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Performance and Vibration Analysis of Electric Outboard Propulsion using Propeller Variations Based on Experiment

Adhi Iswantoro[1)*)], Juniono Raharjo[1)], Yonathan Iwangsa Sima[1)]

[1)] Department of Marine Engineering, Faculty of Marine Technology, Institut Teknologi of Sepuluh Nopember, Surabaya, 60111, Indonesia
[*)] Corresponding Author: adhi.iswantoro@gmail.com

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Abstract

The demand for electric vehicles, including electric outboard propulsion for small ship, is on the rise due to growing environmental concerns. To optimize the performance of electric outboards, propeller selection, particularly propeller pitch, is crucial. This research evaluated the impact of varying propeller pitches 8, 9 and 12 degrees on the performance of an electric outboard propulsion. Through both laboratory and field tests, measurements of water flow velocity, energy consumption, boat speed, and vibration levels were conducted. The objective was to identify the optimal propeller pitch that maximizes propulsive efficiency and minimizes energy consumption. Results indicated that a propeller pitch of 8 degrees produced the highest water flow velocity, implying the greatest thrust. Field tests corroborated these findings, with the 8-degree pitch achieving an average speed of 10 km/h and a roundtrip time of 3.48 minutes. However, the 8-degree pitch also exhibited the highest energy consumption at 0.31366 kWh. Vibration levels were minimal across all pitches, suggesting no structural damage. These findings hold significant implications for the design and selection of electric propulsion systems in small ship, especially for patrol boats.

1. Introduction

The increasing number of electric-powered motors is attributed to growing public awareness of environmental health. This aligns with the government's initiative to promote achieving Net Zero Emission by 2050 [1]. It also correlates with the Sustainable Development Goals (SDGs) program, which aims to develop initiatives that undoubtedly contribute to building environmentally friendly technologies, as part of its agenda [2]. Through these programs, society is shifting from using fossil fuel-based energy to electric power. One example is the propulsion systems used in the maritime industry [2].

Indonesia's fishing industry is characterized by a large number of small-scale fishing vessels. In fact, these small boats, typically equipped with electric outboard propulsion, constitute the overwhelming majority of the country's fishing fleet. This aligns perfectly with the optimal application of outboard drive propulsion. According to Indonesian law, small-scale fishermen are defined as those using vessels up to 5 Gross Tonnage (GT) for their livelihood. This legal classification underscores the significance of this sector. Out of Indonesia's total 394,630 fishing boats, an astonishing 85%, or approximately 335,510 vessels, fall into the small-scale category [3].

Electric motors are devices that transform electrical energy into mechanical energy. This conversion is achieved through a fascinating interplay between magnetism and electricity. Essentially, an electric motor generates a magnetic field. When an electric current is passed through wires coiled around the motor's central shaft, this magnetic field interacts with the current, producing a force known as torque. This torque compels the shaft to rotate. The resulting rotational motion powers countless applications in daily lives [1].

Electric motors have several advantages over fossil fuel engines. For instance, they produce zero emissions, which is beneficial for the environment. Electric motors also generate low noise and vibration. Additionally, they require easy and inexpensive maintenance since they do not need regular oil changes. Moreover, electricity costs less than fossil fuel like gasoline [4].

While electric outboard propulsion offers promising environmental benefits and operational advantages, achieving their maximum performance still requires further development. Speed and energy efficiency are crucial factors for the successful operation of boats or vessels. To maximize efficiency in speed and energy consumption, choosing the right propeller is essential. Factors such as diameter, number of blade leaves, and propeller pitch are examples of specifications that influence the performance of the propeller itself. The increasing popularity of electric outboard propulsion for small boats or vessels can be attributed to their eco-friendly nature and affordable fuel costs. To achieve optimal results, selecting the right propeller pitch is crucial [5].

Propeller pitch refers to the theoretical distance a propeller would move forward in one revolution. Propeller pitch significantly impacts speed and fuel efficiency. Pitch is the translation distance traveled by the propeller in one round [6]. Propeller pitch defines the theoretical distance the propeller would travel in one revolution through water [7]. However, due to the propeller being fixed to a shaft, it doesn't physically move forward itself; rather, it impels the ship forward. The actual distance the boat moves forward in one rotation is typically less than the pitch value. In high-speed vessels, pitch ranges typically between 9 inches to 24 inches [8].

Propellers come in two common types, that are fixed pitch propellers (FPP) and controlled pitch propellers (CPP). Each type has its own advantages and disadvantages, and selecting the right type of propeller for a particular vessel depends on various factors, including vessel type, desired functionality, and operating conditions [9]. Fixed pitch propellers (FPP) are characterized by a pitch angle that cannot be adjusted. They excel in scenarios requiring constant speed, where FPPs demonstrate higher efficiency. Due to their efficiency and cost-effectiveness, FPPs are widely used in recreational boats and other vessels with general propulsion need. Controlled pitch propellers (CPP), on the other hand, offer the advantage of adjustable pitch angles, allowing for adjustments to meet specific operational requirements. This flexibility makes CPPs more efficient across various speed ranges compared to FPPs. As a result, CPPs are commonly found on vessels that require high maneuverability capabilities, such as tugboats and cruise ships [10].

Thrust is the force that propels a ship forward, overcoming the resistance of the water. A propeller is the device that generates this thrust. It's essentially a rotating underwater wing that, when turned by a prime mover, creates a force known as lift. This lift, acting on the propeller blades, pushes the ship forward [11].

With choosing the right propeller, the effectiveness of electric outboard performance increased. Such as the energy consumption. The electrical energy consumed by an electric outboard propeller is measured in kilowatt-hours (kWh). Essentially, a kWh represents the amount of electricity used in one hour. Higher kWh consumption indicates greater energy usage. Factors such as power output, speed, load, water conditions, motor efficiency, battery health, and operating style all influence the kWh consumption of an electric outboard [12].

The performance of an electric outboard drive can also be analyzed through vibrations. However, the effect of propeller variations is very small because the electric motor produces very little vibration and noise. Vibration analysis is carried out to analyze the damage that occurs on the parts of the electric outboard. Using this technique, a rotating equipment can be monitored at specific positions to assess its condition. The primary goal is to safeguard the equipment, predict potential failures, and reduce maintenance costs [13]. A lack of direct current power equipment industry and technical issues hinders the direct current power transmission. There is need development in direct current protection devices [14]. Reducing of acceleration time with adaptive pitch control strategy from 0 to 15 knots with the slam start by 32% compared to the maneuver and by 63% compared to the transit [15].

Ship propellers should be designed to maximize propeller efficiency while minimizing noise and maintaining excellent cavitation behavior. Controllable pitch propellers are widely used in ships because they are more maneuverable and do not require much energy compared to fixed-pitch propellers. They can change the propeller's thrust and direction by changing the pitch of the blades so that the ship can move forward or backward. A controllable pitch propeller VP1304 with four distinct pitch ratios, that are $P0.7/D$ = 0.635, 1.135, 1.635, and 2.135. To verify the method of this current numerical study, the hydrodynamic coefficients and cavitation behavior of the propeller are compared with the experiment. The simulated cavitation behavior essentially matches the experimental phenomena, and the average error of hydrodynamic coefficients is less than 5%. The corresponding advance coefficients at the maximum efficiency points are 0.4, 0.9, 1.4, and 1.8 when the pitch ratio of $P0.7/D$ rises from 0.635 to 2.135 [16].

The hydrodynamic performance of the propeller is intimately linked to its cavitation. Propeller cavitation lowers the propeller's hydrodynamic performance, as measured by the thrust and torque coefficients, when it operates in a cavitating flow. Propeller cavitation has a detrimental effect on propeller thrust, and this effect is strongly correlated with both the cavitation number and propeller advance ratio. Additionally, as the advance coefficient rises and the cavitation number falls, the propeller's thrust and torque will drop. Furthermore, the cavitation number increases the sensitivity of the propeller characteristic. In order to prevent increased propeller rotation speed in heavy cavitation situations, it is crucial to alter the propeller structure and control approach [17].

More accurate propulsion performance prediction is needed since the Energy Efficiency Design Index (EEDI) requirements limit the propulsion engine's capability. Propeller performance in waves is primarily influenced by the pitch and heave motions of ships. A tendency that is quite similar to the propeller performance based on the change of the fixed immersion depth is seen in the propeller performance with heave motion in calm water. Overall power and torque somewhat decreased as a result of the grids being reduced to improve numerical simulation efficiency [18].

One of the most important aspects of ship design is hull-engine-propeller matching. It significantly contributes to increasing ship navigation's economy and safety. The engine's factory acceptance test and the ship's sea acceptance test are often the foundation for hull-engine-propeller matching. Using a simulation approach, the relationship between a ship's hull, diesel engine, and propeller during self-propulsion is examined. The exterior features of the diesel engine under the influence of the hull-engine-propeller interaction are anticipated, and the interaction between the hull, diesel engine, and propeller when the ship is moving forward at different speeds is examined. Ship-engine-propeller matching is based on the findings. Additionally, it establishes the groundwork for the subsequent investigation of the relationship between the hull, engine and propeller on maneuvering [19].

The creation of ships necessitates the use of suitable mathematical models to recreate motion characteristics during ship maneuvers. The model uses a piecewise linear approximation and is based on a small set of parameters. To determine the necessary minimum parameters for a specific propeller blade angle, experiments were carried out. As a result, forces at every blade angle can be estimated by the model. The motion features of the yaw moments and sway force brought on by imbalanced hydrodynamic forces can also be simulated by the model [20].

This research examines how altering propeller pitch affects the performance of an electric outboard propulsion with a 3-kW power output. Specifically, the study quantifies the influence of propeller pitches 8, 9 and 12 degrees on water velocity, boat speed, energy consumption, and vibration levels generated by the electric outboard propulsion. For small ships or boat, which are usually using propeller with pitch 8, 9 and 12, but more often pitch 12. The propeller pitch defines the theoretical distance the propeller will travel in one revolution through the water, at a given propeller blade degree. So, with different propeller blade degree will generate different distances or pitch.

2. Methods

2.1. Tools and Materials

There are two types of experiments in this research, each of which involves slightly different equipment and materials, yet they are interconnected and interrelated. In the laboratory testing, the analysis of water flow speed produced by electric outboard propulsion with various propeller configurations requires an electric outboard as the propulsion system under investigation. The research also involves propellers with varied pitches as the objects of variation. Additionally, it necessitates batteries as the energy source for these electric outboard propulsion. Furthermore, it requires a flow meter to measure the water flow velocity as a sensor during operation, a tachometer to measure rotation per minute (RPM), a camera for documentation, and a computer for recording and data processing. In the second experiment, the direct field trial, aside from the equipment mentioned in the preceding paragraph, naturally involves a boat as the platform where the electric outboard propulsion is installed. There is also a speedometer to measure the speed generated by the boat fitted with the electric outboard propulsion. The specifications of electric outboard propulsion and boat shown in the Table 1 and Table 2. And the documentation of electric outboard propulsion and ZPRO 420 rubber boat shown in Figure 1(a) and 1(b).

