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e-ISSN: 2689-4934

ESTEEM Academic Journal Vol 20, September 2024, 53-64

ESTEEM Academic Journal (EAJ)

Design selection of experimental test rig for static thrust on micro size propeller using Pugh method

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ARTICLE INFO

Article history:
Received 18 June 2024
Revised 5 August 2024
Accepted 21 August 2024
Online first
Published 25 September 2024

Keywords:
Static thrust test rig
Propeller Thrust Measurement
Micro sized propellers
Pugh Method
Aircraft Propeller testing
Test rig analysis

DOI:
10.24191/esteem.v20iSeptember.1754.g1707

ABSTRACT

This paper aims to propose a simple, straightforward, yet robust test rig design to measure the static thrust magnitude for small propellers. Although there were advanced tools like multi-axis force or torque sensors, sophisticated equipment and complex mechanisms were required to capture the accurate thrust magnitude. Therefore, providing simple and effective test rig design for small-sized propellers is quite challenging. In this work, Pugh matrix analysis was used to evaluate three new designs of Propeller Thrust Measurement Rig (PMTR) and compare the designs against a benchmark model. The evaluation covered important design criteria during test operation, such as measurement accuracy, stability, ease of development, assembly, maintenance, versatility, electronic integration, airflow interference, adaptability for tilt angle studies, and resemblance to multicopter flight conditions. The results reveal that the PMTR-1 design scored the highest in the analysis and emerged as the most suitable candidate among the proposed designs. It showed potential superior performance in stability, ease of development and assembly, versatility, simplicity, airflow management, and adaptability for future studies. PMTR-3 demonstrated some potential but needs more enhancement in electronic integration and structural development. However, PMTR-2 faces significant potential challenges in providing stability, versatility, electronic integration, and adaptability for effective and safe operations.

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https://doi.org/10.24191/esteem.v20iSeptember.1754.g1707

1. INTRODUCTION

Propellers are crucial in aeronautical engineering, especially for drones and Unmanned Aerial Vehicles (UAVs). Assessing the thrust of propeller designs is key to understanding their effectiveness and performance under different conditions [1]. The static thrust of a propeller directly impacts an aircraft's ability to take off, climb, and manoeuvre [2-3]. Measuring this thrust can be complex and challenging, requiring sophisticated equipment and precise techniques [1], [4-5]. Recent advancements in microelectronics and load cell technologies have improved the accuracy and reliability of these measurements [1], [6]. However, designing simple and effective test rigs for small-sized propellers remains difficult [7-8]. This study aims to fill that gap by proposing a straightforward yet robust test rig design for measuring static thrust in small propellers.

Designing a small-sized propeller static thrust test rig is a crucial aspect of drone development [9-10] and optimization. It allows hobbyists, researchers, and engineers to accurately measure the performance characteristics of various propeller designs under controlled conditions [7]. One primary objective when designing a static thrust test rig is to achieve accurate and reliable measurements of the thrust generated by a given propeller configuration [11]. Recent advancements in measurement techniques and instrumentation have significantly enhanced the accuracy and reliability of static thrust data [10]. However, incorporating of specialized instrumentation, such as multi-axis force/torque sensors capable of capturing thrust, torque, and other relevant parameters, would require more sophisticated equipment [4]. Moreover, such test rigs would require complex mechanisms and great measurement precision methods. Therefore, the availability of a simple test rig design for measuring the static thrust of small-sized propellers is very limited and still open to be explored.

In response to these issues, this work aims to explore and propose a simple yet robust test rig design that is reliable in measuring the static thrust for small-sized propellers. To simplify and ease the complexity of the force measurement system, a common weight scale was used in each proposed design, which is commonly used by hobbyists or remote-control enthusiasts [12]. Each design was focused on propeller size with a maximum diameter of 10 inches, which is also commonly used for small-sized drones or quadcopters. In this work, three different designs of test rigs were proposed, and their working mechanisms were explained in brief. The Pugh method is employed to determine the best design rig for ensuring thrust measurement accuracy and reliability. Eight design criteria are implemented in the analysis not only to ensure propeller thrust measurement accuracy but also to provide reliable performance, ease of use, and adaptability to future needs.

