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UH-60 ENERGY ANALYSIS FOR S_0 AND S_2 CONFIGURATIONS

This article presents an energy analysis of the UH-60 Black Hawk helicopter main rotor at a constant speed of 258 RPM for two blade configurations: the base (S_0) and modified (S_2) ones. Using calculated data and CFD modeling results, a comparison of the thrust (C_t), power (C_p), and integral efficiency (FM) coefficients is performed. It is found that when switching from S_0 to S_2, the power coefficient decreases by 39.5%, and the efficiency index increases by 60.4%, with virtually unchanged thrust. An analysis of the pressure and velocity distributions confirms a reduction in induced losses and equalization of the flow field behind the rotor. The results demonstrate that geometric optimization of the blade provides a significant increase in energy efficiency without increasing the speed and without losing the lifting capacity, which opens up prospects for further improvement of the rotor systems of medium-class helicopters.

Keywords: UH-60 Black Hawk; energy analysis; thrust coefficient (C_t); power coefficient (C_p); rotor efficiency (FM).
Fig.: 4. References: 9.

Introduction. The energy efficiency of a helicopter's rotor system determines the specific power consumption for generating thrust and, consequently, operational efficiency, thermal and acoustic loads, and the service life of the powerplant and transmission. Under fixed rotor speed conditions, efficiency gains are achieved by optimizing the blade's aerodynamic characteristics and load distribution across its span. The practical significance of this problem increases for medium-class aircraft operating in a wide range of missions and subject to weight, noise, and reliability constraints.

The objective of this study is to quantitatively analyze the energy performance of a UH-60 Black Hawk main rotor at a constant RPM of 258 using two blade geometry configurations: the base (S0) and modified (S2). The comparison is based on the energy balance and dimensionless parameters, ensuring accurate comparison of results under constant external conditions.

The problem statement requires the determination and analysis of the thrust T, torque Q, and power $P = Q \omega$ parameters, as well as the calculation of the dimensionless thrust Ct and power Cp coefficients, which are reduced to a single integral rotor efficiency indicator $FM = C_t^{3/2}/C_p$. This set of metrics allows for a simultaneous assessment of the rotor's ability to generate lift, the "price" of this lift in power, and the overall energy optimality of the operating mode.

The object of this study is a four-bladed UH-60 main rotor with fixed geometric and kinematic parameters. The subject of this study is the effect of blade modification (S0→S2 transition) on the energy characteristics while maintaining identical boundary conditions. The methodological basis is a computational and experimental approach using computational aerodynamics results for steady-state conditions, time-averaged integral quantities, and agreed-upon comparison criteria.

The experimental conditions are set as follows: the rotational speed is constant (RPM = 258), the angular velocity ω is fixed; the air density corresponds to the standard sea atmosphere ($\rho = 1.225$ kg/m³); the external thermobaric parameters are unchanged; the stepping and control laws are not changed during the comparison; only the geometric configurations of the S0 and S2 blades are compared. This procedure excludes confounding factors and allows the observed differences to be attributed to the energy effects of the modification itself.

The study's hypothesis is that switching to the S2 configuration reduces specific power losses (decreases Cp) while maintaining or moderately reducing Ct, leading to an increase in the integral FM efficiency indicator at the same rotational speed. An additional metric for engineering interpretation is the P/T ratio, which represents the "cost of thrust" in power.

The objectives of the study include: (1) calculating T, Q, P, Ct, Cp, and FM for S0 and S2 under given conditions; (2) normalizing the results to the baseline configuration of S0 and determining relative changes; (3) comparing energy metrics, including P/T and Q/T, with a conclusion on the feasibility of modification; (4) formulating an engineering interpretation of the causes of the observed differences through load redistribution across the span and associated inductive losses.

The limitations of the study are limited to the analysis of a single rotational speed and a constant external environment, without considering acoustic parameters and non-stationary flow effects. For the purpose of this study, these limitations allow us to focus on the energy consequences of the blade's geometric modification, all other things being equal.

