Dynamic Evaluation of Electric Propulsion System Performance of Unmanned Aerial Vehicle (UAV)

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***Abstract*— Unmanned Aerial Vehicle (UAV) propulsion system is significantly related to the UAV's flight performance as it is the core of UAV power produced. Propulsion systems include energy sources and power units such as engines and motors. Electric motors are used to generate thrust, which the thrust produced can affect the UAV performance. Thus, this study aims to investigate the best combination of electric motors and propellers for UAVs for high efficiency of thrust production. The experimental work involved electric motors and various small-scaled propellers (fixed and folding) with diameter ranges between 10 to 15 inches using a subsonic speed open loop wind tunnel. The wind tunnel was set to various speeds (0 m/s to 15m/s) to investigate the effects of static and dynamic thrust produced. Then, the efficiency of each motor and propeller combination is calculated based on the thrust produced and the best combination is determined. The significance of this work is to provide a reference when selecting a particular combination propeller (fixed or folding) and motors for specific uses of UAVs with the highest efficiency. As a result, a fixed propeller is proven to be more efficient than a folding propeller based on the thrust produced.**

Keywords— Unmanned Aerial Vehicle (UAV), propulsion system, efficiency motor and propeller combination, static and dynamic thrust, motor, and propeller

I. Introduction

Unmanned Aerial Systems (UAS) are defined as systems that do not carry a human operator but instead fly autonomously or are remotely piloted [1]. The equipment involved in UAS includes the command, control, and communications system. Unmanned aerial vehicles (UAVs) are classified according to size and flight speed [2]. Classification based on the size includes the mini, micro, and nano scales, whilst the flight speed includes low-speed, subsonic, transonic, supersonic, and hypersonic. Miniature UAVs are as having the smallest range and flying height. Long-endurance solar-electric UAVs are known as solar-powered UAVs. This type of UAV can fly for longer due to the combination of solar cells and batteries that are used to power the UAV. Solar-powered UAVs are environmentally friendly, and have a high-flying height, stability, a vast coverage area, and an extraordinary load capacity [3][4].

UAVs have witnessed exponential growth in their applications across numerous industries, such as the delivery of goods and medical supplies, monitoring, farming, search and rescue mission and surveying [5], taking advantage of their compact size and ease of operation. In recent years, UAVs can fly in increased ranges with advanced technology, such as battery technology improvements, autopilot systems' increased independence, and efficient electrical propulsion systems. Thus, advanced technologies made these applications possible [6]. Developing various UAV technologies is vital for countries in worldwide to accommodate the diverse mission requirements.

The core of the UAV power is the propulsion system that generates thrust, which allows the UAV to be controlled and to hover in the air. Propulsion system components are included electric motors [7], electronic speed controllers (ESCs) [8], power sources, and control systems that allow for efficient operation [9]. The propulsion system can be classified into three groups such as fuel, hybrid (fuel-electric), and electric [2]. Electrical energy is converted into mechanical energy by the electric motor, thus rotating the propeller to generate the required power for the UAV. A propeller is used to increase the speed of a large volume of air by converting the rotational energy of the shaft into forward motion. The propeller efficiency is determined based on the propeller's ability to convert engine torque into axial trust [10].

Thrust is the force that propels an aircraft through the air [11][12]. In order to accelerate the aircraft by increasing engine power and propeller rotations, thrust must be greater than drag. To propel the plane forward, air will accelerate across the propeller blades, creating a significant pressure differential. These characteristics will influence the propeller performance, producing static or dynamic thrust. Static thrust refers to the forward or reverse thrust produced by the propulsion system while the aircraft is stationary. The significance of static thrust is to establish a thrust model using static thrust data to estimate takeoff and landing distance and time [13]. Dynamic thrust is defined as the differential between the slipstream velocity of the air through the rotating propeller and the forward velocity of the aircraft to the air moving around the aircraft. The drag and dynamic thrust data can disclose an aircraft's top speed, most efficient cruising altitude, and other performance characteristics [11]. The experimental work that has been done by the Z. Sahwee et al. regarding the drag assessment can be referred in reference [14].

