

Investigation of the Effects of Blade-Tip Planform Shape on the Aerodynamic Coefficients of Helicopter Rotor Blades Using Computational Fluid Dynamics (CFD)

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Abstract—

This study uses Computational Fluid Dynamics (CFD) to analyze how blade-tip planform shape affects helicopter rotor blade aerodynamics. Four configurations (rectangular, trapezoidal, swept, and variable-swept) were developed and compared with consistent geometric parameters. Numerical simulations with ANSYS Fluent assessed lift coefficient variations with angle of attack and drag coefficient with Mach number (at zero-lift). Results show blade-tip geometry significantly impacts aerodynamics, especially at moderate-to-high angles of attack and high speeds. The variable-swept tip improves lift and reduces drag at high Mach numbers, while the rectangular tip is less efficient at high speeds. These differences are linked to changes in pressure distribution, tip-vortex strength, flow separation, and local shock-wave development. Optimizing blade-tip planform geometry can enhance rotor blade aerodynamic performance, providing a useful basis for design.

Keywords— Helicopter rotor blade; blade-tip planform; aerodynamic characteristics; lift coefficient; drag coefficient; Computational Fluid Dynamics (CFD); ANSYS Fluent; tip-vortex flow.

I. INTRODUCTION

Helicopter rotor blades generate aerodynamic forces through their interaction with the surrounding airflow. Due to the combined rotational and translational motions of the rotor, the flow velocity and aerodynamic loading vary along the blade span. The blade-tip region, where the relative velocity is highest, is particularly susceptible to complex flow phenomena, including tip-vortex formation, flow separation, and local shock-wave development. These effects significantly influence the lift, drag, and overall aerodynamic performance of the rotor blade.

The blade-tip planform is therefore an important parameter affecting the aerodynamic characteristics of helicopter rotor blades. Changes in tip geometry can modify the spanwise load distribution, tip-vortex strength, induced drag, and compressibility effects. This study investigates the effects of different blade-tip planform shapes on the lift and drag coefficients of a helicopter rotor blade using Computational Fluid Dynamics (CFD). The results provide a basis for evaluating blade-tip configurations and supporting the aerodynamic design and optimization of helicopter rotor blades.

II. METHODOLOGY AND PROBLEM FORMULATION

A. Theoretical Background

Methods for determining the aerodynamic characteristics of rotor blades can be classified into four main groups: analytical, theoretical/experimental aerodynamic, experimental, and numerical methods.

Analytical methods are based on simplified assumptions and are limited when dealing with complex geometries and

nonlinear flows. Wind-tunnel experiments provide reliable results but generally require considerable time and resources and cannot readily cover a wide range of operating conditions. In contrast, Computational Fluid Dynamics (CFD) enables detailed simulation of three-dimensional flow fields, flexible variation of parameters, and efficient evaluation of different blade geometries.

Based on these considerations, the present study employs the CFD method using ANSYS Fluent to investigate the flow around the rotor blade, with particular attention to the blade-tip region where complex aerodynamic phenomena, such as tip-vortex formation and flow separation, may occur.

B. Numerical Procedure

The numerical investigation consists of three main stages.

First, three-dimensional models with different blade-tip planform shapes are developed in SolidWorks. The main geometric parameters, including blade span and planform area, are kept constant to ensure a consistent comparison of the effect of blade-tip geometry.

Second, the computational domain is established and discretized using a refined mesh near the blade surface and blade-tip region. Appropriate boundary conditions are applied, including inlet, outlet, and no-slip wall conditions. Simulations are then performed to determine the variation of the lift coefficient with angle of attack and the drag coefficient with Mach number under zero-lift conditions.

Finally, the numerical results are processed and compared using aerodynamic characteristic curves. The comparison is used to quantify the effects of blade-tip planform geometry on the aerodynamic characteristics and to analyze its influence on pressure distribution, tip-vortex development, and flow energy losses.

