Investigation and Performance Optimization of Propulsion System for an Indoor Plane

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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:

STATEMENT 1

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

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ABSTRACT

This research focus on the propulsion system for a Mini Stick scale indoor plane which consists of a rubber band and a propeller. The effect of the rubber band on the performance of the indoor plane is analyzed by using a torque meter. Different thickness and thickness of rubber band are tested to search for the most suitable thickness and length of rubber band that is able to sustain the rotation of propeller for 5 minutes. The factors that affect the thrust generated by the propeller are studied through numerical solution and experimental analysis. The numerical solution is done by using MATLAB programming software and some assumptions are made to simplify the analysis as well as the algorithm. The experimental analysis is done by using the load balance and the propeller is tested at different pitch angle with different thickness of rubber band. From the research, the torque of the rubber band increases with the thickness of the rubber band and the thrust generated by the propeller increases with the pitch angle of the propeller. However, the torque and the thrust must be in an optimum value. This is because a high torque will use up the energy stored in a rubber band at a faster rate and a high thrust will causes the indoor planes to accelerate. Both of these will lead to poor endurance performance of an indoor plane. Hence, for the propeller for an indoor plane to sustain for 5 minutes, the most suitable thickness of rubber band is 1.5875 mm and winded up to 3300 turns. The pitch angle of the propeller blade must be in 48°. This research can be further improved by designing the propeller blade into different geometry. For example, an elliptical-shaped propeller will reduce the tip vortex which might contribute to a better performance of propeller for an indoor plane.

ABSTRAK

Kajian ini bertujuan untuk mengkaji sistem pendorongan oleh pesawat ruang tertutup dalam skala Mini Stick yang terdiri daripada getah dan bebaling. Kesan getah terhadap prestasi pesawat ruang tertutup dianalisa dengan menggunakan meter daya kilas. Ketebalan dan kepanjangan getah yang berbeza diuji untuk mencari getah yang paling sesuai untuk mencapai masa penerbangan selama 5 minit. Faktor-faktor yang memberi kesan kepada daya pendorong yang dihasilkan oleh bebaling dikaji melalui penyelesaian berangka dan analisis eksperimen. Penyelesaian berangka dilakukan dengan menggunakan perisian pengaturcaraan MATLAB dan beberapa andaian telah dibuat untuk memudahkan analisis serta algoritma MATLAB. Analisis eksperimen dilakukan dengan menggunakan imbangan beban dan bebaling diuji dalam sudut bilah bebaling dan ketebalan getah yang berbeza. Hasil daripada kajian, daya kilas getah meningkat dengan ketebalan getah dan daya pendorong yang dihasilkan oleh bebaling meningkat dengan sudut bilah bebaling. Walau bagaimanapun, daya kilas dan daya pendorong mestilah dalam nilai yang optimum. Hal ini disebabkan oleh tork yang tinggi akan menggunakan tenaga yang disimpan dalam getah dengan kadar yang lebih cepat dan daya pendorong yang tinggi akan menyebabkan pesawat tertutup mengalami pecutan. Kedua-dua ini akan membawa prestasi ketahanan yang lemah kepada pesawat tertutup. Oleh itu, untuk menyokong putaran bebaling selama 5 minit, ketebalan getah yang paling sesuai adalah 1.5875 mm dan sudut bilah bebaling haruslah dalam sudut sebanyak 48°. Keputusan daripada kajian ini boleh menambahbaikkan dengan mereka bentuk bebaling dalam bentuk yang berbeza seperti dalam bentuk bujur dan bukannya hanya bentuk segi empat tepat dalam kajian ini.

