# A COMPUTATIONAL SIMULATION OF ROTOR–FUSELAGE FLOW INTERACTION IN HOVERING AND FORWARD FLIGHT

MOHAMAD HAFIZ BIN ISMAIL

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# ABSTRACT

A helicopter rotor-fuselage flow interaction has been studied theoretically and numerically. The study began with the analysis of the induced velocity by helicopter rotor both in hovering and forward flight by using Momentum Theory, Blade Element Theory and Blade Element Momentum Theory. Three-dimensional steady and unsteady simulations of rotor-fuselage flow interaction have been conducted using Computational Fluid Dynamics (CFD) commercial software FLUENT 6.2 on ROBIN and AS355 helicopter. The study on ROBIN is to justify the method used in CFD simulation for this current research on AS355 is correct. The study emphasizes on flow generated during hovering and forward flight onto the helicopter fuselage. Aerodynamic forces on the fuselage have been obtained through theoretical analysis and numerical simulation. The *Spalart-Allmaras* turbulent model has been utilized to model the physics of flow related to the helicopter fuselage. This model is chosen in terms of its reliability, practical and proven to be effective in modeling the rotor-fuselage flow interaction. The simulation was first carried out in steady state using Moving Reference Frame capability in FLUENT 6.2. this is then followed by unsteady simulation using Sliding Mesh Model, which is a time accurate simulation. Unsteady simulation was carried out because the nature of rotor-fuselage flow characteristic that is unsteady and periodic with time along azimuth angle. From this research it is found that the flow on the helicopter fuselage can be divided into two parts, which is a complex unsteady aerodynamic interaction that occur during hovering and low advance ratio, and a steady aerodynamic condition that occur at high advance ratio. At high advance ratio the rotor wakes flows above the body and only interacts with the fuselage pylon, and at this point the flow field of the helicopter fuselage is dominated by free stream velocity. A fully three dimensional and an unsteady computational method using Sliding Mesh Model has successfully model the rotor-fuselage flow interaction in AS355, a 5-seater helicopter. These results however provide preliminary understanding for designing the fuselage for optimal aerodynamic characteristics.

## ABSTRAK

Interaksi aliran udara melalui bilah rotor dan fiuslaj helikopter dikaji secara teori dan secara kaedah berangka. Kajian ini dimulakan dengan analisis halaju teraruh daripada bilah rotor utama dalam keadaan apungan pugak dan penerbangan kehadapan dengan menggunakan Teori Momentum, Teori Elemen Bilah dan Teori Momentum Elemen Bilah. Simulasi tiga-dimensi dalam keadaan mantap dan tidak mantap untuk aliran bilah rotor-fiuslaj dijalankan menggunakan perisian Dinamik Aliran Berkomputer (CFD), FLUENT 6.2 terhadap helikopter ROBIN dan AS355. Simulasi terhadap ROBIN dijalankan untuk mengesahkan teknik yang digunakan terhadap AS355 adalah betul. Kajian meliputi aliran udara yang dihasilkan semasa apungan pugak dan penerbangan kehadapan serta kesan aliran tersebut ke atas fiuslaj helikopter. Daya-daya aerodinamik ke atas fiuslaj helicopter ditentukan secara teori dan simulasi berangka. Persamaan gelora *Spalart-Allmaras* digunakan untuk permodelan aliran di sekitar helicopter fiuslaj. Persamaan ini digunakan kerana terbukti keberkesanannya dalam memodelkan interaksi aliran bilah-fiuslaj. Pada mulanya, simulasi dijalankan dalam keadaan mantap menggunakan kaedah Kerangka Rujukan Bergerak dalam FLUENT 6.2. Kemudian, diikuti dengan Model Gelincir untuk keadaan tidak mantap, di mana kaedah ini adalah model yang sesuai bagi masalah simulasi masa tepat. Simulasi keadaan tidak mantap dijalankan kerana keadaan sebenar aliran bilah rotor-fiuslaj sendiri yang bergantung dengan masa dan berkala bagi setiap pusingan bilah. Daripada kajian ini, didapati bahawa aliran udara terhadap helikopter fiuslaj boleh dibahagikan kepada dua bahagian, iaitu interaksi aerodinamik yang kompleks pada nisbah kehadapan rendah dan keadaan yang mantap pada kelajuan nisbah kehadapan yang tinggi. Pada nisbah kehadapan yang tinggi, aliran daripada bilah adalah tidak menyentuh fiuslaj dan hanya berinteraksi dengan pylon sahaja dan pada keadaan ini, aliran udara adalah dipengaruhi oleh aliran udara bebas. Kajian ini juga menunjukkan bahawa kaedah tidak mantap Model Gelincir dapat memodelkan interaksi aliran bilah rotor-fiuslaj secara 3 dimensi pada AS355, iaitu helicopter 5 penumpang dengan jayanya. Hasil kajian ini dapat digunakan sebagai panduan awal untuk merekabentuk fiuslaj dalam keadaan yang optimum dari segi ciri-ciri aerodinamik.

