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STUDY OF AIRCRAFT PROPELLER –
STRUCTURAL STRENGTH

CHIN WAI PICK

This report is submitted in
partial fulfilment of the requirements for the award of the
Degree of Bachelor of Mechanical Engineering (Design and innovation)

Faculty of Mechanical Engineering
University Technical Malaysia Melaka

MAY 2010

DECLARATION

"I hereby, declare this thesis is the result of my own research
except as cited in the reference"

Signature	: …………………………
Author's Name	: …………………………
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PENGAKUAN

"Saya akui laporan ini adalah hasil kerja saya sendiri kecuali ringkasan dan petikan yang tiap-tiap satunya saya telah jelaskan sumbernya"

Tandatangan : …………………………

Nama Penulis : …………………………

Tarikh : …………………………

Specially dedicated

to my family and beloved companion

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The last but not least, I am grateful to everyone that has come alongside of mine and showed me help in one way or another. Your generosity in lending your helping hands has indeed contributed to the success of this project.

ABSTRACT

A propeller is part of the propulsive system of an aircraft. It is powered by an internal combustion engine which is used to turn propeller blades and transform rotary power into forward thrust. The rotating propeller, being one of the high risk parts of aircraft are constantly subjected to various dynamic loads. Therefore, it is often desired to analyze and check the strength of propeller to ensure safe operation. This project is purposed to analyze the propeller blade strength. It is carried out through two approaches, namely the theoretical approach and finite element method. The beam theory presented by D. W. Taylor has been employed and used in the theoretical analysis. Results obtained through calculations were tabulated and corresponding graphs were plotted to show the distribution of stress on the propeller blade. This approach suggested that stresses decrease in proportion toward the blade edges and with increase in blade radius from the center of hub. Meanwhile, the finite element method presented a more accurate result than the theoretically approach but still having results with similar trends as the theoretical approach. Both results are compared against each other and rational discussions are made. The result is used to compare against the material ultimate stress to obtain the safety factor for safe operation.

ABSTRAK

kipas adalah sebahagian daripada sistem dorongan sebuah pesawat. Ia dikuasakan oleh satu enjin pembakaran dalam yang digunakan untuk menjana putaran kipas serta mengubah kuasa putaran itu kepada daya tolakan untuk pesawat. Kipas yang berputar ini menjadi satu bahagian yang berisiko tinggi kerana sentiasa dibebankan oleh pelbagai daya dinamik. Oleh itu, analisis terhadap kekuatan kipas dijalankan bagi memastikan operasi yang selamat. Projek ini bertujuan untuk menjalankan analisis kekuatan terhadp bilah kipas. Ia dilaksanakan melalui dua cara, iaitu cara teoritikal dan kaedah unsur terhingga. Teori yang disampai oleh D W Taylor telah diambil dan digunakan dalam teori analisis. Keputusan-keputusan diperolehi melalui pengiraan telah dijadualkan dan graf-graf yang berkaitan telah dilukis untuk menunjukkan taburan tekanan yang bertindak di bilah kipas. Cara ini mencadangkan bahawa semakin besar jejarinya daripada pusat kipas itu, semakin menurun taburan tekanan itu. Sementara itu, kaedah unsur terhingga itu telah menghasilkan keputusan lebih tepat berbanding dengan cara teoritikal, namum masih mengandungi sifat-sifat dan tren keputusan yang serupa dengan cara teoritikal. Kedua-dua keputusan yang didapatkan itu telah dibanding antara satu sama lain dan perbincangan yang rasional telah dilakukan. Keputusan itu juga digunakan untuk perbandingan terhadap stres utama bahan untuk mendapatkan faktor keselamatan bagi memastikan operasi yang selamat.

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LIST OF SYMBOLS

σ	Normal stress
P	Force acting on member
A	Area prependicualr to force
M	Moment about the neutral axis
y	Perpendicular distance to the neutral axis
I	Second moment of area
T	Torque
T_{max}	Maximum shearing stress
c	Distance from shaft axis where stress is maximum
{u}	Displacement vector
$[k]_e$	Stiffness matrix
{U}	Displacement vector, primary variable
$\{f\}_e$	Load vector, secondary variable
w	Weight of propeller
g	Acceleration due to gravity
ω	Angular velocity
r	Distance of particle from center of rotation
N	Propeller RPM
A	Cross section area
ρ	Density of material
b	Blade width
h_u	Upper chamber
h_L	Lower chamber
y_t	Distance from mutual axis to outermost surface

LIST OF ABBREVIATIONS

RPM	Round per minute
CAD	Computer Aided design
FEM	Finite element method
CMM	Coordinate measuring machine
FS	Factor of safety

CHAPTER 1

INTRODUCTION

1.1 Overview

Thrust is the force required by the aircraft to travel forward through the air. Thrust is often greater than drag both to achieve the forward acceleration during take-off and to increase speed during level flight. Most aircrafts in the early designs had utilized the propeller to generate thrust. The propeller that pushes aircraft through the air is a pusher propeller, while the propeller that pulls the aircraft through the air is a tractor propeller. Both applied the same principle of Newton's Third Law and provide thrust for the aircraft as needed.

A propeller consists of two or more blades attached to a central hub that is mounted on engine crankshaft. It is powered by an internal combustion engine which is used to turn the propeller blades and transform rotary power to forward thrust. As the propeller blade is rotated, a slipstream of fast moving air will be created and produces pressure difference across the blade. The pressure difference causes large amounts of air to be accelerated through the plane of the propeller to produce the thrust that propels aircraft forward. Aircraft with more blades will lead to relatively higher noise level than those with lesser blades. However, with the advanced material and design; much reduced vibration and noise are generated even though high numbers of blades are used in current designs.

A propeller with ideal efficiency is able to convert energy supplied from engine fully into forward thrust. The geometry of blade plays an important role to optimize the efficiency of propeller. Propeller blade is generally long and thin. It is often thought as a rotated wing due to their shape of airfoil section which is similar to the wing. When the blade is rotated, the tip moves faster than the hub. The blade is therefore made to be twisted along the edge as it proceeds from hub toward the tip to ensure that each cross section meets the air at about the same time. Besides, the blade thickness also varies along the radius, which is higher thickness in the hub area than the tip to prevent failure due to intense stress.

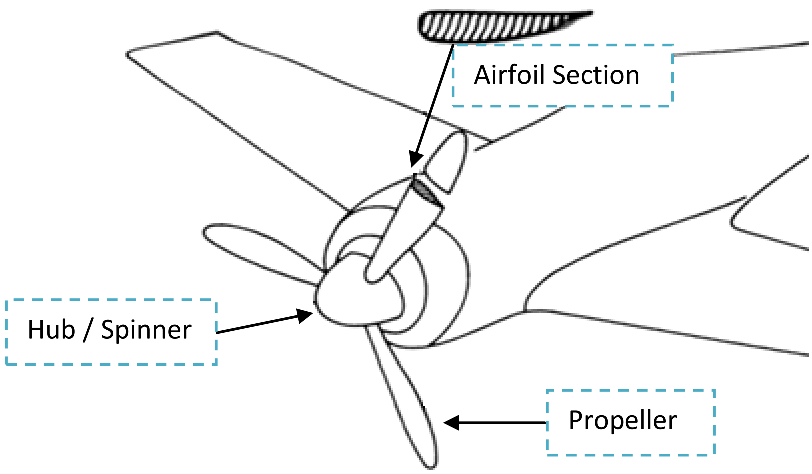

Figure1.1: The airfoil cross section of airplane propeller

(Source: Philip W.F. 2004, *Mechanics of Flight*, John Wiley&Sons, New Jersey, pg 131)

Propeller propulsion system was the primary system in all aircrafts for forty years after the first flight of Wright brothers until the development of jet engines during World War II. Today, propellers are still used on general aviation and private aircraft due to the performance of propeller that is suited to the weight and height of the level flight of the aircrafts.

1.2 Problem Statement

The rotating propeller, being one of the high risk parts of aircraft are constantly subjected to various substantial loads. A great deal of attention is therefore paid to provide for its reliability and avoid failure. This failure of propeller, if occurred, may results in high material cost by means of replacement and higher consumption of fuel in aircraft. Besides, the structural failure of propeller shall lead to undescrible damage in the course of just one short flight, some cases reported that failure happened can be as soon as five second after take-off. The incident of propeller failure is never uncommon among all aircraft accidents. One of the major accidents recorded in propeller failure history was Stratocruiser N1039U that crushed into the Brazilian dense jungle with no survivors. In close examination, the cause of the propeller failure was due to the application of force upon the propeller structure is beyond which it was designed. Therefore, it is extremely important to analyze the propeller blade strength after the design process to ensure that the propeller has met the desired performance and sufficient strength for safe operation.

However, the problem with strength analysis of propeller is it often involves high complexity. The stressed state of blades is mainly determined by the aerodynamic load which, in turn, depends on propeller blades geometry and velocity of aircraft. The integration of these parameters has caused the strength analysis to be complicated, especially due to the non-uniformity cross section of propeller blade that causes periodic variations in loads acting on blade. A list of stress formulation for propeller blade has been developed through the effort of various researchers as a guide for the designers to make their analysis on propeller designed. Even though the usage of Finite Element Analysis is in rise, the formulation method is still widely used today. This had caused the concerns by designers on how well the results from both methods comply with each other in order to ensure accurate evaluation in strength of propeller.

1.3 Motivation and Aim

Determining propeller strength is complex and research in the aeronautical application has for long been dedicated to this analysis. Lately, the application of turboprop in aircraft propulsion has marked the expansion of propeller technology. Turboprop engines are a type of aircraft powerplant that use a gas turbine to drive a propeller. The most recent Airbus A400M is one of the examples that powered by four turboprops TP400 engines. The propeller technology has been the motivation to investigate the capabilities of propeller, particularly in strength analysis. The project is carried out with the aim to examine and analyze the strength of the propeller blade. The details of the aim can be stated as follow:

- To research on the propeller blades profile based on a selected model of propeller-driven aircraft.
- To derive analytical blade strength of propeller through cantilever beam calculations method.
- To verify and validate the results from calculations using simulation in FEM

1.4 Scope of Project

A specific case of blade failure of the UAV propeller is calculated to illustrate the application of theoretical and FEM analysis method. The project shall involve a specific field on the propeller blade analysis. The scopes are as stated below:

- Literature research to understand aircraft propeller in general
- Theoretical hand calculation for the propeller strength
- Simulation of propeller blade on structural strength using Finite Element Analysis (MSC Nastran / Patran).
- Make comparisons and draw corresponding conclusions on the strength of propeller blade analyzed.

1.5 Baseline Model

In order to study effectively both the stress formulation and FEM analysis, a model of propeller driven aircraft was chosen as project baseline model. The chosen representative propeller design is used in the locally manufactured ALUDRA UAV (Unmanned Aerial Vehicle). This model was chosen due to its reasonable size and specification which can be used as the input data for the project. However, to ease the analysis, the structural material used for UAV has been changed from composite material to iron. The analysis on composite material requires a great deal of considerations on material since it is not the isotropic material and made up from layers of composite material.

Being the first UAV deployed by Malaysia Military, the ALUDRA (Alianced Unmanned Development Research Aircraft) was developed primarily for battlefield surveillance and reconnaissance, and also regarded suitable for Maritime patrol, air enforcement, border patrol and monitoring of forest fires or other hazardous situation. It has a 2.44m (8ft) wing span, gross weight of 15kg (33Ib), and remotely piloted from a tactical Grand Control Station. The detail specification of the UAV is as follow:

- Gross Weight: 15kg
- Structural Material: Composite (Glass Fibre, Carbon Fibre, Foam)
- Dimension: Length 14ft, Wing Span 8ft
- Endurance: 6 Hours
- Max. Cruise Speed: 120 Knots (220km/h)
- Powerplant: 50hp, Twin Cylinder Gas Engine, Propeller Driven
- Max. Altitude: 12,000 Ft
- Data Link Range: 150km
- Take Off Distance: 250m

1.5 Organization of Report

This report presents the strength analysis for both computational method and Finite Element Method. Chapter 1 of this report is introduction, covering the overview, problem statement, motivation and aim of project and scope of project. Chapter 2 is dedicated to literature review, where the relevant theory of propeller is adopted and presented. Previous findings are also illustrated. Meanwhile, methodology and approach to the project is given in details in chapter 3. A list of formulation is developed and presented through the methodology chapter. The following chapter shall present the results and discussion obtained from both the theoretical and simulation analysis. Lastly, a brief conclusion is included to summarize all the theories and findings presented.

CHAPTER 2

LITERATURE REVIEW

Theoretical methods used to predict the force exerted on propellers blade began to be developed in the late nineteenth century. The most notable of the early findings was that of Rankine, with his momentum theory, which was then closely followed by the blade element theories of Froude. The chapter is dedicated to review and examine the development of propeller and its strength formulations. Theories and findings besides Rankine's and Froude's were also presented. Literature review carried out has been part of the factors contributed to successful analysis of propeller in this project.

2.1 Development of Propeller

The creation of the propeller can be traced back to Leonardo da Vinci's helical screw helicopter which believed is the ancestor of the air propeller. The first idea of a propulsive airscrew, however, belongs to J.P. Paucton, a French mathematician found during the late 1700 to early 1800. After several experimentations, it was concluded that more propulsive power could be obtained by straightening out the surface of the airscrew blades. In 1875, Thomas Moy finally created a large model that had twin 12-foot propellers with 6 blades each. These massive propellers produced 1,100-pounds of thrust each during full power while rotating at 425rpm. However, this jumbo creation did not last long when it suffered an extensive damage during a test flight.

In human history, the most influential aviation pioneers were the Wright brothers' propeller. They had concluded that a propeller was simply a whirling wing. They learned that large propeller diameters would produce high thrust for a given power input. On their first aircraft, they utilized 8-foot propellers installed behind the aircraft to minimize airflow disturbance and incorporated counter-rotating propellers to eliminate the gyroscopic problems. They have also gained thrust efficiency by reducing the blades rotational speed using a chain and sprocket transmission. The Wright brothers' propeller was 66% efficient which was much higher than any other propeller of the time.

Figure 2.1: Wright Brothers' propeller between 1911 and 1903

(Source: Robert L.Ash et al. (2000), *Evolution Of Wright Flyer Propeller Between 1903 and 1912,* Aerospace Engineering Department, Old Dominion University, Norfolk)

By 1910, experiments with metal propellers and variable pitch blades were developed. Results showed that the metal propeller could be made thinner than a comparable wooden propeller, which allowed for faster cruising speeds due to less drag. It allowed operations in all climates where the wooden propeller would easily fail in extreme conditions. The only drawbacks to the early metal propeller were their weight. After WWII, the rising of the Turboprop brought a few changes to the propeller. Many large propeller transports switched to this new system for its reliability and pilot friendly features. It is expected a saving of 25% in fuel costs through Turboprop.