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NOMENCLATURE

$C_{d,f}$	Skin Friction
Re_x	Reynold Number
ρ	Density of Air
v	Velocity of Airflow
c	Chord Length
μ	Viscosity of Air
C_l	Lift Coefficient
q	Dynamic Pressure
S	Area
α	Angle of Attack
β	Induced Angle
γ	Pitch Angle
V_{plane}	Velocity of Indoor Plane
V_{inflow}	Inflow Velocity of Propeller
r	Radius of Propeller Blade
n_{rps}	Rate of Rotation of Propeller Per Second

CHAPTER 1: INTRODUCTION

Indoor planes can be described as the simplest form of aircraft. It offers the students a chance to understand the basic flying mechanism of real aircraft. Indoor planes can be divided into three main categories depending on the size of the indoor planes which are large ($100\ cm \times 75\ cm$), medium ($51\ cm \times 46\ cm$) and small ($26\ cm \times 18\ cm$). Typically, indoor planes are constructed from balsa wood and usually have masses from about 0.5 to 10 grams [1].

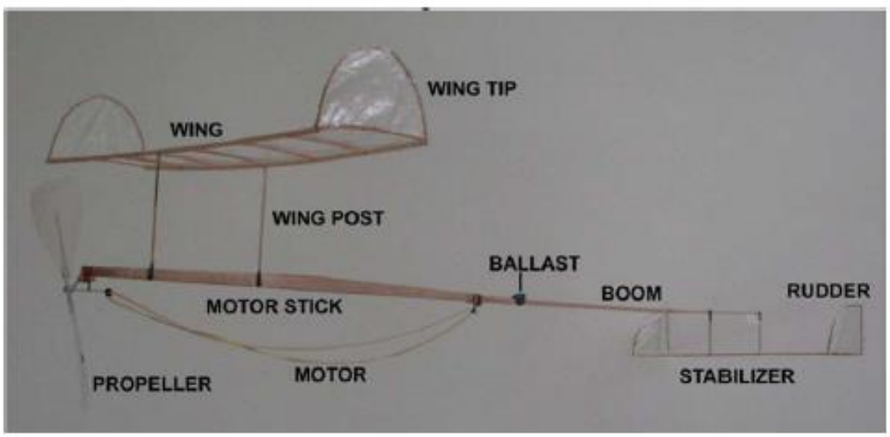

Figure 1: Typical Indoor Plane

An indoor plane is composed of 4 main parts: the airframe, lifting surface, stabilizer and propulsion system. In this thesis, the discussion is limited to the propulsion system of indoor planes. The propulsion system of indoor planes consists of a rubber band and a propeller. The function of the rubber band is to act as a motor that is responsible for torque generation for the rotational motion of the propeller. The torque of the rubber band is a key factor that affect the overall performance of the indoor planes. This torque is varied with the thickness of the rubber band. High thickness of rubber band often guarantee a high torque generation. The function of the propeller is to produce a sufficient amount of thrust in overcoming the drag caused by the propeller as well as the aerodynamic drag of the whole structure of the indoor plane. The critical factor that affect the performance of a propeller is the pitch angle of the propeller blade. Different pitch angle settings will result in different thrust generation by the propeller. The focus of this thesis is to examine the effect of rubber band thickness on torque generation and the effect of propeller pitch angle on thrust generation. All of the discussion below are limited to small scale indoor plane i.e., the Mini Stick and taking MiniSlick indoor plane as reference model.

1.1 Motivation

In conjunction to the Secondary School Outreach Program organized by the School of Aerospace Engineering, Universiti Sains Malaysia, there is an event namely AEROFAIR which involved the participation of secondary school students. The main aim of the AEROFAIR is to promote science and engineering to secondary school students through exciting aerospace engineering activities as well as to establish educational spirit in aviation industry. Indoor flight is one of the competitions in AEROFAIR and it requires students to build and compete for the best flight time. Through indoor plane building and flight testing, students are able to understand the working principles behind an aircraft in real life, for example: why thrust is needed for an aircraft to operate and how lift is generated? Theory is best learned when it is practiced by using a real model and immediate applications. The process in building and modifying the indoor planes to achieve a longer flight time is quite challenging and it requires the students to do some research based on available resources. This subsequently will facilitate and motivate the self-learning process of the students.

Figure 2: AEROFAIR 2016 with Lecturers from School of Aerospace Enginnering, Organizing Committee and Participants from Secondary School

1.2 Problem Statement

Several indoor planes are built and competed during the latest AEROFAIR event. It is found that those indoor planes are only able to score a flight time about 1 minute.

