Effect of Blade Twist on the Hover Efficiency of a Helicopter Main Rotor

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***Abstract*— Blade twist is an important geometric parameter affecting the aerodynamic performance of helicopter rotors in hover. Due to the radial variation of tangential velocity along the blade span, rotors with constant pitch angles tend to produce non-uniform aerodynamic loading and reduced efficiency. This study investigates the influence of blade twist on the hover efficiency of a helicopter main rotor using a parametric aerodynamic analysis. The results show that blade twist improves the spanwise distribution of aerodynamic loads and significantly enhances rotor efficiency. The results provide useful guidance for the aerodynamic design and optimization of helicopter rotor blades.**

Keywords*— *Helicopter rotor; blade twist; hover performance; rotor efficiency; rotor aerodynamic.

I. INTRODUCTION

The aerodynamic performance of a helicopter rotor plays a critical role in determining the efficiency and power requirements of rotary-wing aircraft. In hover conditions, the tangential velocity of rotor blades increases linearly with the radial distance from the hub, resulting in a non-uniform distribution of aerodynamic loading along the blade span.

If the blade pitch angle remains constant, the outer blade sections operate at higher effective angles of attack, leading to excessive loading near the blade tip and reduced rotor efficiency. To address this issue, helicopter rotor blades are commonly designed with geometric twist, which gradually reduces the pitch angle from the root toward the tip.

Blade twist improves the spanwise distribution of aerodynamic forces and reduces induced power losses, thereby enhancing rotor hover performance. This study analyzes the effect of blade twist on the hover efficiency of a helicopter main rotor and identifies the twist range that provides optimal aerodynamic performance.

II. THEORETICAL BACKGROUND

Rotor Hover Efficiency

The performance of a helicopter rotor in hover is commonly evaluated using rotor efficiency, often expressed in terms of the figure of merit or the ratio between useful aerodynamic power and the actual power consumed by the rotor.

Rotor efficiency in hover can be expressed as

$$\eta_0 = \frac{T v_i}{P} \tag{1}$$

Where:

T – rotor thrust;

v_i – induced velocity in the rotor wake;

P– power required to drive the rotor.

Using nondimensional parameters, rotor efficiency can also be expressed as

$$\eta_0 = \frac{C_T^{3/2}}{2 m_k} \tag{2}$$

where

C_T– thrust coefficient;

m_k– power coefficient.

This formulation shows that rotor efficiency depends on both thrust generation capability and power consumption.

Blade Twist Concept

Blade twist refers to the variation of blade pitch angle along the rotor radius. The total blade twist angle is defined as

$$\Delta\varphi_\Sigma = \varphi_{root} - \varphi_{tip} \tag{3}$$

where

φ_{root}– pitch angle at the blade root;

φ_{tip}– pitch angle at the blade tip.

For helicopter rotors, negative geometric twist is typically applied, meaning the pitch angle decreases toward the blade tip. This configuration allows the rotor blade to maintain a more uniform aerodynamic loading along the span.

III. RESEARCH METHODOLOGY

Rotor Configuration and Parameters

The analysis was conducted for a representative helicopter rotor configuration with the following parameters:

Number of blades: k=4

Rotor solidity: σ=0.08

The rotor performance was evaluated under hover conditions for different blade twist angles within the range

$\Delta\varphi\Sigma = 0^0 - 24^0$

This range represents typical blade twist values used in helicopter rotor design.

Analytical Procedure

The research methodology consists of several steps:

1. Definition of blade geometric twist distribution along the rotor span;

2. Evaluation of aerodynamic load distribution for different twist configurations;
3. Calculation of rotor thrust and power coefficients;
4. Determination of rotor hover efficiency;
5. Comparison of rotor performance for different blade twist angles.

The aerodynamic analysis is based on classical rotor aerodynamic theory, which considers the influence of blade geometry, rotational velocity, and aerodynamic forces acting along the blade span.

IV. RESULTS AND DISCUSSION

Effect of Rotor Blade Twist on Hover Performance Efficiency

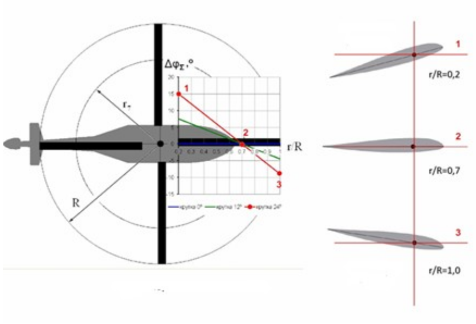

Fig. 1. Effect of Main Rotor Blade Twist on Hover Figure of Merit

Figure 1 illustrates the variation of rotor blade pitch angle at different spanwise locations along the blade, specifically at r/R=0.2, 0.7, and 1.0. Along the blade span, the pitch angle decreases linearly, and at the blade tip, it may even attain negative values. The implementation of blade twist plays a critical role in improving the aerodynamic performance and overall efficiency of the rotor blade.

