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Design and Analysis of a Ten-Passenger Electric Aircraft Named Djinn

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Abstract: As aircraft industries contribute more than 12% of the carbon emission globally, the urgency to develop a more sustainable and reliable source of energy to power aircrafts has become greater. Regarding that concern, an electric-powered aircraft is proposed to become the solution for the search of green technology. An electric aircraft has been proven to be capable of reducing carbon emission and sound emission. Despite of the advantages, the use of electric aircraft is still very scarce since there are a lot of considerable issues such as low energy density power sources, reliability problems, and the lack of design references. As a contribution for the development process, an electric aircraft by the name of "Djinn" has been designed, in hope that this aircraft can be an addition to the references for future endeavors. The methods used for designing the aircraft is similar as the methods used for developing conventional aircrafts, with slightly modified approximation and assumptions.

Keywords: carbon emission; electric aircraft; sustainable energy; aircraft design

1. Introduction

Fossil-fueled aircraft transportation is considered to cause environmental damage, contributing to 12% of carbon dioxide emissions in transportation [1]. These emissions have an adverse impact on the environment, so electrification of aircraft is considered the most promising solution to minimize these risks. Not only can electric aircraft reduce air pollution, they can also reduce noise pollution. By 2030, the electric aircraft market is estimated at 27.7 trillion USD with a CAGR of 14.8% [2].

However, there are various hurdles in the implementation of electric aircraft, including the very low density of available batteries [3], lack of references in design procedures [4], as well as reliability, certification, and public acceptance issues. With current technology, electric aircraft require batteries weighing 30 times that of conventional fuels to cover the same distance [2]. Therefore, realizing an aircraft design with the most efficient performance possible, through optimizing the size, weight, and smoothness of the aircraft shape [5], has been a major challenge and is still ongoing.

Currently, there are various designs (prototypes) of electric aircraft types. Aircraft that have been confirmed for production include Alice Eviation, Pipistrel Alpha, and Zunum Electric. Meanwhile, the only FAA-certified electric aircraft is the Pipistrel Alpha Elektro, which has a capacity of 2 people, weighs 368 kg and has a travel time of up to 60 minutes [5].

On the other hand, the demand for private aircraft with a small number of passengers shows an increasing trend due to the COVID-19 pandemic. The private aircraft market is estimated to grow by 5-10% compared to pre-pandemic times [6]. Therefore, there is a potential intersection between aircraft electrification and the need for small-capacity aircraft (≤ 10 passengers).

This paper discusses the preliminary design of an electric aircraft with a passenger capacity of 9 persons and a range of 600 km, and follows CASR 23 as the basis for certification. The design process includes obtaining DRO compliant performance and being able to carry the required batteries. Limited references, batteries, and adequate engines posed challenges to the design. Therefore, the discussion in this journal will cover the aircraft airframe design, aircraft configuration, performance analysis, stability validation, and sales price estimation.

2. Materials and Methods

The design process begins with a conceptual design, then a preliminary design is determined which is still rough but has been calculated in general, then a detailed design is carried out which will define all parts of the aircraft as a whole. Each process mentioned almost certainly contains iterations that make the design process a long process, therefore the initial limitation that will be carried out is to limit the design process to preliminary design. The design process carried out in this paper will follow the following figure 1 and figure 2.

