INVESTIGATION AND DESIGN OPTIMIZATION OF AN INDOOR PLANE

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Investigation and Design Optimization of an Indoor Plane

Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Date:

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This thesis is the result of my investigations, except where otherwise stated. Other sources are acknowledged by giving explicit references. Bibliography/references are appended.

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Acknowledgement

In the name of Allah the Most Compassionate, The Most Merciful. Praise be to Allah, Lord of the universe, praise, and salam upon His Final Prophet, Muhammad (pbuh).

The opportunity I had for Final Year Project was a great chance for learning and professional development. Therefore, I consider myself as a very lucky individual as I was provided with an opportunity to be a part of it.

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I perceive as this opportunity as a big milestone in my study development. I will strive to use gained skills and knowledge in the best possible way, and I will continue to work on their improvement. Hope to continue cooperation with all you in the future.

Abstract

The aim of this project is to improve the performance of indoor plane that been used in the outreach program by the School of Aerospace Engineering and determine the performance of a thin camber airfoil against the flat plate airfoil to be utilised for the wing of the indoor plane. The project is carried out by doing some calculation of the differences in the performance of coefficient of lift for the thin camber airfoil compare to the flat plate airfoil. After that, the fabrication process for the wing of the thin camber airfoil is conducted to figure the best step of creating the mould and the way to cut the balsa wood. Then, the test will be done by timing the flight duration of the models and compare it with the previous layout. The outcome of the result is that the average flight duration for the model is 2 minutes which is an improvement to the previous design that could only achieve flight duration of about 1 minutes. However, the time reach does not meet the objectives of the project which is flight duration of 5 minutes. The reason due to the unreach goal is due to the limit put to maintain the dimension similar to previous design. The next step is to remove the limit like aspect ratio. Meanwhile, the result obtained from the used of thin camber airfoil show that it can improve the performance of the previous layout for the outreach program.

Abstrak

Tujuan projek ini adalah untuk meningkat prestasi kapal terbang dalam yang digunakan semasa program jangkauan, Aerofair dan untuk menentukan prestasi oleh aerofoil kamber nipis dengan plat rata aerofoil yang akan digunakan sebagai sayap untuk kapal terbang dalam Projek ini dilaksanakan dengan menjalankan pengiraan tentang perbezaan prestasi dari segi pekali daya angkat bagi aerofoil kamber nipis dengan plat rata aerofoil. Selepas itu, proses fabrikasi untuk sayap bagi aerofoil kamber nipis dijalankan bagi menentukan langkah yang terbaik bagi mencipta acuan dan cara untuk memotong kayu balsa. Seterusnya, uji kaji akan dijalankan untuk merekod data masa pernerbangan dan bandingkan dengan reka bentuk yang lepas. Data yang direkodkan oleh masa pernerbangan model baru adalah 2 minit dan 3 saat yang boleh dikatakan sebagai peningkatan prestasi apabila dibandingkan dengan reka bentuk yang lepas hanya mampu selama 1 minit. Walau bagaimanapun, masa yang dicatat oleh aerofoil kamber nipis tidak dapat mecapai objektif pernerbangan selama 5 minit. Alasan pretasi tersebut kerana terdapat had dalam reka bentuk supaya sama dengan saiz reka bentuk yang lepas. Langkah seterusnya adalah untuk hilangkan had itu seperti nisbah aspek. Manakala, keputusan yang diperolehi dari pergunaan aerofoil kamber nipis menunjukkan terdapat peningkatan dari segi prestasi dengan reka bentuk yang lepas digunakan semasa program jankauan, Aerofair.