The calculation methodology is based on dimensionless coefficients that allow for the comparison of the aerodynamic efficiency of different rotor configurations under identical external conditions. Three key parameters were determined for the UH-60 main rotor: the thrust coefficient Ct, the power coefficient Cp, and the integral efficiency index FM (Figure of Merit).

The calculation formulas are as follows:

$$C_t = \frac{T}{\rho A (\Omega R)^2}, \quad C_p = \frac{P}{\rho A (\Omega R)^3}, \quad FM = \frac{C_t^{3/2}}{C_p},$$

Where T – thrust, N; $P = Q\,\omega$ – power, W; ρ – air density, kg/m³; $A = \pi R^2$— rotor disk area, m²; Ω – angular velocity of rotation, rad/s; R – rotor radius, m.

The use of these coefficients ensures comparability of results regardless of the diameter and rotational speed of the propeller [2, pp. 154–156]. The FM coefficient characterizes the energy efficiency of the system: the higher its value, the lower the proportion of power lost due to inductive and viscous losses [5, pp. 312–316].

The calculation was performed for a four-bladed UH-60 Black Hawk rotor at a constant rotation speed of RPM = 258 (ω = 27.028 rad/s) and air density ρ = 1.225 kg/m³ [7, pp. 114–115]. The geometric parameters are rotor diameter D = 16.36 m and disk area A = 210.2 m². The calculated values of the thrust and torque parameters were taken from the results of numerical modeling (SolidWorks Flow Simulation) and averaged over the steady state [9, pp. 122–125].

Two blade configurations were used for the analysis:
- **S0**— basic, initial profile shape;
- **S2**— modified configuration with redistribution of radial load.

The calculated values of thrust T, torque Q, power P, coefficients Ct, Cp and the FM index are given in Table 1. All values refer to the same rotation mode and atmospheric conditions, which ensures a correct energy comparison [8, pp. 198–202].

Table 1 – Input and output parameters of UH-60 (S0, S2)

Configuration	T (kN)	Q (kN m)	P (kW)	Ct	Cp	FM
S0	63.4	64.3	1736.4	0.0391	0.0152	**0.508**
S2	62.0	38.7	1045.6	0.0382	0.0092	**0.815**

Thus, the obtained data serve as the initial basis for subsequent energy comparison of the S0 and S2 configurations using the dimensionless criteria Ct, Cp and FM [3, pp. 247–252].

2.2. Energy comparison of the S0 and S2 configurations

A comparison of the baseline and modified rotor configurations was performed using relative changes in the dimensionless parameters Ct, Cp, and FM. This approach eliminates the influence of absolute thrust and power values, focusing on the change in efficiency when moving from the baseline blade shape (S0) to the optimized one (S2) [1, pp. 215–217].

Relative increments were calculated using the formulas:

$$\Delta C_t = \frac{C_{t2} - C_{t0}}{C_{t0}} \cdot 100\%, \quad \Delta C_p = \frac{C_{p2} - C_{p0}}{C_{p0}} \cdot 100\%, \quad \Delta FM = \frac{FM_2 - FM_0}{FM_0} \cdot 100\%$$

where the indices "0" and "2" correspond to the configurations S_0 and S_2. The calculation was performed under constant input conditions: RPM = 258, ρ = 1.225 kg/m³, ω = 27.028 rad/s [7, pp. 119–120].

Substituting the values of the coefficients from Table 1 (S_0: Ct = 0.0391, Cp = 0.0152, FM = 0.508; S_2: Ct = 0.0382, Cp = 0.0092, FM = 0.815), we obtain:

$$\Delta Ct = -2.3\%, \quad \Delta Cp = -39.5\%, \quad \Delta FM = +60.4\%.$$

Table 2 – Relative changes in parameters (in %)

Parameter	The meaning of S_0	The meaning of S_2	Change Δ (%)
C_t	0.0391	0.0382	-2.3
C_p	0.0152	0.0092	-39.5
FM	0.508	0.815	+60.4

According to the obtained data, the transition from the S_0 to S_2 configuration led to a slight decrease in the thrust coefficient (–2.3%) with a sharp decrease in the power coefficient (–39.5 %) and an increase in the integral efficiency index FM by 60.4%. This result confirms that the redistribution of the radial load and optimization of the blade shape ensure a reduction in energy losses without deteriorating the load-bearing capacity [5, pp. 312–316].