Table 1. Electric outboard propulsion specification

Parameter	Value	Unit
Model	E301	-
Gear Position	Forward/Reverse	-
Type of Cooling	Nature Cooling	-
Gear Ratio	27:13	-
Rated Voltage	64	V
Rated Output Power	3	kW
Rated Running Speed	5500	RPM
Battery Capacity	100	Ah

Table 2. Boat Specification

Parameter	Value	Unit
Model	ZPRO 420	-
LOA	4.2	m
Inside Length	3.03	m
Inside Wide	0.93	m
Maximum Power	35	HP
Passengers	8	Person
Maximum Payload	850	kg
Nett Weight	85	kg

(a) (b)

Figure 1. (a) Electric outboard propulsion, and (b) ZPRO 420 rubber boat

2.2. Design Experiment

Independent Variable (Control Variable): This is the factor that the researcher actively changes or controls. It's the cause or the element being manipulated to see its effect on something else. In your example, the propeller pitch, namely 8, 9 and 12 are the independent variable. The researchers are changing the pitch to see how it affects the performance of the electric outboard propulsion.

A. Control variable in laboratory testing
- Propeller Pitch: The pitch of the propeller, defined as the distance a propeller would advance in one revolution if it were moving through a solid medium. In this research, three propeller pitches namely 8, 9 and 12 are used as the independent variable.
- Power Input: The constant power input to the electric outboard propulsion, maintained throughout the experiments. It can be adjusted by the current input which:
    a. Laboratory testing for average water velocity and Δv, the current input is 6, 12, 24, 36, 48, 60, 72, 84 and 90 Ampere.
    b. Laboratory testing for energy consumptions, the current input is 24, 60 and 90 Ampere.

B. Control variable in direct field trial
- The power input is periodic in 60 and 90 Ampere round-trip.
- Distance: is the distance during trip which is 1km.

Dependent Variable is the factor that measures and expects to change in response to the independent variable. It's the effect or the outcome being observed due to the manipulation of the independent variable. In this case, the performance metrics (water flow velocity, thrust, travel time, etc.) are the dependent variables. Measured these metrics to see how they are affected by the different propeller pitches. There are performance metrics, the performance metrics of the electric outboard propulsion, including:

A. Control variable in laboratory testing.
- Water velocity (v): The velocity of the water flowing through the propeller, measured in meters per second (m/s).
- Difference water velocity ($\triangle v$): The difference of water velocity before and after the propeller, measured in m/s.
- Energy consumption: The electrical energy consumed by the motor during the trial, measured in watt-hours (kWh).

B. Dependent variable in direct trial testing.
- Travel time: The time taken by the boat to travel a specified distance, measured in seconds (s).
- Average boat speed: The average speed of the boat during the trial, measured in m/s.

2.3. Schematic

There are two types of experiments that is open water test and trial test. In Figure 2 is shown the design experiment for open water test in laboratory.

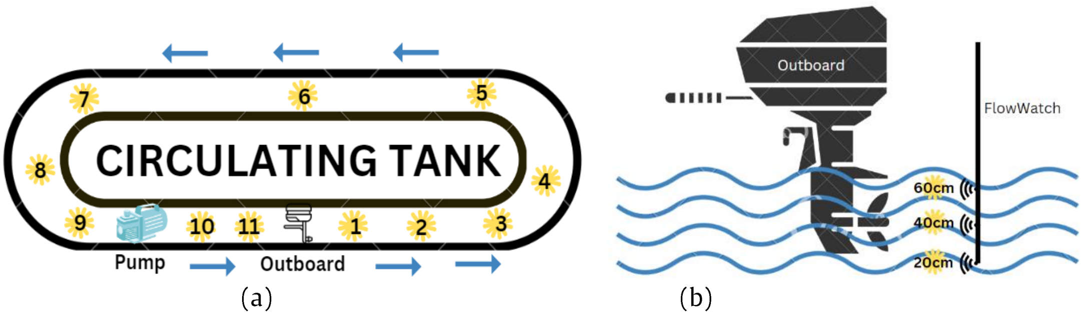

Figure 2. (a) Open water test schematic in laboratory, and (b) propulsion system set-up

There is a circulation tank or flume tank as depicted in Figure 2(a) for open water test, featuring 11 data collection points for water flow velocity. A pump is located between points 9 and 10 to increase water flow speed. The electric outboard propulsion is positioned between points 11 and 1. At each data collection point, there are three variations in height: 20 cm, 40 cm and 60 cm from the baseline of tank, shown in Figure 2(b) as propulsion system set-up.

In the direct trial test is conducted at Kalimas river in Surabaya, a boat owned by the Government of Surabaya was utilized. The route covered a round-trip distance of 1 km. Data collected included the average speed for the outbound and return journeys, as well as the round-trip travel time. Figure 3 show the route of boat on trial test in the river.

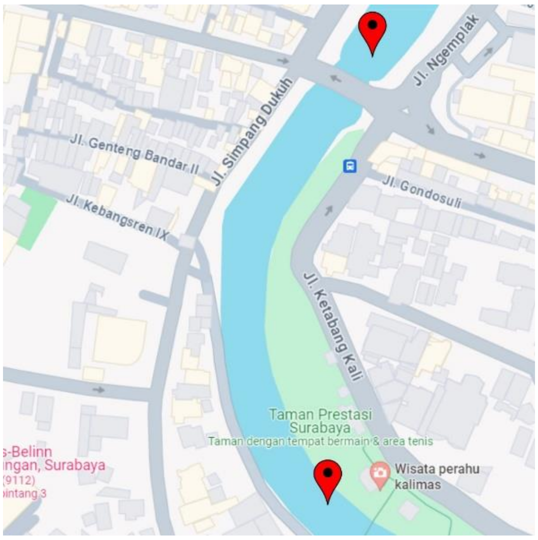

Figure 3. Trial test route

2.4. Methods of solving along with the procedures used to examine.

2.4.1. Water Flow Analysis

The research began by measuring the water velocity, a direct indicator of thrust, for different propeller pitch namely 8, 9 and 12. Various input currents, ranging from 6, 12, 24, 36, 48, 60, 72, 84 and 90 Amperes in 6-Ampere steps, were applied while keeping the voltage constant at 64 volts. The corresponding power input can be calculated using:

$$P = V \times I \tag{1}$$

Where P is power (Watt), V is voltage (Volt) and I is current (Ampere)