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Nomenclature

C_l	Coefficient of lift of an airfoil
α	Angle of attack
e	Oswald factor
AR	Aspect ratio
M	Mach number
b	Wingspan
S	Wing surface area
C_{Di}	Coefficient of induced drag of wing
$C_{D_{of}}$	Zero-lift drag coefficient of fuselage
C_{ff}	Skin friction coefficient of fuselage
f_{LD}	Ratio of fuselage length to diameter function
f_M	Mach number function
S_{wet_f}	Wetted area of the fuselage and wing reference area
Re	Reynolds number
ρ	Air density
V	Actual speed
μ	Air viscosity
L_f	Length of fuselage
D_f	Diameter of fuselage
$C_{D_{ow}}$	Zero-lift drag coefficient of wing
$C_{D_{oh}}$	Zero-lift drag coefficient of horizontal tail
$C_{D_{ov}}$	Zero-lift drag coefficient of vertical tail

$\bar{C}$	Mean aerodynamics chords
C_{fw}	Skin friction coefficient of wing
C_{fh}	Skin friction coefficient of horizontal tail
C_{fv}	Skin friction coefficient of vertical tail
f_{tc_w}	Function for thickness ratio of wing
f_{tc_h}	Function for thickness ratio of horizontal tail
f_{tc_v}	Function for thickness ratio of vertical tail
C_r	Root chord
C_t	Tip chord
λ	Taper ratio
$\left(\frac{t}{c}\right)_{max}$	Maximum thickness to chord ratio
S_{wet_w}	Wetted area of wing
S_{wet_h}	Wetted area of horizontal tail
S_{wet_v}	Wetted area of vertical tail
$C_{d_{min}}$	Minimum drag coefficient of the airfoil cross section
L	Lift force
D	Drag force
C_L	Coefficient of lift of wing
C_D	Coefficient of drag of wing

1. Introduction

The indoor plane is a part of the free flight for model aviation that includes any aircraft without external active control after launch. It can be considered as a hobby aeromodelling that the goal is to build and launch a self-control aircraft to achieve longest flight duration with different sort of class parameter. Free flight divided into four types which are Glider, Rubber-powered, power by electric or another type of energy and lastly the indoor plane. Some of the classes focus more on the scale, or semi-scale replicas of a man carrying aircraft and some unusual feature configuration are ornithopters, helicopters or autogiros. Indoor flight modelling is now about century years old activity from the United States involvement in the World War 2 began in 1941 to 1942. As the title above, the focus of this project is the indoor plane that is designed to fly indoor. The indoor plane is usually very light regarding weight because they cannot withstand the condition of the wind, and external weather condition. The indoor plane is supervised by the FAI (Fédération Aéronautique Internationale) that also the international organising body for all air sports worldwide. The FAI also organise the final indoor free flight competition that usually held in the West Baden Springs Hotel in the United States of America. Beside in United States, one other location that have the privellege to held the event is the mine in Romania 120 meter underground. The main attraction during this tournament is the well known F1D indoor plane model that has the minimum weight of 1.4 grammes and a maximum wingspan of 55cm. Furthermore, this model is constructed from a very light balsa wood sheet or strip, carbon fibre, boron filament and a transparent sheet of plastic films that thinner than 0.5 millimetres thick. The source of power for this models are 0.4 grammes of the rubber band in a single loop of about 23 cm that can be wound up to 1500 times. The models require a large space, such as a hall, aircraft hangar or an atrium. The F1D indoor plane model could have a single flight that approaches 40 minutes. The focus patterns in this project are the segment of size between Mini-Stick or Limited Penny-plane. The Mini-Stick model have the span wing of 18 cm and minimum weight of 0.43 grammes while the Limited Penny-plane has the wingspan of 46 cm and weight of 3.1 grammes[1]. The Penny-plane is suitable for a beginner because it has larger dimension thus make it a lot easier to build and the Mini-Stick is a lot lighter which is difficult due to the dimension. The only similarities they have are the power source for the thrust and some of the design are almost identical other than the scale of the plane. Some others classes are the Gyminnie Cricket, F1l, F1R and F1M.