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# NOMENCLATURE

| Symbol | Definition |
|---|---|
| $\lambda$ | inflow ratio |
| $A$ | rotor disc area |
| $\Delta C_{TN}$ | Incremental of thrust over an element |
| $\lambda_i$ | Local inflow ratio |
| $C_{l\alpha}$ | lift curve slope |
| $\frac{dC_T}{dr}$ | Thrust gradient |
| $C_d$ | drag coefficient |
| $C_l$ | lift coefficient |
| $F$ | Induced velocity correction factor |
| $C_T$ | thrust coefficient |
| $c$ | local chord length |
| $E$ | energy |
| $\overrightarrow{f_{cen}}$ | Centrifugal force |
| $D_v$ | vertical drag |
| $dA$ | area at typical element |
| $\overrightarrow{f_{corr}}$ | Corriolis force |
| $\psi$ | azimuth angle |
| $dC_T$ | incremental of thrust |
| $dT$ | local thrust |
| $d\dot{m}$ | mass flow rate |
| $dr$ | very small radius element |

| | |
|---|---|
| $q$ | Dynamic pressure |
| $f$ | equivalent flat plat area |
| $g$ | gravity acceleration |
| $C_{dn}$ | Drag coefficient at segment |
| $A_n$ | Segment area |
| $\alpha_{TPP}$ | Angle of tip path plane |
| $\mu$ | Advance ratio |
| $N_b$ | number of blade |
| $R$ | blade radius |
| $r$ | point position at the blade from the root |
| $U_P$ | out-of-plane velocity component |
| $U_r$ | resultant velocity |
| $V_c$ | vertical free stream velocity |
| $T$ | total thrust |
| $U_T$ | in-plane velocity component |
| $V_\infty$ | freestream velocity |
| $v_h$ | hovering induced velocity |
| $v_i$ | induced velocity |
| $\alpha$ | angle of attack |
| $\Omega$ | rotor rotational speed |
| $\rho$ | air density |
| $\Delta r$ | radius elements of annulus |
| $\phi$ | inflow ratio angle |
| $\theta$ | collective pitch angle |
| $\Delta T$ | increment of thrust on typical annulus |

| **Acronym** | **Definition** |
|---|---|
| **CFD** | Computational Fluid Dynamic |
| **NASA** | National Aeronautic & Space Administration |
| **FUN3D** | Fully Unstructured Three Dimensional |
| **V/STOL** | Vertical or Short Take Off Landing |
| **ROBIN** | Rotor Body Interaction |
| **LV** | Laser Velocimetry |
| **LDV** | Laser Doppler Velocimetry |
| **PIV** | Particle Image Velocimetry |
| **BET** | Blade Element Theory |
| **BEMT** | Blade Element Momentum Theory |
| **GDWT** | Generalized Dynamic Wake Theory |
| **CAD** | Computer Aided Design |
| **PUMA** | Parallel Unstructured Maritime Aerodynamics |
| **NLDE** | Non-Linear Disturbance Equation |
| **EC120** | Eurocopter Colobri Model 120 |
| **EC145** | Eurocopter Colobri Model 145 |
| **AS355** | Eurocopter Aerospatiale Model 355 |
| **RANS** | Reynolds Average Navier-Stokes |

# CHAPTER 1

# INTRODUCTION

## 1.0 Background

Helicopter flight was probably the first type of flight envisioned by man. The idea dated back to ancient China, where children played with homemade tops of slightly twisted feathers attached to the ends of sticks. The flying Chinese top was a stick with a propeller on top, which was spun by hands and released **[1].**

The helicopter, or direct lift airplane obtaining its support from the vertical thrust of propeller turning in a horizontal plane instead of from the air reaction on wings. Its most important advantage is its ability to rise vertically from a standing start, eliminating the necessity for the long preliminary run characteristic of the airplane. It offers the possibility of hovering motionless over a given spot, a feature of tremendous usefulness for military purposes **[2]**.