The major problem is the rubber band used in the indoor flight competition. The thickness of the rubber band is too thick and hence, the torque generated by the respective rubber band is too high. A high torque indicate a faster rotational motion of propeller as the energy stored inside the rubber band is higher. However, a faster rate of rotation of a propeller does not imply a longer endurance performance. It will cause the energy stored in the rubber band used up in a faster rate and unable to support the indoor plane for a longer flight.

The thrust of the propeller is another problem that contributed to the poor endurance performance. The thrust generated by the propeller is too small to overcome the aerodynamics drag of the structure of the indoor plane. Hence, the indoor plane landed after a very short period of flight time. Generation of thrust is affected by the pitch angle of the propeller blade. This infer that the pitch angle of the propeller blade is not set to an ideal value.

From other perspective, the short flight time of the indoor plane might be due to the thrust generated by the propeller is too high. A high thrust will causes the indoor plane to accelerate and increases the parasitic drag (combination of form drag, skin friction and interference drag) [3]. Up to a certain velocity, the drag of the indoor plane will become so high that the thrust generated by the propeller is not enough to overcome the total drag of the indoor plane. Hence, the indoor plane landed.

1.3 Objectives

This research is conducted to achieve the objectives as shown below:

I. Design the experimental facility for rubber band torque measurement and investigate the effect of thickness and length of rubber band on the torque generated by the rubber band.

II. Design experimental facility and build a numerical algorithm to investigate the effect of pitch angle of propeller balde on the thrust generated by the propeller and compare the results.

III. Build a real propeller model that is able to sustain for 5 minutes flight time as well as with local available materials.

1.4 Research Approach and Scope

The experimental analysis of the rubber band, torque measurement is conducted with a torque meter. The working principle behind the torque meter is studied so that the right procedure are conducted when using the torque meter in experimental works.

The experimental analysis of thrust measurement is done by using load balance. The concept and the building of the setup are learnt to minimize any human-made errors when handling the load balance for propeller thrust measurement. The experiment must be conducted in a close space to avoid any disturbances from surrounding environment as the load cell has a high sensitivity.

The numerical analysis of thrust measurement is done by using MATLAB platform. The theories behind the propeller are studied so that the right equations are applied in the programming algorithm. This is to increase the accuracy of the numerical results and also to identify the critical factors that affect the performance of the propeller. The limitation in this approach is that everything in theory are assumed to be ideal. Hence, there is always difference when comparing the numerical results with experimental data.

CHAPTER 2: BACKGROUND

This chapter highlights the theories involved in designing the experimental facility for propeller thrust measurement. The equations used in building the numerical algorithm for thrust measurement are shown as well. The theories used in the design of propeller are introduced and the previous studies on propeller are included to facilitate the understanding of propeller dynamics.

2.1 Theory

This section consists of technical knowledge of propeller and assumption made in analyzing the propeller for indoor flight.

Propeller can be described as a wing that rotate. In some simple shape, the propeller blades are paddle shape as shown in Figure 3 [4]. The blades are set to an angle and known as pitch angle, γ, so that propeller blades can produce thrust at right angles to the plane of rotation.

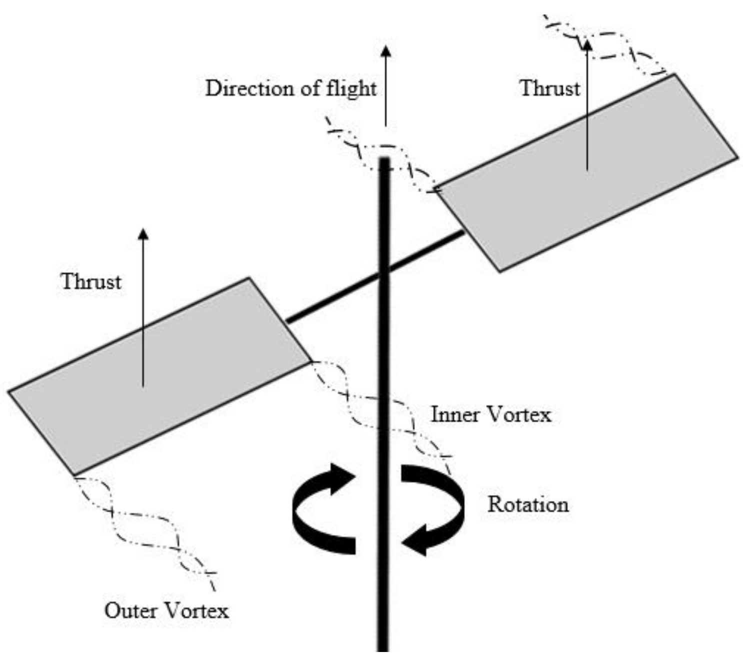

Figure 3: A Simple Paddle-type Propeller

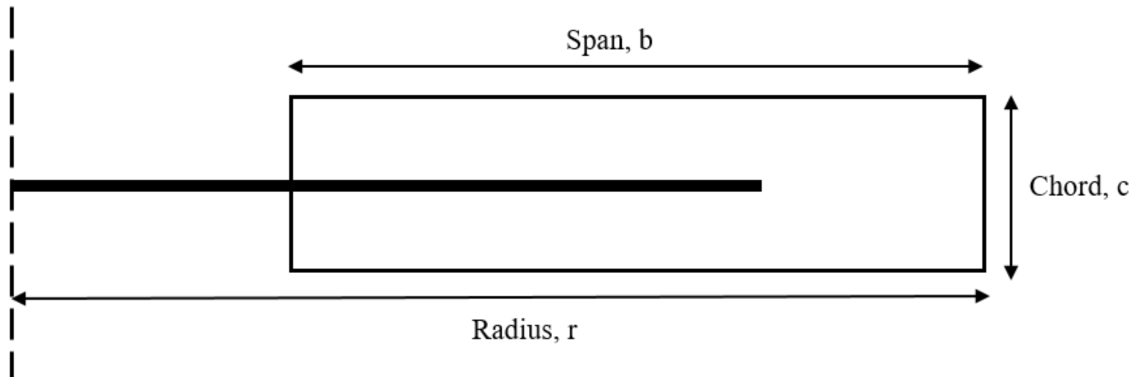

Figure 4: Propeller Blade

The propeller blades are also subjected to the drag forces. The drag forces resist the rotational motion of the propeller, producing a torque reaction against the drive shaft. The propeller blade is subjected to two kind of drag, vortex-induced drag and profile drag. Profile drag is composed of form drag and skin friction. Form drag results from the turbulent wake caused by the separation of airflow from the surface of a structure. Skin friction is caused by surface roughness [5]. However, in the numerical algorithm, the propeller blades are assumed to be subjected to skin friction only [1]. The main reason for this simplification is due to skin fiction drag can be calculated easily through formula while form drag requires a more sophisticated approach by using a wind tunnel to measure the value. The equation for skin friction is shown below:

$$C_{d,f} = \frac{1.328}{\sqrt{Re_x}} \tag{1}$$

$$Re_x = \frac{\rho v c}{\mu_\infty} \tag{2}$$

Like a wing, the cross-section of a propeller blade is an airfoil profile. However, in this thesis, the propeller blade is assumed to be a thin flat plate to simplify the analysis in the numerical thrust measurement. This assumption is actually made based on Kutta-Joukowski theorem. In this theorem, it is stated that the lift slope of a thin flat plate is equal to 2π and the theoretical lift coefficient is linearly proportional to angle of attack. The equation for lift coefficient is shown below:

$$C_l = 2\pi\alpha \tag{3}$$

$$Lift\ slope = \frac{dC_l}{d\alpha} = 2\pi \tag{4}$$

Hence, the lift of a propeller blade can be calculated based on the information provided in the Kutta-Joukowski Theorem. The equation for lift is shown below:

$$L = qSC_l \tag{5}$$

The lift produced by the propeller blade depends on the flight velocity of indoor plane and the inflow velocity of the propeller blade. The resultant airflow is expressed in both speed and direction by the diagonal line as shown in Figure 5 below.

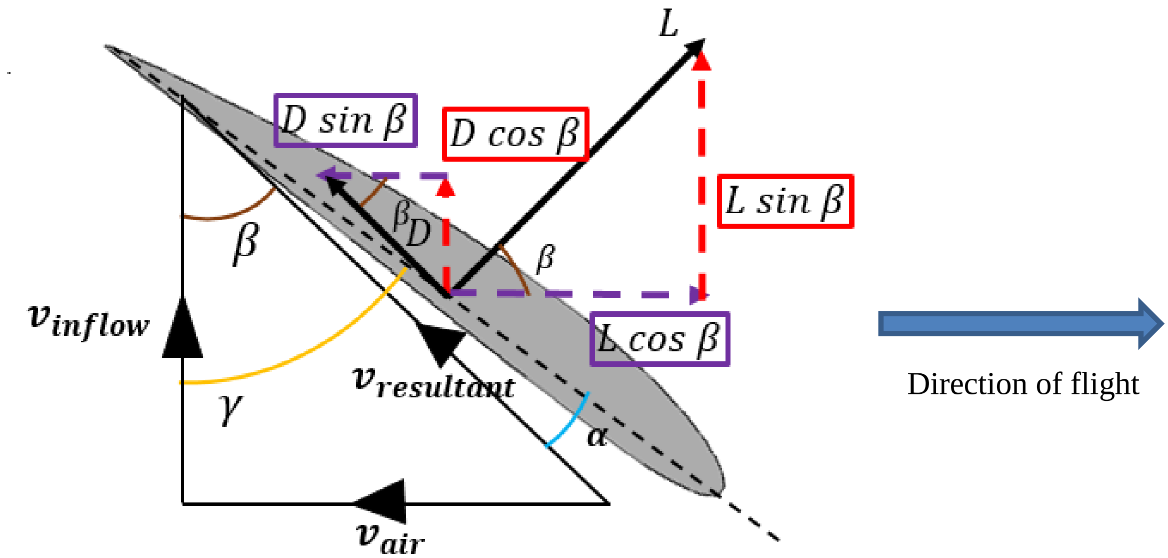

Figure 5: Forces Acting on Cross-section of a Propeller Blade

The angle of attack, α of the propeller blade is measured from the geometric chord up to the resultant airflow line. β is the induced angle of the propeller. The equation for induced angle shown below:

$$\beta = \tan^{-1}\left(\frac{V_{plane}}{V_{inflow}}\right) \tag{6}$$

$$V_{inflow} = 2\pi r n_{rps} \tag{7}$$

The angle of attack of the propeller blade is the difference between pitch angle and the induced angle of the propeller blade. The equation for angle of attack is shown in below:

$$\alpha = \gamma - \beta \tag{8}$$

Obviously, the angle of attack of the propeller blade is less than the pitch angle, γ. As long as the angle of attack of the propeller blade is greater the aerodynamic zero of the cross-section, lift will be produced at the right angles to the resultant airflow.

The lift produced and the drag induced are resolved into vertical and horizontal component. From Figure 5, the horizontal component is actually the thrust generated by the propeller blade while the vertical component indicate the amount of torque required to drive the propeller. The equations are shown in below:

$$Thrust, T = L\cos\beta - D\ \sin\beta \tag{9}$$

$$Torque, Tq = (\ L\sin\beta + D\ \cos\beta)\ \times r \tag{10}$$

$$D = qSC_{d,f} \tag{11}$$

Equation (7) shown that the inflow velocity of the propeller blade is directly proportional to the radial distance of the propeller blade measured from the propeller hub.

$$V_{inflow} \propto r \tag{12}$$

Hence, at the root of the propeller hub, the inflow velocity of the propeller blade is smaller as the radial distance is shorter. This in turn causes a higher induced angle and smaller angle of attack at the root of the propeller blade. Since, the lift generated by the propeller is directly proportional to the angle of attack, the propeller will generate a lower lift at the root or any radial distance close to the hub. This explain why the propeller is twisted to a higher pitch angle at the root of the propeller. It is used to increase the angle of attack at the root of the propeller blade so as more lift is generated at the root.