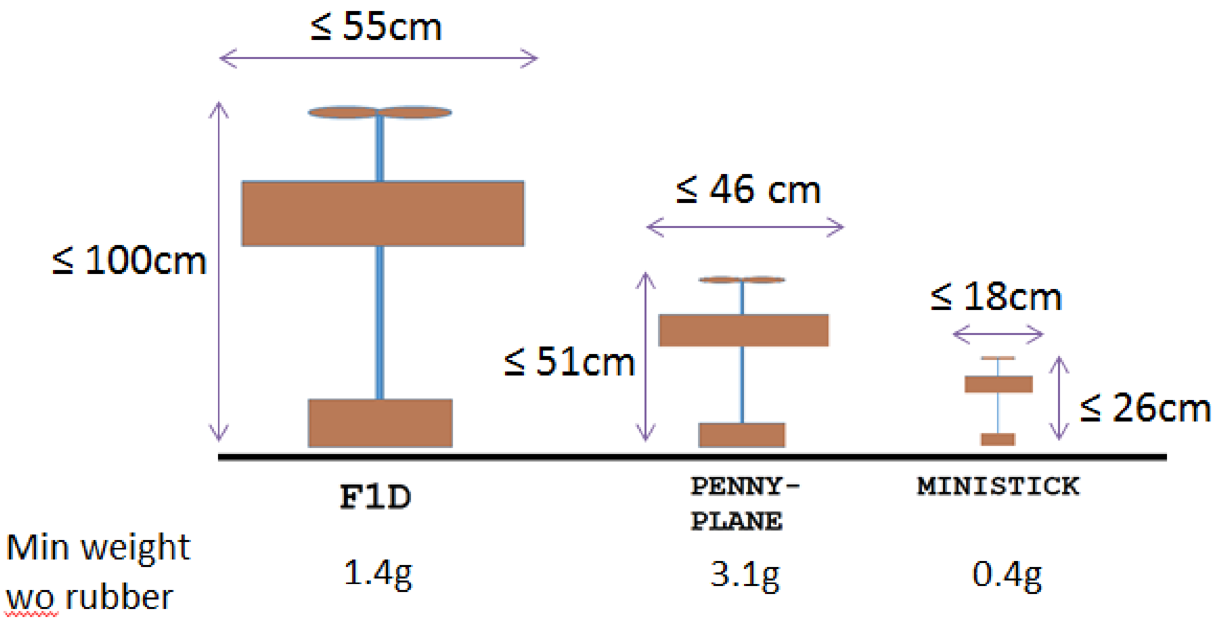

Figure 1.1 : Indoor Plane Size Comparison

Figure 1.2 : F1D Indoor Plane Model

1.1. Motivation

In United States of America, the indoor flight that powered by rubber band are quite attractive by adults and even children. In the United States, the FAI almost annually held the world championships in West Baden Spring that attract a lot of attention from adults and children to participate. The event catches the interest of children to learn more about indoor plane thus making them liking the fields of science.

In Malaysia, there was a report that in 2012 indicates that up to 80 % of students in secondary school level were taking the art stream and the rest 20 % of them are taking the science stream. This is a very concerning issue due to the national target of our country is 2020 is to have 60 % of secondary school students to take the science stream[2]. Furthermore, it illustrates that in Malaysia there is an issue concerning the interest of students in the field of science and math. Thus, it is a wise choice to bring this event related to indoor flight model to Malaysia because of it is capable of becoming an attraction to children and increase the chance of children to take an interest in the field of science and math.

The motivation for this project is to help the kid to play more and doing it while learning the mechanic of flight. Thus, the use of the indoor flight model catch the interest of children to learn while still playing. One of the ways that can expose this kind of activity to children is at the tertiary education level to hold an outreach program to educate children. At the School of Aerospace Engineering Universiti Sains Malaysia, there is an outreach program held annually to secondary school students to learn of the mechanic of flight from the indoor flight model. This outreach program, Aerofair and to find out more about it can go to this website http://www.flyoutreach.com/. The purpose of Aerofair is to increase the interest of secondary school students in science and math by introducing the excitement of flying vehicle through the learning about the mechanic of flight and indoor flight demonstration. The personal motivation for this project is that to ensure the younger generation can obtain any opportunity or chance to improve themselves and to make sure that the program like Aerofair be more exciting as it changes the life of many.

1.2. Problem Statement

Despite the availability in current design in indoor flight, there were analysis done to improve the current performance and its capability. The current design of the indoor flight has the endurance of airborne time just around 1 minutes with typically used of balsa and microfilm. Besides, balsa woods and microfilm was difficult to be obtained for ordinary people without going through a proper channel like college and university as a consequence give dilemma to some especially to children to choose material as it becomes a limitation in

Malaysia. Correspondingly decrease the interest of children or students to venture into the world of science primarily related to aerodynamics.

