The Critical Threshold of The Relationship Between Take-Off Load And Powertrain Load of the Aircraft

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Abstract. The critical threshold of the relationship between take-off load and powertrain load of the aircraft has long intrigued researchers and posed significant challenges. Delving into this subject, extensive research has been conducted to comprehend the intricate dynamics between these two variables. This thesis aims to contribute to this ongoing investigation by analyzing and drawing conclusions based on observed load variations and their impact on power system functionality. The study encompasses a comprehensive examination of various aircraft types, ranging from ultralight aircraft to wide-bodied aircraft and Unmanned Aerial Vehicles (UAVs). Each aircraft category presents unique characteristics and demands distinct engine requirements, further complicating understanding the take-off load to powertrain load relationship. By meticulously studying the changes in loads during the crucial take-off phase, this research aims to uncover valuable insights into the essentiality of an efficient power system. The findings of this study have the potential to enhance aircraft design and operations, ultimately leading to safer and more optimized flight experiences.

Keywords: Aircraft; Critical Threshold; Take-Off Load; Powertrain Load.

1. Introduction

The relationship between take-off load and the needed thrust produced by turbofan engines, or any other kinds of power system, is a topic of great importance to study. In a study on a new electric power system for civil airliners in 1983 NASA already proposed that the advanced one will reduce the take-off load [1], which means an increase in the capability of transporting goods. For the last two decades, the direction of academic research turns their focus on what exactly the relationship is. M.J.Martin and K.P.Johnston published a paper in 2001 [2] to propose that the specific status of the plane need determine the threshold. Then in 2008 [3], M.J.Marsden et al found that it wasn't a simple linear relationship that was influenced by several factors including barometric, tempe3rature, humidity and so on. A clearer view of the relationship, coming out with the publication of the dissertation of Y. Zhang et al in The Aeronautical Journal in 2012 [4], is that a non-linear relationship exists among the take-off load, engine power and the fuel consumption rate. The three cases reflect the frontier of the area and that is what the meaning of the paper is based on.

According to a previous experiment, a handmade model plane weighed 82 grams, making its flying distance 6 meters long and 5 meters in max height in one of its test flights. The experiment records focus on the gliding angle, which is 45 degrees of the plane. This gave an idea that if the plane needs to decrease the angle, how to put on the power system and how to balance the take-off load and the thrust. A successful model plane needs a power system with an appropriate thrust-to-weight ratio and for those makers, the parameters of making a power system are hard to decide. So, the essay is written to be helpful for the model aircraft enthusiasts when deciding whether the model needs a power system to keep it in air and to provide scientific evidence for better models.

Simply thinking, four forces act on an aircraft in flight: lift, weight, thrust, and drag. Usually, the relationship of thrust and weight according to $\frac{F}{W} = \frac{a}{g}$ [5], where a is the plane's acceleration (in the direction of the thrust), while g is the gravitational acceleration. High thrust to weight is an indication of the thrust efficiency of the engine [5]. This is a significant factor that needs to be referred to, not just the heavier the wight, the higher the thrust.

This paper delves into the intricate connection between the aircraft's take-off load and powertrain load. The study addresses the longstanding challenge of understanding how these two variables

interplay and impact aircraft performance. By conducting thorough analyses, this study aims to determine the critical threshold where the relationship between take-off load and powertrain load becomes crucial. The findings of this paper hold significant implications for aircraft design, operation, and safety. Understanding the critical threshold of this relationship can inform improvements in power system design and ultimately contribute to enhanced flight performance.

2. Basic principles

Thrust-to-weight ratio is a very clear way to demonstrate the relationship between take-off load and the power system. However, in most situations, the ratio does not guarantee anything, and only effective for aerial engines. So, what's more informative is to include all the significant factors such as wingspan, airfoil, engine efficiency, power/fuel supply and so on.

2.1. Unmanned Aerial Vehicles (UAVs)

Unmanned aircraft is the most usually used as model planes. However, vertical take-off landing (VTOL) unmanned aerial vehicles are commonly more popular than sliding take-off UAVs. For most model airplane enthusiasts, modifying their UAVs is a significant issue because not all modified products work. Here take Mugin 3600 for an example in Fig.1 [6].