2.2 Previous Studies

This section consists of previous research on propellers design theories that are used to predict the thrust generated by the propellers. The assumptions in each theory are studied and analyzed to serve as a basic in building up the numerical algorithm and experimental facility for propeller thrust measurement.

There are three theories that are used in for propellers design, momentum theory, blade element theory and vortex theory. Only the first two theories are in used. This is mainly due to the mathematical complexity of the vortex theory.

Momentum theory is based on the hypothesis of a stream-tube, which exactly encloses the propeller disk as shown in Figure 6. The stream-tube is assumed to extend from a plane indefinitely far upstream from the propeller disk to a plane indefinitely far downstream [7].

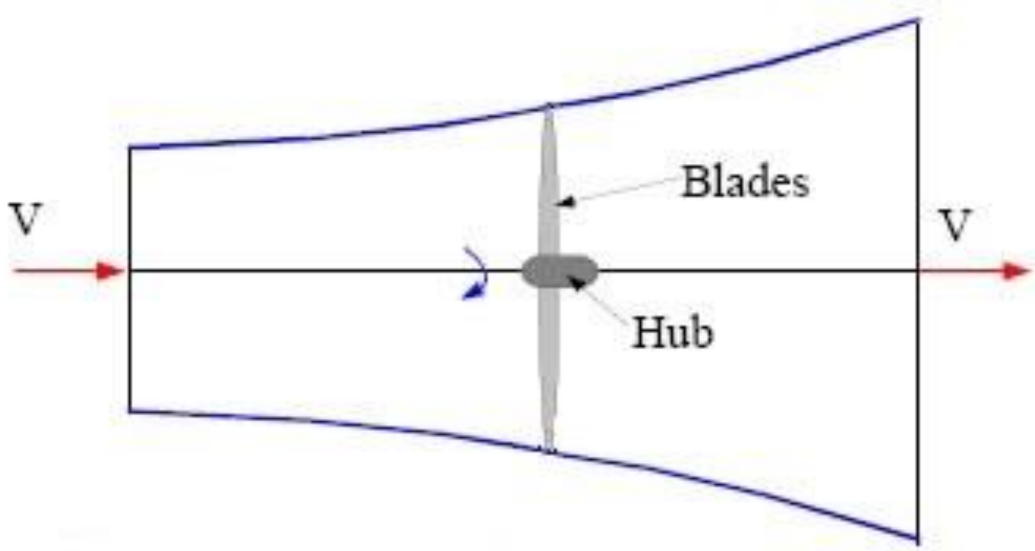

Figure 6: Classical Momentum Theory Model

Momentum theory model is based on the assumption: inviscid and incompressible airflow and an infinite number of propeller blades. Most of the assumptions are ideal unrealistic for actual condition. Hence, this theory is only useful in predicting the ideal propeller efficiency.

Based on momentum theory, the thrust generated by the propeller is the mass per unit times the total change in velocity per unit time through a control volume.

$$Thrust, T = \rho A(V + v)2v \quad (13)$$

$$v = V - V_1 \quad (14)$$

The primary limitation of the momentum theory is that it provides no information on how the propeller blades should be designed to produce a given thrust. In 1920, S. Drzewiecki performed a further mathematical research on the behavior of the propeller after D. W. Taylor in 1893. The theory is known as blade element theory and most of the propellers were designed using this theory.

Later in 2011, Q T Truong, Q V Nguyen, V T Truong, H C Park, D. Y. Byun and N. S. Goo modified the blade element theory to estimate the forces generated by a beetle-mimicking flapping wing system [10]. According to Truong [10], in blade element theory, the wing is divided into many sections. The aerodynamic forces acting on each wing section are then calculated by considering the wing section as a two-dimensional airfoil. By integrating the forces acting on each wing section over the entire length, the forces produced by the flapping wing can be computed.

