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Design and calculation of mechanical system for solar-powered electric boat

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Abstract. Indonesian government has a flagship program that is to promote the nation through the maritime sector and make Indonesia as Global Maritime Fulcrum. To achieve that, sea transportation is very important for the development of Indonesia. But sea transportation is also the highest contributor to the air pollution and global warming. In order to reduce the source of global warming Indonesian Government has a strategic plan to gradually replace the use of fossil energy with renewable energy. One of the renewable energy that can be used effectively in Indonesia is solar energy, because Indonesia located along the equator and has a high intensity of sunlight that means it has excellent solar energy availability. In attempt to contribute to the Government's energy strategic plan, the research is aimed to design a solar-powered electric boat with single pilot. The project is a further development of the solar boat created by the Universitas Indonesia team that participated in the International Solar-boat Challenge competition in the Netherlands. The paper is focused on the design and calculation of its mechanical system. The system is divided into propulsion system, steering system, and bilge pump system. The research is conducted based on literature study, discussion with experts, and surveys to the solar-powered electric boat had been designed previously for the race. Collected data are then used as input for the calculation and simulation of the vessel being designed. It is expected that the study could optimize the mechanical system of the solar-powered electric boat, and can be developed for recreational use in Indonesian waters.

1. Introduction

The Indonesian government has a flagship program that is to promote the nation through the maritime sector and make Indonesia as Global Maritime Fulcrum. As has been known that Indonesia is the largest archipelagic country in the world with more than 17,000 islands and 65% of the territory is covered by sea [1]. This make Indonesia has high potential in the maritime sector like fishery, tourism, shipping etc. Marine transport is one of the most important players to exploit the potential of maritime sector for the transportation and connectivity between islands in Indonesia.

In recent years, global warming effect is a major problem in almost all parts of the world including Indonesia. Transportation is the biggest contributor for this global warming effect [2]. Therefore trend towards using renewable and alternative energy sources on land has gathered momentum over the last decade or so as the general public and policy makers tackle the issues of pollution, energy security and climate change [3]. Indonesian government needs to replace the use of fossil fuels with renewable energy as an alternative to reduce this effect. One of the renewable energy that can be used in

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Indonesia is solar energy, because Indonesia’s geographical location along the equator, which has a high intensity of sunlight [4].

In attempt to contribute to Indonesia’s strategy to replace the use fossil fuel to solar energy, this research’s objective is to design a solar-powered electric boat with single pilot, which has a 6000 mm length, which is a further development of the solar boat created by Universitas Indonesia’s team that participated in International Solar Boat Challenge competition held in the Netherlands in 2016.

The most important thing in building a solar powered boat is the efficiency of the electricity [5], to ensure the efficiency of the electric motor to reach the desired speed service and have a long cruising time. Mechanical system is one the most important thing to make an efficient solar-powered boat. This paper is focused onto the design and mechanical system of the boat, which is divided into 3 systems i.e. propulsion system; steering system; and pumping system.

2. Methodology and Results

The methodology being used to get the best electric-motor propulsion system is by analyzing the dimensions and specification of the first Universitas Indonesia’s solar-powered boat, with the main particulars as follows: Ship type, Single pilot Monohull Semi-Trimaran; Maximum speed, 20-25 km/h (~13 knots); Length over all, 6 m; Width moulded, 2.3 m; Draft at full load, 0.12 m; Propulsion system, electric; Battery capacity, 48V. These data is used as an early reference to the design and calculation of the boat’s mechanical systems, and then combined with literature study and discussion with experts so as to get more accurate results.

2.1 Propulsion System

In this method, the propulsion system being used for solar boat is determined. Propulsion is a system that will provide a force to push the ship to achieve the desired service speed. In determining the type propulsion, several factors need to be considered such as the dimensions of engine room, cooling system, motor mounting, and steering system. A PODSEM propulsion "POD Steerable Electrical Motor" is chosen. This propulsion combines outboard motor with a steering system as shown in figure 1. The reason for using this is because the engine room of the boat is considerably small i.e. 1000 mm long, 740 mm of width, and 330 mm of height. The propulsion system allows making flexible mounting between the motor and steering system, which will make better maneuverability, moreover this type of propulsion can make the cooling system much easier too.

