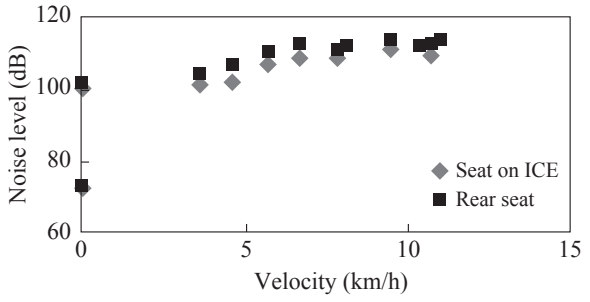
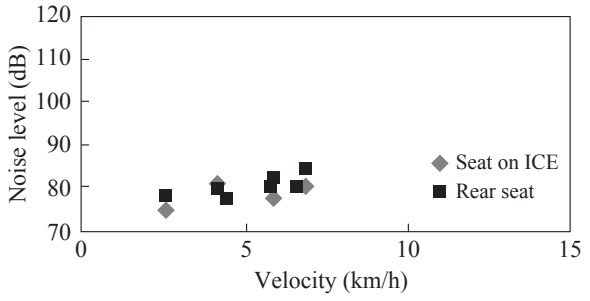


Figure 3: An experimental result of CO_2 reduction by ICE and electric motor driven

Note: The reduction factor of about 50 % is obtained.



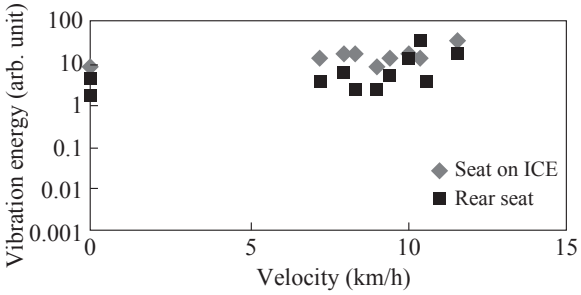
(a) ICE driven



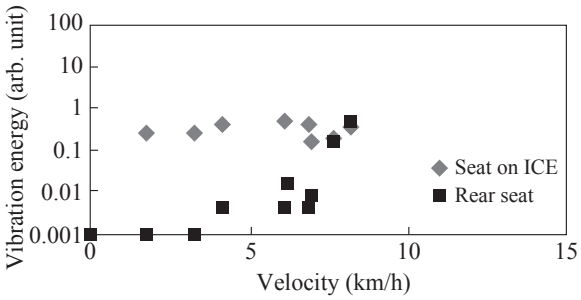
(b) Electric motor driven

Figure 4: Effective reduction of noise during the different running velocity by ICE and electric motor

good performance for silence, little vibration and no pollution characteristics as well as the reliability of a diesel engine. A block diagram of this boat (PHEB-1) is shown in Figure 1. This hybrid boat has 10 kW of electricity power using a stored battery of 10 kWh and can utilize external electric energy from a grid. One single propeller is driven by either an electric motor or diesel engine (65 kW). The electric motor can also be used as a generator [Minami et al., 2013]. The good performance of PHEB-1 was demonstrated in public as shown in Figure 2. The use of an electric motor makes it possible to reduce CO_2 emissions as shown in Figure 3. Running of a boat by electric motor provides outstanding reduction of noise and vibration of



(a) ICE driven



(b) Electric motor driven

Figure 5: Effective reduction of vibration during the different running velocity by ICE and electric motor

1,000 to 10,000 times as shown in Figures 4 and 5.

2.2 A fishing PHEB, PHEB-2

In principle, to spread the type of PHEB-1, it is necessary to modify a used boat instead of a new one, because quantity is important to contribute to energy saving and to clean the environment. The way of utilizing used boats results in a better cost merit than a new boat. Recently in Japan, only about 2000 new boats are released per year in the market. Japan has about 200,000 small boats that can be modified as PHEB.