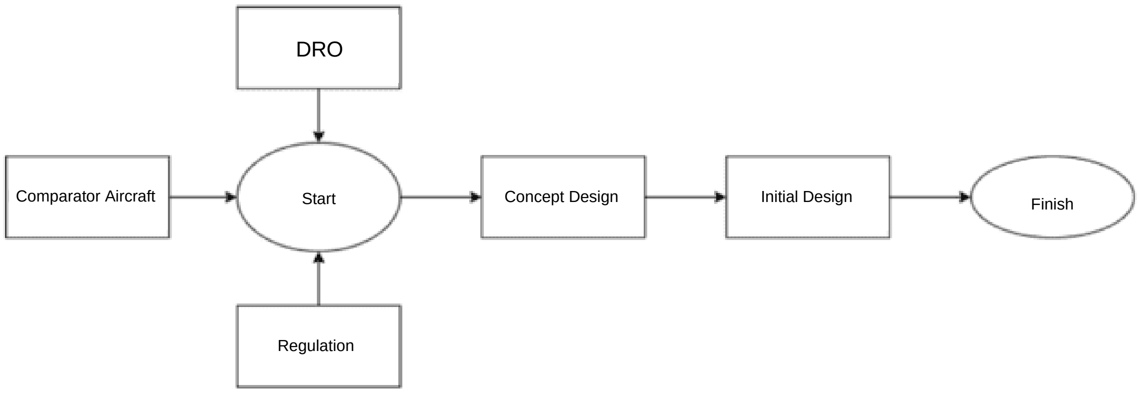

Figure 1. Flowchart of the overall design process

Before starting the design process, documents are first collected and a study is carried out on the Design Requirements and Objectives (DRO) given [7], the Regulations governing if the DRO is realized, then a comparison aircraft similar to the aircraft mentioned in the DRO. The results of the study are then used to determine the initial configuration of the aircraft. In the determination process, almost all data is determined by assuming its value. The reference used in assuming the value is the comparator aircraft data. Because of this, choosing the right comparator aircraft will greatly assist the conceptual design process. In the case of this design, the comparator aircraft was selected based on the engine type, i.e. an electric or semi-electric aircraft that has a number of seats close to the DRO request or that has a maximum take-off weight close to the DRO request. After the process of determining the configuration of the outer shape of the aircraft will already be visible so that further estimation of the weight of the aircraft is carried out.

To determine the estimated weight of the aircraft, a calculation method is used by looking at the weight of the aircraft in certain aspects, namely engine weight, battery weight, passenger and crew weight, operational weight and empty weight of the aircraft. Furthermore, each aspect is calculated separately. To calculate the engine weight, the equation found in reference [8] is used. In the equation, the parameters needed are the value of the engine power to weight ratio, wing loading, engine efficiency, and take-off weight will be iterated so that an initial guess is needed. The value of the efficiency and power to weight ratio of the engine is assumed based on the efficiency and power to weight ratio of the comparison aircraft engine. Furthermore, to calculate the power loading of the aircraft, the equation contained in reference [8] is used. The equation is determined by the variables whose values are obtained from the results of the comparator aircraft study and the DRO request. Furthermore, to calculate the battery weight, the equation contained in reference [8] is used.

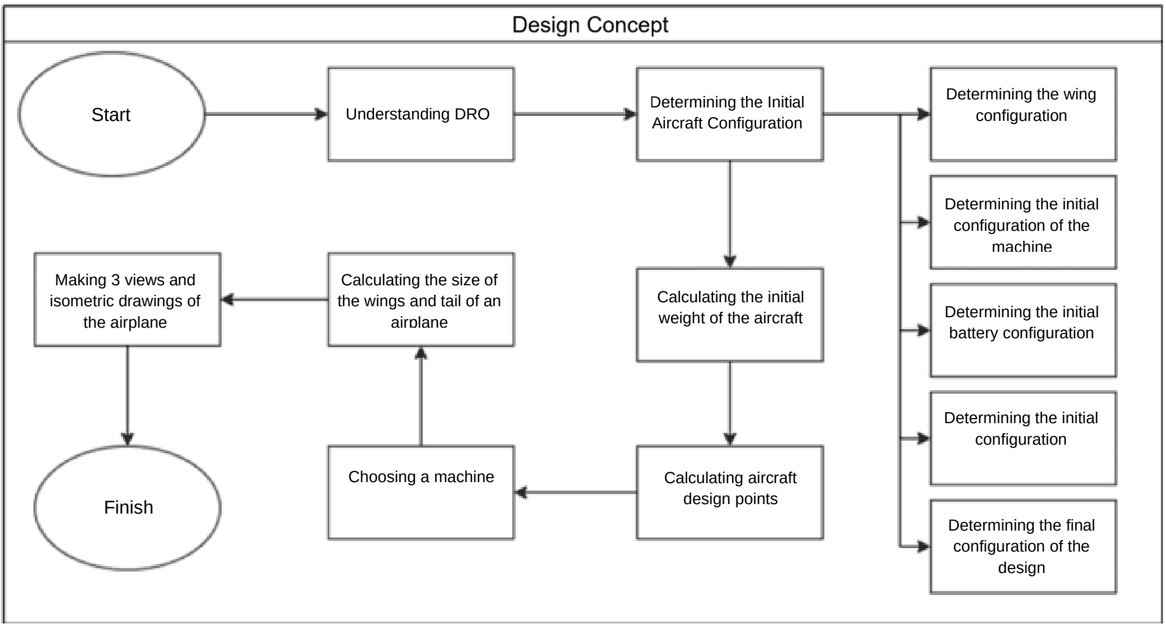

Figure 2. Flowchart of design concept

In the equation, the value of flight distance (range), and flight altitude is determined by the DRO while other variables are determined from the results of the comparator aircraft study. Furthermore, the weight of passengers and crew is determined according to the DRO's request and the operational weight is assumed to be appropriate. The empty weight was determined by collecting data on the take-off weight and empty weight of the electric comparison aircraft. With this data, a logarithmic curve is made to find the MTOW position of the aircraft to be designed which has been determined by the DRO. From the MTOW position, the estimated empty weight of the aircraft to be designed is obtained.