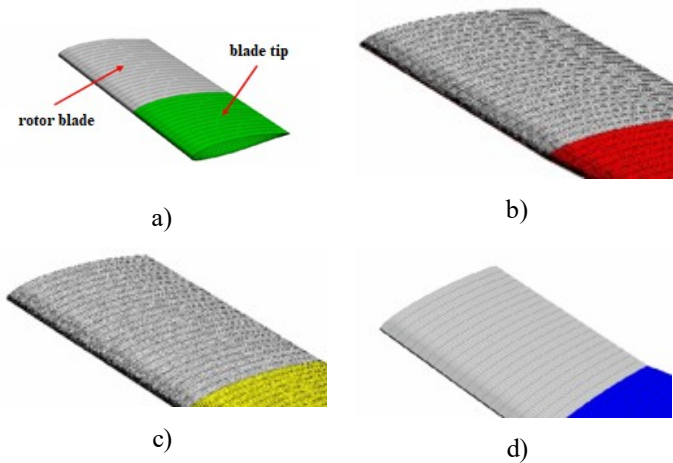


Fig. 1. Models 3D of different blade-tip planform shapes**

- (a) 3D model of the rectangular rotor blade
- (b) 3D model of the rotor blade with a trapezoidal tip
- (c) 3D model of the rotor blade with a swept tip
- (d) 3D model of the rotor blade with a variable-swept tip

Computational mesh generation is a critical step in the numerical simulation process, as the accuracy of the solution strongly depends on mesh quality and resolution. The computational model and mesh must adequately capture the geometric features of the problem while remaining compatible with the available computational resources.

In principle, a finer mesh provides a more detailed representation of the flow field, particularly in regions with large flow gradients, such as the boundary layer near the blade surface and the blade-tip region. However, increasing the mesh density also significantly increases the number of computational elements, resulting in longer computational time and greater hardware requirements. Therefore, in this study, the mesh generation process was optimized by investigating several mesh configurations with different numbers of elements. The meshes were evaluated based on solution convergence and variations in key aerodynamic quantities. The mesh configuration providing an appropriate balance between computational accuracy and cost was then selected to ensure the reliability of the numerical results while minimizing computational time and simulation resources.

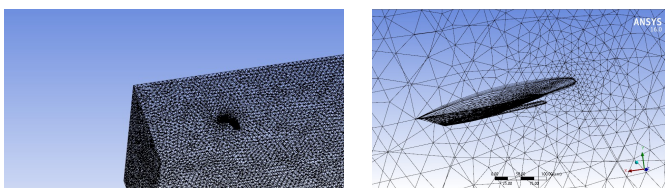


Fig. 2. Computational domain mesh

III. RESULTS ANALYSIS

Based on the numerical results, plots were generated to illustrate the variations in aerodynamic forces for the four selected blade-tip planform configurations under different operating conditions. The results are presented in Figures 3 and 4.

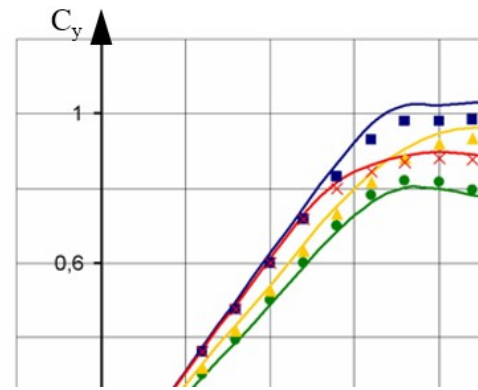


Fig. 3. Variation of the lift coefficient with angle of attack for different blade-tip planform shapes

Based on the results presented in Figure 3, it can be concluded that blade-tip geometry has a significant effect on the lift characteristics, particularly in the moderate- and high-angle-of-attack regimes. At low angles of attack, the characteristic curves are nearly linear and closely coincide for the different blade-tip planform configurations. This behavior is consistent with linear aerodynamic theory, in which the flow remains largely attached to the blade surface and lift is primarily governed by the angle of attack, with relatively limited influence from detailed blade-tip geometry.

However, as the angle of attack increases beyond a critical value, the differences among the blade-tip planform configurations become more pronounced. This is mainly attributed to the development of the boundary layer and the onset of flow separation, which increasingly govern the aerodynamic characteristics. In this regime, blade-tip geometry plays an important role in modifying the pressure distribution and the strength of the blade-tip vortex.

The variable-swept tip configuration exhibits the highest maximum lift coefficient and reaches its maximum value at a higher angle of attack than the other configurations. This indicates that this configuration can delay boundary-layer separation by reducing the strength of the blade-tip vortex and improving the spanwise lift distribution. In contrast, the rectangular blade-tip configuration tends to reach its maximum lift coefficient at a lower angle of attack and with a lower peak value, owing to a less favorable lift distribution and stronger blade-tip vortex development, which increases induced-drag losses.