2. METHODOLOGY

2.1 THE PROPOSED TEST RIG DESIGN

Fig. 1 to Fig. 3 displays the three proposed designs for a small-size propeller test rig, referred to as the Propeller Thrust Measurement Rig (PTMR). Each design accomodates a weight scale as the primary force measurement tool and is suitable for small-sized propellers with a maximum diameter of 10 inches. The weight scale was chosen over a load cell for this PTMR's development based on several reasons. Weight scales offer a simple, cost-effective, and readily available solution for measuring thrust. They are easy to set up and use. In fact, it required minimal calibration and technical expertise compared to load cell usage. Using a load cell shall increase the PMTR development's complexity and require additional instrumentation (e.g., data logger and personal computer, to name a few) for precise measurements. On the other hand, weight scales provide direct readings in units such as kilograms or grams, simplifying the data collection process. Additionally, weight scales are robust and can handle varying force ranges, making them suitable for diverse experimental conditions without the need for specialized equipment. This makes weight scales

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a practical choice for applications where accuracy is balanced with cost and simplicity, ensuring reliable thrust measurements with less technical complexity.

Each design shares the same primary function: measuring the static thrust induced by a small-size propeller. into ensure uniform force generation, all designs implemented the same static thrust generator system (propulsion system), which included the brushless motor, propeller, and propeller adapter to secure the propeller position. Each design manipulates the basic swing arm geometry, which is primarily used to transfer the thrust force based on a fulcrum or pivoting system. The weight scale is also used as the force measurement system in all designs in order to maintain simplicity in measuring the thrust force induced by the propeller [12]. Both PMTR-1 and PMTR-3 utilize a fulcrum or pivot point, allowing the swing arm to move freely at a pivot point and transmit the thrust force to the measurement system (weight scale). PMTR-1 has simpler features based on a traditional swing arm with a single pivot point and vertical rod to transfer the force to the scale. Meanwhile, the PMTR-3 has 900 swing arms to accommodate the vertically positioned propeller combined with a vertical rod for force measurement. On the other hand, the PMTR-2 design employs a direct converting system to transmit the thrust generated by the propeller into a measurable force measured by the weight scale.