Furthermore, the design point is calculated which will be used as further design considerations such as determining the wing area and thrust force of the aircraft. Determination of the design point by building a matching chart curve. The matching chart curve is a description of the power loading and wing loading that is varied. The matching chart curve is composed of various lines that represent stall speed, take-off, climbing, rate of climb, and landing performance, as well as cruising speed. The equations used to calculate are obtained from references [9-10].

The next process is to determine the engine that will be used for the aircraft to be designed. The parameter used to select the engine is the power required which can be calculated from the power loading while the power loading has been determined in the process of determining the design point. After determining the engine to be used, then determine the initial size of the tail of the aircraft. The parameters determined in determining the tail size are tail area and tail dihedral. The equations needed to calculate these variables can be obtained from reference [11]. After determining the initial size of the tail, the conceptual design process ends with the formation of three-view and isometric images using SolidWorks and rearranging the configurations that have been calculated and determined previously.

Furthermore, aerodynamic analysis is carried out in the design process starting with the determination of airfoils and flaps where the airfoil is based on the coefficient of lift and the amount of lift/drag of the airfoil that has been determined in the conceptual design and the flaps are adjusted in such a way as to produce a predetermined performance with take-off and landing conditions equalized because it refers to the design points that provide the same stall speed for both. The CDO is calculated using OpenVSP and CD is calculated using XFLR5.

Final weight and balance analysis of the aircraft will then be conducted as a basis for consideration of landing gear design, stability analysis, DRO compliance and initial weight estimation. The aircraft components which include several major parts such as structure, fixed equipment, battery system, and payload will have their respective weights detailed by empirical calculation method based on references [11-12], and the location of each center of gravity is detailed based on the design configuration. Based on these two sources, the final aircraft weight value and center of gravity location can be determined.

After the details of the weight and location of each aircraft component are described, the shifts in the aircraft center of gravity for various payload loading conditions are analyzed. This process is done by creating various payload loading scenarios (including baggage and passengers) and taking the center of gravity and aircraft weight for each loading condition and process. When this process is completed, the values of the forward and aft center of gravity can be obtained.

The layout of the Djinn aircraft structure is determined based on the needs and existing joints; between fuselage-wing, fuselage-tail, fuselage-landing gear, wing-landing gear, and wing-engine. The components on the wing, especially the wingbox, such as ribs and spars consider the necessary joints, while the distance between ribs and spars is determined based on the ROSKAM reference [10]. The same was done for the fuselage components (longeron, frame, bulkhead). Based on weight and balance calculations, composite materials were used for the wings and tail to compensate for the weight of the battery.

Then, the landing gear design is carried out by taking into account the applicable provisions; lateral and longitudinal tip-over angles that will determine the position of the landing gear on the aircraft, and the static load received by the landing gear as a function of the center of gravity. These provisions are sourced from Raymer's book [11]. Then, tire selection is done based on the static load received and the desired tire inflation pressure. The landing gear tire database is taken from Michelin.

The design process continued with aircraft stability and control analysis, including static stability (able to return to the trimmed position when disturbed) and longitudinal control capacity under several conditions. With the help of XFLR5 software, the stability analysis was performed by (1) obtaining the longitudinal (CL,a, Cm,a, Cm,q, CL, Cm) and lateral (CY,b, Cl,b, Cl,p, Cn,b, Cn,r) stability coefficients, (2) comparison with typical conditions and figures [12], and (3) determination of the aircraft trim point by plotting CL vs CM at variations in angle of attack, elevator deflection, and c location. g. Calculation of aircraft control capacity including cruise flight conditions (short period oscillation), takeoff rotation, and landing using reference [13]. The control capacity calculation results in a plot of SHTP/Sw vs xcg/MAC as the horizontal design area limit of the tailplane for a given weight point location.