Fig. 1. Test vehicle a modified Mugin 3600 VTOL unmanned aircraft.

The EQBAL team's design of small-scale turbine-electric engines in UAV applications is introduced, and the physical structural defects in this design are analyzed. The second case, researchers at Oklahoma State University, focused on creating an analytical model to convert existing engines into turbine electric systems and apply them to drone platforms. The experiment took place in a laid-out ground, which has 4 Mics. Mic 0,1,2 is almost collinear and are 100ft in between. From Mic 1 to 3 is the runway's length, which is 209ft, which forms a 'T' shape with the other Mics. Since the UAV is modified, the simple structure is provided as shown in Fig.2.

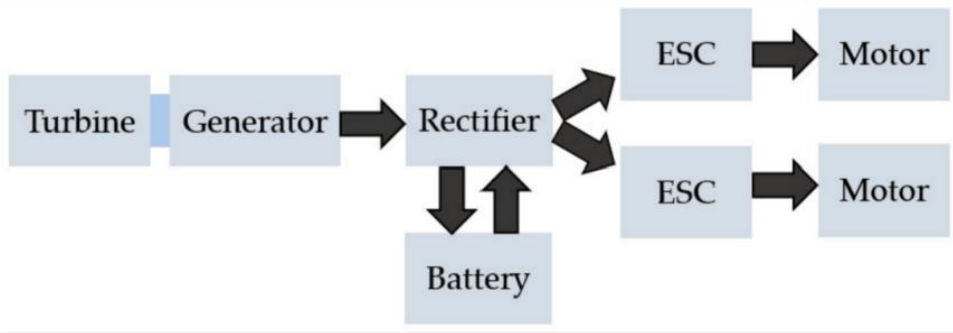


Fig. 2. Simplified structure diagram of the UAV.

The test flight of the modified plane shows a comprehensive result. The maximum instantaneous power being used by the vehicle was determined to be about 14 kW. The acceleration, vibration, and airspeed are also measured, matching the thermocouple outcome inside the fuselage and rectifier. The reasons why small turbine engines are attractive for further research are discussed. The impact of increased power batteries on reliability is mentioned and is given suggestions on. It also proposed that active cooling requirements should be fulfilled for safe operation and ensure safe operation for battery management.

2.2. For ultralight aircraft (UA)

As Fig.3, the ultralight aircraft is needed to be investigated as an important part of the research. A study proposed a series/parallel hybrid electric power system, for ultralight aviation designed to improve safety and, possibly, reduce fuel consumption, HEPS (Hybrid Electric Power System) and energy management strategies (EMSs) engines can provide larger thrust than one piston engine in a short period and more efficient [7].



Fig. 3. The ultralight Promecc Freccia.

Table 1. Specification of the Promecc Freccia.

Parameter	Unit	Value
Wingspan	m	8.777
Wing area	m^2	10.13
Max. take-off mass	kg	450
Take-off distance	m	250
Take-off power	kW	73.5

The reference aircraft, Promecc Freccia, using quasi-static modeling methods to calculate the energy flow within the aircraft engine and present its mathematical model to show the plane's performance. According to Table 1, the max. take-off mass is 450kg. So, it is assumed that the Wankel engine is working to carry a load of 450kg here.

Table 2. Specification of the hybrid electric configuration compared with the baseline case

Specification		Baseline	Hybrid
Engine	Peak power	73.5kW @ 5800 rpm	65 kW @ 6000 rpm
	Type	Piston	Rotary
	Displacement	1352 cm^3	654 cm^3
	Fuel	AVGAS	Avgas
Electric machine *EM*1	Continuous max. power	-	30kW
	Max. torque	-	245 Nm
Electric machine *EM*2	Continuous max. power	-	50 kW
	Max. torque	-	400 Nm
Gearbox	Zs	-	30
	Zc	-	23
	Zr	-	78
	τ final gear ratio		2.1
Battery	Capacity	-	6.5 Ah
	Voltage	-	273.6 V
	Max. current (discharge)	-	80 A
	Max. current (charge)	-	50 A
	Specific Energy	-	33 Wh/kg
	Specific Power	-	420 kW/kg
Overall aircraft	Take-off weight	450 kg	540 kg
	Installed power	73.5 kW	97 kW
	Power-to-weight	160 W/kg	179 W/kg