A new type of PHEB system has been developed. As shown in Figure 6, an electric propulsion system is installed independently from the previously installed diesel engine propulsion system. This system can be applied to different boat propulsion systems. To show the performance of PHEB-2, a 4 tons existing 38 ft diesel (140 kW at maximum output power) inboard propeller fishing boat was used. An electric motor driving system with a stern drive, a propeller, and helm station were installed. By such a method, the electric motor system (an induction motor of 50 kW at maximum and an inverter) does not influence the performance of the diesel engine system installed previously. A photograph of PHEB-2 is shown in Figure 7 [Minami, 2013; 2015]. A photograph of the control room is shown in Figure 8. The steering wheel for electric propulsion is added independently to the previously installed ICE propulsion system. The goal of

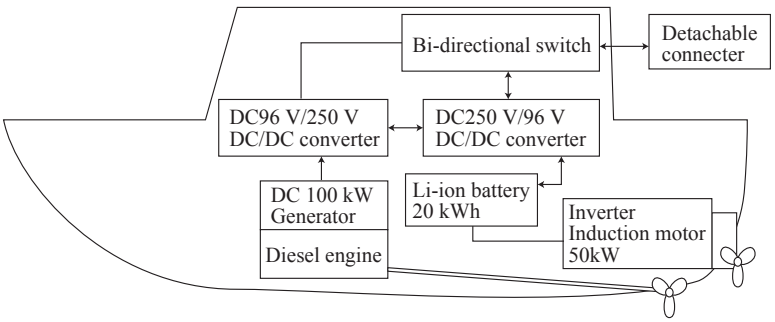


Figure 6: A block diagram of PHEB-3

Figure 7: A photograph of PHEB-2

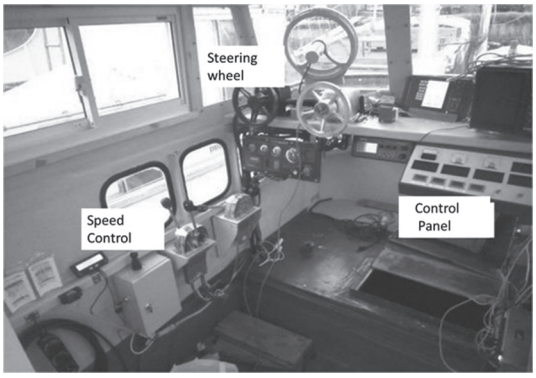


Figure 8: A photograph of the control room

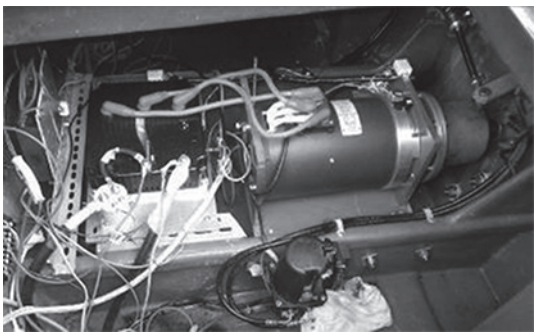


Figure 9: A photograph of electric motor installed near the tail of a boat, PHEB-2

PHEB research is to spread converted plug-in hybrid systems to used boats. An electric motor is installed near the tail of a boat not to disturb the previously installed population system as shown in Figures 9 and 10.

Figure 10: A photograph of the propeller propulsion system at the tail of the boat, PHEB-2

2.3 Effective CO_2 reduction by the use of PHEB

It is shown in section 2.1 that CO_2 reduction of 50 % can be achieved by the use of an electric motor instead of an ICE system. In this section, it is shown that more effective CO_2 reduction can be obtained when PHEB system is used [Minami et al., 2015]. It is shown that 80 % of CO_2 reduction is performed by fixed point fishing. The high performance of the PHEB system was proved at an official collaboration research campaign during 2012-2014 using a fishing PHEB (PHEB-2). Such results were provided mainly by the idling stop function of an electric motor. The power consumption during a fixed point fishing operation using electric motor propulsion show the average power is small (Figure 11). While ICE wastes fuels even without the use of propulsion as shown in Figure 12. A photograph of the fixed fishing operation is shown also. The idling stop function provides lot of advantage to the fisherman because of no local pollution gas emission and low noise as well as a fuel economy.

A performance test was conducted to investigate the power consumption during fixed point cruising. PHEB-2 shows a typical electric power consumption during the fixed point fishing operation conducted. Such high performance is because of the high efficiency of the electric motor system and the idling stop function. It is also well known that CO_2 emission from

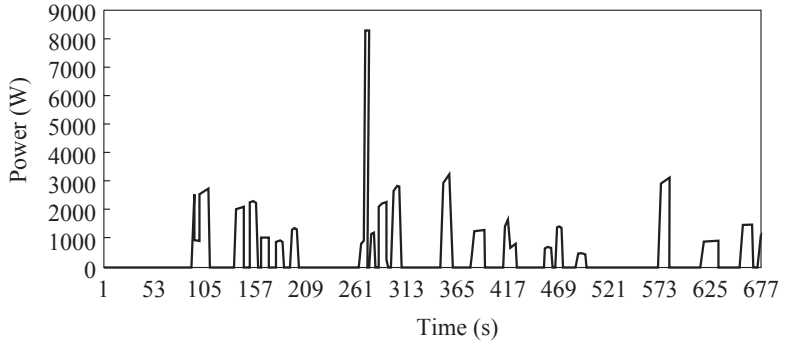


Figure 11: An example of the power consumption during fixed point fishing operation using electric motor propulsion