Flight performance analysis consists of aircraft parameters, engine chart, take-off performance, landing performance, climb performance service ceiling performance, BFL, and flight envelope. For the engine chart, the assumption is used that the thrust generated varies from static thrust when zero airspeed conditions to thrust at maximum level airspeed conditions, the assumption is sourced from the book [14]. Take-off performance is assessed from the take-off distance value required by the aircraft, where the value will determine whether the available airport runway can accommodate aircraft designed to perform take-off maneuvers. The take-off distance which is divided into ground distance and airborne distance is calculated using several payload loading configurations to see the trend of the take-off distance value required by the aircraft. Similar to the take-off distance, landing performance is calculated as two parts where the ground distance is divided into two phases, when the aircraft moves freely on the runway and when the aircraft moves with the deceleration provided by the braker. For climb performance, the calculation begins by finding the aircraft's flight angle from the aircraft's equation of motion based on reference [11]. Then, the rate of climb can be found by using the excess power of the aircraft by using the equation on the power graph with speed and using the predetermined speed and altitude values. Service ceiling performance is obtained by using the equation on the rate of climb graph with a rate of climb condition of 0.5 m/s. BFL on the aircraft is taken from the average between the stop take-off distance. Finally, the flight envelope is based on CASR 23 which includes maneuvering envelope and gust envelope. The maneuvering envelope is limited by the maximum and minimum lift coefficient and maximum and minimum load factor, and the gust envelope is calculated based on the gust speed in CASR 23 [15].

3. Results and Discussion

3.1. Airplane Concept and Weight Estimation

Prior to the design process, a comparative study of aircraft with similar configurations to the Djinn was conducted. Aircraft specifications considered for comparison were passenger capacity, and power source (electrical). Four comparison aircraft were found; Eviation Alice, Zunum Aero 10, Beechcraft Denali, and Beechcraft 1900D. Beechcraft 1900D. Thus, the Djinn aircraft weight estimation is shown in Table 1.

Table 1. Weight estimation results

WTO_{guess} [kg]	$W_{payload}$ [kg]	$W_{electric\ motor}$ [kg]	$W_{battery}$ [kg]	W_{empty} [kg]	WTO_{calc} [kg]	$\%diff$ [%]
5322.3	**1250**	**67.9**	**1647.7**	**2356.6**	**5322.2**	**0.00123**

3.2. Design Points

The Djinn aircraft matching chart (see figure 3) used to determine the selected design points (see table 2) for further testing in this study.

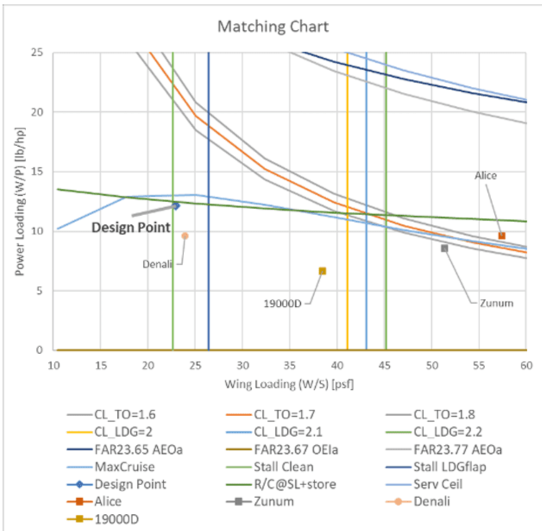

Figure 3. Matching chart of the Djinn Aircraft

Table 2. Design point selected from the matching chart

Design Point Parameters		
Wing Loading (W/S)	39.69	[psf]
	1900.00	[N/m^2]
Power Loading (W/P)	11.02	[lb/hp]
	49.00	[N/hp]
Landing distance	950	[m]
Take-off distance	900	[m]
Rate of Climb AEO	1600	[fpm]
Stall Speed	81	[knots]
Clmax (clean)	1.8	[-]

3.3. General Configuration

The general configuration of Djinn aircraft then designed and presented in a 3-view drawing and isometric view of Djinn aircraft result is presented on figure 4.

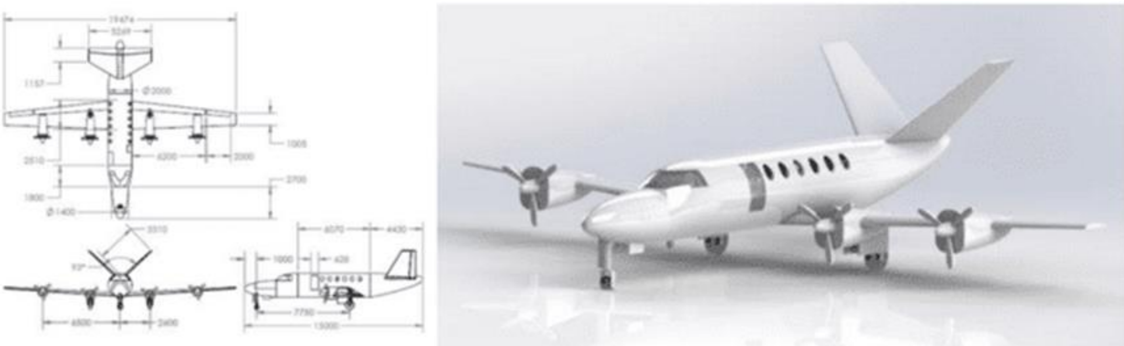

Figure 4. 3-view drawing (left) and isometric view (right) of Djinn aircraft

3.4. Analysis of aerodynamics

The aerodynamic analysis of the aircraft was calculated using XFLR5 software. The properties sought were Cl vs alpha and polar drag of the entire aircraft. The conditions were taken for unloaded and lowered flaps at 30 degrees. The flaps lowered condition indicates take off condition and the flaps not lowered condition indicates cruise condition which results in having different properties such as Reynold's number, etc. The results can be seen from the figure 5.