Ensuring that this situation does not remain as it is, it becomes an obligation as someone who creates a better future to create a path for children that is easily accessible. Furthermore, if we create any data analysis of the performance of indoor flight especially regarding the material selection from our surrounding availability, we already create a bridge for them to continue to interest.

Currently, at University Sains Malaysia, School of Aerospace Engineering held an outreach program for secondary school to expose them to aerospace by making a competition of indoor flight. The current design that we have can only fly around 1 minutes longest. Thus, the flight time is too short to attract the intention and interest of students to fundamental science of a flying plane.

1.3. Research Approach and Scope

The primary focus of this project will be on the wing and the body of the indoor plane. The current design used in the outreach program Aerofair are thin plate style of wings and will consider a change to the thin airfoil theory which has higher lift compare to the flat plate at a variable angle of attack.

Next, the part concerning the body goal is to reduce as much weight as possible because the weight is a drag to the plane. The other goal for the body is to find a better way to attach the wing to the body as of now the design in Aerofair used a small balsa stick that quickly breaks whether during launching or landing environment. This will be approached by experimental and fabrication method to determine the advantage of a precise design of the attachment and the shape of the body.

Also, determining the placement of the wing, empennage and the propulsion system will be done thru Matlab code to consider the location of the CG and the equilibrium moment for stable flight. The requirement for this project in term of software is Matlab, Solidworks and MS Excel.

1.4. Objectives

The project work described in this thesis is performed based on the following objectives:

1. To produce or fabricate an indoor plane that capable of having the duration of flight close to 5 minutes.
2. To optimize the performance of the wing of the indoor plane correspond to the current design used in Aerofair.

1.5. Thesis Outline

This thesis comprises five chapters. Chapter 1 will provide a general overview of the indoor plane and the different types available. Then, the motivations for undergoing this project with the outreach program Aerofair are interpreted. Next, the problem statement for this project is also explained in this section. Finally, the objectives and approach of the project are defined.

Chapter 2 reviews all the related theory that is related to this work. The focus is on the wing of the indoor plane such as the type of airfoil used and the shape of the wing. For the indoor flight, the design of the airfoil for the wing will be related to the thin airfoil theory. The other parts that will be dicussed are the relation of an infinite wing to finite wing and also the zero-lift drag coefficient for the body, tail and wing.

Chapter 3 explains the methodology used in this research. This part will showcase the calculation and Matlab program to determine the parameters for the indoor plane. Furthermore, the parameter will be draw in SolidWork and the optimization is focus mainly on the wing of the indoor plane. This section provides information regarding the steps utilised in this study including the process involved to produce all the fabrication of the indoor plane. Besides, the method used in testing the flight duration of the indoor plane to achieve the target result.

Chapter 4 provides the results and discussions obtained from all the testing that had been carried out through this study. The results and discussions are mainly about the reason for choosing the thin airfoil than a flat plate airfoil. Also, the discussion will be on the transformation of an infinite to finite wing and the downside of a camber airfoil when converting to a finite wing. This chapter also will debate the hardship when fabricating the indoor plane and the cause of the difficulty. Next, is the performance of the indoor plane and its weight compare to the previous layout.

Last but not least, Chapter 5 concludes the overall research findings from the projects, and suggests a number of improvements that can be made in future research projects to increase the flight duration for the indoor plane.

2. Background

This chapter will explain the understanding behind the project regarding the theory and the equations that will be used out the whole project. Inside the first subsection, there will be three smaller subsections that will explain the Kutta-Joukowski theorem, thin airfoil theory, finite wing correction and the zero-lift drag coefficient. This segment also will list any previous study that has been done regarding the theory or the indoor plane model.

2.1. Theory

2.1.1. Thin Airfoil Theory

Based on Kutta-Joukowski theorem for a thin plate, the lift coefficient, c_l of a thin plate airfoil is linearly proportional to the angle of attack, α.

$$C_l = 2\pi\alpha$$

where 2π is the theoretical lift slope plate.