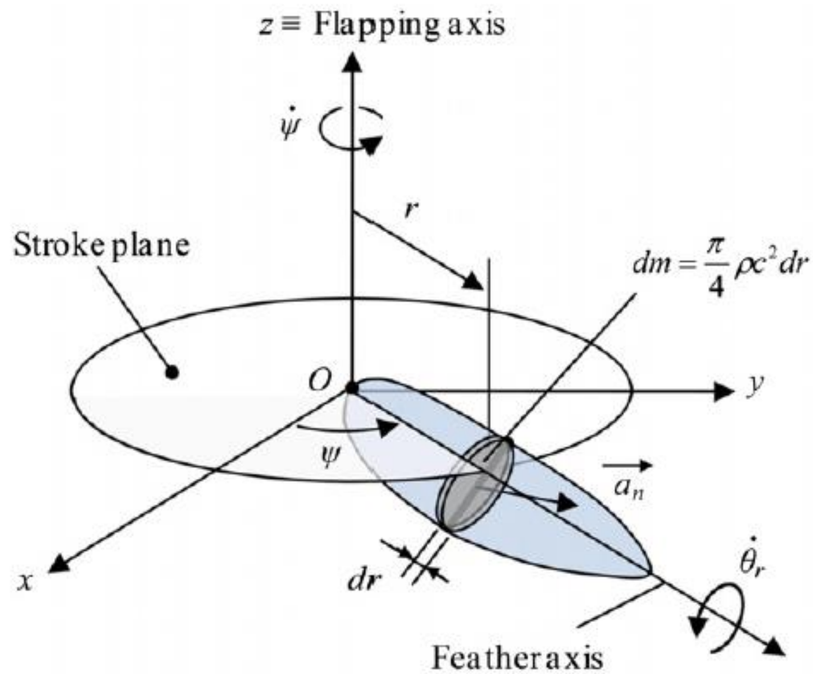

Figure 7: Truong's Model in Blade Element Theory for Flapping Wing [10]

Also in 2011, E. Kulunk [8] summarized the blade element theory in analyzed the aerodynamics of wind turbines. Kulunk divided the turbine blade into many elements as shown in Figure 8.

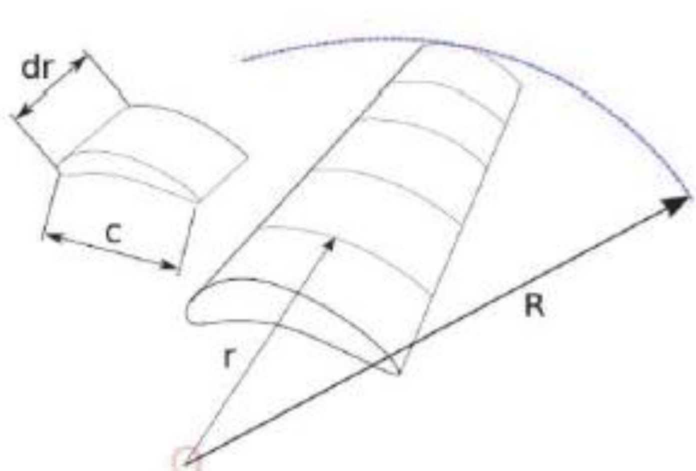

Figure 8: Kulunk's Model in Blade Element Theory

Based on Kulunk, each of the blade elements has a different rotational speed and experience a slightly different flow. Hence, blade element theory involves dividing up the blade into a sufficient number (usually between ten and twenty) [8] of elements and calculating the forces acted on each element. Overall performance characteristics of the blade are then determined by numerical integration along the blade span.

For research purpose, the blade element theory is used as a basic in building the numerical algorithm for propeller thrust measurement for indoor plane. This is mainly due to the blade element theory utilizing the same equations in computing the lift and drag force as shown in the previous section.

In 2006, Nelson. D. Leon and Matthew N. D. Leon [1] conducted aerodynamic simulation of indoor flight by using Science Olympiad and F1D virtual indoor plane as reference. According to Leon [1], controlled flight for indoor plane is made possible by the interaction of several forces. Once those forces are identified, the flight equations can be simply derived by applying Newton's second law of motion, $F = ma$. The lift and drag is modelled by using the lifting line theory. Leon also restricted the simulation to two-dimensional flight where only pitch is important. This approximation is to simplify the analysis. In the simulation, Leon simulated the thrust generated by the propeller of Science Olympiad indoor plane over the time. The thrust decreases with time.