To determine water velocity, a flow watch was employed, as illustrated in Figure 2. Data was collected at 11 points, with the primary measurement taken at a depth of 40 cm above the base due to its consistently higher velocity readings. This depth was selected for all power inputs and propeller configurations. The rationale behind choosing a 40 cm depth is that higher water velocities correspond to increased mass flow rates, which in turn result in greater thrust.

$$T = \dot{m} \times \Delta v \tag{2}$$

Where T is thrust (N), $\dot{m}$ is mass flow (kg/s), and Δv is change of different velocity of fluids (m/s)

Furthermore, the change in water velocity before and after the propeller, denoted as Δv, was calculated at each measurement point. This Δv value directly correlates with the thrust generated, as outlined in Equation 2. This correlation is rooted in the principle of momentum conservation, which states that the change in momentum of a system is equal to the net force acting on it. In this case, a higher Δv indicates a greater change in momentum, resulting in a larger thrust force. The Δv was determined by subtracting the water velocity at point 1 from the velocity at point 11, as illustrated in Figure 2 using this equation:

$$\Delta v = v1 - v2 \tag{3}$$

Where Δv is change of different momentum fluids (m/s), $v1$ = water velocity point 1 (m/s) and $v2$ is water velocity point 11 (m/s)

2.4.2. Speed of Boat Based on Direct Field Trial

Having obtained the water velocity and Δv parameters as described in the previous subsection, then verify these findings by analyzing the speed generated by various propellers on an electric outboard propulsion attached to a boat. Using a 1.2 km roundtrip route for each propeller, the power input was adjusted from 60A for the first 300 meters to 90A for the next 300 meters. The time taken to complete the route and the average speed were recorded and calculated using the following formula:

$$Time\ to\ depart + time\ to\ arrive = Time\ to\ travel\ (minutes) \tag{4}$$

$$\frac{Speed\ to\ Depart\ (km/h) + Speed\ to\ Arrive\ (km/h)}{2} = Average\ Speed \tag{5}$$

2.4.3. Energy Consumption Based on Laboratory Testing

To determine the energy consumption of the electric outboard propulsion in this experiment, the difference in battery capacity before and after operation was measured using propeller variations which is 8, 9 and 12 with current input 24, 60 and 90 Ampere. Electric outboard running in 10 minutes in every treatment of power input. The energy consumption can use this equation:

$$\text{AH Capacity} = \text{AH}'' - \text{AH}' \quad (6)$$

Where is AH′′ is capacity after running (Ah) and AH′ is capacity before running (Ah)

Then the energy consumption can be converts in kWh using this equation:

$$\text{kWh} = \frac{(\text{AH x V}) \text{ x Time to Running (hour)}}{1000} \quad (7)$$

2.4.4. Vibration

Electric outboard propulsion generates small noise and vibration but still can recorded by the vibration meter. Vibration by the electric outboard displayed by the vibration meter monitor. The experiment used ampere variation such as 24, 60 and 90 amperes current input for every pitch of propeller such as pitch 8, 9 and 12.

3. Result and Analysis

Based on data of water velocity rate, the result of water velocity and Δv can be shows in the Table 3 for propeller pitch 8, Table 4 for pitch 9 and Table 5 for pitch 12.

Table 3. Water Velocity on Height 40 cm from Baseline (Pitch 8), in m/s

Power Input (W)	RPM	v1	v2	v3	v4	v5	v6	v7	v8	v9	v10	v11	Δv
384	1616	1.5	0.6	0.5	0.3	0.2	0.2	0.2	0.2	0.2	0.3	0.3	1.2
768	2400	1.9	0.8	0.5	0.4	0.3	0.3	0.3	0.3	0.3	0.4	0.3	1.6
1536	3800	2.6	1.0	0.5	0.5	0.3	0.3	0.4	0.4	0.4	0.6	0.4	2.2
2304	4300	3.1	1.1	0.9	0.6	0.5	0.4	0.5	0.5	0.5	0.6	0.5	2.6
3072	5200	3.3	1.6	0.8	0.6	0.5	0.5	0.5	0.5	0.5	0.7	0.6	2.7
3840	6500	3.4	1.7	0.8	0.6	0.5	0.6	0.6	0.6	0.6	0.8	0.7	2.7
4608	7000	3.5	1.8	0.9	0.5	0.6	0.6	0.7	0.7	0.7	0.9	0.8	2.7
5376	7414	3.3	1.8	0.8	0.7	0.6	0.6	0.5	0.6	0.6	0.7	0.8	2.5
5760	7600	3.1	1.5	0.9	0.7	0.6	0.6	0.6	0.6	0.6	0.8	0.8	2.3

Table 4. Water Velocity on Height 40 cm from Baseline (Pitch 9), in m/s

Power Input (W)	RPM	v1	v2	v3	v4	v5	v6	v7	v8	v9	v10	v11	Δv
384	1467	1.4	0.5	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	1.1
768	2387	1.6	0.8	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.3	1.3
1536	3000	2.5	0.8	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	2.1
2304	3989	3.0	0.9	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.6	0.5	2.5
3072	5014	3.2	1.4	0.7	0.6	0.6	0.4	0.5	0.6	0.6	0.6	0.6	2.6
3840	6497	3.3	1.6	0.9	0.6	0.7	0.6	0.7	0.7	0.7	0.8	0.7	2.6
4608	6855	3.4	1.7	1.0	0.6	0.6	0.4	0.7	0.7	0.7	0.9	0.8	2.6
5376	7300	3.0	1.7	0.8	0.7	0.6	0.6	0.5	0.7	0.5	0.8	0.8	2.2
5760	7549	2.9	1.5	0.6	0.7	0.5	0.5	0.5	0.5	0.5	0.8	0.8	2.1