Two types of propellers involved in this experimental work which are fixed and folding propellers. A fixed propeller has the simplest design, and the angle of attack is fixed and not allowed to change during aircraft operation. The blade angle compromises the optimum pitch for takeoff, climb and cruise [15]. The propeller is connected to the engine mechanically, and its rotational speed depends on the engine speed. The pitch of the propeller is determined by two main variables which is the UAV's airspeed and RPM of the UAV's motor [16]. On the other hand, a folding propeller blade is used to provide thrust at various required flight conditions. When the propeller is not used, it will reduce the propeller drag by aligning the blade length with the freestream flow [17].

This paper aims to study the evaluation of propulsion system performance based on the propeller and motor combination. The experimental work focuses on the thrust produced using the wind tunnel, and the efficiency of each propeller and motor combination will be calculated. Lastly, it demonstrates which propeller is more efficient, either fixed or folding.

II. EXPERIMENTAL SETUP

For this experimental work, the main components used are listed in Tables I, II and III below. The choice of various ranges and sizes of propellers are used in the application of long duration monitoring and the weight of the solar powered UAV maximum is 2 kilograms.

TABLE I. THE COMPONENTS INVOLVED FOR THE EXPERIMENTAL WORK

Components	*Number*
Propeller	15
Electric motors	3
Electronic Speed Controller (ESC)	1
Lithium Poli (LiPo) battery	1
RCbenchmark 1520 series thrust stand	1
Subsonic low speed open loop wind tunnel	1

Fig. 1: The fixed propeller (left) and folding propeller (right) used for the experimental work

TABLE II. THE DESCRIPTION OF FIXED AND FOLDING PROPELLER BASED ON THE DIAMETER AND PITCH.

	Fixed propeller		**Folding propeller**	
	Diameter (inch)	*Pitch (inch)*	*Diameter (inch)*	*Pitch (inch)*
1	10	6	10	6
2	10	7	11	6
3	11	7	11	8
4	12	6	12	6.5
5	12	8	13	6.5
6	13	6.5	13	8
7	14	7	14	8
8	15	8		

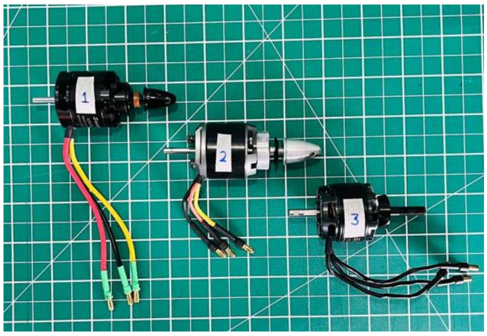

Fig. 2: Three different motors (brand and model) used in this experimental work

TABLE III. THE BRAND AND MODEL USED FOR THE MOTOR IN THE EXPERIMENTAL WORK

No.	**Brand**	**Model**
1.	SunnySky	SunnySky X2814-7
2.	NTM	NTM Prop Drive Series 35-36A 910Kv / 350W
3.	T-Motor	T-Motor AS2814 Long Shaft

The propulsion system performance was investigated by measuring the power consumption of three electric motors and fifteen various small-scaled propellers (fixed and folding) ranges of 10 to 15 inches in diameter. The propellers used in this experimental work are shown in Fig. 1, whilst the motors are shown in Fig. 2. The measurements were conducted in the subsonic low-speed wind tunnel with various wind speeds to imitate the natural wind as shown in Fig. 3. Open circuit tunnels are used due to low cost, resistant to temperature fluctuations and significant disturbances in return flow. The open loop tunnel draws air from the environment and then release it into the same environment. The drawback of this system is frequently impacted by the external weather, particularly the wind.