Then still, the literature uses the data in Table 2 to establish mathematical model. The fourth part is a study of electric powertrains for series/parallel hybrids, discusses the selection of components for the powertrain, identifies six constraints on selection, discusses the reasons why engines such as Wankel and Mazda may be selected, and establishes mathematical models in which these engines are evaluated (data analysis). HEPS has two levels of control, the authors control it by setting fixed points to use multiple drives, and in this study the set points are determined by a rule-based heuristic energy management strategy whose main goal is to control the efficiency of the Wankel engine. The engine differences make sense for the UA (ultralight aircraft) because the UAs (ultralight aircrafts) usually have only one engine to provide thrust.

2.3. For wide-bodied aircraft (WBA)

Different from ultralight aircraft, the wide-bodied take off with a much larger load. Apparently, the relationship between engines and its take-off load varies. Wang, Z. et al focus on how if a wide-body aircraft is equipped with a low-powered engine, its take-off performance will be affected. [8] First, the author determines the minimum thrust required in each given condition by calculating the quantitative relationship between take-off weight and thrust requirements. The authors then compare this minimum thrust with the actual engine thrust and find that the actual engine thrust is not enough to meet the minimum demand. On this basis, the authors further analyze the impact of insufficient power on take-off performance, including take-off run distance, climb rate, maximum altitude, and maximum range.

By establishing numerical models and conducting extensive numerical simulations, the authors finally concluded that in the case of insufficient power, the take-off performance of wide-body aircraft

would be significantly limited, the required run distance would increase, the climb rate and maximum altitude would decrease, and the maximum range would be shortened. At the same time, the authors also propose some possible solutions, such as updating more powerful engines or retrofitting the aircraft to a lightweight version to improve take-off performance. Therefore, this paper has great practical significance for understanding the impact of underpowered engines on the take-off performance of wide-body aircraft and solutions. Analyze the quantitative relationship between take-off weight and thrust requirements to determine the minimum thrust required under given conditions. A comparison of the actual engine thrust shows that the actual engine thrust is not sufficient to meet the minimum requirements. According to the situation of insufficient power, a numerical model is established, and many numerical simulations are carried out to analyze the impact of insufficient power on take-off performance, including take-off run distance, climb rate, maximum altitude and maximum range.

2.4. For different requirements on power system

Zheng et al focused on addressing the limitations of traditional microturbine engine (MTE) technology in meeting the high energy/power density and low-cost power requirements for small aircraft, particularly long-endurance drone swarms [9]. To tackle these challenges, the study proposes a compact concept called a double-sided composite impeller (DSCI) that enhances the thrust-to-weight ratio (TWR) of MTEs. The paper explains the principles, structure, and advantages of the DSCI concept through theoretical analysis, followed by a detailed examination of the DSCI and its design principles and parameters. Preliminary designs and weight estimations of the DSCI and supporting jet engine are conducted. The researchers then employ theoretical and numerical simulations to analyze the performance parameters of the DSCI jet engine, revealing promising results. Compared to the JetCat P500-PRO-GH, the DSCI jet engine exhibits a 39.4% increase in TWR and a 36.82% decrease in specific fuel consumption (SFC). This study lays a solid foundation for future high energy/power density MTEs, addressing the critical relationship between take-off load and powertrain load in aircraft.

2.4.1 Thrust requirements.

The paper from Perera et al mainly discusses the effect of take-off weight on the thrust requirements of turbofan engines. [10] Through theoretical derivation, the paper proves that there is a certain relationship between take-off weight and turbofan engine thrust, that is, as the take-off weight of the aircraft increases, the thrust required by the engine will also increase accordingly. Then, through a literature review, the paper further verifies this conclusion and studies the influence of engine size on the relationship between weight and thrust. Although the paper does not provide specific experimental or data analysis results, through theoretical derivation and literature review, an important discovery is made and provides in-depth thinking and understanding of the key performance parameters of turbofan engines in flight.