Table 5. Water Velocity on Height 40 cm from Baseline (Pitch 12), in m/s

Power Input (W)	RPM	v1	v2	v3	v4	v5	v6	v7	v8	v9	v10	v11	Δv
384	1411	1.3	0.6	0.3	0.1	0.1	0.2	0.1	0.2	0.2	0.3	0.3	1.0
768	2400	1.6	0.6	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.3	1.3
1536	3100	2.3	0.6	0.3	0.4	0.3	0.3	0.4	0.3	0.3	0.4	0.4	1.9
2304	3550	2.8	0.8	0.5	0.4	0.3	0.3	0.4	0.4	0.3	0.5	0.5	2.3
3072	4000	3.1	0.8	0.6	0.4	0.4	0.4	0.4	0.4	0.4	0.6	0.6	2.5
3840	4500	3.2	0.8	0.6	0.6	0.7	0.6	0.4	0.4	0.3	0.7	0.6	2.6
4608	4700	3.3	0.9	0.7	0.5	0.4	0.4	0.4	0.4	0.4	0.8	0.7	2.6
5376	5800	2.9	1.0	0.8	0.5	0.4	0.4	0.4	0.4	0.4	0.8	0.8	2.1
5760	6400	2.8	1.2	0.8	0.6	0.5	0.5	0.4	0.5	0.5	0.7	0.8	2.0

Referring to the open water test data in Tables 3, 4, and 5, detailed analysis of the water velocity graph at point 1 can be performed. Point 1 was chosen for this analysis due to its consistently high water velocity values compared to other measurement points, and the point 1 position is behind the propeller directly, as shown in Figure 4.

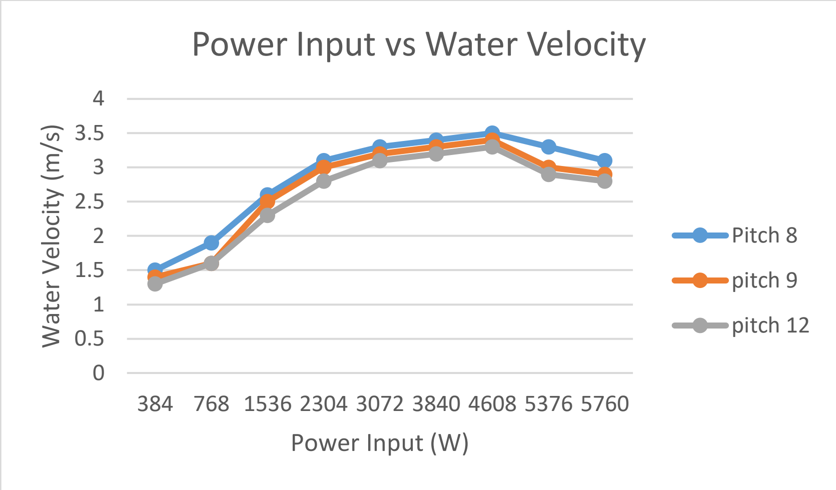

Figure 4. Graph of power input against water velocity at point 1

Figure 4 depicts the relationship between the power supplied to electric outboard propulsions equipped with different propeller pitches namely 8, 9 and 12 degrees, and the resulting water velocity. A clear positive correlation exists, indicating that water velocity for all propeller types increases as power input increases. In essence, there is a direct proportional relationship between power and water velocity. A closer examination of Figure 4 reveals that the propeller with a pitch 8 demonstrates the most rapid increase in water velocity as power input rises. This implies that for a given power level, a propeller with an 8-degree pitch generates the highest water velocity, leading to greater boat speed. Conversely, the propeller with a pitch 12 shows the least increase in water velocity for the same power input, resulting in lower overall speed and thrust.

Based on Equation 2, higher water velocity higher mass flow. Higher mass flow higher thrust. So, based on Equation 2 pitch 8 generates highest value of water velocity rate constantly in every single power input. Based on Δv, the graph in Figure 5 can be shows to analyze.

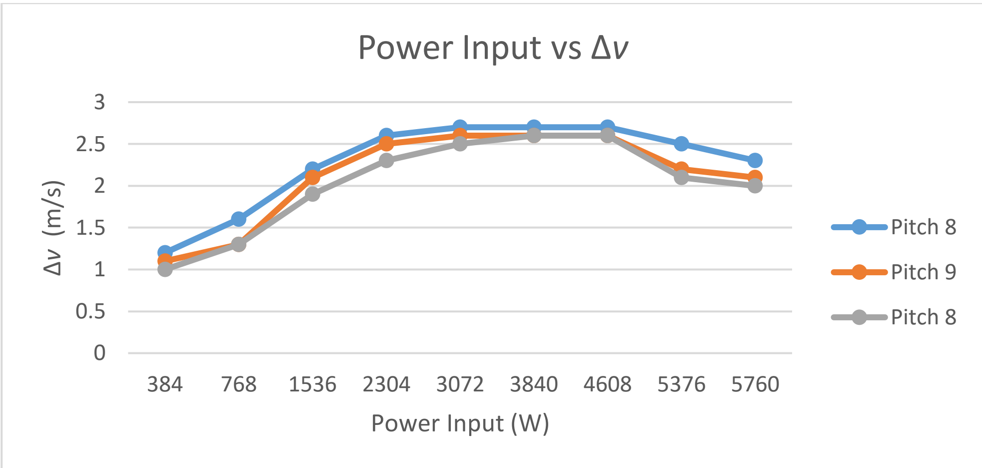

Figure 5. Graph of power input against Δv

Figure 5 showing the impact of different propeller pitches on water momentum or Δv. The data reveals a positive correlation between power input and the resulting change in Δv or difference water momentum. Momentum law said that the value of difference of momentum fluid in a system equal with the force at that system. Propellers with a pitch 8 consistently induced the greatest change in Δv or water momentum. This directly translates to higher thrust generation for the pitch 8 propeller when installed on the electric outboard compared to the other tested propellers. Consequently, based on these findings, a propeller with an 8-degree pitch is optimal for achieving maximum speed.