Helicopters have come a long way since the first ones flew in the early twentieth century. Modern designs are capable of flying higher and faster than their predecessors. In conjunction with the advances made thus far, tilt-rotors helicopter will be expected to have even greater demands for improved performance and reliability.

Recently, Universiti Teknologi Malaysia (UTM) has taken a big step to start the study of helicopter technology through research and development and also through the offering of the subject “helicopter technology” as an optional subject for the final year degree of mechanical engineering (aeronautic) course. This is aimed at the fulfillment of the country's needs and in the long run to minimize the dependence on foreign technology and expertise. The purchasing of the 2-seater helicopter is to support teaching and learning and also for reverse engineering purposes. Faculty of Mechanical Engineering, UTM has also formed a helicopter R&D group to design and build a 4-seater helicopter as the first Malaysia made helicopter. The aerodynamic and structural designs of helicopter are very vital and must be fully and well understood. In order to reduce drag and also for good vertical take-off and fast forward flight, the effect of interaction of flows from the helicopter main rotor to the fuselage in vertical take-off and forward flight has to be studied in order to establish the aerodynamics of the helicopter. This fact triggered the research that has been taken and detailed in this thesis.

## 1.1 Problem Statement

It is well known that rotary wing aircraft aerodynamics is complicated. Unlike fixed wing aircraft, on which a steady-state flight condition implies steady-state aerodynamics, a rotary wing aircraft experiences a significant unsteady aerodynamic environment in all flight conditions, even in level, unaccelerated flight, due to the presence of the rotating wings. For fixed wing aircraft, the flow on the fuselage body can be treated solely by free-stream velocity but in rotary wing aircraft, both free-stream velocity and rotor wakes interact with the fuselage body. Therefore, a study on the rotor-fuselage flow interaction is necessary in order to understand the flow physics that leads to the proper aerodynamic design for the fuselage body.

The rotor and fuselage interact in a complex, nonlinear fashion, making it difficult to obtain reliable results from simple method. Most of the aerodynamic research on helicopters done previously concerned with the prediction of the main rotor forces and induced velocities. Aerodynamic analysis is important for helicopters design because of unexpected aerodynamic behavior can affect the aircraft in many ways, such as:

i. *Performance*: Poor aerodynamics reduces the aircraft's ability to accomplish its mission.

ii. *Handling*: Poor aerodynamics can also lead to reduced control system effectiveness, degrading the stability characteristics of the aircraft.

iii. *Vibration*: The periodic aerodynamic loading can lead to structural vibrations and can be a source of annoyance to the pilot.

iv. *Maintenance*: Unexpected aerodynamic loading can lead to increased fatigue on components forcing them to require more frequent repair.

v. *Noise*: A variety of aerodynamic interactions can increase the noise generated by the aircraft during operation.

Therefore, before any complicated design for a helicopter being done, one must first determine the aerodynamic behavior of the helicopter especially of the helicopter fuselage since the fuselage drag has been shown to account for up to one-third of total helicopter drag **[3]**. In addition, the helicopter main rotor should be included in any numerical simulation since rotor-fuselage interaction may have a major influence on the helicopter flow field physics. The physics of the helicopter flow field are shown below.