2.4.2 Size requirements.

Engine size also matters since the wakes will be much stronger, which means the thrust difference. The influence of engine size on take-off thrust and weight will be then explored. Studies have shown that engine size directly affects take-off thrust, and high-power engines can produce greater take-off thrust, allowing the aircraft to carry more weight. At the same time, larger aircraft require larger engines to provide enough take-off thrust to cope with their high weight loads. In practice, designers need to weigh the relationship between take-off thrust, weight, and engine size to achieve an optimal design.

3. Analysis

3.1. Graphic analysis for UAV

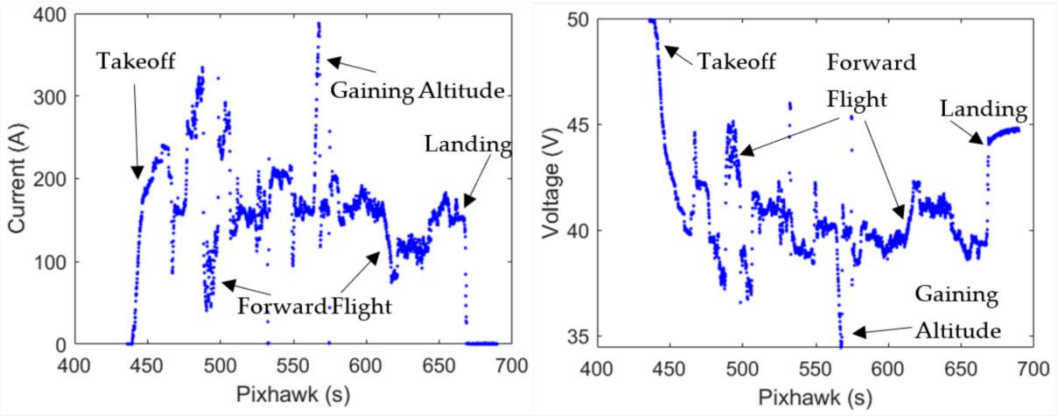


Fig. 4. (a)Current change in the test flight**,** (b)Voltage change in the test flight.

The Mugin 3600 (modified) UAV, like many unmanned aerial vehicles (UAVs), relies on electric motors and turboprops to generate thrust. A crucial factor influencing its performance is the power system, which can either be electrical or fuel-driven. The test flight conducted at the OSU Unmanned Aircraft Flight Station for the modified Mugin 3600 involved collecting data from four different scenarios, introducing a certain level of uncertainty. In this research, particular emphasis was placed on two key factors: power and airspeed. Fig. 4(a) reveals a sharp increase in current during take-off, as the motor necessitates a larger current to generate greater rotational force, achieve higher rotational speeds, and generate the required lift to support the take-off load. The current decreases during the subsequent forward flight phase, albeit it does not reach zero. This indicates that the vertically operating turboprops continue to contribute lift, while the wings primarily sustain the mean maintenance level. Consequently, the UAV can accommodate larger take-off loads. However, if the load becomes excessively heavy, the motors may experience overload due to the increased current required for take-off. Conversely, Fig. 4(b) demonstrates an inverse relationship compared to Fig. 4(a). The power remains relatively consistent, albeit with a maximum value of 14kW. The rapid increase in current during take-off showcases the critical role of power supply in enabling the necessary thrust. Furthermore, the sustained current during forward flight indicates the continued contribution of the vertically operating turboprops to lift generation. The observed trends in power consumption provide valuable insights for optimizing the UAV's operational efficiency and load-carrying capacity.

3.2. Data comparison for UA

Addressing the relationship of ultralight aerial vehicles is both theoretical and graphical. For UA, take-off speed, engine power, take-off distance are all unignorable factors and for simplicity, the analysis discusses the engine efficiency and power using mathematical models.