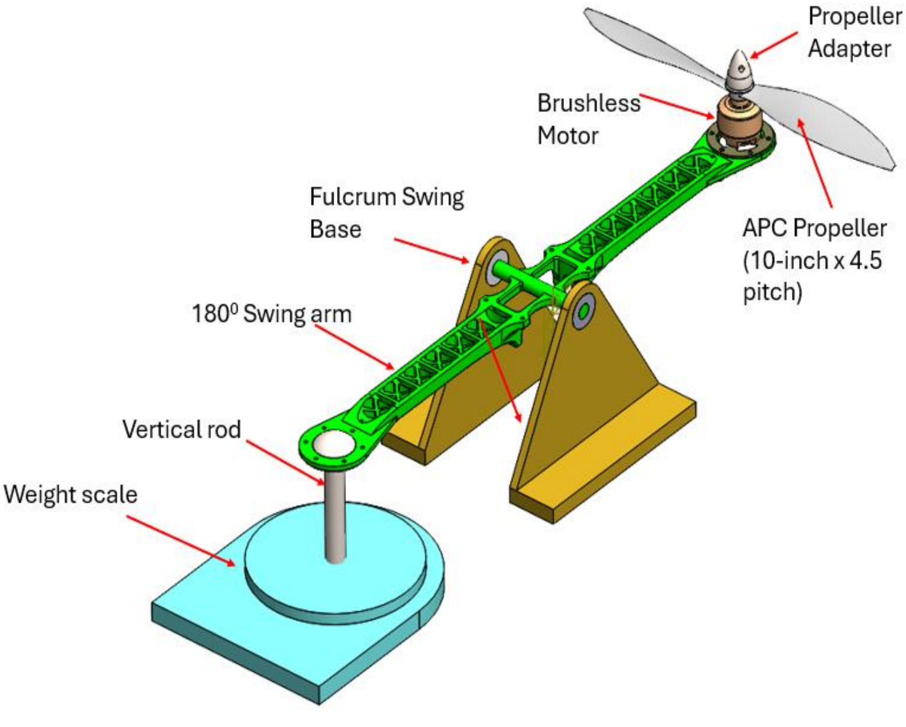

Fig. 1. PMTR-1

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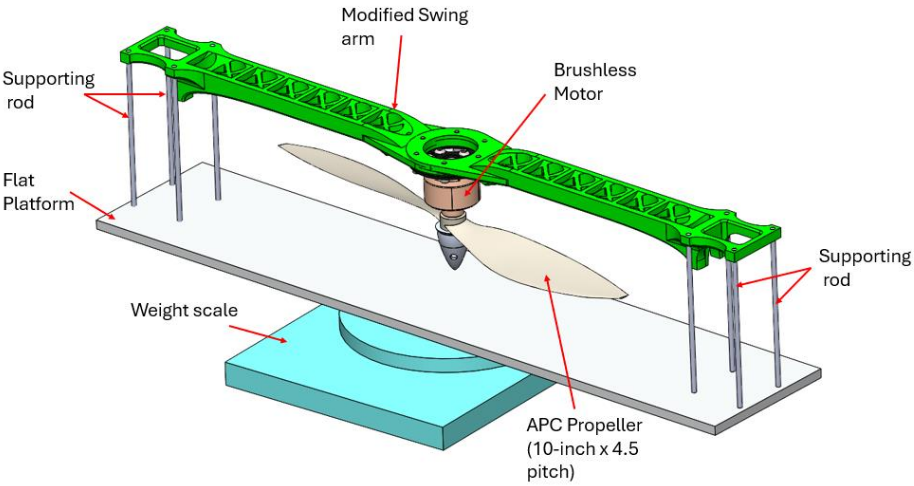

Fig. 2. PMTR-2

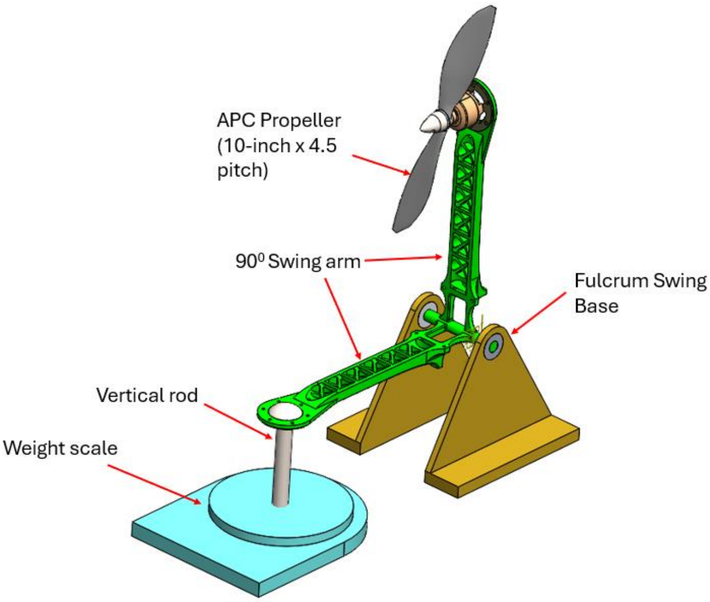

Fig. 3. PMTR-3

2.2 Working principle of PMTR-1

PMTR-1 (Fig. 1) has the basic components of a Fulcrum Swing Base and 180° Swing Arm as the main component in transmitting the force induced by the rotating propeller. The working principle behind PMTR-1 design is based on fulcrum motion. As the propeller is driven by the motor, the thrust force is created and drags the 180° Swing Arm towards the upper direction and creates a vertical displacement, as shown in Fig. 4. The displacement on the right-side swing arm is translated to the left-side swing arm, due to the pivot mechanism at the fulcrum swing base. The upward displacement (on the right side) was translated into downward displacement on the other side, which creates vertical movement on the vertical rod. The movement of the vertical rod was translated into contact force since it was positioned to be slightly

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in contact with the weight scale. The contact force is measured by the weight scale as the translated thrust force induced by the propeller in a gram-force unit.