Influence of Blade Twist on Rotor Hover Efficiency

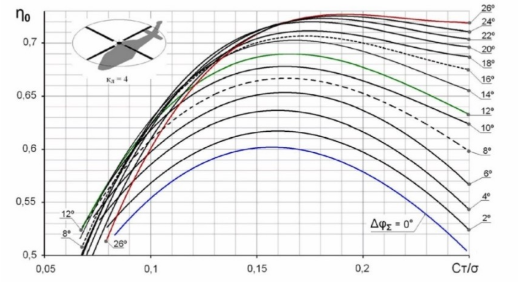

Fig. 2. Effect of Blade Twist on Rotor Performance in Hover

Changing the rotor blade twist affects the hover performance of a helicopter rotor. Specifically, increasing the blade twist leads to higher aerodynamic efficiency. Additionally, the performance is influenced by the ratio of the rotor thrust coefficient to the rotor solidity (C_T/σ). For blades with constant pitch (no twist), as this ratio increases, the hover efficiency rises to a certain value (around 0.15) and then begins to decrease.

Effect of Rotor Blade Twist on Hover Performance Losses

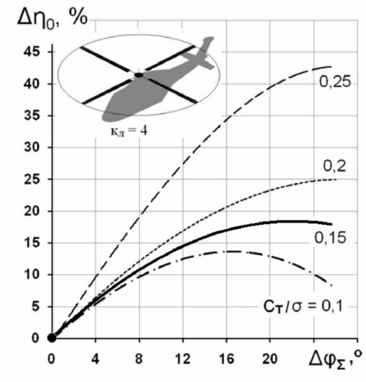

Fig. 3. Rotor Performance Losses as a Function of Blade Twist Angle in Hover

Figure 3 shows the variation of helicopter rotor performance loss in hover with respect to blade twist angle and the ratio of thrust coefficient to solidity. When the blade twist angle is constant, an increase in the thrust coefficient to solidity ratio leads to higher performance losses. Conversely, for a constant ratio, increasing the blade twist initially increases the performance loss, but after reaching a peak, the loss begins to decrease.

V. CONCLUSIONS

The analysis of the three figures provides comprehensive insight into the influence of rotor blade twist on helicopter hover performance and efficiency, highlighting both aerodynamic benefits and trade-offs in design. Blade twist is a fundamental geometric parameter that directly affects the distribution of aerodynamic loading along the rotor blade span, influencing the Figure of Merit (FoM) and performance losses during hover.

Blade Twist and Aerodynamic Efficiency: Increasing the blade twist improves the spanwise lift distribution, bringing it closer to the ideal elliptical profile. This reduces induced drag and better aligns local angles of attack with the spanwise variation in relative velocity. As shown in the figures, twisted blades exhibit higher FoM values than untwisted blades across a wide range of thrust coefficients, demonstrating that proper twist is essential for maximizing rotor efficiency, particularly at high thrust loading conditions.

Dependence on Thrust Coefficient to Solidity Ratio (C_T/σ): Hover performance is strongly influenced by the ratio of thrust coefficient to rotor solidity. For untwisted blades, increasing (C_T/σ) initially increases efficiency up to a threshold (~0.15), after which efficiency begins to decline due to overloading of the blade tips and non-optimal lift distribution. Twisted blades, in contrast, maintain higher efficiency over a broader range of thrust loadings, highlighting the importance of twist for operational flexibility and high-performance hover.

Performance Loss Trends and Design Trade-offs: Performance losses increase with both higher blade twist and higher (C_T/σ). For a fixed thrust-to-solidity ratio, increasing blade twist initially increases losses due to underloading or overloading of certain blade sections, but beyond an optimal twist angle, further twist reduces losses by improving spanwise load distribution. This demonstrates a key design trade-off: maximizing efficiency requires careful selection of twist to minimize losses while avoiding adverse aerodynamic effects at the blade root or tip.

Application in Helicopter Design: Understanding the relationship between blade twist, FoM, and performance losses is critical for rotorcraft design. Optimizing blade twist allows designers to achieve higher hover efficiency, reduce power consumption, and expand the safe operational envelope. In practice, this informs decisions on rotor geometry for different mission profiles-such as high-altitude hover, cargo lift, or maneuvering-by tailoring twist to balance thrust generation, induced drag, and structural considerations. Furthermore, twist optimization can reduce mechanical stress and vibration levels by achieving smoother aerodynamic loading along the blade span, contributing to longer rotor life and lower maintenance costs.

In conclusion, blade twist is a key design parameter for helicopter rotors. Properly optimized twist not only maximizes hover performance and minimizes efficiency losses but also provides practical benefits for rotorcraft operation, including higher operational flexibility, reduced power requirements, and improved structural longevity. These insights reinforce the need for careful aerodynamic and structural analysis during rotor blade design to achieve both performance and reliability objectives in modern helicopter engineering.

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