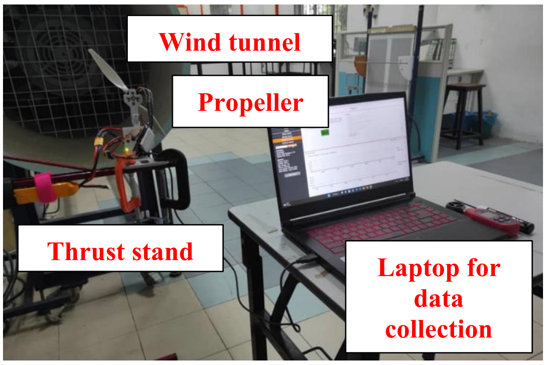

Fig. 3: The setup for the measurement of thrust produced by the fixed and folding propeller conducted in wind tunnel

The preliminary static and dynamic thrust experiment was initially performed at various wind speeds, starting from 0 m/s (static), 2 m/s, 4 m/s, 6 m/s, 8 m/s, 10 m/s, and 12 m/s. The results obtained from the preliminary experimental work were analyzed, and the best combination of the propeller (fixed or folding) and the motor was chosen to run in the wind tunnel with various wind speeds varying from 10 m/s to 15 m/s. The data obtained from the experiment were recorded using RCbenchmark open-source software that provides users with simple control and data recording.

Series 1520 thrust stand is a propulsion testing tool for analyzing the UAV propulsion system for thrust below 5kgf. The test stand provides an excellent method for gathering necessary data, which can be operated manually or automatically using any modern desktop operating system, including Windows, Linux, Mac OS, and Chrome OS. RCbenchmark is the software that runs on the test stand, and communicates with the computer through a Universal Serial Bus connection (USB). The collected data are plotted using MATLAB software. Pre-written test scripts can also be edited to measure the thrust, voltage, current, rpm, and overall efficiency. The static thrust can be calculated by determining the power transmitted to the propellers using the motors in revolutions per minute (rpm). Equation 1 is the formula used to obtain the efficiency.

$$(kgf/W)*1000 \qquad (1)$$

Using static thrust calculations, the overall efficiency is calculated to determine the best combination of electric motors and propellers (fixed and folding). It is important to note that the final static thrust calculations are estimates rather than actual values. To fly the UAV at specific velocity, the power system of this UAV must produce a net thrust equal to drag as shown in equation 2 [18].

$$T_R = D = q_\infty S C_D \qquad (2)$$

where the T_R = required thrust, D = drag, q_∞ = dynamic pressure, S = wing area and C_D = coefficient of drag

III. Result and Discussion

This section presents and discusses the experimental data that was conducted in the open loop tunnel. From eight fixed propellers and seven folding propellers with different sizes that has been tested in the preliminary experimental work, the best three fixed and folding propellers in terms of efficiency were chosen as samples in the second experiment. The three fixed and foldable propellers of various diameters (12, 13 and 14 inches), were compared with various wind speeds(10 m/s, 13 m/s, and 15 m/s). Fig. 4 shows the thrust and efficiency produced by a) fixed propeller and b) folding propeller and the wind speed was set at 10 m/s and the throttle level was increased. The thrust was set to 0 kg and increased slightly until 1 kg. Based on the thrust's results, the 13-inch fixed propeller produced the highest thrust but had the lowest efficiency. The 12-inch fixed propeller is the highest efficiency but has the lowest thrust. The efficiency of folding propellers was reduced from 6.0 to around 3.0 kg/W. The 14-inch folding propeller produced the most thrust but had the lowest efficiency. The slope of the graph that depicts the efficiency of the 14-inch folding propeller is steeper than that of another propeller. The 13-inch folding propeller has the highest efficiency at 10m/s wind speed.