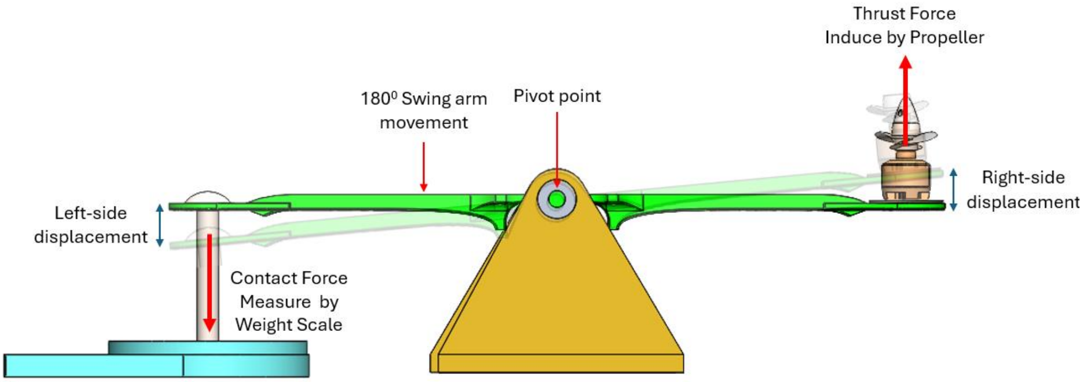

Fig. 4. PMTR-1 working principle

2.3 Working principle of PMTR-2

PTMR-2 design (shown in Fig. 2) has a horizontally oriented configuration with a modified swing arm directly connected to the motor unit. As the brushless motor rotates, it drives the 10-inch propeller to induce the thrust force in a vertical downward direction. The induced force drags the swing arm downward and transmits uniform displacement on the swing arm. Here, the swing arm is expected to have uniform displacement (in a downward direction), which translates into uniform downward motion at the left and right side of the swing arm, as shown in Fig. 5. Consequently, the flat platform and supporting rods move downward, translating thisdisplacement into contact force on the weight scale. This contact force, generated by the thrust is measured in gram force units.

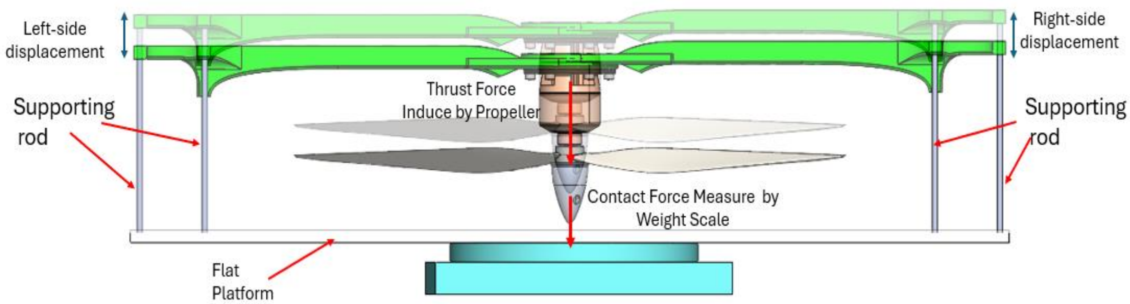

Fig. 5. PMTR-2 working principle

2.4 Working principle of PMTR-3

(PMTR-3 design configuration is based on a 90° swing arm mechanism to measure the static thrust produced by a vertically mounted propeller. Basically, the working principle for PMTR-3 is almost similar to PMTR-1. However, However, in PMTR-3, the 90° swing arm leverages horizontal thrust force (generated by the propeller) and converts it into vertical contact force measurable by a weight scale.. As the propeller rotates, it generates a static thrust force in a horizontal direction, as shown in Fig. 6. The force also drags the swing arm to rotate, causing a horizontal displacement on the vertical swing arm. Due to the fulcrum mechanism, the horizontal displacement is converted into vertical downward displacement on the

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horizontal swing arm and vertical rod. This downward displacement is transferred to the weight scale as contact force, corresponding to the thrust's reaction force.