Equation 2 supports the observed relationship between the change in water momentum and thrust generation. At a power input of 384 watts, the pitch 8 propeller produced a change in water momentum of 1.2 m/s, exceeding the values obtained for the pitch 9 with 1.1 m/s and pitch 12 with 1 m/s propellers. This directly corresponds to higher thrust generation by the pitch 8 propeller. Furthermore, this trend is consistent across different power input levels, as demonstrated by throttle adjustments during the laboratory testing.

Having obtained water velocity data for each propeller and power input level, the next step involved conducting field trial on a boat in the Kalimas river. The primary objective was to validate the laboratory test results under real conditions and compare the performance of the electric outboard propulsion with different propeller configurations. Table 6 show the trial data of electric outboard propulsion, namely time to travel and boat speed.

Table 6. Result of total time to travel and average speed

Pitch Propeller Variation	Time to Travel (minute)			Speed (km/h)		
	Round Trip		Total Time	Round Trip		Average Speed
	Depart	Arrive		Depart	Arrive	
8	1.26	2.22	3.48	11.5	8.5	10
9	1.50	2.35	3.85	10.5	7.5	9
12	2.16	2.42	4.58	9.5	6.5	8

Based on data in Table 6, the result of time to travel and average speed can be shows as the graph in Figure 6 to analyze.

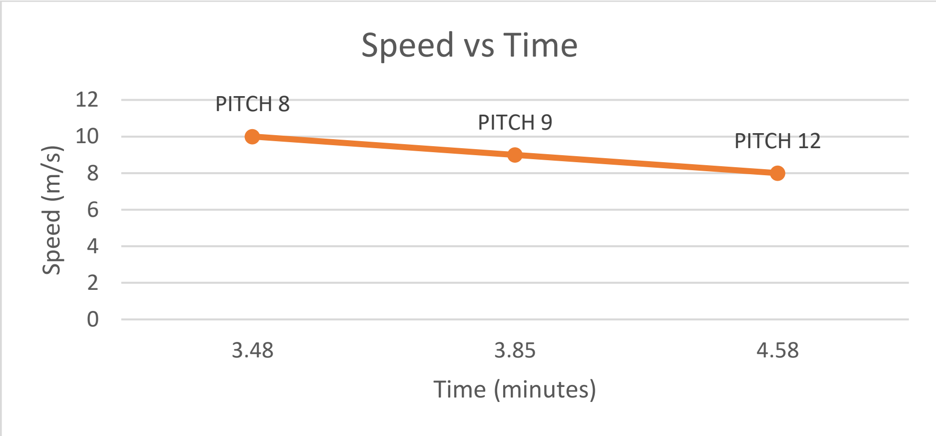

Figure 6. Graph of time to travel against speed of boat in roundtrip

The Figure 6 showing that speed-time of the electric outboard equipped with a pitch propeller 8 achieved the fastest roundtrip time of 3.48 minutes and a maximum average speed of 10 km/h. These results highlight the 8-pitch propeller as the optimal choice for boats, which prioritize rapid response times. In contrast, the electric outboard with a pitch propeller 12 recorded a travel time of 4.58 minutes and an average speed of 8 km/h. This slower performance renders the 12-pitch propeller unsuitable for boats, where speed is a critical factor. The superior performance of the 8-pitch propeller can be attributed to its ability to generate higher RPM due to its lower pitch angle especially for this research. Then the laboratory and direct field trial generate same result which is propeller pitch 8 produce highest speed.

The other performance that can be analyze in electric outboard is the effect of propeller variations to the energy consumption of electric outboard. The result of energy consumption shown in Table 7.

Table 7. Energy Consumption

Pitch Propeller Variations	P Input (W)	Running Time (minute)	Ampere -hour (Ah)	Voltage (V)	Energy (kWh)	Cost	Total Cost per 0.5 hour
Pitch 8	1536	10	4.1	64	0.04374	Rp 74	Rp 539
	3840	10	10.4	64	0.11096	Rp 189	
	5760	10	15.2	64	0.16217	Rp 276	
Pitch 9	1536	10	4.1	64	0.04374	Rp 74	Rp 531
	3840	10	10.1	64	0.10775	Rp 183	
	5760	10	15.1	64	0.16110	Rp 274	
Pitch 12	1536	10	4.1	64	0.04374	Rp 74	Rp 525
	3840	10	9.9	64	0.10562	Rp 179	
	5760	10	15.0	64	0.16003	Rp 272	

From data in the Table 7, can be served as the graph in Figure 7 to analyze correlation between the power input against energy consumption.