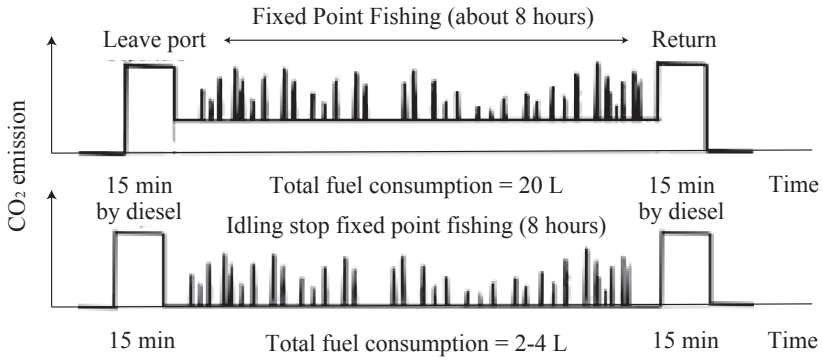


Figure 12: The CO_2 reduction by the use of PHEB-2 compared to a normal ICE boat during fixed point fishing operation

Note: Each boat went to the point by ICE and returned also by ICE. During fishing, the idling stop function of PHEB effectively reduced the CO_2 emission by 70-80 % every day.

the electric motor is reduced by about 50 % compared to the diesel running during the same driving speed. The CO_2 emission from a diesel engine (assuming the efficiency of 20 %) is 1.3 kg-CO_2/kWh, while an electric motor (assuming the efficiency of 85 %) emits 0.65 kg-CO_2/kWh when the CO_2 emission to make electricity is 0.5 kg-CO_2/kWh. This is the reason why the CO_2 emission by an electric motor is roughly 50 % compared to the diesel engine operation.

From this fact, it is possible to estimate the CO_2 emission. When the renewal energy is used for electric propulsion, it is said that the CO_2 is no longer emitted during the fixed point fishing of 8 hours.

Based on such an assumption, the total fuel emission as well as the CO_2 emission can be calculated. The only parameter is the velocity to access to the fishing point and the return. Figure 12 shows the CO_2 reduction by the use of PHEB-2 compared to a normal diesel engine boat. The velocity of the boat to access to the fishing point and to return to the port is assumed to take 30 minutes totally. It is shown that the drastic CO_2 reduction by the use of PHEB-2 is obtained for the different velocity of the boat to access.

When the electric power can be obtained from renewable energy resources as shown in Figure 13, more effective CO_2 reduction and environmentally friendly fishing can be obtained, which effect is also proved during the 2012-2014 campaign at the detached island, Nushima, in Japan.

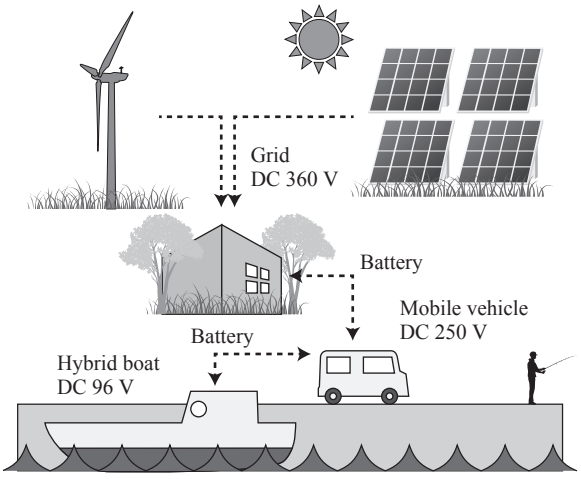


Figure 13: An illustrated operation of PHEB-2 using renewable electric power energies by the solar cells and the wind generator performed in 2012-2014

Figure 14: A photograph of working PHEB made in 2011

Such a PHEB system will provide effective CO_2 reduction and environmental improvement used by working boats. Figure 14 shows the produced PHEB as a working boat made in 2011. The working boat goes to the working point by ICE and at the working area ICE is stopped and the cleaning operation is made at a sightseeing place providing low noise performance and no pollution gas emission.