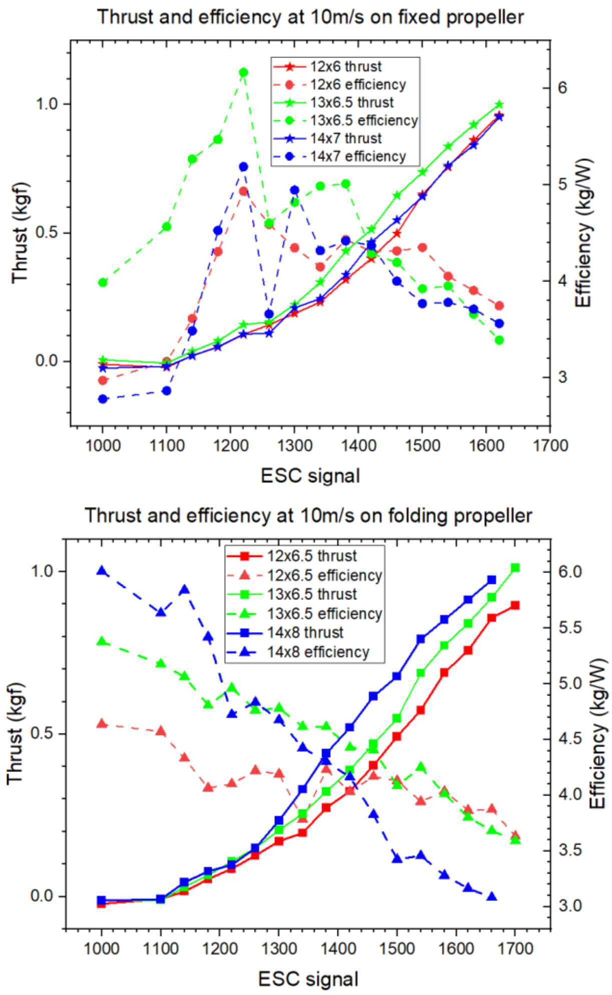

Fig. 4: Thrust and efficiency graph at 10 m/s wind speed for a) fixed propeller and b) folding propeller.

Next, using the same experimental, the wind speed is increased to 13m/s. The 14-inch fixed propeller produced the highest thrust but was the least efficient, as seen in Fig. 5a). However, the 12-inch fixed propeller has the highest efficiency results. The graph in Fig. 5b) shows the force value increases from 0 kg to nearly 0.9 kg. The efficiency decreases from 6.0 kg/W to around 3.0 kg/W over the throttle percentage. The 14-inch folding propeller produced the highest thrust but the least efficiency whilst the 12-inch diameter has the highest efficiency.