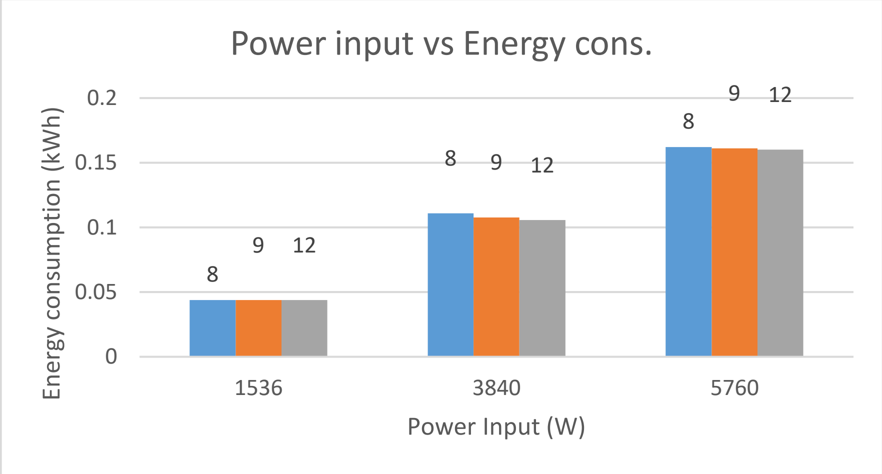

Figure 7. Graph of power input against energy consumption in kWh

Figure 7 showing the correlation between energy consumption and power input. In terms of energy efficiency, the propeller with a 12-degree pitch outperforms both the 8 and 9-degree pitches. For instance, at a power input of 3840 watts, the 12-pitch propeller consumes 0.106 kWh, whereas the 8 and 9-pitch propellers consume 0.110 kWh and 0.108 kWh, respectively. A similar trend is observed at a power input of 5760 watts, with the 12-pitch propeller demonstrating lower energy consumption. Given that higher energy consumption translates to increased costs, the 12-pitch propeller's efficiency becomes a significant advantage. This improved efficiency can be attributed to the propeller's ability to achieve the desired thrust with fewer revolutions due to its higher pitch angle.

Electric outboard propulsions generate minimal noise and vibration, although these can still be measured using a vibration meter. The present study employed a vibration meter to quantify the vibrations produced by electric outboards under varying conditions. Current inputs of 24, 60 and 90 amperes were tested for each propeller pitch, namely 8, 9 and 12 degrees. The resulting vibration data for each propeller configuration is presented in Table 8.

Table 8. Vibration Measurement Data

Pitch Propeller	Current Input (A)	Power Input (Watt)	Vibration (mm/s)
Pitch 8	24	1536	0.3
	60	3840	0.3
	90	5760	0.4
Pitch 9	24	1536	0.3
	60	3840	0.4
	90	5760	0.4
Pitch 12	24	1536	0.4
	60	3840	0.4
	90	5760	0.4

Then, the result of vibration measurement shown in the Figure 8 to analyze correlation between the power inputs from battery to supply electric motor propulsion against the vibration that produce by electric motor.

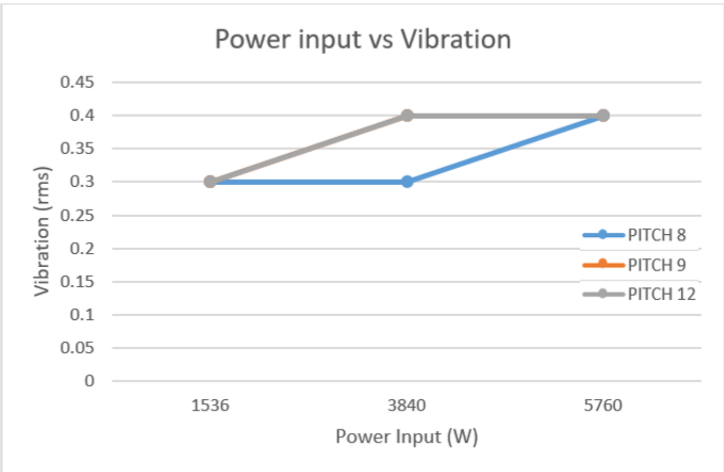

Figure 8. Graph of power input against vibration

Figure 8 provides a comprehensive analysis of the correlation between power input, vibration levels, and propeller pitch under operating conditions. As anticipated, there is a direct relationship between power input and vibration magnitude, aligning with the fundamental principles of mechanical vibration.

Surprisingly, the influence of propeller pitch on vibration levels was found to be negligible, between 0.3 mm/s - 0.4 mm/s. This observation is consistent with the general understanding that electric motors generate significantly less vibration compared to internal combustion engines, especially reciprocating type. The inherently quiet operation of electric outboards is a key factor contributing to their popularity in applications requiring minimal noise and vibration. The study emphasizes that vibration in electric outboards is primarily attributed to component wear, such as bearing degradation. Consequently, regular maintenance and inspections are crucial for preserving optimal performance and extending the lifespan of these systems.

4. Conclusion

The research aims to analyze the performance of electric outboard using propeller as a variation in the several treatments. The research demonstrates a strong correlation between propeller pitch, water flow velocity, and the change in velocity (Δv). Among the tested pitches of 8, 9 and 12, the 8 pitch consistently produced the highest water velocity. The result of propeller test with low power input 384 W, for 8 pitch propeller producing water velocity 1.2 m/s, for 9 pitch propeller producing water velocity 1.1 m/s and for 12 pitch propeller producing water velocity 1.0 m/s. The result of propeller test with high power input 5760 W, for 8 pitch propeller producing water velocity 2.3 m/s, for 9 pitch propeller producing water velocity 2.1 m/s and for 12 pitch propeller producing water velocity 2.0 m/s.

For the direct field trial as the prove of laboratory testing confirmed the positive correlation between propeller pitch, travel time, and average boat speed. The trial result for 8 pitch propeller achieved the fastest roundtrip time with total travel time is 3.48 minutes and average speed is 10 km/h. The trial result for 9 pitch propeller achieved the fastest roundtrip time with total travel time is 3.85 minutes and average speed is 9 km/h. The trial result for 12 pitch propeller achieved the fastest roundtrip time with total travel time is 4.58 minutes and average speed is 8 km/h.