2.4 A newly developed cruising boat, PHEB-3

The PHEB-3 is designed to be used for the cruising of 30 passengers with the velocity of up to 10 km/h on rivers or lakes. The boat selected had the LOA of 9.66 m and the beam of 3.10 m. In Japan, there are still very few places for electric charging near boat terminals. It is actually necessary to generate on-board to charge the battery for a battery boat.

The maximum power of the electric motor was 10 kW continuous to obtain the velocity of 10 km/h. The permanent magnet DC brushless motor for 96 V nominal battery voltage was selected to obtain high efficiency and safety. The battery of 10 kWh was used for the 1 hour continuous cruising. It is necessary to set two electric motors with 2 propeller shafts which have to be installed beside the main engine as shown in Figure 15. It is possible to charge the battery at any time by the on-board generator. The generator of 11 kW, single phase 200 V, was used.

For chemical safety, reliability and good fuel efficiency, a diesel engine was selected for the main thrust power. Figure 16 shows a unique outboard diesel engine, model S403X (maximum power of 40 hp), made by Yanmar Co., Ltd.

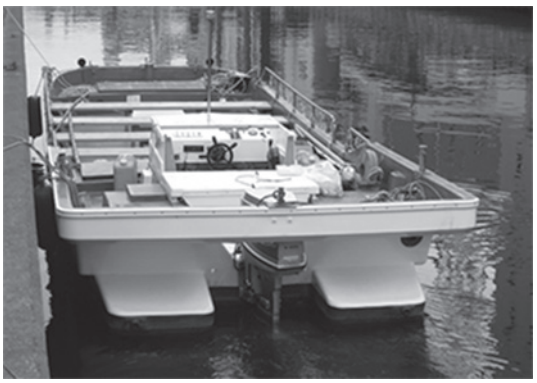


Figure 16: A photograph of PHEB-3

The purpose of the construction of PHEB-3 was to demonstrate the usefulness of a plug-in hybrid boat to gain revitalization of marine industries in the future. The PHEB-3 was used in public to show the excellent performance of such a plug-in system for quietness and no polluted gas emission from the electric drive train. The easy operation of the continued cruising for almost all day long was demonstrated as an established fact in September 2016 on Wakayama River cruising in Japan. Almost 30 people on board each cruise reported an enjoyable trip throughout the campaign.

3. DISCUSSION AND CONCLUSION

The remarkable reduction of oil consumption is due to the high efficiency of the electric motor and the idling stop function during fixed fishing operation. The

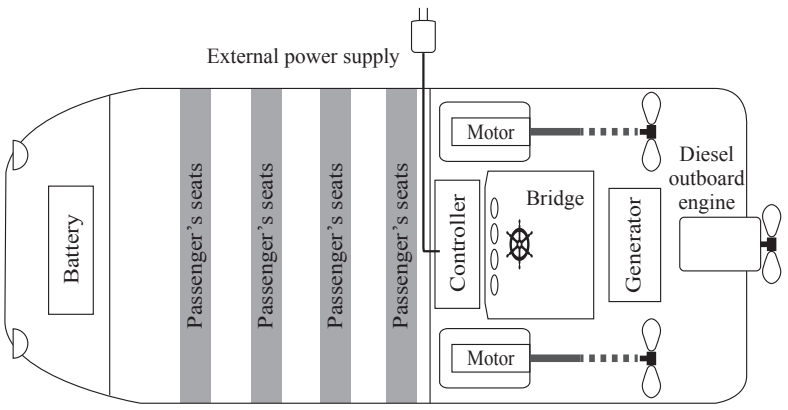


Figure 15: The arrangement of PHEB-3

PHEB-2 system, by modifying a normal diesel engine fishing boat, would have a high potential to spread because it is easier and the cost is lower for productions. The PHEB-2 has a generator of 10 kW, so that it is possible to send electricity to the island when a natural disaster happens.

The PHEB-3 system for cruising was examined by a newly developed 30 passenger river cruising plug-in hybrid boat. The result shows a successful performance of technological usefulness as well as the passenger's full satisfaction for river cruising. The energy density of the battery is still very low for the long range as well as high speed boating. From the reliability point of view, such a pure battery boat cannot be the showcase for the future spread of boats. Actually in Holland in 2016, many pure battery electric boats could be seen and the country luckily has many marinas to charge batteries.

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The boat construction was performed by Daimatsu Shipyard in Wakayama, Yokota Iron Works, Co. in Wakayama, and Nanshin Shipyard in Osaka, Japan. The authors would like to show their sincere thanks for their helpful support with their warmest passion to complete this research.

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