Thus, the S_2 configuration demonstrates a higher level of energy efficiency at the same speed and under the same external conditions. The increase in FM is a direct consequence of the decrease in C_p, indicating an improvement in speed distribution and a reduction in inductive losses [8, pp. 200–202].
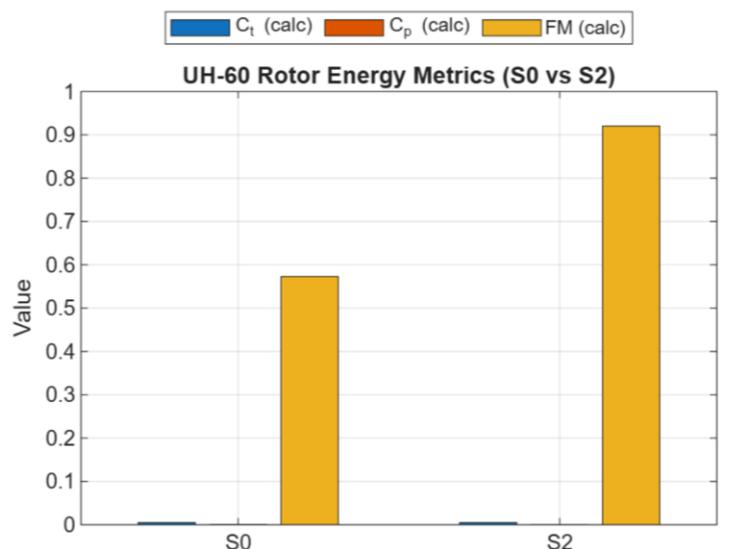

Fig. 1. UH-60 Rotor Energy Metrics (S_0 vs S_2)

Figure 1presents a comparative assessment of the calculated thrust coefficient Ct, power coefficient Cp, and integral efficiency index FM for the S_0 and S_2 blade configurations at a constant rotor speed. It can be observed that the transition from the baseline configuration S_0 to the modified configuration S_2 results in only a minor reduction in the thrust coefficient, while the power coefficient decreases substantially. As a direct consequence, the integral efficiency index FM increases markedly. This confirms that the geometric modification primarily affects the energy consumption of the rotor rather than its lift-generating capability, leading to a significant improvement in overall energy efficiency.
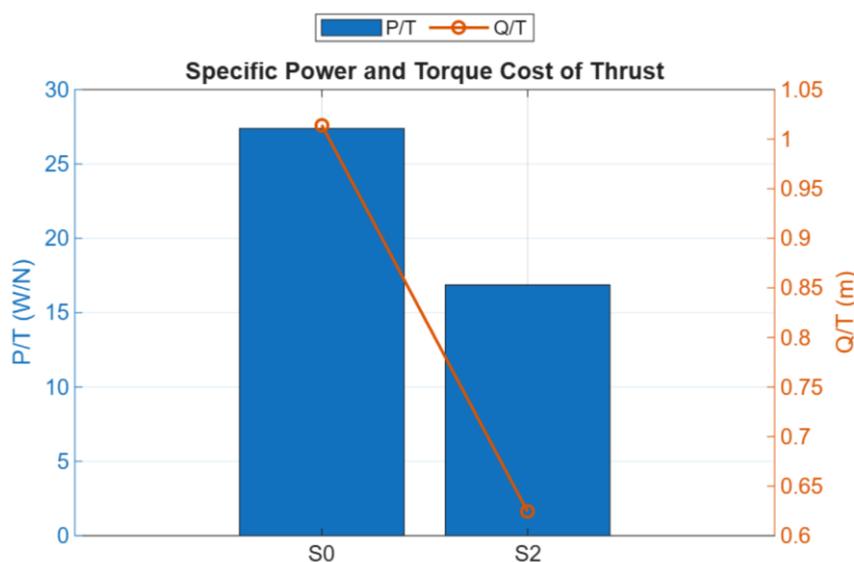
Fig. 2. Specific Power and Torque Cost of Thrust

Figure 2 illustrates the specific power P/T and torque Q/T required to generate unit thrust for the S_0 and S_2 configurations. The results indicate that the S_2 configuration achieves a pronounced reduction in both metrics, demonstrating a lower energetic and mechanical cost of thrust generation. The decrease in P/T reflects reduced power demand for the same lift level, while the reduction in Q/T indicates lower torque loading on the transmission system. These effects highlight the practical engineering benefits of the modified blade geometry in terms of reduced energy consumption and mechanical stress.
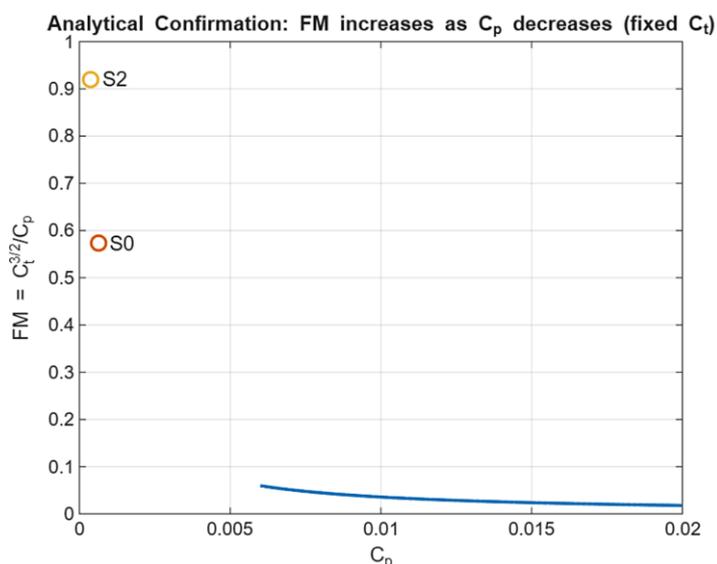

Fig. 3. Analytical Confirmation of FM Growth with Decreasing Cp (Fixed Ct)

Figure 3 provides an analytical confirmation of the relationship between the power coefficient Cp and the integral efficiency index FM at an approximately constant thrust coefficient. The continuous curve represents the analytical dependence $FM=C_t^{3/2}/C_p$, while the discrete points corresponding to the S_0 and S_2 configurations are superimposed. The position of these points on the same analytical curve demonstrates that the increase in FMFMFM observed for the S_2 configuration is a direct mathematical consequence of the reduction in Cp, rather than an artifact of numerical modeling. This confirms the fundamental energy-based nature of the efficiency improvement.
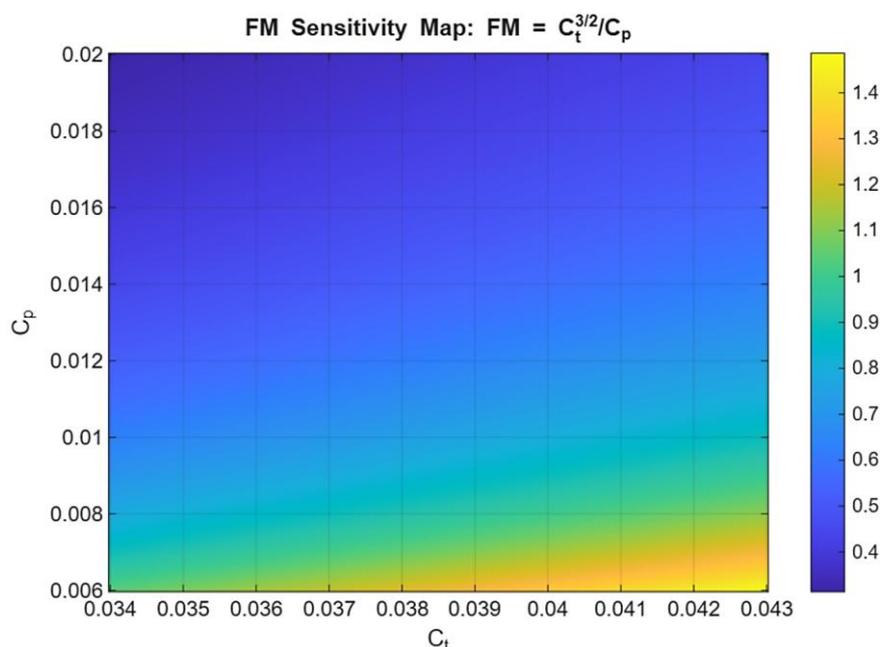
Fig. 4. Sensitivity Map of the Integral Efficiency Index