After deciding the type of propulsion, next step is to calculate the amount of power required for the electric motor to get the desired speed of the vessel to reach 25 km/h. Based on Harvald's method [6] the effective power is obtained based on the following equation:

$$PE[W] = RT[N] x V\left[{}^{m}\!/_{s}\right] \tag{1}$$

$$PM[W] = {}^{PE[W]}\!/_{\eta h x \eta p} \tag{2}$$

$$\eta h = {}^{(1-t)}\!/_{(1-w)} \tag{3}$$

Where: *PE* is Effective Power; *RT* is Total Resistance; *V* is Speed of Vessel; ηh is hull efficiency; ηp is propulsion efficiency; *t* is thrust deduction factor; and *w* is wake fraction.

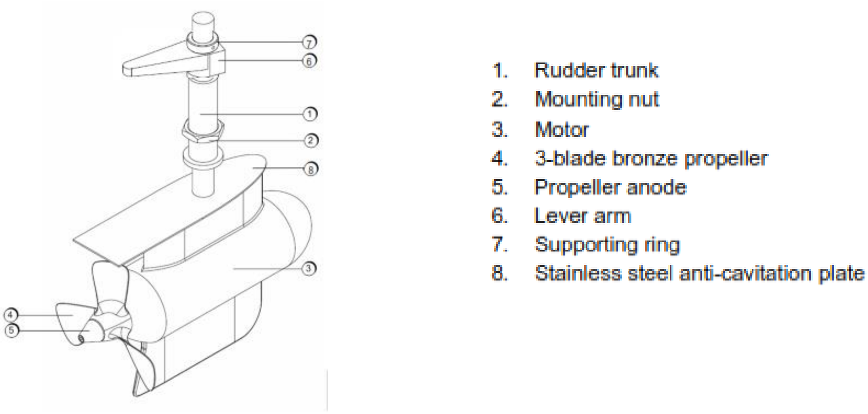

Figure 1. POD propeller

From the calculation, the results obtained are: that the value of RT is 600 (N) and V is 6.94 (m/s), then PE is 4164 (W). Furthermore, based on the calculation results the characteristics of the propulsion are obtained that: t = 0.3; w = 0.35; and ηh ≈ 1.07, while based on the available data chart for POD electrical motor the ηp is 92%. Thus the minimum power used for the motor is PM = 4230 (W).
Based on the obtained results the specifications of POD Drive Propulsion is shown in table 1, then the ship resistance was simulated using maxsurf resistance software by using slender body method. Parameter included in the simulation is 60% efficiency of hull resistance, where the results of this analysis are the relationship between motor power vs vessel velocity is presented in figure 2.

Table 1. Electric PODSEM Specification

Model	Voltage	Power	RPM	Current	Efficiency	Weight	Motor Type
UF 43	48 DC	4300 W	1550	96A	92%	27kg	Asynchronous

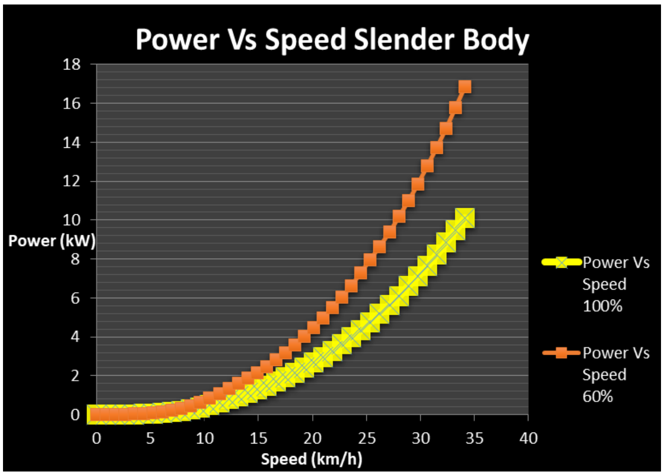

Figure 2. Power vs speed maxsurf resistance using slender body method

Using hull resistance data, the amount of power needed by each percentage used in throttle variations of the ship propulsion system was determined in order to match with the ship's operating characteristics [7]. This will follow the procedure of determining electrical current needed for motor by selected output power divided by electrical system voltage, as shown in Figure 3 and Table 2.
After determining the power, the required current of the motor, and the speed of the vessel for each variation of the throttle were obtained. The data were processed in accordance with energy

consumption procedure [8], using 60 km sailing range as targeted distance and maximum PV charging at daylight condition. With data from figure 2 and figure 3 speeds to be used to fulfill 60 km sailing range was determined, in constant speed mode, as shown in table 3 and table 4.