However, for thin airfoil theory is not just straight thin plate. Thin airfoil theory is a very thin cambered thin plate. To simplify the solution for the common two-dimensional airfoil section can be done by neglecting the thickness effects and using only a mean line section model known as the thin airfoil theory. The assumption for this theory is that the airfoil thickness is really thin compared to the chord and the angle or slope is small. An example of angle or slope $\sin\alpha \approx \alpha$, $\cos\alpha \approx 1$ and $slope \approx angle$. Also, the airfoil can only be slightly disturbed by the free stream $u', v' \ll V_\infty$. This is perfect for the condition of the indoor flight face during airborne condition and environment[3][4][5].

$$A_0 - \sum_{1}^{\infty} A_n \cos n\theta = \alpha - \frac{dz}{dx}$$

Then multiply both sides by $\cos n\theta$ and integrate from 0 to π:

$$A_0 = \alpha - \frac{1}{\pi}\int_0^{\pi} \frac{dz}{dx} d\theta$$

$$A_n = \frac{2}{\pi}\int_0^{\pi} \frac{dz}{dx} \cos n\theta \; d\theta$$

In particular, the expressions for the local pressure difference and integrated lift and moment about the leading edge are:

$$Lift = \rho\, U_\infty \int_0^1 y\, dx$$

$$cl = \frac{Lift}{\frac{1}{2}\, \rho\, {U_\infty}^2\, c} = \frac{2}{U_\infty\, c}\int_0^1 y\, dx$$

Thus

$$cl = 2\pi\, (A_0 + \frac{A_1}{2})$$

$$c_{p1} - c_{p0} = \frac{\rho\, U_\infty\, y}{\rho \frac{{U_\infty}^2}{2}} = 4\, [\, A_0 \cot\frac{\theta}{2} + \sum_1^{\infty} A_n \sin n\theta$$

$$M_{l.e} = \int_0^1 \rho\, U_\infty y x\, dx \quad or \;\; c_m = -\frac{\pi}{2}\left(A_0 + A_1 + \frac{A_2}{2}\right) = -\frac{C_1}{4} - \frac{\pi}{4}(A_1 - A_2)$$

(The expression relating to Cp and y only applies for thin airfoil)

Before proceeding forward, first, need to understand how to use the theory that involves the thin airfoil theory. Example:

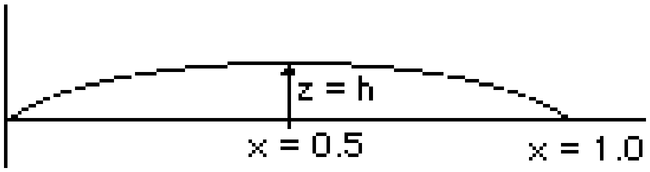

Figure 2.1: Example calculation of thin airfoil

Determine the equation of the parabolic camber mean of the thin airfoil.

Assume $z(x) = 4hx(1-x)$

$$\frac{dz}{dx} = 4h(1-2x) = 4h\cos\theta$$

$$A_0 = \alpha - \frac{1}{\pi}\int_0^{\pi} 4h\cos\theta\, d\theta = \alpha$$

$$A_1 = \frac{2}{\pi}\int_0^{\pi} 4h\, \cos^2\theta\, d\theta = 4h$$

General equation:

$$c_l = 2\pi\alpha + 4\pi h = 2\pi(\alpha + 2h)$$

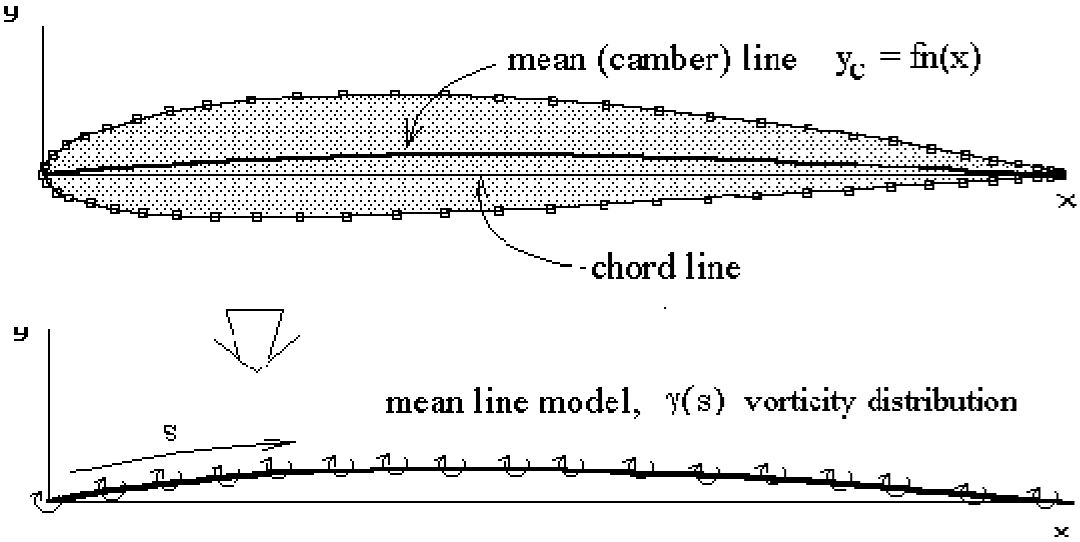

Figure 2.2 : The mean camber line of an airfoil

The figure above illustrate that the mean camber line of an airfoil is used as a thin airfoil for the calculation and shape of the thin airfoil.

2.1.2. Finite Wing Correction

These methods of computing the circulation distribution enable to calculate the pressure difference along the airfoil. The next step is to transform the coefficient of lift of an aerofoil into a wing. The angles of attack of a 2D airfoil (α_o) need to be changed to fit the 3D wing (α_{comp}) by using finite wing correction[5]. It can be solved as follow:

$$\alpha_{comp} = \frac{\alpha_o}{\sqrt{1 - M_\infty{}^2} + \frac{\alpha_o}{\pi e AR}}$$

$$\alpha_{comp} = \frac{\alpha_o}{\sqrt{1 - M_\infty{}^2 + \left(\frac{\alpha_o}{\pi e AR}\right)^2} + \frac{\alpha_o}{\pi e AR}}$$

The equation above are for high aspect ratio for the straight wing (subsonic compressible), and the bottom ones are for the low aspect ratio for the straight wing (subsonic compressible). The AR is the aspect ratio of the wing that can be defined as follow:

$$AR = \frac{b^2}{S}$$

Where b is the wingspan, and the S is the area of the wing. The e is an Oswald factor. The other component that is missing in 2D is the induced drag (C_{Di}), which is the drag generated by a wing simply because it has a finite dimension. The difference in circulation produced by each airfoil has an influence over the whole wing[7]. It can be defined as follow:

$$C_{Di} = \frac{C_L{}^2}{\pi e AR}$$

2.1.3. Zero-Lift Drag Coefficient

Also the drag that coming from the fuselage will be calculated with the zero-lift drag coefficient by the following equation:

$$C_{D_{of}} = C_{ff} f_{LD} f_M \frac{S_{wet_f}}{S}$$

Where, C_{ff} is the skin friction coefficient of the fuselage, and is a non-dimensional number. It can be determined based on the Prandtl relationship as follows:

$$C_{ff} = \frac{0.455}{[\log_{10}(Re)]^{2.58}}$$

The equation above is for turbulent flow while the ones below are for laminar flow.

$$C_{ff} = \frac{1.327}{\sqrt{Re}}$$

Where Re is the Reynolds number and has a non-dimensional value. It can be defined as:

$$Re = \frac{\rho V L_f}{\mu}$$

The parameter of ρ is the air density, V is the actual aircraft airspeed, L is the length of the component in the direction of flight, and μ is the air viscosity. For the case of a fuselage, the L_f is the length of the fuselage while for the wing and tail it will be the mean aerodynamic chord[8]. The parameters, f_{LD} is a function of fuselage length to diameter ratio. It is defined as:

$$f_{LD} = 1 + \frac{60}{\left(L_f/D_f\right)^3} + 0.0025\left(\frac{L_f}{D_f}\right)$$

Where L_f is the length of the fuselage, and the D_f is the maximum diameter of the fuselage. If the cross section of the fuselage is not a circle, use the equivalent diameter. The parameter, f_M is a function of Mach number (M). It can be defined as follow: