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Wind Tunnel Investigation of Propeller Characteristics and Wing-Propeller Interaction

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Bachelor of Engineering. (BEng Honor)

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October, 2017

الآية

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

وَقُلِ اعْمَلُوا فَسَيَرَى اللَّهُ عَمَلَكُمْ وَرَسُولُهُ وَالْمُؤْمِنُونَ وَسَتُرَدُّونَ إِلَى عَالِمِ الْغَيْبِ وَالشَّهَادَةِ فَيُنَبِّئُكُمْ بِمَا كُنْتُمْ تَعْمَلُونَ (105)

سورة التوبة، الآية (105)

Abstract

The main goal of this project is to review the mechanisms and describe the phenomena that play a role in the aerodynamic interference between the propeller and a wing. Therefore, the characteristics of the isolated propeller (the propulsion relationship and the efficiency with the flight speed) were studied. The results were then compared with the propeller characteristics installed on the wing or on the fuselage. The results showed a drop in thrust with increasing the flight speed for an isolated propeller, and a decrease in efficiency was also observed due to the presence of wing or fuselage (due to pressure drag).

التجريد

الهدف الرئيسي من هذا المشروع هو استعراض الآليات ووصف الظواهر التي تلعب دورا في التداخل الديناميكي الهوائي بين المروحة والجناح. لذلك، تمت دراسة خصائص المروحة المعزولة (علاقة الدفع والكفاءة مع سرعة الطائرة). ثم تمت مقارنة النتائج مع خصائص المروحة المثبتة على الجناح أو على جسم الطائرة. وأظهرت النتائج انخفاضا في الدفع مع زيادة سرعة الطيران للمروحة المعزولة، كما لوحظ انخفاض في الكفاءة بسبب وجود الجناح أو جسم الطائرة (بسبب زيادة أعاقة الضغط).

Acknowledgement

First, we would like to thank Allah for the knowledge, endurance, perseverance and strength that made this project possible.

Many thanks are due to or families who have sacrificed many hours in order to allow us to complete this project.

We owe special thanks to our supervisor Dr. Intisar Abdel Fattah Mohammed Khattab for his valuable insights and for his encouragement and inspiration which made this work possible.

We would like also to thank all of our colleagues and friends for their support during the preparation of this project.

The efforts in this project would not have been possible without the kind support and help of many individuals; we would extend our sincere thanks to all of them.

Dedication

Man can't inherit the past.........

He has to recreate it ....

To our families...............

To our teachers................

To our partners................

As they seek to create.........

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List of Abbreviations

AFM	Airplane Flight Manual
DC	Directive current
FIM	Full Interaction Mode
NTS	Negative Torque System
SIM	Single Interaction Mode
SRF	Swirl Recovery Factor
UAV	Unmanned Arial Vehicle

Symbols

A	Propeller Disk Area
AR	Aspect Ratio
B	Blockage Ratio
D	Propeller Diameter
D_{fus}	Fuselage Maximum Diameter
E_{lost}	Energy Losses
G_P	Propeller Geometry
I_W	Interference effect of the wing on the flow around the propeller
J	Advance Ratio
$\dot{m}$	Mass Flow Rate
n	Revolution per Second
P_d	Power Absorbed by Propeller
$P_{1_{dynamic}}$	Upstream Dynamic Pressure
$P_{2_{dynamic}}$	Downstream Dynamic Pressure
P'_o	Pressure at the Propeller Disc
r	Reduce of Propeller
T	Propeller Thrust
U_o	Increase in Velocity
V_{rot}	Rotational Velocity
V_{rel}	Relative Airflow
V_d	Velocity at the Propeller Position
V_o	Upstream Velocity
V_s	Downstream Velocity
V_∞	Free Stream Velocity
ΔV	Different between upstream & downstream Velocity
X, Y, Z	Coordinates in flow axis

α	Angle of Attack
$\alpha_{P_{eff}}$	Effective Propeller Angle of Attack
β	Blade Angle
$\beta_{0.16R}$	Blade Setting
η	Propeller Efficiency
φ	Geometric Pitch
$\boldsymbol{\rho}$	Density

Chapter One
Introduction

1 Chapter One: Introduction

1.1 Overview

A propeller introduced in a flow of air, will change this flow by its action. This change called the disturbance of the flow caused by the propeller. If there are other bodies present, the change of the flow accompanied in general by a change of the force acting on them. This change called the influence of the propeller on the bodies. On the other hand, the introduction of a body will change in general the forces acting on the propeller.

The problems concerning the interference between the propeller and the other parts of the airplane may be thus divided into two groups. The first is formed by those cases in which the attention is directed primarily to the influence of other bodies on the propeller, whereas the second includes those relating to the influence of the propeller on other parts of the airplane structure.

1.2 Aim and Objectives

1.2.1 Aim

This project aims to develop the manufacturing of the propeller to achieve the optimum performance. By presented an accurate study of propeller characteristics to increase the propeller efficiency and reduce the losses, so that operation become economic.

1.2.2 Objectives

The objective of this work was to measure, through the propeller test experimentation:

- Study the aerodynamic characteristics.
- The effects of the wing and fuselage on the propeller characteristics (performance).

A corollary of this work was the documentation of propeller influences on Static stability for high - power geometries incorporating modern Propeller designs. The results of this investigation will aid in future predictions for Propeller effects on stability, and are of value to designers and testers involved with similar airplane configurations and propeller designs.

1.3 Problem Statement

The propeller is a device using to convert the power developed by the engine into a useful force called 'Thrust'.

The problem lies when converting the power to thrust is that it would be there loss of power during the operation of aircraft in the air.

The problems concerning the interference between the propeller and the other parts of the airplane may be thus divided into two groups. The first is formed by those cases in which the attention is directed primarily to the influence of other bodies on the propeller, whereas the second includes those relating to the influence of the propeller on other parts of the airplane structure.

1.4 Proposed Solution

Study the propeller characteristics to determine the efficient condition of operation with minimum losses in power delivered from the engine, and maximum performance of the aircraft.

1.5 Motivation

The recent advances in propeller technology have led to an increased interest in understanding the effects of the slipstream on nearby aircraft components. Since the motor driven propeller actively affects the propulsion, aerodynamics and stability of the aircraft.

It has become imperative to understand the interaction of a propeller configuration with the supporting structures such as fuselage and wings in order to determine optimal system integration. For this reason, experimental as well as numerical studies of propeller-body interaction have been undertaken in previous research work placing emphasis on understanding effects on the body rather than looking at the system as a whole.

1.6 Methodology and Methods

This project had been accomplished using an experimental technique (testing was performed using the wind tunnel laboratory in Aeronautical Engineering Department at Sudan University of Science and Technology). At first, wooden models for wing and fuselage had been made. Then, the propeller had been mounted in a shaft and connected directly to the wind tunnel test section box. The wind tunnel was used to generate a velocity which is considered as flight speed. The dynamic pressure change in the test section had been measured upstream and downstream the propeller using Pitot tube in four different sections distributed along the propeller diameter from a digital indicator. By using Microsoft Office Excel was draw the curves of efficiency and applying the momentum theory was calculated the aerodynamic characteristics of the propeller.

This experiment had been repeated with another two different configurations, fuselage mounted propeller configuration and wing mounted propeller configuration. A comparison between the three different configurations was took place.

Equipment list:

1. AF100 subsonic wind tunnel
2. Pitot tube
3. 12V Brushless Motor 1000KV “12000RPM”
4. 0.18m diameter Propeller

5. DC Power Supply 12V
6. Electronic Speed Control
7. Simple speed control application
8. Wing model
9. Fuselage model

1.7 Thesis Outlines

This thesis has been organized into six chapters, including chapter one is the introduction of the project, chapter two include historical background and the basis of propeller and propeller principles, chapter three is the interactions of the propeller and the airplane, chapter four is the calculations, chapter five is the discussion and results, and finally, chapter six include conclusion, recommendations and future work.

Chapter Two
Literature Review

2 Chapter Two: Literature Review

2.1 Historical Background

In 1900 and 1901 Stefan. K. Drzewiecki, a Polish mathematician and mariner presented two papers in Paris on his blade element, or “strip” theory (Carrol, 2005). Based on Bernoulli’s principles they provided a way of determining forces and moments by representing the blade as a number of aerodynamically independent cross-sections. The characteristics of each of these sections were assumed to be the same as an airfoil at that angle of attack. The main drawback of the theory was that, as the operation of a cross-section was indirectly related to that of a two-dimensional airfoil, Experimental two-dimensional airfoil data was thus needed a priori.

The Wright brothers were the first of the early aircraft design pioneers to realize that a propeller worked on the principle of a rotating wing generating forward lift as opposed to the previous concept of a propeller pushing the air rearwards (Carroll & Carroll, 2005). Despite their relatively basic understanding of the aerodynamic principles involved their designs exhibited high efficiencies - even when compared to modern designs. While they utilized the blade element theory of Drzewiecki, they realized that it was not able to predict the induced velocities required to produce the correlation between an airfoil in axial flow and a rotating airfoil. They realized that it had to be combined with the earlier momentum theory of Rankine and Froude in order to complete the analysis. In 1903 they had produced a propeller that demonstrated a maximum efficiency of 66% and by 1905 they had achieved an efficiency of 81.5% (Carrol 2005). These efficiencies were not achieved by other designers until after World War I (Ash, 2001) and are high even by modern day standards.

In 1919 Albert Betz published a paper while working as a researcher at the University of Gottingen Aerodynamic Laboratory on minimum energy loss propellers (Betz, 1919). In this paper he illustrated that there was a particular radial propeller blade loading which would minimize the energy loss in the wake. He also showed that the induced power required by a propeller was minimized if the slipstream had the same velocity at all radial points and if each cross section of the slipstream rotated around the rotation axis in a rigid fashion.

Betz followed this with a paper translated into English titled, “The Theory of the Screw Propeller” (Betz, 1922). This work was a summary of the understanding at the time of the flow phenomena around propellers. In particular, he mentioned the requirement for a combined blade element and momentum theory that made it possible to evaluate the induced velocity field and therefore predict the inflow conditions assumed by the blade element theory. Betz (1922) also noted that the use of aerodynamic data as used on the wing airfoil should be used with caution when applied to propellers.

Ludwig Prandtl, a German physicist and a pioneer of subsonic aerodynamics, wrote the appendix to Betz’s 1919 paper in which he described an approximate solution to this minimum energy loss, radial force distribution *(Prandtl and Betz, 1919)*. He recognized that the slipstream velocity would move at a fixed fraction of the free stream velocity (Larrabee, 1984a). He approximated this fraction using an analogy to the flow between semi-infinite plates moving normal to the free stream in terms of an edge distance / plate spacing parameter. This was the first approximate attempt at predicting a minimum loss blade loading.