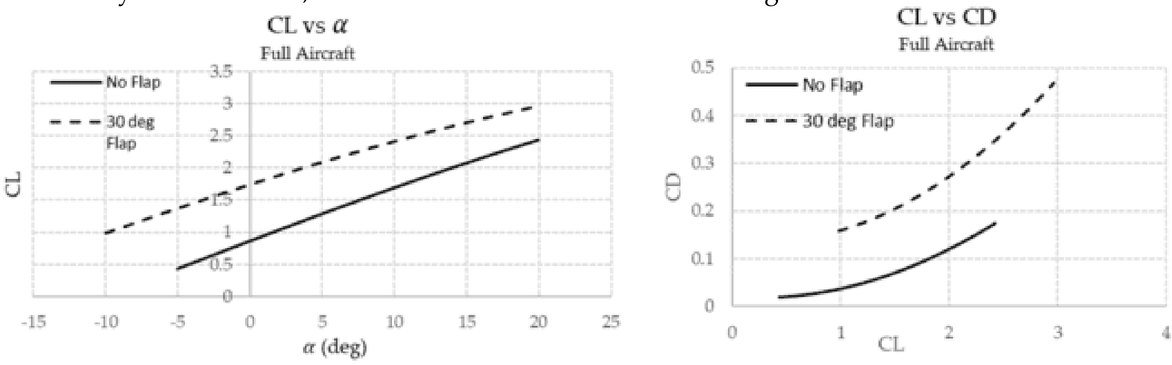

Figure 5. The lift force coefficient vs. angle of attack α (left) and graph of drag force coefficient vs. lift force coefficient (right)

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3.5. Weight and Balance

The weight of the detailed aircraft is calculated based on references [11-12]. Details of the aircraft weight are in Table 3.

Table 3. Aircraft weight details

Aircraft component	Component weight	Mass fraction
Aircraft sturcture	2053.86 kg	36.32%
Fixed equipment	699.26 kg	12.36%
Aircraft batery	1812.47 kg	32.05%
Payload	1000.00 kg	17.68%
Kru penerbangan	90.00 kg	1.59%
	Total	
MTOW	5655.59 kg	100.00%

The aircraft balance specifications consist of the location of the forward and aft center of gravity (C.G.) for aircraft flyable conditions. Details of the balance values are in Table 4.

Table 4. Aircraft balance details for flyable conditions

Payload Configuration	TOW	x/MAC	Operation Condition
MOEW	4700.48 kg	16.40%	*Minimum operating empty weight*
1 pax	4755.12 kg	19.23%	Back side C.G.
4 pax	5055.12 kg	15.75%	*Maximum range*
MTOW	5655.12 kg	13.86%	Front side C.G. *maximum take-off weight*

3.6. Layout structure

The concept of the Djinn aircraft fuselage is semi-monocoque with aerospace aluminum material. The layout of the fuselage structure is shown in figure 6.

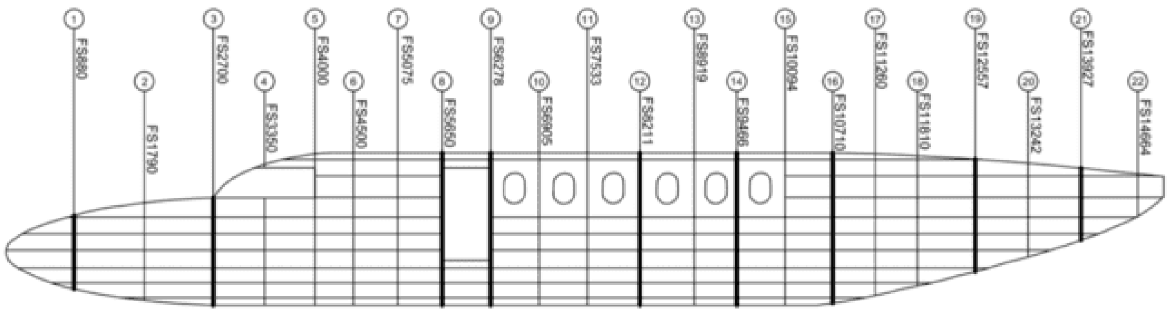

Figure 6. Layout fuselage structure

The materials used for the wings and tail of the Djinn aircraft are composites, namely CFRP and GFRP. The wing and tail structure layout is shown in figure 7. The tail configuration of the Djinn aircraft is V-Tail.