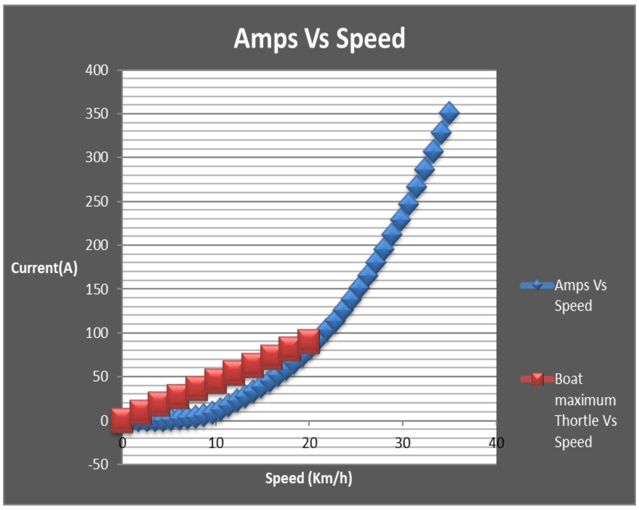

Figure 3. Amps vs speed

Table 2. Throttle variation

Throttle Percentage (%)	Current (A)	Power (kW)	Speed (km/h)
100	89.58	4300	20.67
90	80.63	3870	19.83
80	71.67	3440	18.93
75	67.19	3225	18.44
70	62.71	3010	17.96
60	53.75	2580	16.88
50	44.79	2150	15.71
40	35.83	1720	14.39
30	26.87	1290	12.96
25	22.39	1075	12.18
20	17.92	860	11.42
10	8.96	430	9.58

Table 3. Energy consumption

Speed (Km/h)	Input Current	Battery Capacity	Output Current (to motor) (A)	Throttle Percentage (%)	Battery Discharge Load(A)
	PV Panel (A)	Battery (80%) (Ah)			
20.67	21.67	26.4	89.58	100	67.92
19.83	21.67	26.4	80.63	90	58.96
18.93	21.67	26.4	71.67	80	49.99
18.44	21.67	26.4	67.19	75	45.52
17.96	21.67	26.4	62.71	70	41.04
16.88	21.67	26.4	53.75	60	32.08
15.71	21.67	26.4	44.79	50	23.13
14.39	21.67	26.4	35.83	40	14.17
12.96	21.67	26.4	26.88	30	5.21
12.18	21.67	26.4	22.395	25	0.73
11.42	21.67	26.4	17.92	20	-3.75
9.58	21.67	26.4	8.96	10	-12.71

Table 4. Energy consumption

Battery Draining Time Until 20%		**Sailed Distance (S= Vxt) (Km)**	**Distance to Travel**
Hours	**Minutes**		
0.39	23 minutes 32 seconds	8.03	51.97
0.45	27 minutes 26 seconds	8.88	51.12
0.53	32 minutes 8 seconds	10.00	50.00
0.58	35 minutes 19 seconds	10.69	49.31
0.64	38 minutes 59 seconds	11.55	48.45
0.82	49 minutes 37 seconds	13.89	46.11
1.14	1 Hour 8 minutes 27 seconds	17.93	42.07
1.86	1 Hour 51 minutes 12 seconds	26.82	33.18
5.07	5 Hours 4 minutes 2 seconds	65.69	-5.69
36.21	36 Hours 12 minutes	> 60 km	> 60 km
Battery Charging	Battery Charging	More than 60 km	>60 km
Battery Charging	Battery Charging	More than 60 km	>60 km

2.2 Steering System

The steering system to be used on solar boats is determined so that the boat can maneuver with a minimum turning angle of 40 degrees. In determining the type of steering system the compatibility with the propulsion system need to be considered, therefore the Hydraulic Steering System has been chosen, Hydraulic Steering System utilizes fluid oil from the steering wheel that passed through the cable to the actuator to move the piston, this piston movement is used to set the rudder direction on the shaft Pod propulsion by using the connecting rod [9]. Based on the trigonometric mathematical equations as shown in figure 4 and equation 4 [10].