Therefore, blade-tip geometry affects not only the maximum lift coefficient but also the mechanism governing the spanwise distribution of lift along the blade. Optimization of blade-tip geometry can thus be an effective approach to improving lift-generating capability and extending the stable operating range of the rotor blade.

The results presented in Figure 4 show that the effect of blade-tip geometry on the drag coefficient strongly depends on the flow regime, particularly at high Mach numbers. At low Mach numbers, the different blade-tip planform configurations exhibit nearly identical drag coefficients, indicating that drag in this regime is dominated primarily by skin-friction and pressure drag and is relatively insensitive to blade-tip geometry.

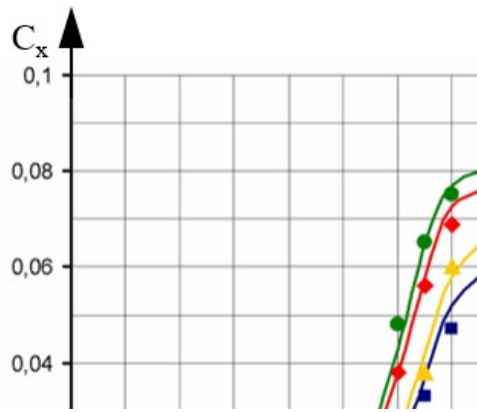


Fig. 4. Variation of the drag coefficient with Mach number at zero lift coefficient for different blade-tip planform shapes

However, as the Mach number increases into the high-subsonic regime (approximately [Mach number]), the drag coefficient increases rapidly, and distinct differences among the blade-tip planform configurations become evident. This behavior is mainly attributed to the formation of local shock waves and the development of supersonic flow regions, resulting in a rapid increase in wave drag. Under these conditions, blade-tip geometry directly affects the pressure distribution and three-dimensional flow structure, particularly the strength of the blade-tip vortex and the location of local shock-wave formation and supersonic regions.

The rectangular blade-tip configuration exhibits the highest drag coefficient because it provides limited capability for increasing the critical flight speed, resulting in greater energy losses. In contrast, the variable-swept tip configuration produces the lowest drag coefficient over the entire range investigated. This can be attributed to the increase in critical flight speed associated with the sweep angle, thereby significantly reducing the wave-drag component.

Therefore, under high-speed operating conditions, blade-tip geometry plays a decisive role in aerodynamic efficiency by controlling local shock-wave phenomena and the development of supersonic flow regions. Appropriate selection and optimization of blade-tip planform geometry are therefore essential for reducing drag and improving the aerodynamic efficiency of rotor blades, particularly for aircraft operating in the high-subsonic speed regime.

IV. CONCLUSION

This study employed a Computational Fluid Dynamics (CFD)-based numerical simulation approach to investigate the effects of blade planform geometry, with particular emphasis on the blade-tip region, on the aerodynamic forces acting on helicopter rotor blades. The numerical results demonstrate that blade-tip geometry has a significant influence on the aerodynamic characteristics, particularly under operating

conditions involving high angles of attack and high flight speeds.

Specifically, the variable-swept tip configuration exhibits favorable aerodynamic characteristics by providing a higher lift coefficient, improved performance at high angles of attack, and a lower drag coefficient at high flight speeds. In contrast, the rectangular blade-tip configuration shows relatively lower aerodynamic efficiency, characterized by a lower lift coefficient and a higher drag coefficient under high-speed conditions.

From an overall engineering perspective, however, the rectangular blade-tip configuration offers significant structural advantages, including high load-bearing capability, structural durability, and ease of manufacturing, assembly, and maintenance. Consequently, this configuration remains widely used in many helicopter applications, particularly where high aerodynamic efficiency is not the primary requirement.

Based on the results obtained, the following recommendations can be made:

Design - For helicopters requiring high technical and operational performance, such as high flight speed, high maneuverability, or improved aerodynamic efficiency, advanced blade-tip configurations, such as variable-swept tips, should be considered to enhance overall aerodynamic performance. These configurations should be combined with other design solutions, such as blade twist distribution and airfoil-section optimization, to achieve improved overall performance.

Structure and manufacturing - In applications where structural strength, reliability, and manufacturing cost are important considerations, the rectangular blade-tip configuration remains a practical option. Local modifications to the blade-tip region may be considered to improve aerodynamic performance without significantly increasing structural complexity.

Overall, the selection of blade-tip planform geometry should be based on a balance between aerodynamic performance and structural and technological requirements, thereby ensuring an appropriate design solution and effective operational performance.

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