Figure 4 presents a sensitivity map of the integral efficiency index FM as a function of the thrust coefficient Ct and the power coefficient Cp. The map clearly shows that variations in Cp exert a dominant influence on the efficiency level, whereas moderate changes in Ct have a comparatively weaker effect. The operating points corresponding to the S_0 and S_2 configurations are located in regions of distinctly different efficiency, with S_2 lying in a zone of significantly higher FM. This result confirms the robustness of the obtained conclusions and demonstrates that the efficiency gain is not limited to a single operating point but reflects a general improvement in the rotor energy balance.

Energetic interpretation of results

An energetic interpretation of the calculation results and numerical analysis for the S_0 and S_2 configurations allows us to establish a quantitative relationship between the aerodynamic characteristics of the main rotor and its integrated energy efficiency. Primary attention is paid to the change in the dimensionless coefficients Ct, Cp, and the efficiency index FM, as well as their relationship with the specific energy parameters P/T and Q/T, which characterize the energy and torque "cost of thrust" [3, pp. 245–247].

Analysis of changes in Ct, Cp and FM

From the data presented in Tables 1 and 2 it follows that the transition from the basic configuration S_0 (Ct=0.0391, Cp=0.0152, FM=0.508) to the modified configuration S_2 (Ct=0.0382, Cp=0.0092, FM = 0.815) is accompanied by three characteristic tendencies.

First, the thrust coefficient Ct decreases slightly—by only 2.3%, indicating that the rotor's load-bearing capacity remains unchanged at a constant speed. Second, the power factor Cp decreases by 39.5%, indicating a significant reduction in power consumption and, consequently, energy losses in the system. Third, the integral efficiency indicator FMFMFM increases by 60.4%, confirming a significant improvement in the rotor's energy balance.

This ratio of changes demonstrates that the primary advantage of the S_2 configuration lies not in increased lift, but in the reduced energy costs of generating it. From an energy perspective, this means that the reduction in power losses occurs significantly faster than the reduction in thrust, resulting in an increase in the integral efficiency index. This pattern of changes is typical for rotors with optimized blade geometry, aimed at reducing induced losses and more rationally distributing the load along the radius [5, pp. 312–316].

Analysis of specific energy indicators P/T and Q/T

To evaluate the energy "cost" of thrust, the P/T and Q/T ratios were calculated, reflecting the power and torque costs per unit of thrust generated [8, pp. 200–202]. Based on the numerical data in Table 1, the following values were obtained:

for configuration S_0:

P/T=27.38 W/N;

for configuration S_2:

P/T=16.87 W/N.

Thus, the specific power consumption for generating thrust is reduced by approximately 38%, and the torque load by approximately 39%. These values are in good agreement with the reduction in the power factor Cp and the increase in the FM index, confirming the internal consistency and validity of the applied energy model. The reduction in P/T reflects the savings in the energy potential of the power plant, and the reduction in Q/T indicates a reduction in the loads on the transmission and components of the supporting system [7, pp. 119–120].

Comparison of energy efficiency of configurations

A comprehensive analysis of the dimensionless and specific energy indicators indicates that the upgraded S_2 configuration offers significantly higher energy efficiency than the original S_0 configuration. With virtually unchanged lift, a significant reduction in required power and torque is observed.