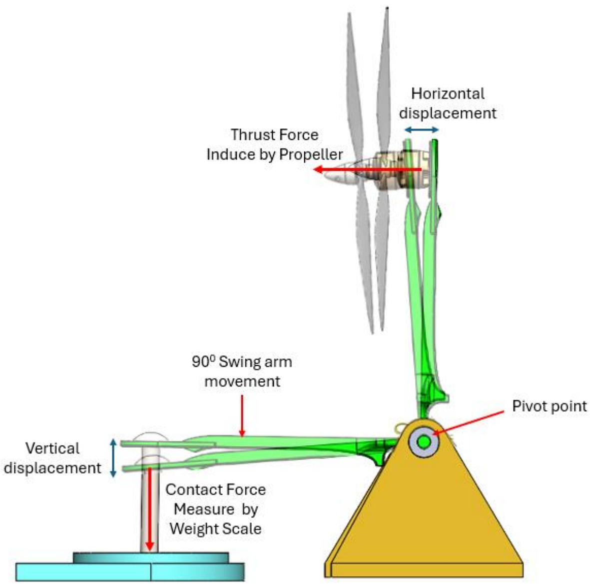

Fig. 6. PMTR-2 working principle

2.5 Criteria for design selection.

The Pugh Method [13] was used for the selection of the PTMR designs. The method evaluates and compares four different test rig designs (3 PMTRs and a benchmark model), which involve critical aspects of the test rig in terms of development, performance, usability, and feasibility for current and future studies. Eight main criteria were incorporated in this analysis, as illustrated in Table 1. The criteria involve measurement accuracy, stability, development, assembly, maintenance, versatility, electronic integration, airflow interference, adaptability for tilt angle studies, and similarity to multicopter configuration and flight conditions. The Pugh Method provides a clear comparison of the designs by highlighting the strengths and weaknesses of each design in various aspects. This structured approach supports objective decision-making, ensuring the selected design meets the requirements.

Table 1. PMTRs criteria for Pugh Method analysis

Criteria No	Criteria	Description
1	Measurement Accuracy	The ability of the test rig to provide precise and consistent thrust measurements.
2	Stability	The design structural stability to withstand the vibrations and movements during operation.
3	Development, Assembly, and Maintenance	The simplicity in fabricating, assembling, and maintaining the rig.
4	Versatility	The ability of the design to accommodate different micro-sized propellers and motor types. Adaptability for wind tunnel testing
5	Electronic Integration	The ease of integrating electronic controls to drive the motor and propeller's rotational speed reading (tachometer position)
6	Airflow Interference	The level of interference between the rig's structure and airflow around the propeller.
7	Adaptability for Tilt Angle Studies (Future Studies)	The ability of the design to adapt to future studies involving tilt angle thrust mechanism.

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Criteria No	Criteria	Description
8	Similarity to Multicopter Configuration and Flight Conditions (Future Studies)	The level of similarity of the design mimicking the configuration and operating conditions of a Multicopter.

2.6 Benchmark model.

Fig. 7 shows the benchmark test rig model for the Pugh Method analysis. The rig is known as the 10 kg Motor Thrust Tester Propeller Power Tension Measurement for RC Model Racing Drone. The test rig is compact, robust, and available on-shelf for static thrust tests, especially for small propellers. The model features the following key components: base platform, propeller mounting, load cell, tachometer, control, and display unit. It's working mechanism is similar to the PMTRs concept. As the propeller rotates, it generates thrust by accelerating the air backward. The thrust force is transmitted to the load cell, which converts the force into an electrical signal. The control unit processes the signal and displays the thrust magnitude on the display unit. This benchmark model serves as a robust and reliable reference for evaluating the performance of PMTR designs, offering good precision, durability, and user-friendly features for measuring thrust and propeller rotational speed.