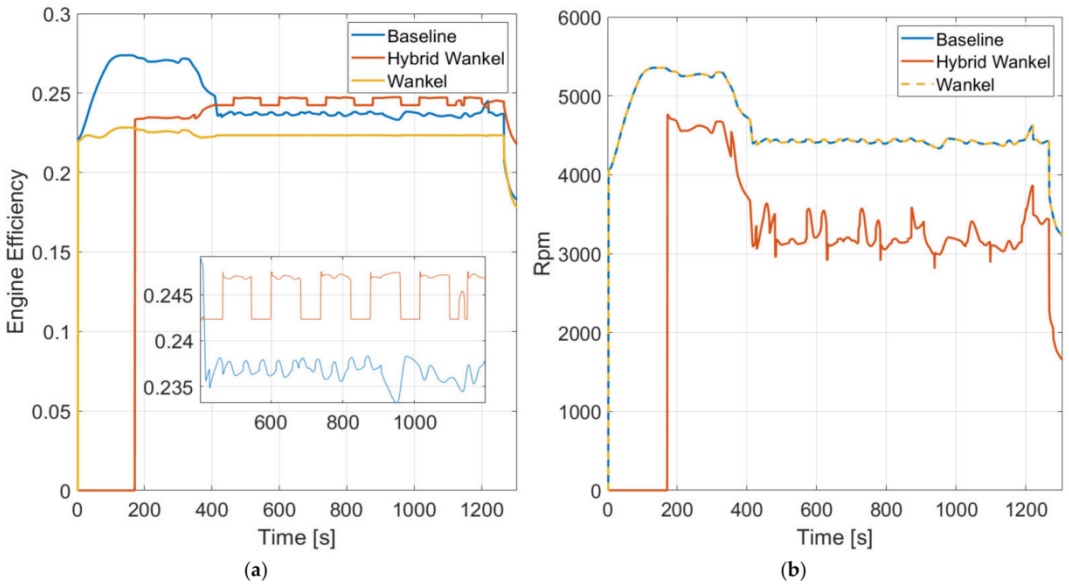


Fig. 5. Comparison of Hybrid Wankel and Wankel engines for efficiency (a) and speed (b)

In Fig.5, Graph (a) presents a comparative analysis of engine improvements specifically designed for ultralight aircraft. The efficiency of the hybrid engines, indicated by an average value of 0.245, surpasses that of the original Wankel series engine. This finding highlights the advancements achieved in enhancing the overall efficiency of the hybrid engine design compared to its Wankel counterpart.Moving on to Graph (b), it depicts the performance characteristics of the Wankel engine in relation to the hybrid engine. Notably, the Wankel engine exhibits a higher ultimate power output during the test flight, particularly evident at around 5400 RPM. Consequently, aircraft equipped with the Wankel engine, such as the PF (Promecc Freccia), can achieve a higher maximum cruise speed. However, it is important to consider the trade-off associated with this advantage. The Wankel engine's superior power output comes at the cost of a shorter operational lifespan, implying that it may have a reduced longevity compared to the hybrid engine. These findings presented in Fig.5 shed light on the comparative performance of the hybrid and Wankel engines for ultralight aircraft. While the hybrid engine showcases superior efficiency, the Wankel engine demonstrates a notable advantage in terms of ultimate power and maximum cruise speed. However, the Wankel engine's shorter lifespan suggests a need for careful consideration when selecting an engine for ultralight aircraft, weighing the trade-offs between performance and durability.

3.3. Different requirements

This paper discusses the factors influencing the total take-off of aircraft, including take-off speed, take-off run, distance and altitude, and explains the relationship between these factors and engine thrust. [11] It also discusses how different types of engines adapt to different take-off weights and how to optimize the design of engines to improve engine performance. In addition, the relationship between engine thrust and take-off speed and how to improve the thrust performance of the engine under the limitation of take-off run distance are studied. In general, the paper deeply studies the relationship between aircraft take-off weight and engine thrust demand and provides important reference and guidance for aircraft design and performance optimization.