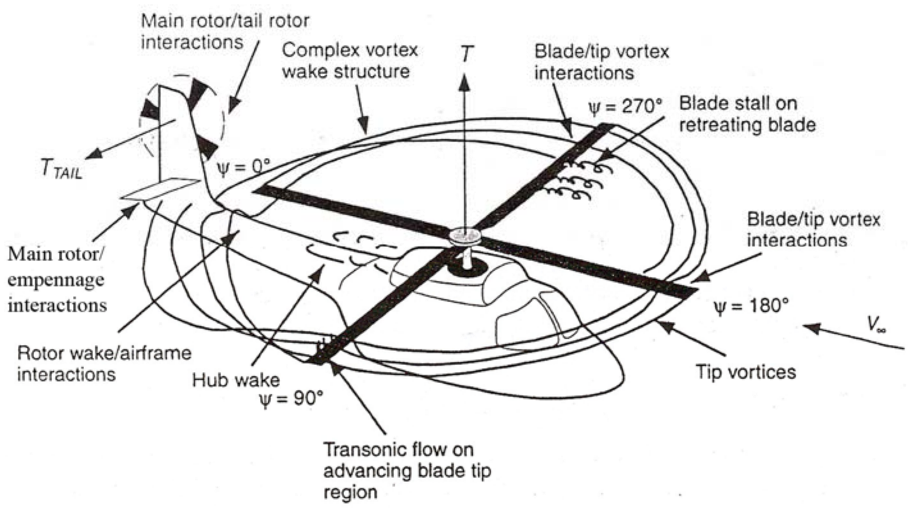


**Figure 1.1: Flow structure and some aerodynamic problem areas on a helicopter in forward flight [4]**

Rotor-fuselage flow interaction by experimental study which is normally conducted by wind tunnel testing is very expensive and time consuming. Computational method on the other hand has lately gained popularity as an alternative tool. Furthermore, increased in computer storage capacity and computation speed, increases the ability to simulate complex flow problem with high accuracy and at less cost compare to experimental test. In this study, a commercial CFD software from FLUENT Inc. is used since FLUENT had been widely used in aeronautic and related industries. Moreover, UTM had already subscribed the FLUENT software and there are a number of expert FLUENT users in the Faculty of Mechanical Engineering that could be referred in time of necessity.

## 1.2 Research Objective

The main objective of the present research is to study and obtain rotor-fuselage flow interaction both in hovering and forward flight. By understanding the rotor-fuselage flow interaction, aerodynamic forces on the helicopter fuselage can be determined, leading to a proper design of the helicopter fuselage.

## 1.3 Research Scope

The research work will cover the following scopes:

i. Theoretical determination of the aerodynamic characteristics of an existing helicopter.
ii. Studying the governing equations, methods and assumptions in Computational Fluid Dynamics (CFD) simulation.
iii. Using computational method to study and obtain flow characteristic of an existing helicopter fuselage for the following conditions:
    1. Isolated rotor blade during hovering and forward flight.
    2. Isolated fuselage in forward flight.
    3. Rotor with fuselage during hovering and forward flight.

## 1.4 Research Methodology

This research will be carried out as follow:

i. Literature review on the previous work of rotor-fuselage aerodynamics
ii. Theoretical analysis on helicopter aerodynamics; concentrating on the effects of wakes and induced velocity of the rotor onto the helicopter fuselage
iii. Numerical analysis on helicopter in hovering and forward flight by using FLUENT 6.2, a commercial CFD software package.
iv. Comparing the results obtained from theoretical and numerical analysis and the previous work

## 1.5 Thesis Outline

This thesis is organized in seven chapters. The chapters are briefly described as follows. Chapter 2 reviews the previous works on helicopter aerodynamics generally. The works include the development of the theories, wind tunnel testing and computer simulation for cases of helicopter rotor-fuselage flow interactions.

On the other hand, chapter 3 provides the basic theory of the helicopter aerodynamics. The flow fields around the helicopter were studied by using Momentum Theory, Blade Element Theory and Blade Element Momentum Theory.

Chapter 4 explains the governing equations in CFD. It also describes the calculation method, turbulence modeling and commercial CFD software FLUENT 6.2. Chapter 5 describes how the simulation is carried out in FLUENT 6.2 including the mesh boundary conditions and the methods used. It also provides the description of the real helicopters and the simulation models.

Chapter 6 provides data comparison of the research and those of the previous work. The comparison is carried out in order to validate the results obtained and the method used. In this chapter the results of theoretical analysis and CFD for hovering and forward flight are also presented. Lastly, chapter 7 summarizes the works that have been done and provides concluding remarks for all the findings. Recommendations for future study have also been provided.