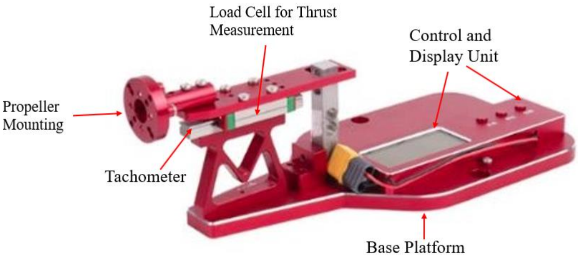

Fig. 7. Benchmark Model: 10 kg Motor Thrust Tester Propeller Power Tension Measurement for RC Model Racing Drone

3. RESULTS

3.1 Pugh method analysis

Table 2 presents the Pugh matrix results with the eight given criteria for PMTRs design analysis. The results show the scores (+, 0, -) based on comparison with the benchmark design. The given score indicates whether a design performs better (+), equal (0), or worse (-) relative to the benchmark model. The score justification for each criterion is given in sections 3.2 to 3.10.

3.2 Criteria 1: Measurement accuracy

Measurement accuracy is very crucial to ensure the reliability and effectiveness of a test rig. In this Pugh analysis, the measurement accuracy was assessed from the perspectives of rig calibration and mechanical alignment Due to the simple design of each PMTR, the calibration process is expected to be straightforward. A simple design is also conducive to component alignment, and the generated thrust force can be effectively transmitted and measured. Based on this criterion, the results suggest that each PMTR is able to provide good measurement accuracy levelling with a benchmark with a "0" score. However, further studies are required to improve accuracy in terms of load cell (weight scale) quality, vibration resistance, reliable data acquisition, environmental control, and high-quality materials. Such studies are beyond the scope of this work.

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3.3 Criteria 2: Stability

During operation, the rig is expected to experience vibrations caused by propeller torque and rotations [14]. A rig that can withstand vibrations has an advantage over others. The decision-making for stability criterion is considered based on the safety during its operation by maximizing the rig base contact area (sturdy foundation) with the fixed platform. Stable rigs ensure a safe operation, preventing tipping during use. An unstable rig easily tips over, is exposed to catastrophic failure during operation, and is dangerous to operators and the environment. Based on the current PMTR design, only PMTR-2 (with a "-" score) is prone to topple if exposed to excessive vibration levels during rig operation. This is due to the lack of a sturdy foundation in the PMTR-2 design compared to other designs. The PMTR-1 and PMTR-2 (with a "+" score) look more solid and sturdy if the fulcrum base is fixed and secured to the fixed testing platform. Howeveradditional factors like component resonance, propeller or motor imbalance, structural flexibility, and complex interactions, which were not considered here, could also affect stability. These factors can only be assessed during the actual rig operation.

Table 2. Pugh matrix for PMTRs analysis

No	Criteria	Benchmark (Datum)	PMTR-I	PMTR-2	PMTR-3	Totals
1	Measurement Accuracy	0	0	0	0	0
2	Stability	0	+	-	+	1
3	Development, Assembly, and Maintenance	0	+	-	-	-1
4	Versatility	0	+	-	+	1
5	Electronic Integration	0	-	-	-	-3
6	Airflow Interference	0	+	-	+	1
7	Adaptability for Tilt Angle Studies (Future Studies)	0	+	-	+	1
8	Similarity to Multicopter Configuration and Flight Conditions Future Studies	0	+	-	+	1
		Totals	5	-7	3	
		Rank	1	3	2	

3.4 Criteria 3: Development, assembly, and maintenance

Development, assembly, and maintenance are important factors in determining the practicality and feasibility of each PMTR design. Evaluation of this criterion focused on ease of assembly, modularity, component accessibility, and calibration simplicity. Based on these factors, only PMTR-1 has a "+" score in this criterion due to their simple construction and modular design, which suggests easier assembly and maintenance work than the benchmark design. PMTR-1 likely benefits from modular components, easy calibration, and clear assembly instructions due to their simplicity. Meanwhile, PMTR-2 and PMTR-3 designs with "-" scores have more complicated structural construction, which contributes to additional components (supporting rods) and additional fabrication safety measures (to maintain the 90° angle on the swing arm). The complexity might require specialized tools and more time-consuming calibration, directly impacting the ease of assembly and maintenance.