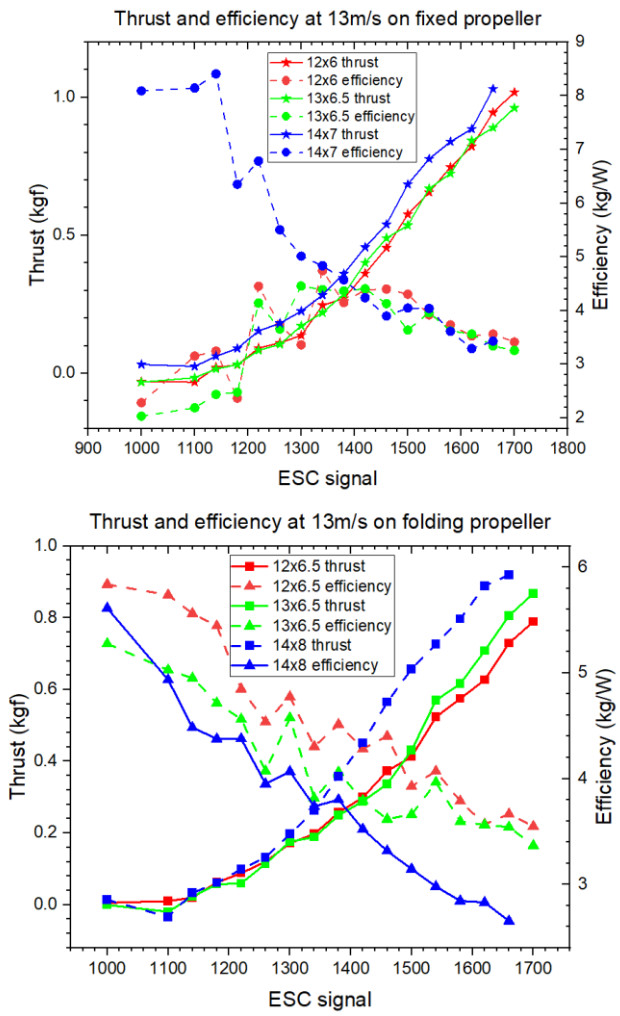

Fig 5: Thrust and efficiency graph at 13 m/s wind speed a) Fixed propeller b) Folding propeller

Fig. 6 below shows the thrust and efficiency produced by a) the fixed propeller and b) the folding propeller when the wind speed is set to 15 m/s. The thrust data show that the 13-inch fixed propeller produces the most thrust but the least efficient. The 12-inch fixed propeller, on the other hand, provides the highest efficiency results. Each propeller's thrust increases from 0 kg to around 0.9 kg. The efficiency reduces the same as other wind speed settings. The folding propeller with 14 inches produced the most thrust but was the least efficient and the 13-inch has the highest efficiency.

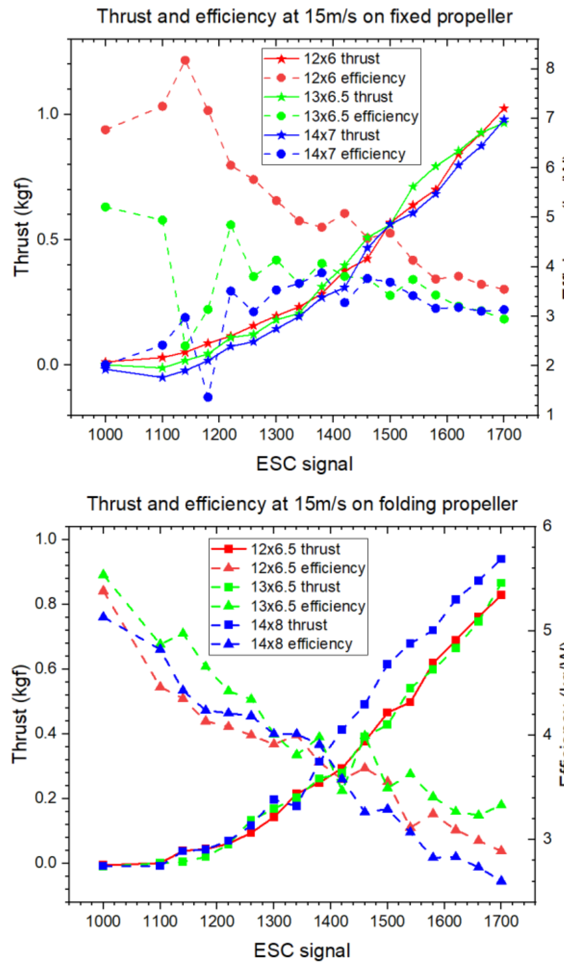

Fig. 6. Thrust and efficiency graph at 15 m/s wind speed a) Fixed propeller b) Folding propeller

Table IV shows the overall result for propeller efficiency at various wind speeds, which are 10 m/s, 13 m/s, and 15 m/s. The 13-inch folding propeller has the highest efficiency, followed by relatively 12-inch and 14-inch folding propellers. The solar-powered UAV requires a minimum of 0.5 kg of thrust to fly, and all the folding propellers could achieve between 0.8 to 1.0 kg of thrust, sufficient to provide lift for the solar-powered UAV. Thus, all the folding propellers are suitable to use for solar-powered UAVs. Only the power consumption of the propellers will be varied for the efficiency that determines the UAV performance. Overall, the graph of the combination of NTM motor and 12-inch fixed propeller was the most efficient compared to the other two motors and propellers.