Goldstein (1929) suggested that a design method existed that would produce a family of minimum induced loss propeller designs with different ratios of induced to profile losses depending on the design parameters used. He did not elaborate on this design method any further. Research into propellers for higher speed aircraft and more powerful engines continued throughout World War II. However, the advent of the gas turbine engine and its ability to thrust aircraft to speeds greater than that of sound brought research into the further understanding of the aerodynamics of the propeller to a virtual standstill by the start of the 1950's.

Many years later, due partly to a renewed interest in man-powered flight and the requirement for highly efficient propellers, the relatively simple design method suggested by Goldstein was developed and published (Larrabee, 1979a). He investigated the connection between propeller design utilizing lifting line theory with induced velocity distributions being induced by helical trailing edge vortex sheets and Glauert's radially graded momentum theory. He showed that through a combination of these two methods a radial twist and chord distribution could be determined that would result in an optimal circulation distribution.

Larrabee (1979a, 1979b) went on to simplify the resulting method in his paper with small angle approximations, assumptions of low disc loading as regards to the displacement velocities and disregarding the viscous terms in the induced velocity expressions. He stated that his method would be most accurate when applied to "relatively lightly loaded" propellers. [1]

A paper on propeller-wing aerodynamic interference had been published. The main goal of this paper is to review the mechanisms and describe the phenomena that play a role in the aerodynamic interference between tractor propellers and a wing. Experiments on propeller-wing configurations reveal a very complex flow with high levels of vorticity and considerable shearing forces in the wing area that is washed by the propeller slipstream. Surface pressure measurements clearly showed the effect of the swirl velocity and the increased total pressure due to the propeller whose local influence is directly coupled to the propeller rotational direction. The force measurements and the surface pressure measurements demonstrated a performance benefit when the propeller rotational direction is inboard up. This finding indicates the possibilities to design optimum wing shapes whose exact shaping and profiling depends on the structure of the incoming slipstream. This paper had been published *L.L.M. Veldhuis (2004).[2]*

Thesis on wing–propeller interaction had been published. This thesis compared a tractor and a pusher configuration for a tilt-body vertical take-off and landing micro air vehicle using an experiment in a subsonic wind tunnel. The results were used to determine that the aerodynamic performance of the tractor configuration was better than for the pusher configuration. And aerodynamic efficiency of the tractor wing were higher than for the pusher wing. Furthermore, the zero-lift drag coefficient of the tractor wing was lower than for the pusher wing. Thus, a tilt-body MAV can obtain great advantage from the tractor wing configuration. This thesis had been published *Kwanchai Chinwicharnam* and *Chinnapat Thipyopas (*February 2016).[3]

Mention that when operating in the proximity of a fuselage, the performance of a propeller can be significantly affected. The blockage ratio, the ratio between the propeller diameter and the diameter of the fuselage, directly impacts the efficiency of the propeller and causes a shift in the advance ratio at which peak efficiency occurs. Whereas well characterized for larger general aviation propellers, the effects of propeller blockage for small propellers used on unmanned aircraft remain largely uninvestigated. The current article presents initial results of wind tunnel tests of small propellers with and without a fuselage installed. It is shown that the blockage effect can be more pronounced for small propellers than for larger propellers and can lead to a reduction in efficiency of close to 20%. A commensurate reduction in endurance can be expected. (*D. Verstraete* and *R. MacNeill*, December 2016).[4]

2.2 Basics of Propellers

A propeller is a device used for creating thrust in a fluid through rotational means. Figure 2-1) is velocity diagram for a cross section of a propeller blade. This illustrates that both the free stream and rotation velocities that are seen by the propeller.

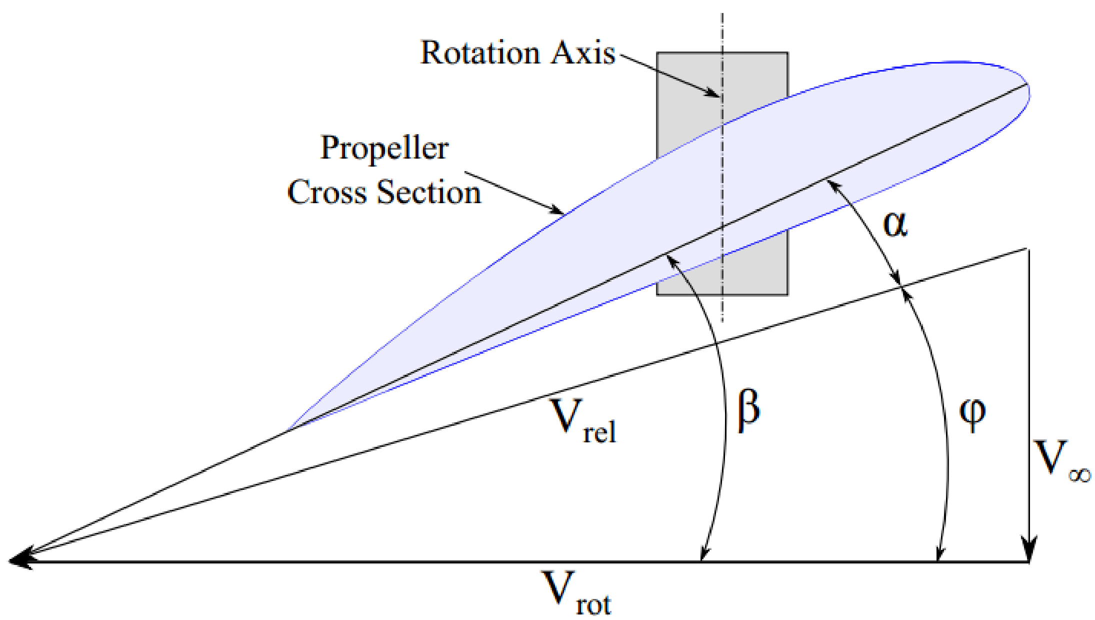

Figure 2-1: Blade Cross Section Velocity Diagram

2.2.1 Geometry

Propellers are very similar to wings. The lifting surface on a propeller is called a blade, and a propeller can have any number of blades. Most propellers have two to four blades Any given point along a blade the cross section has all the same characteristics as an airfoil: leading and trailing edges, mean camber line, chord line, thickness, etc. Where the blades connect is called the hub which is either directly attached to an engine or to a transmission. The root is the area between the hub and the blade, and the tip is end of the blade opposite the hub. The blade angle, β, is the resultant angle between the free stream and rotational velocity components and it shown in the velocity diagram in Figure 2-1. The effective pitch,p_e is the distance a propeller advances in one rotation. While the geometric pitch, φ_e, is the theoretical distance an element of a propeller blade would travel in one rotation and may not be constant along the length of blade[5] [6]. Several of these geometric parameters can be seen in Figure 2-2.

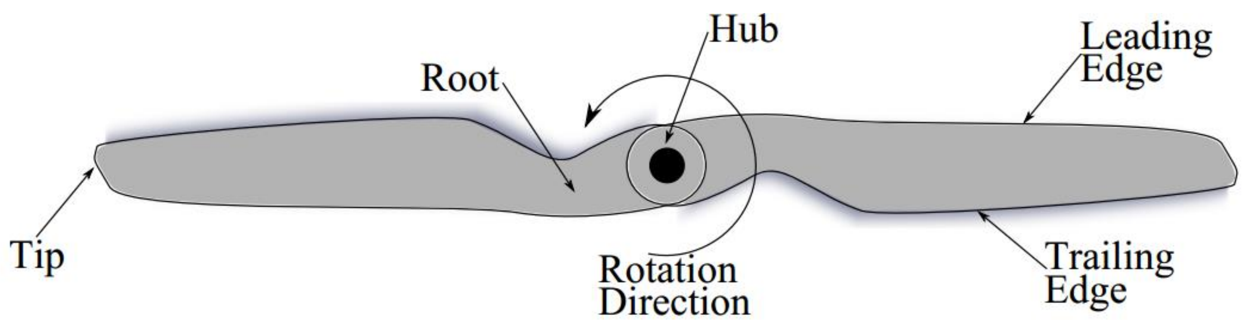

Figure 2-2: Propeller Geometry

2.2.2 Other Parameters

There are many other parameters that are useful in describing propellers. The advance ratio, J, is the ratio between the distance the propeller moves forward through one rotation and the blade diameter.

$$J = \frac{V_d}{nD}$$

Where n is the rotations per second. The aspect ratio, AR, is the tip radius divided by the maximum blade width. A spinner is a conical or parabolic shaped fairing that is mounted over the center of the center of the propeller where it is connected to the hub.

2.2.3 Propeller configurations

Propellers are either tractor or pusher propellers. A tractor propeller is placed in a configuration where the engine is downstream of the propeller and pulls the aircraft. While a pusher propeller is placed where the engine is upstream of propeller and pushes the aircraft.[7]

2.2.4 Types of Propellers

Propellers can also be classed as either fixed or variable pitched propellers. A fixed pitch propeller's blades are rigidly connected to the hub. A variable pitch propeller's blades can be adjusted either on the ground or during flight to allow the propeller to operate at maximum performance throughout its operation range: [7]

2.2.4.1 Fixed-Pitch Propeller

As the name implies, a fixed-pitch propeller has the blade pitch, or blade angle, built into the propeller. The blade angle cannot be changed after the propeller is built. Generally, this type of propeller is one piece and is constructed of wood or aluminum alloy. Fixed-pitch propellers are designed for best efficiency at one rotational and forward speed.

2.2.4.2 Ground-Adjustable Propeller

The ground-adjustable propeller operates as a fixed-pitch propeller. The pitch, or blade angle, can be changed only when the propeller is not turning. This is done by loosening the clamping mechanism that holds the blades in place. After the clamping mechanism has been tightened, the pitch of the blades cannot be changed in flight to meet variable flight requirements. The ground-adjustable propeller is not often used on present-day airplanes.

2.2.4.3 Controllable-Pitch Propeller

The controllable-pitch propeller permits a change of blade pitch, or angle, while the propeller is rotating. This allows the propeller to assume a blade angle that gives the best performance for particular flight conditions. The use of controllable-pitch propellers also makes it possible to attain the desired engine rpm for a particular flight condition.