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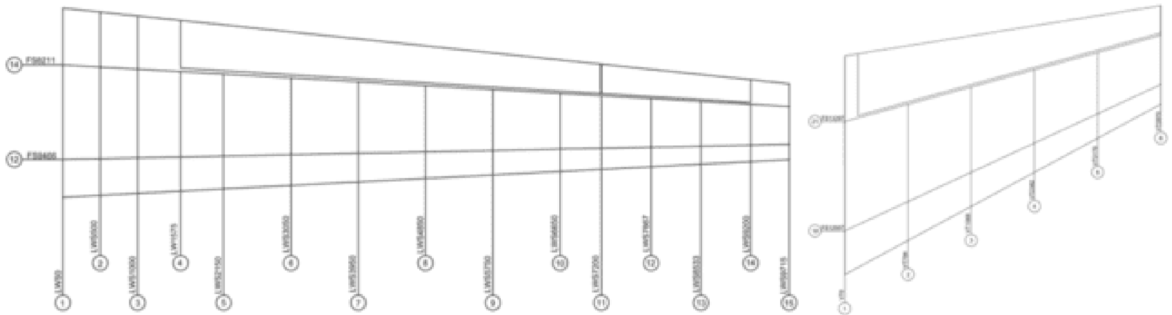

Figure 7. Layout of wing (left) and tail (right) structures

3.7. Landing Gear Design

The Djinn aircraft landing gear concept is a retractable tricycle landing gear. The position of the three landing gears is shown in figure 8 Specifications and fulfillment of requirements [11] and regulations are listed in Table 5.

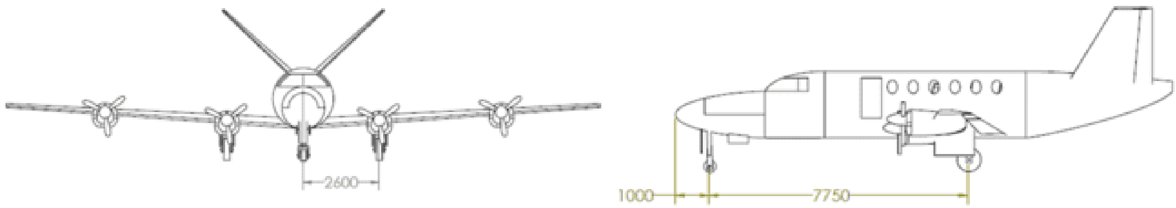

Figure 8. Lateral (left) and longitudinal (right) landing gear location in millimeters.

Table 5. Landing gear specifications

Operational Parameters	Value		Requirement
	Nose	*Main*	
Degree of tip-over longitudinal	-	27.7°	≥ 15°
Degree of tip-over lateral	-	37°	≤ 55°
Static load (in % of WTO)	-	91.34	85 − 92
	9.3	-	8 − 15
Tire diameter (in)	14.2	28.15	-
Tire width (in)	13.2	24.25	-
Foorprint area (in^2)	27.9	95.44	-

3.8. Stability and Control Analysis

The following is the static stability coefficient of the Djinn aircraft design in the longitudinal and lateral-directional dimensions, and it can be concluded that the aircraft design is able to achieve static stability, as on Table 6.

From the trim curves, it can be concluded that the Djin aircraft design is able to trim at AOA 00 and elevator deflection 00 at the forwardmost CG, and requires AOA -2.50 and elevator deflection -4.50 at the aftmost CG, as shown in figure 9.

For the control capacity analysis, it presented in the following graph where the limit values of the HTP area ratio as a function of cg location for various flying conditions and at two altitude conditions, namely at sea level (0 ft) and cruising altitude (10,000 ft). It can be concluded that the Djin aircraft design meets the longitudinal control capacity requirements, as on figure 10.