3.4. Analysis for WBA

This paper delves into the comprehensive examination of thrust requirements for wide-body aircraft (WBA) and the associated parameters crucial in determining the concept of "critical take-off weight" [12]. An in-depth analysis is conducted to understand the precise thrust demands during take-off, encompassing static, climb, and acceleration thrust. Additionally, the study explores the performance characteristics of turbofan engines, identifying influential factors that impact the

engine's thrust output and the corresponding thrust-to-weight ratio. Notably, the "critical take-off weight" is a vital reference parameter for airlines in aircraft operation and design processes. The study acknowledges that changes in turbofan engine performance and parameters significantly influence the critical take-off weight, with thrust being the most prominent variable. Furthermore, the analysis highlights the importance of considering additional factors, including air temperature, air density, and ground friction, as they play a substantial role in determining thrust and take-off distance. The research emphasizes the potential limitations of relying solely on mathematical models for critical take-off weight calculations and the need for correction by incorporating actual data.

3.5. Analysis for powertrain load

One component of this study involved a comprehensive evaluation of the powerplants, particularly turbine engines and gas turbines, during aircraft take-off [13]. The study meticulously analyzed and summarized the performance parameters associated with the powerplants, providing insight into their operation and their fluctuations during the take-off phase. A mathematical model was used to evaluate the powerplant's performance, considering key parameters such as mass flow, thrust and fuel consumption. By modeling the time variation of these parameters, the performance parameters of various powerplants, including thrust, mass, and flow rate, are evaluated and analyzed, suggesting adjustments to the engine inlet design to optimize mass flow and thus improve the overall take-off performance of the aircraft. By addressing the thrust requirements of wide-body aircraft and a thorough analysis of the powertrain loading during take-off, performance, safety and efficiency can be optimized during take-off operations.

3.6. Summary for different loads

Unmanned aerial vehicles has the simplest variables which is capable of being controlled. The take-off load has a maximum value without modification on the power system. However theoretically, UAVs can break its limits if keeping changing for a better turbofan engine (usually electrically) but stay the aerodynamic shape unchanged. Engines on ultralight aircraft usually have power peaks which are the most efficient status of the aircraft and carry a larger load, but for take-off, even a hybrid engine improve no more. Wide-bodied aircraft has a clearer relationship. It turns out to be an additional ton of load need another 2000 pounds of thrust.

In this research, the representative variable is supposed to be the resultant ration, R, which is the ratio of VNE (velocity never exceed) and TOL (take-off load). This is to find out the approximate relationship between the aircraft's take-off load and powertrain load, as VNE can be seen as a kind of the effectiveness of the power system.

Table 3. different aircraft models of different types of aerial vehicles and the resultant ratio

	Model	**Max. TOL**	**VNE**	**R**
UAV	Parrot Disco	0.75kg	80kph	107
	Mugin 3600	39.1kg	160kph	4.09
	ASN-218	40kg	140kph	3.5
UA	Air-Bike 103	185kg (112kg)	129kph	0.697
	Thunder Gull 2000	249kg	102kph	0.410
	Promecc Freccia	540kg	300kph	0.556
WBA	B-777	351534kg	900kph	0.00256
	B-787-8	227950kg	945kph	0.00415
	B-747-8	439985kg	1127kph	0.00256

R here in Table 3, gets about 100 times smaller when the type of the aircrafts varies. In real usage, R is to calculate what the weight of the model is when the velocity is known and vice versa. R can be a decisive parameter to control the model's weight or give a range of speed for the enthusiasts to choose a suitable engine.

4. Conclusion

In summary, this study discusses the key to the relationship between take-off loads and powertrain loads during aircraft operations. The investigation of thrust requirements provides a deeper understanding of the concept of "critical take-off weight" and its significance in aircraft design and operation. An analysis of turbofan engine performance, including factors affecting thrust output and thrust-to-weight ratio, further enhances the understanding of powertrain loading during take-off. In addition, the evaluation of powerplants, particularly turbine engines and gas turbines, reveals the fundamental performance parameters and their variations during the take-off phase. The findings emphasize the need to consider factors such as air temperature, air density, ground friction, and thrust and take-off distance. In addition, the study highlights the limitations of relying solely on mathematical models to calculate critical take-off weights and advocates refining these models by incorporating real-world data. Further research could explore other factors that influence the relationship between take-off loads and powertrain loads, such as environmental conditions and advanced propulsion technologies. This will contribute to ongoing efforts to improve aircraft performance and efficiency, ensuring a safer and more sustainable air transport in the future.

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