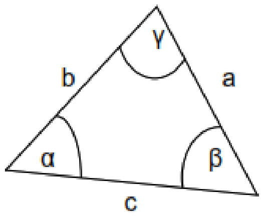

Figure 4. Trigonometric

$$\frac{a}{\sin\alpha} = \frac{b}{\sin\beta} = \frac{c}{\sin\gamma} \tag{4}$$

Since the shaft motion of the Hydraulic Actuator is only 8 cm to the right and 8 cm to the left, the required connecting rod length in this solar boat to connect between POD Propulsion with hydraulic steering actuator based on the sinus equation is obtained to be 12.4 cm. In addition, some other advantages of using a hydraulic steering system is that the force of pilot that need to turn the steering wheel and steer the ship is lighter, so that the use of space of engine room and cabin room can be reduced, and makes the mounting and maintenance much easier.

2.3 Bilge Pump System

The function of bilge pump is for disposing of water inside the vessel that come due to rain or leakage due to mounting Pod Propulsion Motor on the body of the vessel. The installation of bilge pump should be well designed to ensure the bilge pump system can be operated normally without disturbing other systems of the boat, including its capacity and operating processes. For this purpose formulas 5; 6; and 7 are being used.

$$Q_{in}\left(M^3/Hour\right) < Q_{out}\left(M^3/Hour\right) \tag{5}$$

$$Q_{in} = Q_{rain} + Q_{leakage} \tag{6}$$

$$Q = I\left(M/Hour\right) xA\left(M^2\right) \tag{7}$$

Where: Q = Flow Rate; I = Rainfall Intensity; A = Cross Sectional Area.

Based on data from MDPI Journal [11] regarding rainfall in Indonesia, the rate of rainfall intensity in Indonesia is I ≈ 2.15 (M/Hour), the water flow rate of the rainfall that goes into the cabin of vessel with area A ≈ 0.48 (M^2) is Q rain ≈ 1.03 (M^3/Hour), it is also assumed that the incoming water flow rate due to leakage into the vessel is Q leakage ≈ 0.3 (M^3/Hour) so we can get Qin = 1.33 (M^3/Hour). Based on these results it is shown that the value of Q in <Q out. For this purpose Float Switch Automatic Bilge Pump with debit Q out = 1.36 (M3 / Hour) ≈ 360 GPH is chosen, and its specification as shown in table 5.

Table 5. Bilge pump specifications

Model	GPH	Amps@12V	Amps@13.6V	Fuse	Height	Width	Weight	Hose Ø
24	360	2.1	2.5	2.5	0.5”	3/8”	0.5 lbs	¾”

The Automatic Float Switch has the function to activate or deactivate the bilge pump when the water level inside the hull reaches a certain height so that it can save the energy used from the battery.

3. Conclusion

There are 3 sub system that have been determined i.e. propulsion system; steering system; batteries and bilge pump system.

PODSEM "POD Steerable Electrical Motor" type has been chosen for the propulsion system, because it has advantages such as save space of engine room, good cooling system, easy mounting, and flexible steering, moreover it can make better maneuverability. This particular boat will able to travel 60 km in constant speed at 30% throttle opening, which provide the boat with 12.96 km/h sailing speed and sailing time up to 5 hours 4 minutes and 2 seconds.

Hydraulic type steering system has been chosen for the Steering system, because it is easy in operation, easy installation, and does not require a large space.

Finally, in the Bilge Pump System Automatic Float Switch type was chosen in order to keep the efficiency of the battery because the pump can be on / off automatically based on the height of the water inside the vessel.

With this performance, this boat will be a perfect candidate to replace common type of water recreational vehicle in Indonesia.

4. Acknowledge

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