3.5 Criteria 4: Versatility

Several factors were considered for versatility including:

i. The design flexibility of the mounting system to accommodate various sizes and shapes of propellers and motors.
ii. The design allows for easy addition or removal of components to suit different testing needs.
iii. The ability to integrate with wind tunnel testing setups.

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Based on these considerations, the Pugh matrix suggests that only PMTR-1 and PMTR-3 have a "+" score in this criterion. The motor and propeller positioned at the edge of their swing arm offer better adaptability to various sizes and shapes of propellers and motors, easy components removal, and easy wind tunnel testing setups. However, PMTR-2 scored "-" due to limited space between the modified swing arm and the flat platform, restricting its ability to accommodate other motor-propeller combinations and making it unsuitable for wind tunnel testing without modifications.

3.6 Criteria 5: Electronic integration

The benchmark (datum) model has already demonstrated the optimum advantages in terms of electronic integration. These advantages were determined based on the following criteria:

i. optimized electronics component placement
ii. efficient cable management
iii. integrated ESC
iv. accurate tachometer positioning
v. comprehensive data interface, and
vi. effective heat dissipation

None of the PMTRs' designs achieved the same level of electronic integration as the benchmark, resulting in all scoring "-". Therefore, each PMTR has a "-" score in this criterion. However, the PMTR-1 design is more conducive to the aforementioned electronic integration compared to PMTR-2 and PMTR-3. PMTR-1's simple and straightforward design makes it easier for cable management and accessible placement for ESC, battery, and tachometer. Complexity in PMTR-2 and PMTR-3 design may require more complicated placements and protections for electronic components due to their complex structure and vertical design.

3.7 Criteria 6: Airflow interference

Airflow interference in each PMTR design can significantly affect the accuracy and reliability of thrust measurements. Several factors contribute to airflow interference, including:

i. smooth airflow ahead and behind the propeller (inlets and outlets),
ii. potential airflow blockages, and
iii. rig structure and airflow interaction.

Based on these factors, PMTR-1 and PMTR-3 designs (with a "+" score) have advantages over PMTR-2 designs and the datum model. The simplicity of motor-propeller mounting in PMTR-1 and PMTR-3 design allows smoother inlets-outlets airflow, minimizes the airflow blockages, and lesser airflow-rig structure interaction. On the other hand, the PMTR-2 design (with a "-" score) has a larger platform surface area, which may restrict the inlet-outlet airflow and cause more turbulence. The PMTR-2's platform component can contribute to significant airflow blockages, which are very difficult to mitigate without major design modifications.

3.8 Criteria 7: Adaptability for tilt angle studies

Nowadays, it is very important to understand the propellers' thrust behaviour and performance in different orientations. Therefore, this criterion evaluates the adaptability level of each PMTR design toward the tilt angles mechanism for future studies. Based on the Pugh Matrix, PMTR-1 and PMTR-2 have a "+" score due to their simple design, allowing straightforward modifications to implement the tilt mechanism. The propeller-motor components located at the swing arm edge can be easily modified to accommodate a tilt angle mechanism. The "-" score given to PMTR-2 is due to propeller-motor location, which limits the space for the tilt angle mechanism. Again, the complexity of the PMTR-2 design may require significant design modification to accommodate the tilt mechanisms.

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3.9 Criteria 8: Similarity to multicopter configuration and flight conditions

Understanding how propellers and multicopter operations behave under various conditions is very crucial for UAV's safety and reliability. The propeller's physical layout, which is close to the multicopter configuration, is beneficial to understanding the real-flight condition of copters. In this criterion, the adaptability of the design configuration to the multicopter real-flight condition was assessed. Based on Pugh matrix analysis, PMTR-1 and PMTR-3 (with "+" score) have very close designs mimicking the real multicopter condition. The motor-propeller position at the edge of the swing arm is naturally mimicking the copter's configuration. Furthermore, the designs are easily modified to fit the real multicopter configuration. On the other hand, the PMTR-2 design (with a "-" score) platform may require major modifications to mimic the multicopter configurations. The confined motor-propeller spacing and flat platform component do not match the real flight conditions.