TABLE IV. THE RESULT FOR FOLDING PROPELLER SIZE WITH VARIOUS WIND SPEED.

Types of Propellers	**Propeller size**	**Wind speed**			**Overall result**
		10 m/s	***13 m/s***	***15 m/s***	
Fixed propeller	12 x 6	1st	1st	1st	Highest
	13 x 6.5	3rd	2nd	3rd	Moderate
	14 x 7	2nd	3rd	2nd	Lowest
Folding propeller	12 x 6.5	2nd	1st	2nd	Moderate
	13 x 6.5	1st	2nd	1st	Highest
	14 x 8	3rd	3rd	3rd	Lowest

It has been proven that the folding propeller 13-inch has the highest efficiency when the wind speed is set to 10 m/s and 15 m/s and is the most suitable folding propeller for the solar-powered UAV. The 14-inch propeller has the lowest efficiency and is unsuitable for solar-powered UAV operations. The design affects the performance of a folding and fixed propeller. Generally, fixed propellers are typically better in efficiency than folding propellers. This is because a folding propeller can be folded in and out of the hub, thus generating more vibrations than a fixed propeller of the same size and diameter. Folding propellers are used for space-saving capabilities and break resistance due to the folding mechanism.

To verify this hypothesis, the 13-inch folding propeller and the 12-inch fixed propeller were compared. Fig. 7 shows the 12-inch fixed propeller requires 65% of the throttle percentage to generate 0.5 kg of thrust, while the 13-inch folding propeller requires approximately 72% throttle percentage to generate the same thrust. Thus, the 12-inch fixed propeller had a higher efficiency. According to the graph, increasing the throttle percentage will increase the amount of thrust being produced but reduce efficiency. The amount of thrust produced is proportional to the throttle percentage, whereas the efficiency is inversely proportional to the throttle percentage. Therefore, it has been proven that the 12-inch fixed propeller is more efficient than the 13-inch folding propeller.

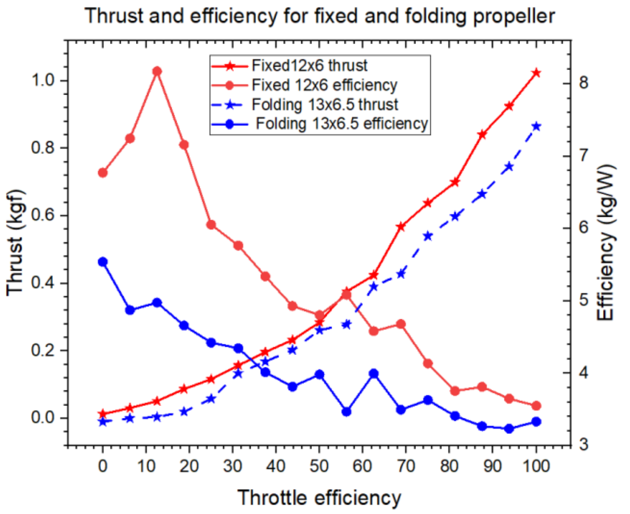

Fig. 7: Thrust and efficiency comparison between fixed and folding propeller

IV. Conclusion

This study investigated the importance of reliable propulsion system by having an efficient thrust production components to generate lift with relatively low power consumption. The combination of propeller and motor will affect the UAV performance. Hence, this study was conducted to determine the best propeller to be used for the solar-powered UAV. The data obtained shown that the 12-inch fixed propeller has higher efficiency compared to the 13-inch folding propeller. The result of this study indicates that fixed propeller performs better in terms of efficiency. However, folding propellers can be folded, thus enable to save space compared to fixed propeller and break-resistance due to its nature and cost-saving. The finding of this work is best only for specific diameter ranges (10 to 15 inches) and certain wind speeds (0 - 15 m/s). Thus, for the further work, flight test will be conducted using the best combination propeller.

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