Table 6. Djinn aircraft static stability coefficient

Load Condition	MTOW		*Flyable Empty Weight*		Requirement
Differencial of longitudinal variables	$C_{L\alpha}$	5.0689	$C_{L\alpha}$	3.7108	> 0
	$C_{m\alpha}$	-1.5342	$C_{m\alpha}$	-0.5722	< 0
	C_{mq}	-12.599	C_{mq}	-11.509	< 0
	dC_m/dC_l	0.3027	dC_m/dC_l	0.1542	0.05-3.00
Differencial of lateral direction variables	$C_{Y\beta}$	-0.4208	$C_{Y\beta}$	-0.3618	< 0
	$C_{l\beta}$	-0.0923	$C_{l\beta}$	-0.07505	< 0
	C_{lp}	-0.5518	C_{lp}	-0.4181	< 0
	$C_{n\beta}$	0.1045	$C_{n\beta}$	0.0293	> 0
	C_{nr}	-0.06199	C_{nr}	-0.04578	< 0

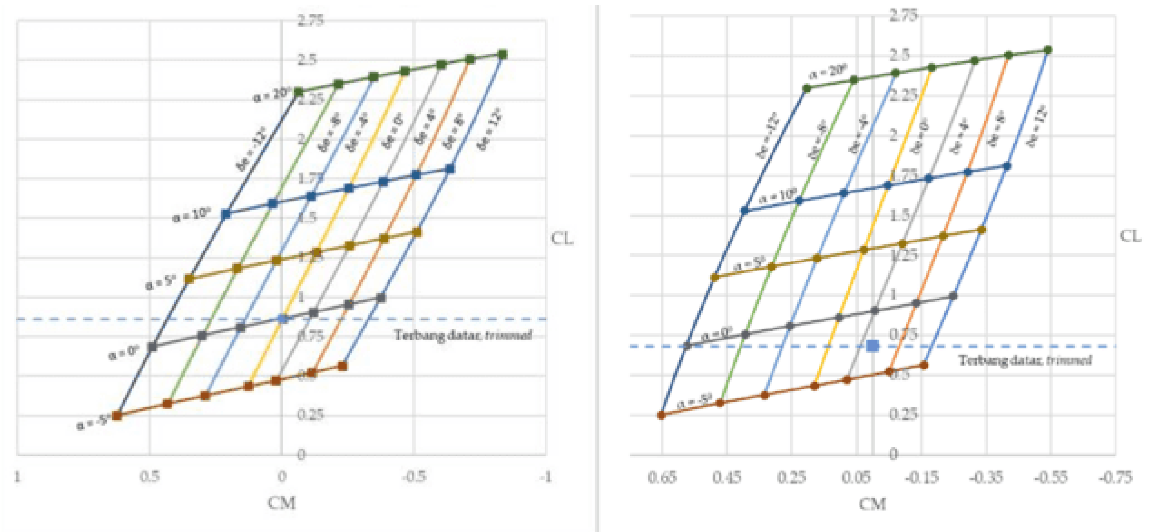

Figure 3. Trim curves for the front-most (left) and rear-most (right) centers of gravity

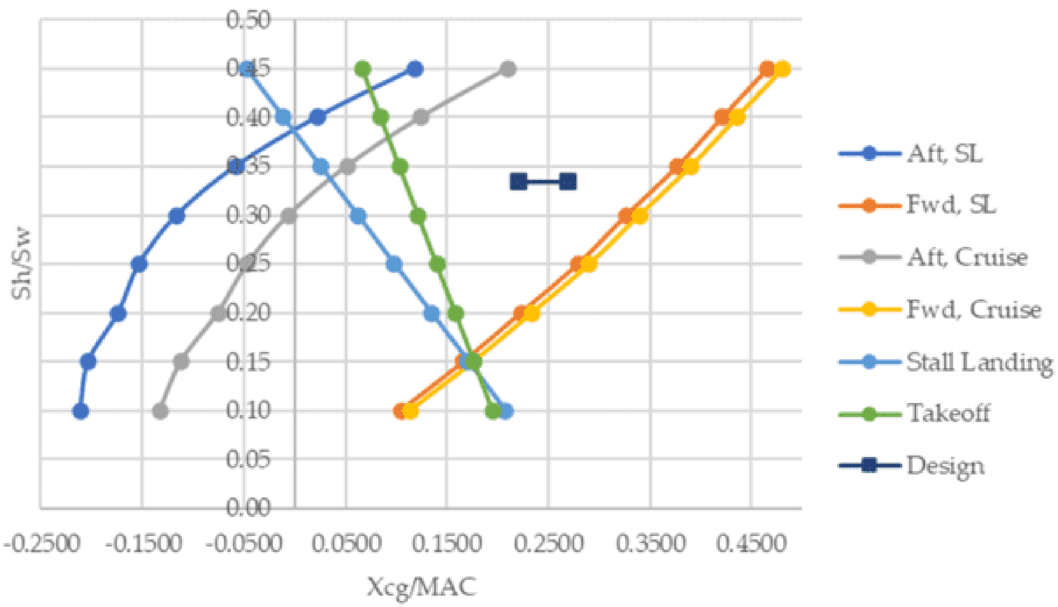

Figure 10. HTP area ratio value limit curve for control

The thrust availability of an aircraft is shown by the following thrust vs velocity curve. The curve shows the aircraft's ability to generate thrust decreases as the aircraft speed increases. The thrust availability of the aircraft at rest is about 120 kN (the value of the thrust vs velocity curve multiplied by the number of engines of the aircraft which is 4) and for cruise conditions the aircraft produces a thrust of about 15 kN, as shown in figure 11.