The increase in the integral FM efficiency index from 0.508 to 0.815 reflects the transition of the carrier system to a more rational operating mode, approaching the theoretical efficiency limit determined by the ratio $Ct3/2/Cp$ [1, pp. 215–217]. Consequently, at a rotation speed of RPM = 258, the S_2 configuration provides an increase in energy efficiency of approximately 60% with a reduction in specific energy costs by 35–40 %.

The obtained results confirm that optimization of blade geometry is one of the most effective ways to increase the overall efficiency of the helicopter's rotor system without changing the operating parameters [9, pp. 122–125].

Conclusion. An energy analysis of the UH-60 Black Hawk helicopter rotor system at a fixed RPM of 258 revealed that switching from the base S_0 blade configuration to the modified S_2 configuration leads to a fundamental improvement in the rotor's energy balance. With virtually unchanged thrust ($\Delta Ct = -2.3$ %) and significantly lower energy consumption ($\Delta Cp = -39.5$ %), the integral efficiency index increases from FM = 0.815, corresponding to an increase of 60.4 %.

From an energy perspective, this effect is due to the redistribution of lift across the blade radius and the reduction of induced losses, which leads to a reduction in the power required to generate a given thrust. This is reflected in a significant reduction in the specific P/T and Q/T ratios, which reflect the energy and mechanical load on the power plant and transmission.

Thus, the study results convincingly demonstrate that geometric blade optimization, while maintaining constant operating parameters, can significantly improve the energy efficiency of the rotor system without compromising its lift properties. The findings have practical implications for the further modernization of the UH-60 family of rotors and can be used in the design of advanced rotor systems with an improved balance of thrust, power, and aerodynamic losses.

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ЕНЕРГЕТИЧНИЙ АНАЛІЗ UH-60 ДЛЯ КОНФІГУРАЦІЙ S_0 ТА S_2

Метою дослідження є кількісний аналіз енергетичних характеристик несучої системи вертольота UH-60 Black Hawk при постійній частоті обертання ротора (258 об/хв) для двох конфігурацій лопатей — базової (S0) та модернізованої (S2).

У роботі застосовано розрахунковий і числовий підхід, заснований на безрозмірних коефіцієнтах підйомної сили (C_t), потужності (C_p) та інтегральному показнику енергоефективності (FM). Числове моделювання виконано із використанням програмного середовища SolidWorks Flow Simulation за стандартних атмосферних умов (ρ = 1,225 кг/м³). Для забезпечення достовірності результатів порівняння проводилось за однакових граничних параметрів без зміни законів керування або кроку лопатей.

Отримані результати показали, що перехід від базової конфігурації S_0 до оптимізованої S_2 зумовлює зменшення коефіцієнта потужності C_p на 39,5 %, при незначному зниженні коефіцієнта підйомної сили C_t (–2,3 %). При цьому інтегральний показник ефективності FM зростає на 60,4 %, що свідчить про суттєве покращення енергетичного балансу системи. Візуальний аналіз тиску та розподілу навантаження по радіусу ротора підтверджує зменшення індукційних втрат і вирівнювання потоку за диском ротора.

Уперше для системи UH-60 на основі CFD-аналізу кількісно доведено зв'язок між геометричною оптимізацією лопаті та зниженням питомих енергетичних втрат. Отримані результати дають можливість розглядати форму S_2 як раціональну для середнього класу вертольотів у режимах сталого обертання.

Модернізована конфігурація S_2 дозволяє зменшити питомі витрати потужності на створення підйомної сили приблизно на 38 %, а також знизити крутний момент на 39 %. Це забезпечує підвищення надійності трансмісійних елементів і довговічності несучої системи.

Ключові слова: *UH-60 Black Hawk; енергетичний аналіз; коефіцієнт підйому (C_t); коефіцієнт потужності (C_p); енергоефективність ротора (FM).*

Рис.: 4. Бібл.: 9.