The The study revealed a clear relationship between propeller pitch and energy consumption. Higher power input results in a higher value of energy consumption. The trial result for the 8-pitch propeller achieved energy consumption of 0.04374 kWh, 0.11096 kWh, and 0.16217 kWh with power inputs of 1536 W, 3840 W, and 5760 W. 9 pitch propeller achieved the energy consumption of 0.04374 kWh, 0.10775 kWh, and 0.16110 kWh with power inputs 1536 W, 3840 W, and 5760 W. And for 12 pitch propeller achieved the energy consumption of 0.04374 kWh, 0.10562 kWh, and 0.16003 kWh with power input 1536 W, 3840 W, and 5760 W.

The vibration measurement result is consistent with the general understanding that electric motors generate significantly less vibration than internal combustion engines, especially reciprocating engines. The vibration values for 8 pitch propellers are 0.3 mm/s, 0.3 mm/s, and 0.4 mm/s with power inputs 1536 W, 3840 W, and 5760 W. For 9 pitch propellers are 0.3 mm/s, 0.4 mm/s, and 0.4 mm/s with power inputs 1536 W, 3840 W, and 5760 W. And for 12 pitch propellers are 0.4 mm/s, 0.4 mm/s, and 0.4 mm/s with power input 1536 W, 3840 W, and 5760 W.

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References

[1] R. A. Aprilianto and R. M. Ariefianto, "Peluang Dan Tantangan Menuju Net Zero Emission (NZE) Menggunakan Variable Renewable Energy (VRE) Pada Sistem Ketenagalistrikan di Indonesia",*Jurnal Paradigma: Jurnal Multidisipliner Mahasiswa Pascasarjana Indonesia*, vol. 2, no. 2, pp. 1–13, 2021.

[2] I. Desti, "Literature RIview: Upaya Energi Bersih dan Terjangkau", *Jurnal Sains Edukatika Indonesia*, vol. 4, no. 1, pp. 8–11, 2022.

[3] S. H. Kim, "Electric Motor Control", *Elsiever*, 2017.

[4] H. işler, "Comparison of Electric (EV) and Fossil Fuel (Gasoline-Diesel) Vehicles in Terms of Torque and Power", 2023, available: https://www.researchgate.net/publication/370553199

[5] A. D. Firmansyah, A. Santoso, D. E. Djatmiko, "Perancangan Controllable Pitch Propeller pada Kapal Offshore Patrol Vessel 80 (OPV80)", *Jurnal Teknik ITS*, vol. 1, no. 1, pp. 230–233, 2012.

[6] R. M. Khozin, I. S. Arief, and T. Bambang, "Pengaruh Variasi Pitch Terhadap Kinerja Ducted Contra Rotating Propeller Dengan Pendekatan CFD", Undergraduate Thesis ITS, 2016.

[7] M. N. Habib, E. R. De Fretes, and S. T. A. Lekatompessy, "Pengaruh Kemiringan Poros Baling-Baling Terhadap Kecepatan Perahu Ketinting", *ALE Proceeding*, vol. 4, pp. 18–22, 2021.

[8] E. Gatete, H. M. Ndiritu, and R. Kiplimo, "A Review on Marine Propeller Performance of High Speed Boat Running on an Outboard Engine", *Proceedings of the Sustainable Research and Innovation Conference*, 2018.

[9] I. M. Ariana, A. Iswantoro, S. A. Fitri, "Combining Optimum Propeller Design on Roro Ship Re-engine", *Kapal: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan*, vol. 20, no. 2, pp. 201-213, 2023.

[10] R. Fauzirahman, "Analisa Pengaruh Propeller Coating Terhadap Kavitasi," Undergraduate Thesis ITS, 2018.

[11] A. Shaikh, "Study of Propeller Design Parameters", *ICITDCEME' 15 Conference Proceedings*, 2014.

[12] D. Satria, R. Lusiani, H. Haryadi, I. Rosyadi, and A. Fauzi, "Analisa Perhitungan Energi Listrik Pada Sepeda Listrik Hybrid", *Jurnal Mesin Teknolog*, vol. 11, no. 1, pp. 9–19, 2017.

[13] D. Bagus Setyawan and Sufiyanto, "Metode Vibration Analysis Dalam Aplikasi Perawatan Mesin", *Transmisi*, vol. 9, no. 2, pp. 921–930, 2013.

[14] C. Nuchturee, Tie Li, H. Xia, "Energy efficiency of integrated electric propulsion for ships – A review", *Renewable and Sustainable Energy Reviews*, vol. 134, pp.1-25, 2020.

[15] R. D. Geertsma, K. Visser, R. R. Negenborn., "Adaptive Pitch Control for Ships with Diesel Mechanical and Hybrid Propulsion", *Applied Energy*, vol. 228, pp. 2490-2509, 2018.

[16] W. Zhu, Z. Li, R. Ding, "Effect of Pitch Ratio on The Cavitation of Controllable Pitch Propeller", *Ocean Engineering*, vol. 293, pp. 1-17, 2024.

[17] Q. Tan, Y. Ding, C. Sui, L. Xiang., "Effects of Propeller Cavitation on Ship Propulsion Performance in Off-Design Operating Conditions", *Ocean Engineering*, vol. 313, pp. 1-16, 2024

[18] M. J. Eom, K. J. Paik, Y. H. Jang, J. Y. Ha, D. W. Park, "A Method for Predicting Propeller Performance Considering Ship Motion in Regular Waves", *Ocean Engineering*, vol. 232, pp. 1-12, 2021.

[19] J. Z. Liu, Z. J. Zou, H. P. Guo, C. Z. Chen, "A Study on The Interaction Among Hull, Engine and Propeller During Self-Propulsion of a Ship", *Ocean Engineering*, vol. 286, pp. 1-15, 2023.

[20] H. Koike, Y. Noborio, S. Wada. A. Maki, "A Simplified Piecewise Linear Characteristic Model of Controllable Pitch Propeller Considering Unbalanced Hydrodynamics Force", *Ocean Engineering*, vol. 298, pp. 1-13, 2024.