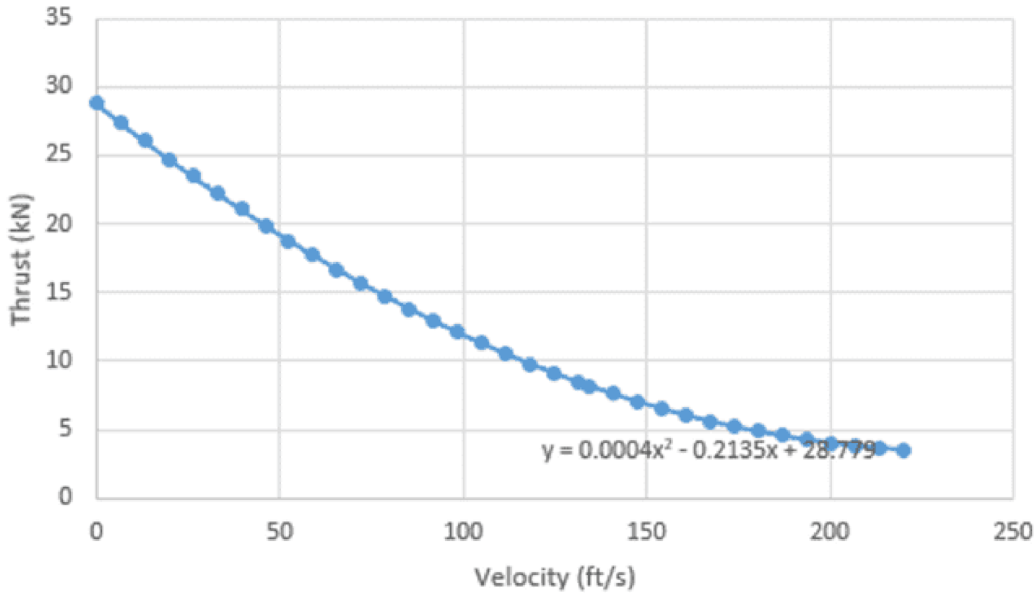

Figure 4. Thrust vs engine speed curve

The quality of the aircraft design that has been produced can be assessed by its fulfillment of the Design Requirements and Objectives (DRO) specifications. A comparison of the design results with the DRO is provided in Table 9.

Table 2. Djinn aircraft design compliance to DRO specifications

Operational Parameters	Value DRO	Value Design	Unit	Value
Cabine and Instrumentation				
Chair capacity	10	10		appropriate
Number of crue	1	1		appropriate
Cabine volume	>9	13.85		appropriate
Bagage volume	>1.6	1.85		appropriate
Aircraft weight				
MTOW	<8000	5655.12		appropriate
Maximum payload	>1000	1000		appropriate
Flight Parameter				
Maximum range (MTOW)	>450	544.73	km	appropriate
Maximum range (4 pax)	>550	678.51	km	appropriate
Maximum reserve (loiter)	>30	30	minutes	appropriate
Service ceiling	>15,000	28,033.66	ft	appropriate
Take-off distance (MTOW)	<900	401.89	m	appropriate
Landing distance (MTOW)	<950	851.99	m	appropriate
Rate of climb maximum	>1600	2,748	fpm	appropriate
Regulation and Certification				
OEI *requirements (CASR 23.67)*	*complied*	*complied*	-	appropriate
Aircraft certificate	2026	2026	year	appropriate
First delivery	2027	2027	year	appropriate
Design Objectives				
Aircraft price per unit	<3,600,000	3,591,346	USD	complied
Maximum flight speed (0.65 MTOW)	>300	240	km/h	not comply

Based on Table 9, the "Djinn" electric engine aircraft has been successfully designed with comprehensive DRO compliance. In fact, some aircraft parameters have better values than the DRO demands, without any parameters sacrificing their compliance with the DRO.

5. Conclusions

The design process of the 10-seater 4-engine electric propeller aircraft "Djinn" has fulfilled all design requirements and 1 design objective given. In this day and age where air pollution is increasingly worrying, electric aircraft can be an alternative in reducing air and noise pollution caused by conventional aircraft. In the future it may consider to design a high-speed aircraft for other purposes using this design concept.

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