2.2.4.4 Constant-Speed Propellers

A constant speed propeller is a propeller with a control system that maintains a constant propeller rotational speed (RPM) setting at any flight condition. To maintain constant propeller RPM, you must adjust the pitch of the propeller blades as you change airspeed and/or engine power. The pitch is adjusted by rotating the whole blade on a bearing in the hub using an actuator that is linked to the control system. When you change the pitch, you change the "bite" that the blades make with the wind. This, in turn, increases or decreases the aerodynamic load on the propeller. The advantages of a modern turboprop constant speed propeller are: better performance over a wider range of flight conditions, the ability to produce reverse thrust during landing rollout and ground handling, and the ability to minimize drag on the aircraft by feathering the propeller in the event of an engine shutdown.

2.2.4.5 Feathering Propellers

Feathering propellers must be used on multi-engine aircraft to reduce propeller drag to a minimum under one or more engine failure conditions. A feathering propeller is a constant-speed propeller used on multi-engine aircraft that has a mechanism to change the pitch to an angle of approximately 90°. A propeller is usually feathered when the engine fails to develop power to turn the propeller. By rotating the propeller blade angle parallel to the line of flight, the drag on the aircraft is greatly reduced. With the blades parallel to the airstream, the propeller stops turning and minimum wind milling, if any, occurs. The blades are held in feather by aerodynamic forces.

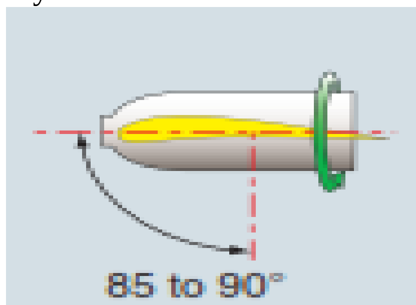

Figure 2-3: Feathering Propellers

2.2.4.6 Reverse-Pitch Propellers

A reverse pitch propeller is a controllable propeller in which the blade angles can be changed to a negative value during operation. The purpose of the reversible pitch feature is to produce a negative blade angle that produces thrust opposite the normal forward direction. Normally, when the landing gear is in contact with the runway after landing, the propellers blades can be moved to negative pitch (reversed), which creates thrust opposite of the aircraft direction and slows the aircraft. As the propeller blades move into negative pitch, engine power is applied to increase the negative thrust. [7]

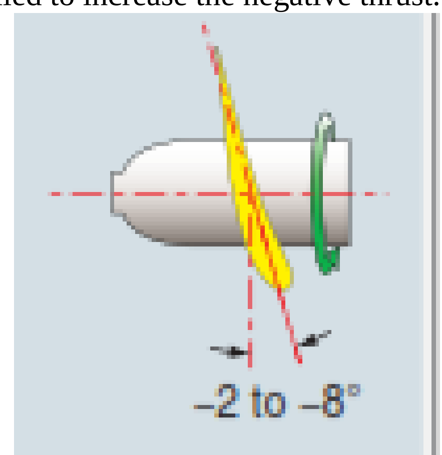

Figure 2-4: Reverse-Pitch Propellers

2.3 General Propeller Principles

2.3.1 Blade pitch

The propeller blade pitch, also more simply called the propeller pitch, is the angle that the blade presents to the plane of rotation of the propeller.

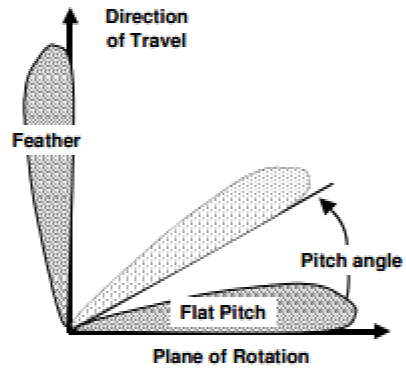

Figure 2-5: Blade Pitch

2.3.2 Blade twist

Propeller blades need to be twisted to optimize the aerodynamic performance of the specific blade design with the angle of attack to the air as they rotate. The angle of the air approaching a blade is a combination of the airplane's forward speed and the propeller's rotational speed. The airplane forward speed is constant along the blade, but the rotational speed increases from the blade root to the blade tip (the tip has to travel farther for each rotation). This means that the propeller blade needs to be twisted to get the optimum amount of lift along the full length of the blade.

2.3.3 Thrust

Propellers produce thrust using the same principle as airplane wings do to produce lift. If you look at a section of a propeller blade, you will notice that it looks like a wing. The air approaches the blade section (airfoil) at an angle of attack that causes a pressure change over the airfoil, producing lift. This lift produces a force to propel the airplane in the direction of flight. The propeller produces the majority of the thrust for the airplane, but the engine also provides a small amount.

2.3.4 Efficiency and speed control

Since all propellers are most efficient within specific RPM ranges, it is desirable to have a propeller with the ability to change thrust while maintaining the most efficient engine RPM possible. In a propeller, this is done by changing the propeller blade pitch, which increases or decreases the load as needed to maintain a constant RPM. The ability of the propeller to change pitch allows both the engine and the propeller to spend most of their time operating in their most efficient range.

2.3.5 Geometric Pitch

The distance the propeller moves forward in one revolution without slip and is measured in inches. A theoretical distance calculated from the blade angle and propeller radius r at a particular blade section. It can be compared with a screw thread LEAD. $\text{Geometric Pitch} = 2\pi r \tan\beta$

2.3.6 Effective Pitch (Advance per Revolution)

This is the actual distance the propeller moves forward in one revolution and is affected by aircraft flight conditions. Effective pitch may vary from zero, when the aircraft is stationary on the ground to approximately 85% of geometric pitch during the most efficient flight conditions. The actual distance moved forward in one revolution is not a fixed quantity and will depend on the aircraft's speed and propeller RPM.

$$\text{effective pitch} = \frac{\text{aircraft speed}}{\text{propeller speed}}$$

2.3.7 SLIP

The difference between Geometric Pitch and Effective Pitch (Advance per Revolution) and is expressed as a percentage. In effect it is a volume of air.[8]

$$\text{slip} = \frac{\text{geometric pitch} - \text{effective pitch}}{\text{geometric pitch}} * 100$$

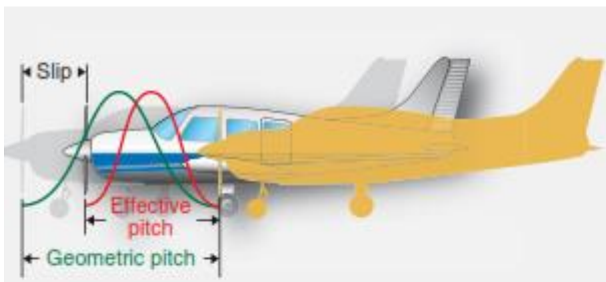

Figure 2-6: Geometric Pitch, Effective Pitch and Slip

2.4 Physical Properties

Propeller is long relative to its width, tapering in thickness from the center hub to the outer tip. The width also varies, flaring slightly outwards from the hub, then tapering to the tip. The blades are also twisted along their length.

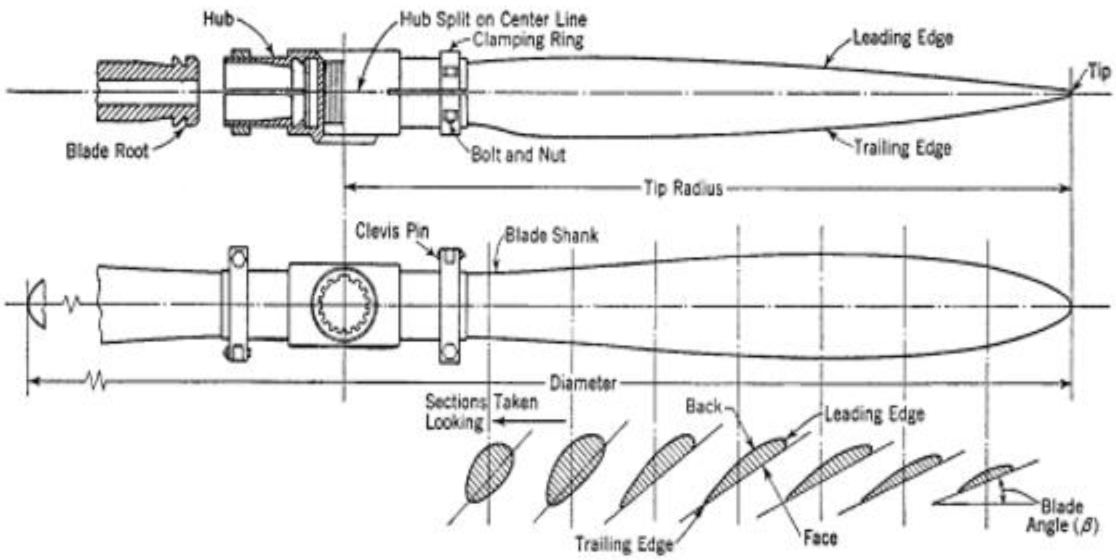

Figure 2-7: Blade Twist or Pitch Illustration

In order to push the air, it must be able to capture or grab the air. If the blades were flat (no twist) and oriented perpendicular to the direction of flight they would not capture any air. The flat blades could be tilted so they 'bite' into the air. This works after a fashion but is very inefficient. So the blades are twisted to improve the efficiency. Figure 2-7 illustrates what happens to a blade when it is twisted.

The objective is to make each piece of the blade along its length advance axially the same distance in one revolution. That way each section produces the maximum amount of thrust at the same time. The pitch is defined as the distance traveled forward in one revolution if there were no slippage; i.e. assuming movement through a solid. Note that the angle of the blade relative to the X-Y plane increases from the tip inward toward the hub. This angle is called the blade angle and is measured on the blades lower surface. The geometric pitch is measured to the airfoil chord line.

The blade moves slowest in distance around the shaft near the hub and fastest at the tip. Thick airfoil shapes generally perform best at low speeds while thin airfoils perform best at high speeds. Increasing the width would increase lift but would also increase drag. Designers have determined that the optimum length to width ratio as defined by the aspect ratio is about 7:1.

Another reason for the thickness and width tapering is mechanical. The greatest stresses occur near the hub so thickness there provides the strength needed. Decreasing the thickness and width with radius also reduces the overall weight and reduces the angular momentum, a desirable property for combating the gyroscopic effects of spinning masses.

While two blades are the most common, three or more blades are sometimes used. Since three blades have more lifting area than two blades of the same size, the blade length can be reduced somewhat while maintaining the same forward speed, rpm and engine shaft power. The blade tips move a little slower so they produce less noise and provide greater ground clearance. Propellers need to be balanced in rotation and aligned symmetrically along the thrust axis. If one blade is heavier than the other, vibration may occur, that can damage the engine and the airplane. Inexpensive prop balances are available that can be used to check for imbalance. Most of propellers are out of balance when new.[9]

2.5 Propeller Theories

2.5.1 Momentum Theory

Momentum Theory is also well known as Disk Actuator Theory. It assumes that:

- The flow is inviscid and steady (ideal flow), therefore the propeller does not experience energy losses due to frictional drag.
- Also the rotor is thought of as an actuator disk with an infinite number of blades, each with an infinite aspect ratio.
- The propeller can produce thrust without causing rotation in the slipstream.[10]

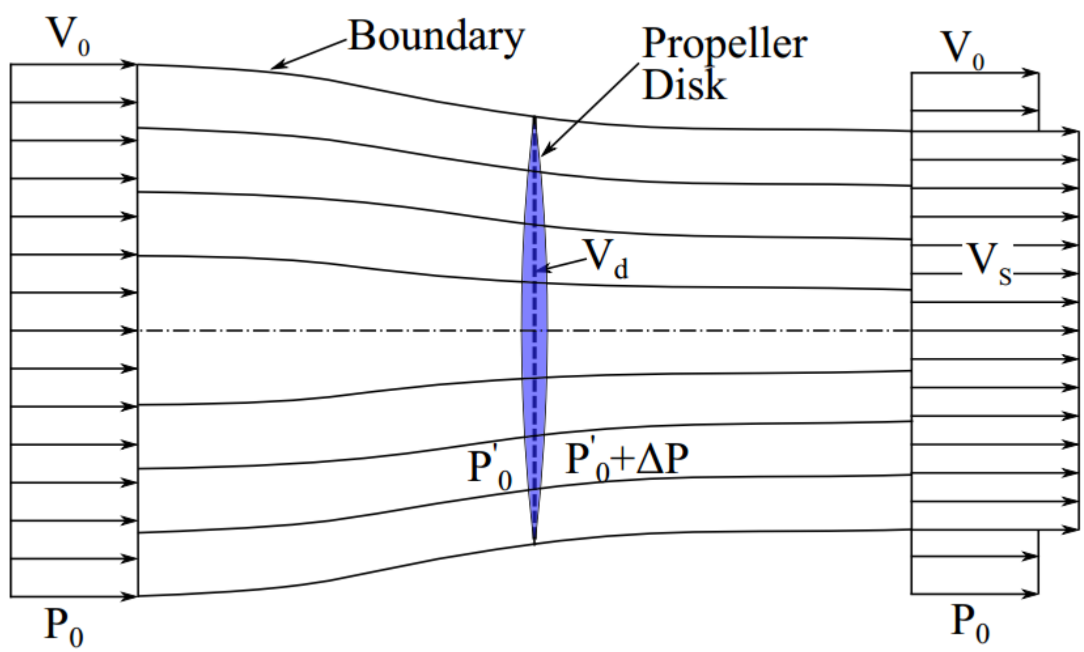

Figure 2-8: Propeller Disc with Stream Tube

The pressure and velocity before and after the disk are shown in Figure **2-8**. The far upstream pressure, P_0, is shown to change by ΔP at the propeller disk then return to P_0 far downstream. It should also be noted that the pressure drops by $P_o - P_o'$ at the beginning of the disk then quickly rises by ΔP before asymptotically returning to P_0.The velocity is shown to start at V_0 upstream and slowly rise to a final value of V_s.[7]

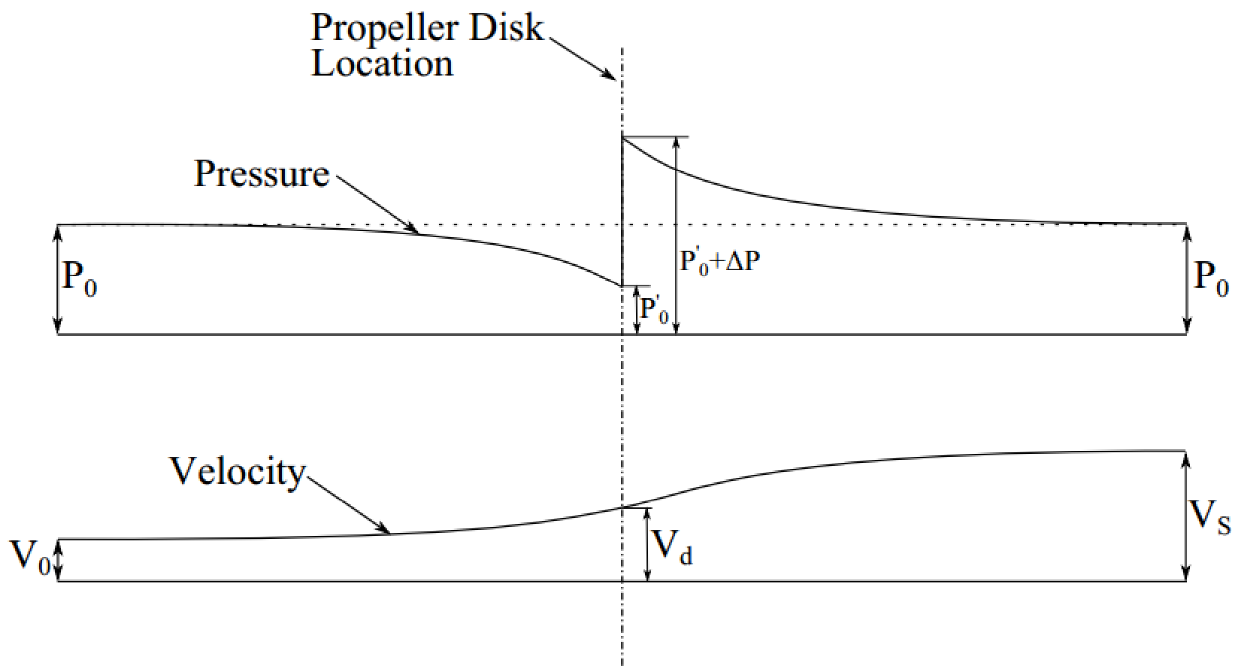

Figure 2-9: Momentum Theory Pressure and Velocity through Propeller Disk

From the basic thrust equation, we know that the amount of thrust depends on the mass flow rate through the propeller and the velocity change through the propulsion system. In the above figure the flow is proceeding from left to right. Let us denote the subscripts "o and s" for the stations assumed to be far upstream and downstream of the propeller respectively and the location of the actuator disc by the subscript "d".

The thrust (T) is equal to the mass flow rate (ṁ) times the difference in velocity (V).

$$T = \dot{m}(V_s - V_o) \tag{1}$$

The power P_d absorbed by the propeller is given by:

$$P_d = \frac{1}{2}\dot{m}({V_s}^2 - {V_o}^2) \tag{2}$$

However, delivered power P_d is also equal to the work done by thrust force:

$$P_d = TV_d \tag{3}$$

By equating Equations. (2) And (3), the velocity at the propeller position becomes:

$$V_d = 1/2(V_s + V_o) \tag{4}$$

The induced velocity in the slipstream represents energy supplied to the flow behind the propeller. This is due to the fact that the fluid gives way when a thrust is exerted to it. The loss of the energy is reflected in an efficiency which is lower than 1. To formulate the efficiency, the propeller disk moves with a velocity V_o and exerts a force T. The power is TV_o. In the slipstream a velocity $2u_o$ is present. With the mass flow expressed as the mass flowing through the propeller disk, which is equal to that flowing through the slipstream, this represents an energy of:

$$E_{lost} = \rho(V_o + u_o)(\frac{\pi}{4}D^2)(2u_o)^2 \tag{5}$$

The efficiency of the propeller can be written as:

$$\eta = \frac{TV_o}{TV_o + E_{lost}} \tag{6}$$

This represents the maximum efficiency which is theoretically possible in an inviscid flow with a propeller not introducing any rotation in the slipstream. It is therefore called the ideal efficiency.

2.5.2 Blade Element Theory

The primary limitation of the momentum theory is that it provides no information as to how the rotor blades should be designed so as to produce a given thrust. Also, profile drag losses are ignored. The blade-element theory is based on the assumption that each element of a propeller or rotor can be considered as an airfoil segment. Lift and drag are then calculated from the resultant velocity acting on the airfoil, each element considered independent of the adjoining elements. The thrust and torque of the rotor are obtained by integrating the individual contribution of each element along the radius.

The thrust produced by a propeller blade is determined by five things: the shape and area of the airfoil section, the angle of attack, the density of the air, and the speed at which the airfoil moves through the air. Before discussing ways of varying the amount of lift produced by a propeller blade, we must understand some of the propeller design characteristics.

The blade element theory considers a propeller blade to be made of an infinite number of airfoil sections, with each section located a specific distance from the axis of rotation of the propeller. Each blade element travels at a different speed because of its distance from the center of the hub, and to prevent the thrust from increasing along the length of the blade as its speed increases, the cross-sectional shape of the blade and its blade, or pitch, angle, vary from a thick, high pitch angle near the low-speed shank to a thin, low pitch angle at the high-speed tip. By using the blade element theory, a propeller designer can select the proper airfoil section and pitch angle to provide the optimum thrust distribution along the blade. This is named propeller twist.

The thrust developed by a propeller is in accordance with Newton's third law of motion. (For every action there is an equal and opposite reaction). In the case of a propeller, the first action is the acceleration of a mass of air to the rear of the aircraft. The reaction is that the airplane is pulled forward. Since the angle of a propeller blade varies along its length, a particular blade station must be chosen to specify the pitch of a blade. [7]

2.6 Forces acting on the Propeller

When a propeller rotates, many forces interact and cause tension, twisting, and bending stresses within the propeller.[11]

2.6.1 Centrifugal Force

Centrifugal force puts the greatest stress on a propeller as it tries to pull the blades out of the hub. It is not uncommon for the centrifugal force to be several thousand times the weight of the blade.

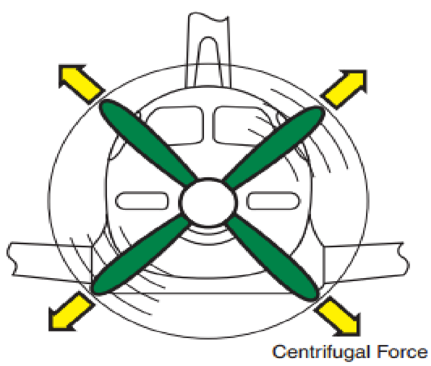

Figure 2-10: Propeller Centrifugal Force

2.6.2 Thrust Bending Force

Thrust bending force attempts to bend the propeller blades forward at the tips, because the lift toward the tip of the blade flexes the thin blade sections forward. Thrust bending force opposes centrifugal force to some degree.

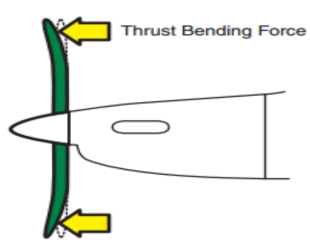

Figure 2-11: Thrust Bending Force

2.6.3 Torque Bending Force

Torque bending forces try to bend the propeller blade back in the direction opposite the direction of rotation.

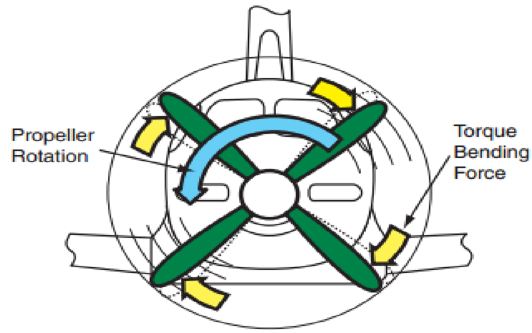

Figure 2-12: Propeller Torque Bending Force

2.6.4 Aerodynamic Twisting Moment

Aerodynamic twisting moment tries to twist a blade to a higher angle. This force is produced because the axis of rotation of the blade is at the midpoint of the chord line, while the center of the lift of the blade is forward of this axis. This force tries to increase the blade angle. Aerodynamic twisting moment is used in some designs to help feather the propeller.

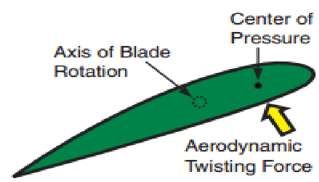

Figure 2-13: Propeller Aerodynamic Twisting Moment

2.6.5 Centrifugal Twisting Moment

Centrifugal twisting moment tries to decrease the blade angle, and opposes aerodynamic twisting moment. This tendency to decrease the blade angle is produced since all the parts of a rotating propeller try to move in the same plane of rotation as the blade centerline. This force is greater than the aerodynamic twisting moment at operational RPM and is used in some designs to decrease the blade angle.[11]

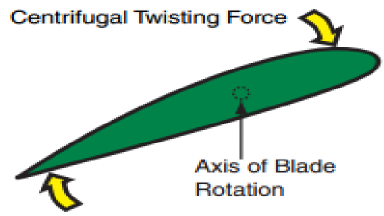

Figure 2-14: Propeller Centrifugal Twisting Moment

2.7 Summary

This chapter introduced history and background of propeller, geometric, parameters and types of propeller, principles and properties, and an overview of propeller theories and force acting on propeller.

The next chapter will interpret the Interaction between the Propeller and the Airplane.

Chapter Three Interaction Effects of the Propeller and the Airplane

3 Chapter Three: Interaction Effects of the Propeller and the Airplane

3.1 Propeller-Wing interactions

The strong swirl velocities in the slipstream combined with increased dynamic pressure generate a considerable deformation of the lift distribution, which has an impact on the aerodynamic behavior and performance of the wing. The wing loading in turn induces a disturbed inflow field for the propellers, especially in the case where the propeller and the wing are closely coupled. Hence the aerodynamic interference for typical tractor propeller wing aircraft may be summarized as propeller effects on the wing and vice versa.

The description of the interactive flow around the propeller-wing configuration requires detailed information about the characteristics of the slipstream. Due to the self-induced velocities produced by the propeller vortex system the slipstream tends to deform and roll up which produces a so-called slipstream tube with strong gradients in various flow quantities both in stream wise and radial direction.

For a selected cruise condition the parameter G_P, $\beta_{0.16R}$ and J are fixed. This means that the problem in the sense of the propeller wing interference is found in the dependency of $\alpha_{P_{eff}}$ and I_W on the propeller position relative to the wing and the aircraft state. A simple solution of the problem is hindered by the fact that the latter parameters in turn are influenced by the form and position of the propeller slipstream. Hence the performance of the complete propeller-wing combination will only be attained by accepting a full interaction between propeller and wing which will be denoted as FIM (full interaction mode). Nevertheless, many researchers have accepted the single interaction mode (SIM), in which the wing effect on the propeller is simply neglected.

Although the propeller exhibits a typical unsteady flow field had been shown by several authors that for most practical design calculations it is acceptable to treat the flow as being steady. This time averaged approach will be adopted during the subsequent analysis of the propeller-wing interference problem. [12] [13] [2, 14]

3.1.1 Regions of influence

The slipstream properties change throughout the local flow field resulting in a strong deformation of the wing loading distribution. In this respect mainly the changes in radial direction and the stream-wise development of the propeller slipstream must be taken into account.

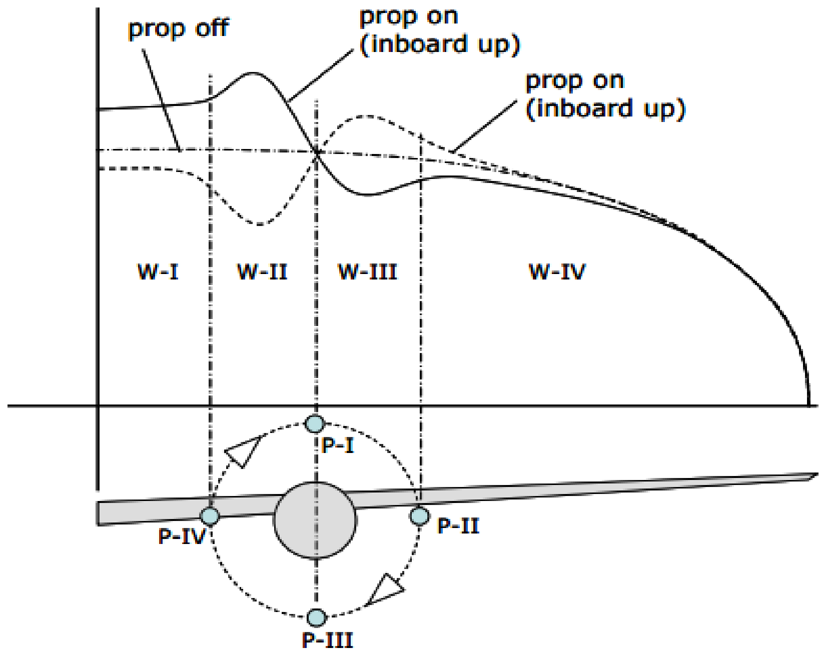

Figure 3-1: Influence areas related to propeller wing interaction based on the loading distributions.

To describe the most important interference effect it is beneficial to split the wing and the propeller in several regions of influence, as sketched in Figure 3-1. [2] [15]

3.1.1.1 Wing regions

Wing regions, W-II and W-III are directly influenced by the slipstream that washes the wing. In W-II the lift effect of the propeller swirl velocity, that changes the local wing angle of attack, is enhanced by the increased dynamic pressure. In W-III these two slipstream effects counteract each other. The result is a smaller difference between the powered and unpowered case in this region. It can be clearly seen that the propeller effect is not limited to the wing part (with a span equal to the contracted slipstream diameter) directly behind the propeller. Due to the changed wing inflow conditions generated by the propeller the loading in W-I and W-IV changes as well, both for the inboard and outboard up running propeller. This is the result of the distorted vorticity sheet that leaves the wing.[15] [2]

3.1.1.2 Propeller regions

To understand the wing effects on the propeller, 4 regions of influence can be defined as shown Figure **3-1**. One should consider that these regions, located at azimuthal positions of θ =0, 90, 180, and 270 degrees are in fact not completely “separated”. Rather, a gradual change of the slipstream properties is found going from one region to a neighboring one. The effect of the presence of the nacelle is a small axial velocity increase in all four Regions. Typical differences at P-II and P-IV are found due to the wing induced up wash. As sketched in Figure **3-2**, the local blade angle of attack increases at the down going blade side (P-II) and decreases on the opposite side (P-IV). The result is a loading asymmetry in the slipstream that has to be accounted for in the propeller-wing interaction model.

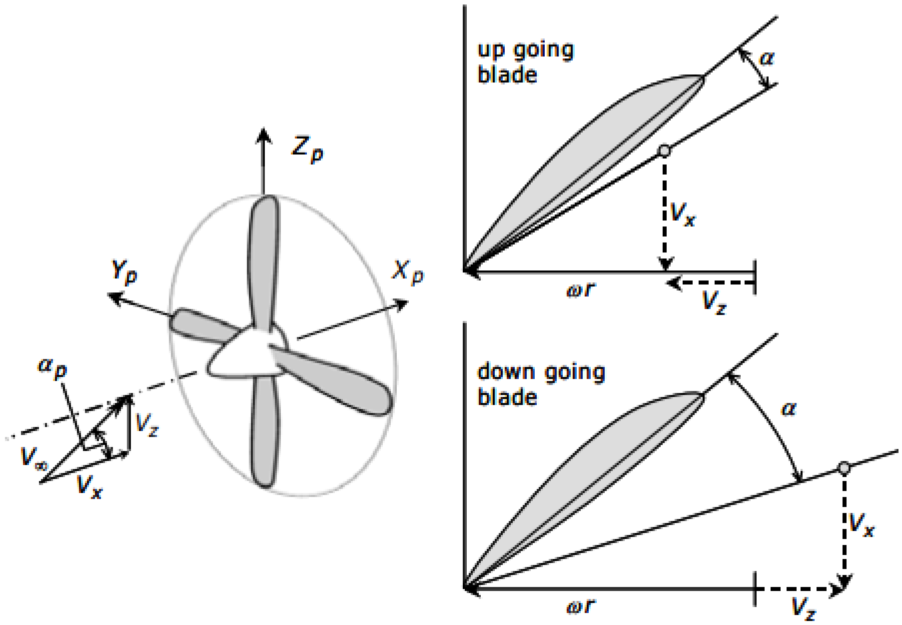

Figure 3-2: Blade angle of attack variation due to propeller pitch angle.

The differences in the induced axial and tangential velocities found for P-I and P-III is attributed to the wing induced axial velocity increase and decrease for the high and low propeller blade position respectively.[2] [15]

3.1.2 Swirl recovery

An important facet in the calculation of the slipstream-induced velocities with simple models is the reduction of the rotational velocity in the slipstream due to the wing. Both experimental and numerical studies have shown that there is a significant reduction in rotation (swirl velocity) due to the presence of the wing. Various wind tunnel tests have indicated that the amount of the reduction in the rotational velocity depends on numerous factors like the propeller position relative to the wing, the power setting, the wing loading and so forth.

It should be noted that while there is some reduction in rotational velocity due to friction and viscous effect, it is more likely that a change in the slipstream helix angle is the main cause for the reduction in the rotation in the rotational velocity. From a conceptual point of view, the reduction in the slipstream helix angle can be attributed to the wing induced up wash (in front) and downwash (behind).

The wing is assumed to reduce the angle of rotation of the slipstream within those annuli that wash over it. It is of vital importance to implement a Swirl Recovery Factor

(SRF) in the simple static slipstream models to arrive at acceptable calculation results. [2, 15]

3.2 Propeller-Fuselage Interactions

The mutual interference between fuselage and propeller, known as fuselage blockage, and its relationship to propeller performance for small scale UAV applications. The fuselage blockage effect is the result of a mutual interference between a propeller and fuselage. Fuselage blockage is comprised of two separate effects which arise from the aerodynamic interaction between a propeller and fuselage in close proximity. The 'body interference effect' results from the perturbed airflow through the propeller due to the influence of the fuselage. The 'scrubbing effect' reduces effective thrust due to an increase in drag when the fuselage is positioned within the propeller slipstream.

The body interference effect is a change in propeller efficiency caused by the proximity of the fuselage. In the regions closest to the rotation axis, the axial velocity of the air is significantly reduced. As a result, airfoil sections experience an increased angle of attack, which leads to an increase in thrust but also an increase in required power. Depending on the operating conditions, the increase in thrust may lead to an 'apparent' increase in propulsive efficiency. This occurs because the local flow velocity is slower than the freestream, so the true advance ratio is lower than the apparent advance ratio, based in the freestream. Since the propeller is operating in a region of reduced velocity, less mass flows through the propeller disk which results in a reduction in net efficiency[16]. If adjusted for the true local velocity, the efficiency decreases as expected, however this velocity is not easy to measure. Due to reduced-velocity flow at the propeller disk, the efficiency also peaks at a different 'apparent' advance ratio when body interference is in effect[17].

The scrubbing effect, also known as slipstream effect, is the reduction in effective thrust due to an increase in drag of a fuselage within the propeller slipstream. In a puller configuration, the large velocity of a propeller slipstream increases the dynamic pressure around the fuselage. Furthermore, there is an increase in turbulence and the addition of a rotational component to the airflow in the direction of propeller rotation. As a result, the body drag of the fuselage increases[18]. The increase in drag of the body reduces the overall propulsive efficiency of the system. This effect is less pronounced with a pusher configuration, as the fuselage is located in the slower propeller inflow region. The blockage effect depends on the blockage ratio, B, which is defined as:

$$B = \frac{D_{fus}}{D}$$

Where, D_{fus} is the fuselage maximum diameter and D is the diameter of the propeller. For general aviation propellers, it is suggested that fuselage blockage is negligible when the blockage ratio is below a critical value. Estimates of the critical blockage ratio range between 0.33 and 0.42[19, 20]. Efficiency reduces by 1% for every 10% increase in the blockage ratio beyond the critical value[4] with a typical decrease of around 5% due to the scrubbing effect for light general aviation aircraft with a puller configuration[21]. For small UAS this effect is expected to be more pronounced as both the propeller and fuselage are operated at significantly lower Reynolds numbers.

3.3 Summary

This chapter presented the interactions between the propeller-wing configuration, and propeller-fuselage configuration.

The next chapter contained the experimental setup and calculations.

Chapter Four
Calculations

4 Chapter Four: Calculations

4.1 Introduction

From the experimental tests in the wind tunnel, readings of dynamic pressure after and before the propeller plane had been obtained at four different speeds of the wind tunnel, for three configurations, isolated propeller and propeller mounted in a wing and fuselage.

Considering that, the airspeed of the wind tunnel is the airspeed of airplane. According of momentum theory to specify the efficiency of propeller this theory assume: no friction, incompressible, and irrational flow, which means propeller working is ideal.

4.2 Test setup

1. Wind Tunnel Geometry

The wind tunnel is an open loop type, with airspeed range of 0 to 36m/s. the selected four wind tunnel speed are:

$V_1 = 12.778\ m/s$

$V_2 = 18.07\ m/s$

$V_3 = 22.131\ m/s$

$V_4 = 25.555\ m/s$

The experiments were carried out in a square test section which has dimensions 305 mm x 305 mm, and 600 mm. width, height and length respectively.

2. Propeller Geometry

Pitch angle =16 Degree

Diameter =0.18 m

Area $= 0.025\ m^2$

3. Wing Model Geometry

Thickness = 3 cm

Chord = 14.80 cm

4. Fuselage Model Geometry

Diameter =6 cm

Blockage Ratio = $B = \frac{D_{fus}}{D} = 0.33$

4.3 Equations to obtain the result

$$P_{dynamic} = \frac{1}{2}\rho V^2 \tag{7}$$

$$V = \sqrt{\frac{2P_{dynamic}}{\rho}} \tag{8}$$

$$\Delta V = V_s - V_o \tag{9}$$

$$V_d = 1/2(V_o + V_s) \tag{10}$$

$$\dot{m} = \rho V_d A \tag{11}$$

$$T = \dot{m}\Delta V \tag{12}$$

$$P = T * V_d \tag{13}$$

$$\eta = \frac{T * \Delta V}{P} \tag{14}$$

$$J = \frac{V_d}{D * n} \tag{15}$$

4.4 Characteristic of Isolated Propeller

Table 4-1 show the pressure reading (Pa) before the propeller (upstream) and after the propeller (downstream) and with five different distances from the propeller hub:

Distance 1: above the propeller hub by 6 cm

Distance 2: above the propeller hub by 3 cm

Distance 3: at the propeller hub

Distance 4: under the propeller hub by 3 cm

Distance 5: under the propeller hub by 6 cm

The pressure reading also had been taken at four different average wind tunnel speed. And the propeller was placed isolated.

Table 4-1: Dynamic Pressure Upstream and Downstream for Isolated Propeller

Speed	12.778m/s	18.07m/s	22.131m/s	25.555m/s	12.778m/s	18.07m/s	22.131m/s	25.555m/s
Distance	Upstream (pressure in Pa)				Downstream (pressure in Pa)			
1	215	294	295	419	131	229	337	429
2	50	135	289	413	133	225	331	421
3	91	109	271	401	130	217	319	411
4	31	81	285	410	119	211	315	391
5	15	120	291	413	113	201	303	383

Using the previous equations, from equation (7) to equation (15), the average velocity V_D had been estimated and the efficiency had been calculated considering:

Assume the sea level, $\rho = 1.225 \frac{kg}{m^3}$

The propeller disc area $A = 0.025\ m^2$

The propeller diameter $D = 0.18\ m$

The RPM of the electric motor $n = 12000\ rpm$

Table 4-2 shows the results of the efficiency (η) for the readings of the dynamic pressure shown in Table 4-1 and Table 4-3 Shows the thrust of the propeller.

Table 4-2: variation of efficiency with velocity for isolated propeller

V_s	V_o	ΔV	V_d	ṁ	T	J	P	η
0	0	0	0	0	0	0	0	0
14.29006	10.88321	3.40685	12.58663	0.39236	1.313224	0.349629	16.52906	0.270672
18.80008	15.11841	3.681671	16.95925	0.52866	1.912175	0.47109	32.42904	0.217089
22.88882	21.61404	1.274779	22.25143	0.69363	0.868698	0.618095	19.32977	0.05729
26.38117	25.9097	0.471466	26.14543	0.81502	0.377505	0.726262	9.870019	0.018032

Table 4-3: variation of thrust with velocity for isolated propeller

V_s	V_o	Δv	V_d	ṁ	T
14.29006	0	14.29006	7.145029	0.222729	3.18281
18.80008	15.11841	3.681671	16.95925	0.528663	1.946364
22.88882	21.61404	1.274779	22.25143	0.693634	0.88423
26.38117	25.9097	0.471466	26.14543	0.81502	0.384254

4.2 Efficiency of Propeller mounting on Wing

By repeating the steps in section 4.4 with wing mounted propeller, the results of the efficiency (η) for the readings of the dynamic pressure shown in Table 4-4, had been obtained in Table 4-5. Also, Figure **4-1** shows the propeller-wing configuration setup inside the wind tunnel test section.

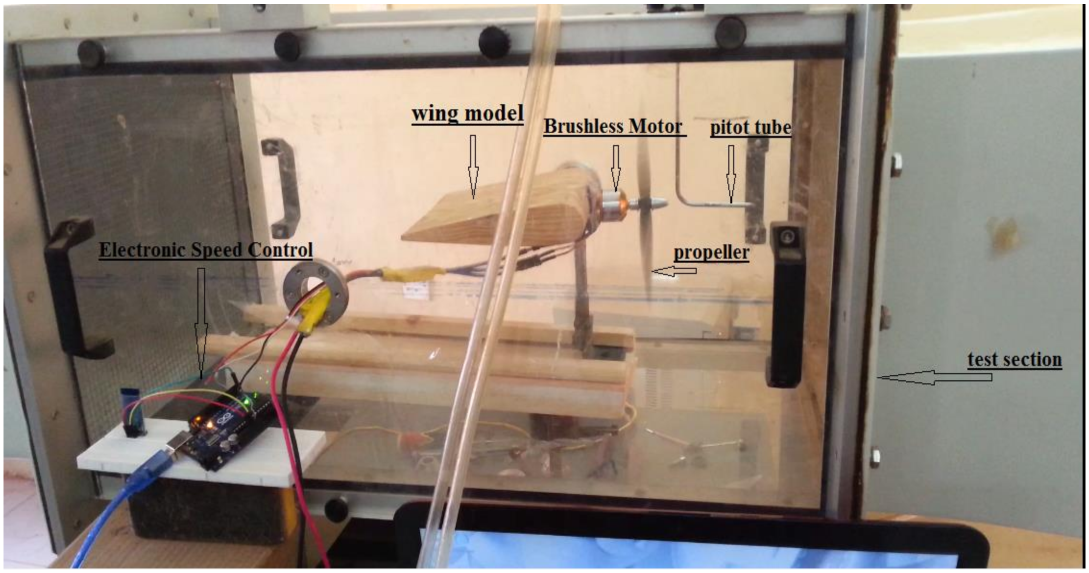

Figure 4-1: Setup of propeller-wing configuration.

Table 4-4: Dynamic Pressure Upstream and Downstream for Propeller Mounting on Wing

Speed	12.778m/s	18.07m/s	22.131m/s	25.555m/s	12.778m/s	18.07m/s	22.131m/s	25.555m/s
Distance	Upstream (pressure in Pa)				Downstream (pressure in Pa)			
1	123	230	317	419	244	309	408	518
2	126	226	324	419	217	317	404	531
3	125	225	319	415	146	127	138	195
4	122	220	317	416	115	137	169	189
5	121	223	315	418	138	163	217	271

Table 4-5: Variation of Efficiency with Velocity for Propeller Mounting on Wing

V_o	V_s	ΔV	V_d	ṁ	T	J	P	η
0	0	0	0	0	0	0	0	0
14.194	17.018	2.824	15.606	0.4864	1.349685	0.4335	21.06318	0.180956
19.157	22.023	2.866	20.59	0.641843	1.80721	0.571944	37.21045	0.139194
22.8	24.016	1.216	23.408	0.729562	0.871714	0.650222	20.40508	0.051948
26.105	26.415	0.31	26.26	0.818591	0.249306	0.729444	6.546772	0.011805

4.5 Efficiency of Propeller mounting on fuselage

Also, repeating the steps in section 4.4 with fuselage mounted propeller, the results of the efficiency (η) for the readings of the dynamic pressure shown in Table 4-6, had been obtained in Table 4-7. Also, Figure **4-2** shows the propeller-fuselage configuration setup inside the wind tunnel test section.

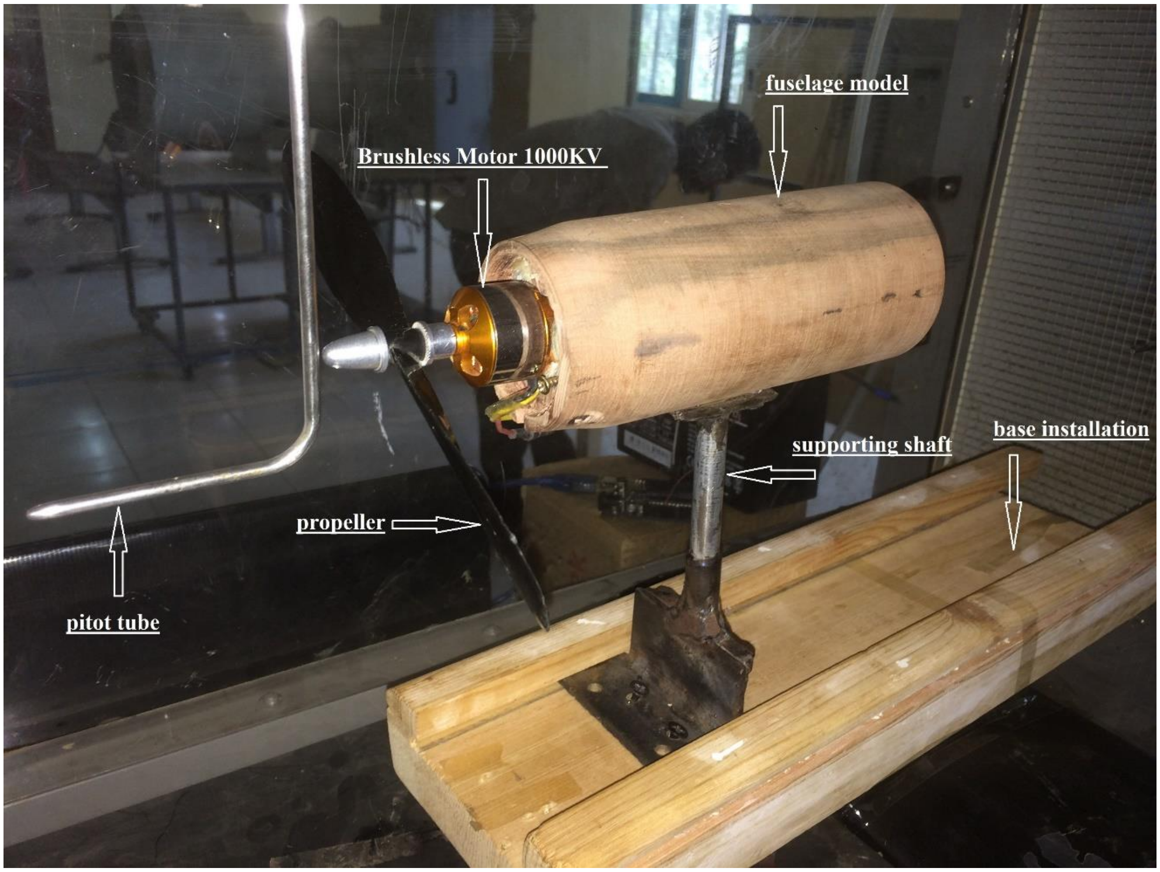

Figure 4-2: Setup of propeller-fuselage configuration.

Table 4-6: Dynamic Pressure Upstream and Downstream for Propeller Mounting on Fuselage

Speed	12.778m/s	18.07m/s	22.131m/s	25.555m/s	12.778m/s	18.07m/s	22.131m/s	25.555m/s
Distance	Upstream (pressure in Pa)				Downstream (pressure in Pa)			
1	107	230	327	436	135	252	330	441
2	103	221	321	419	131	245	327	423
3	100	210	303	407	127	231	309	411
4	101	222	322	421	129	243	325	421
5	99	231	327	431	130	251	331	440

Table 4-7: Variation of Efficiency with Velocity for Propeller Mounting on Fuselage

V_s	V_o	V_d	ΔV	ṁ	T	P	J	η
0	0	0	0	0	0	0	0	0
14.63795	12.93493	13.78644	1.70302	0.429759	0.731888	10.09013	0.382957	0.123529
20.01945	19.20788	19.61367	0.81157	0.611408	0.496201	9.732315	0.544824	0.041378
23.14976	23.00822	23.07899	0.14154	0.719432	0.101828	2.350095	0.641083	0.006133

4.6 Summary

This chapter introduced the setup and experimental readings used for the calculations of the characteristics and efficiencies of propeller, propeller mounted on wing and propeller mounted on fuselage. The next chapter include the results and discussion.

Chapter Five
Results and Discussion

5 Chapter Five: Results and Discussion

5.1 Result

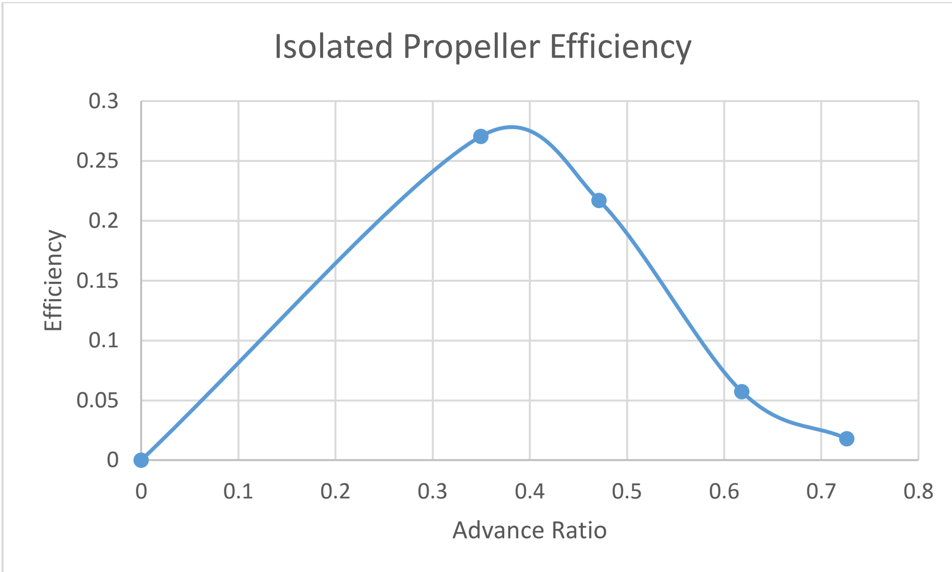

Figure 5-1: Efficiency of Isolated Propeller versus Advance Ratio

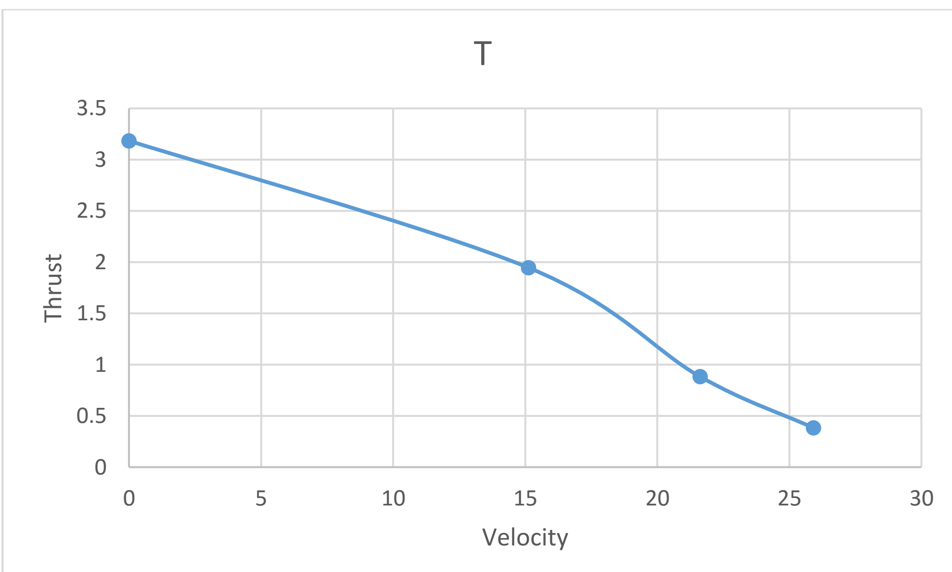

Figure 5-2: Thrust of Isolated Propeller versus Velocity

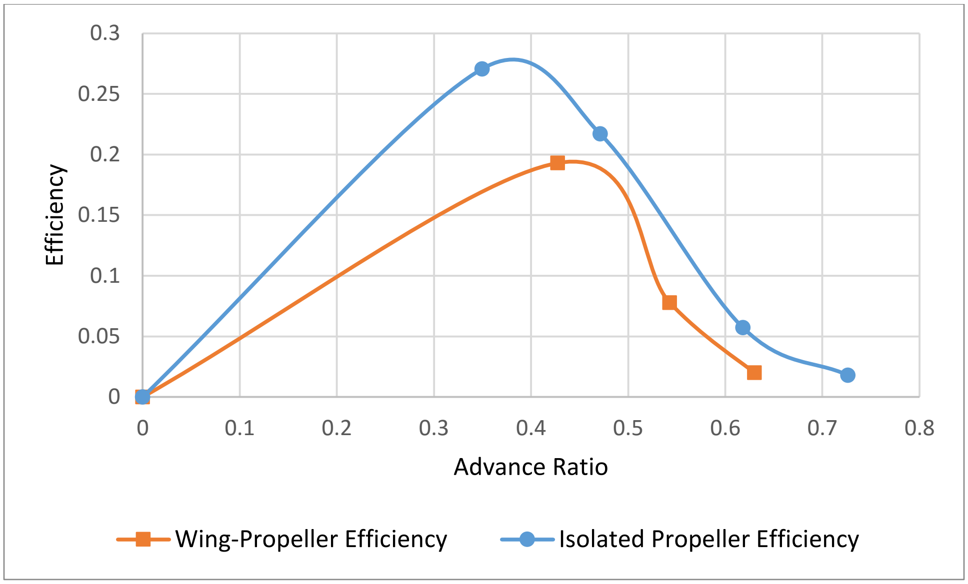

Figure 5-3: Wing-Propeller Efficiency with Isolated Propeller Efficiency

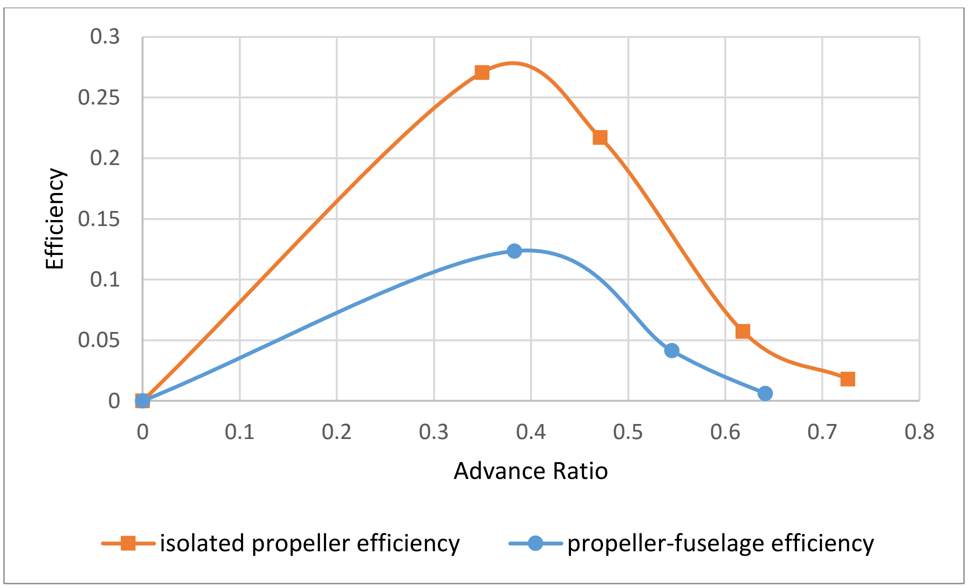

Figure 5-4: Fuselage-Propeller Efficiency with Isolated Propeller Efficiency

5.2 Discussion

It can be seen from Figure **5-2** that, the thrust be maximum at V=0 called the system starting operation, and known as helicopter mode. The thrust decreased gradually with increase in velocity, and by more increasing in the velocity the thrust reach zero value, and this condition called zero thrust mode. In this value the power didn't equal zero, this condition is called propeller mode.

Figure **5-3** shows that, the maximum efficiency of the isolated propeller was higher than the efficiency when the propeller mounting on the wing, due to increasing in the drag. Also it can be noted that, the wing lift is increase, because it works at range of velocity increment.

Also it can be seen from Figure **5-4**| that, the maximum efficiency of propeller was higher than the efficiency when the propeller mounting on the fuselage, due to increasing in the drag.

5.3 Summary

This chapter showed and discussed the results of the characteristics and efficiencies of propeller, propeller mounted on wing and propeller mounted on fuselage.

The next chapter include conclusion, recommendation and future work suggested.

Chapter Six Conclusion, Recommendations and Future Work

6 Chapter Six: Conclusion, Recommendations and Future Work

6.1 Conclusion

This research provided the propeller characteristics and the comparison between the characteristics of the isolated propeller and the installed propeller on the wing or the fuselage. All tests were conducted in the range 12–26 m/s and 12000 RPM of the freestream (wind tunnel airspeed) and the propeller rotation, respectively.

The calculations performed with three different configurations, isolated propeller, propeller mounting on wing, and propeller mounted on fuselage, found in the subsonic wind tunnel experiments. The wing model was 3 cm thickness and 14.80 cm chord. The fuselage model was 6 cm diameter and with blockage Ratio of0.33. The wing and fuselage submersed in the propeller's downstream.

The results showed that, as the free stream velocity increases, for isolated propeller, thrust decreases, as seen in **Figure 5-2**, and approaches zero as the top speed is reached. Also, **Figure 5-3** and **Figure 5-4** had been shown that the efficiency of the isolated propeller is greater than the efficiency of the propeller installed on the wing or on the fuselage.

6.2 Recommendations

We recommend to use numerical and theoretical methods to obtain further results, which can be compared with the available experimental results.

6.3 Future Work

Many experiments can be explored in the field of the propellers aerodynamic characteristics and their influences on the airplane: different configurations such as tractor and pusher, and different positions for the propeller in the wing, outboard, inboard, or mid, different propeller sizes, test different body sizes of fuselage, even different pitch angles and different angles of attack.

7 References

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8 Appendices

8.1 Appendix A

Calculation of the blade angle (pitch φ) to estimate the ranges of efficiency and advance ratio.

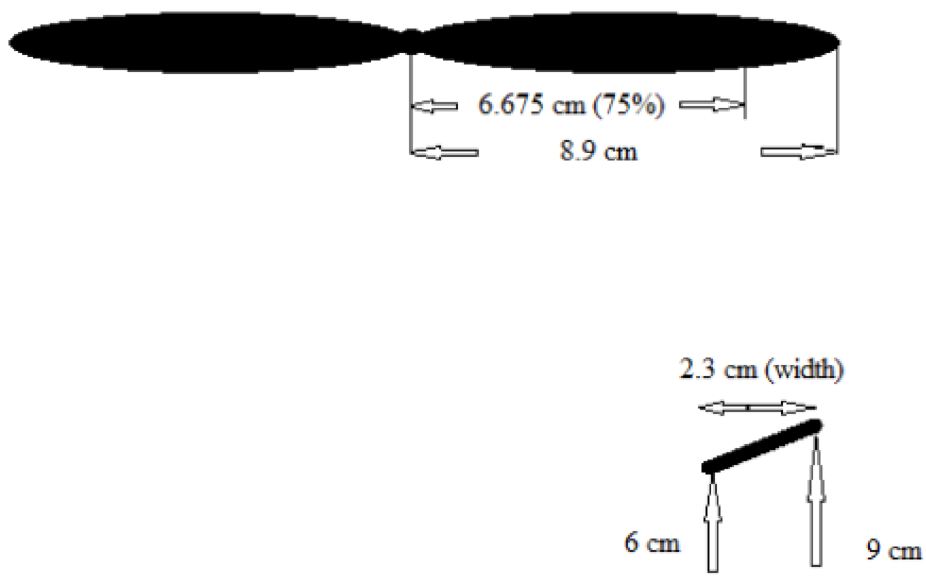

Figure 8-1: propeller dimension

$$\varphi = (y_1 - y_2) * W * 2.36$$

$$= (9-6) * 2.3 * 2.36 = 16.284 \approx 16°$$

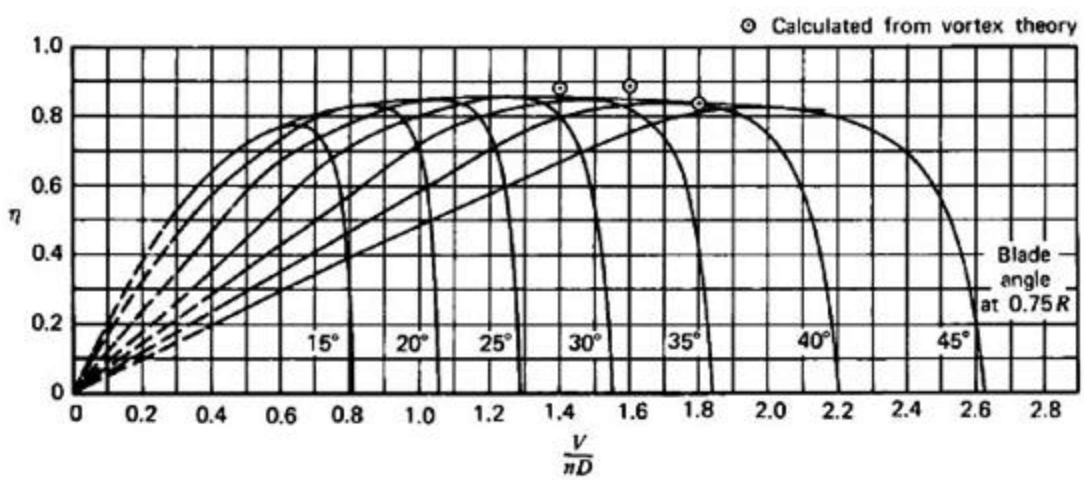

Figure 8-2: Typical Propeller Efficiency Curve as Function of Advance Ratio and Blade Angle (McCormick, 1979)

8.2 Appendix B

An example of the steps of the calculations in chapter four. For Table 4-1 and at wind tunnel speed 1 (12.777m/s), by using the equations from 7 to 15:

$$V_o = \sqrt{\frac{2P_{2dynamic}}{\rho}} = \sqrt{\frac{2*(215+50+91+31+15)/5}{1.225}}$$
$$= 10.883\ m/s$$

$$V_s = \sqrt{\frac{2P_{1dynamic}}{\rho}} = \sqrt{\frac{2*(131+133+130+119+113)/5}{1.225}} = 14.290\ m/ss$$

$$\Delta V = V_s - V_o$$
$$\Delta V = 14.290 - 10.883 = 3.407\ \mathrm{m/s}$$

$$V_d = 1/2(V_o + V_s)$$
$$V = 1/2(10.883 + 14.290) = 12.587\ m/s$$

$$\dot{m} = \rho V_d A$$
$$\dot{m} = 1.225 * 12.587 * 0.025 = 0.385\ kg/s$$

$$T = \dot{m}\Delta V$$
$$T = 0.385 * 3.407 = 1.313\ \mathrm{N}$$

$$P = T * V_d$$
$$P = 1.312 * 12.587 = 16.529\ \mathrm{Watt}$$

$$\eta = \frac{T * \Delta V}{P}$$
$$\eta = \frac{1.313 * 3.407}{16.529} = 0.271$$

$$J = \frac{V_d}{D * n}$$
$$J = \frac{12.587 * 60}{0.8 * 12000} = 0.350$$