3.10 Overall score

PMTR-1 ranks first with a score of +5, demonstrating design strengths in most criteria. PMTR-1 scores the highest due to its simple and straightforward design that suggests easier development, assembly, and maintenance. PMTR-1 offers more stability and versatility due to its modular design, which is also conducive for future studies. It has advantages in minimizing airflow interference and is conducive to tilt angle (thrust vector) studies and mimicking multicopter configurations. However, further study is needed to improve electronic integration to reach the benchmark level. PMTR-3 ranks second with a score of +3 and demonstrates strengths in some of the important criteria. The design has almost similar capability and adaptability to PMRT-1. However, the design challenge lies in the 90° angle of the swing arm, which may require more attention and precision during electronic integration and prototype development.

PMTR-2 ranks third with a score of -7, facing significant challenges across multiple criteria. Stability during operation is the major factor in this design, and it may require further design modification. The confined space between the swing arm and platform component may also cause issues in managing smooth airflow, versatility, and electronic integration. The complexity of the PMTR-2 design also contributes to maintenance difficulties and reduces its practical adaptability for future tilt angle studies. Pugh matrix analysis has initial design insights, highlighting each PMTR's strengths and weaknesses. The results provide a clear path for design improvements for each PMTR design. Detailed design and actual working prototype can support the criterion analysis, especially for measurement accuracy, stability, electronic integration, airflow interference, and adaptability for tilt angle studies.

4. CONCLUSION

The main objective of this work was to explore and propose a simple yet robust test rig design for measuring the static thrust for small-sized propellers. Using a Pugh matrix analysis, three PMTR designs were evaluated and compared against a benchmark model across important criteria involving measurement accuracy, stability, development, assembly and maintenance, versatility, electronic integration, airflow interference, adaptability for tilt angle studies, and similarity to multicopter configuration and flight conditions. The results indicate that PMTR-1 achieved the highest score, with a +5 in the analysis matrix. The design shows superiority in most criteria: stability, development and assembly, versatility, simplicity, airflow management, and future studies adaptability. Thus, the PMTR-1 is the most appropriate candidate for the robust static thrust test rig design. PMTR-3 was ranked second with a +3, showing a strong potential candidate but needs more precision study in terms of electronic integration and structural development. However, PMTR-2 (with a -7 score) facing significant challenges in most criteria, especially in terms of stability, versatility, electronic integration, and future studies adaptability. Based on these findings, detailed design and development of working prototypes are essential to validate most of the criteria. Further assessment of criteria such as measurement accuracy, stability, electronic integration, airflow interference, and adaptability for tilt angle studies will be possible once actual working prototypes are developed. These

https://doi.org/10.24191/esteem.v20iSeptember.1754.g1707

steps ensure the development of an effective and reliable thrust measurement rig that meets the needs of future UAV research and development.

5. ACKNOWLEDGEMENTS/FUNDING

The authors would like to acknowledge the support from Universiti Teknologi MARA Cawangan Pulau Pinang and the Government of Malaysia for providing the facilities and financial support for this research.

6. CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits or commercial or financial conflicts and declare the absence of conflicting interests with the funders.

7. AUTHORS' CONTRIBUTIONS

Noor Iswadi Ismail: Conceptualization, methodology, supervision, project administration, writing – review & editing; **Muhammad Amirul Hakim Amir:** Conceptualization, investigation, data curation, formal analysis, writing – original draft, review & editing; **M. Hisyam Basri:** Formal analysis, validation, software, writing – review & editing; **Hazim Sharudin:** Resources, investigation, visualization; **Sharzali Che Mat:** Methodology, resources, software; **Muhammad Arif Ab Hamid Pahmi:** Investigation, data curation, formal analysis, visualization; **Azmi Husin:** Resources, funding acquisition, supervision; **Rozaini Othman:** Investigation, methodology, writing – review & editing; **Umar Kassim:** Software, visualization.

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