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The influence of the blade pitch angle on the C_t, C_p and FM characteristics of the Mi-8 and UH-60 rotors in S_0–S_3 configurations

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Abstract: The article presents a comparative aerodynamic and energy analysis of the influence of the blade pitch angle on the performance characteristics of helicopter rotor systems representing different scale classes. The study focuses on two representative main rotor configurations and examines four blade geometries (S_0–S_3), ranging from a baseline profile to optimized variants with modified twist and tip geometry. The research is based on a combined theoretical and analytical approach using dimensionless thrust and power coefficients (C_t and C_p), as well as the integral efficiency indicator known as the figure of merit (FM), which enables a unified comparison of rotors with different diameters and loading conditions. Analytical approximations of the functional dependencies $C_t(\theta)$, $C_p(\theta)$, and FM(θ) are constructed to describe the relationship between blade pitch angle and energy balance under steady operating conditions. The results demonstrate that an increase in the pitch angle leads to an approximately linear growth of the thrust coefficient, while the power coefficient exhibits a nonlinear increase due to the combined effects of profile and induced losses. As a consequence, the FM efficiency curve shows a pronounced maximum at an optimal pitch angle range, beyond which further increases in pitch result in a rapid decline in energy efficiency. It is shown that rotors with smaller swept disk areas and higher specific power loading exhibit greater sensitivity of FM to variations in pitch angle, whereas larger rotors demonstrate a wider efficiency plateau and lower sensitivity to tuning errors. The transition from the baseline blade configuration to optimized geometries (S_2–S_3) leads to a noticeable reduction in power losses, an expansion of the high-efficiency operating range, and a decrease in the sensitivity of FM to pitch variations. The scientific novelty of the study lies in the unified analytical framework used to compare pitch-angle-dependent efficiency characteristics across multiple blade configurations and rotor scales. The practical significance of the results is associated with their applicability to the optimization of collective pitch settings and the development of adaptive rotor control strategies aimed at improving energy efficiency and operational stability under variable flight conditions.

Keywords: aerodynamics, C_t and C_p coefficients, installation angle, FM efficiency, rotor.

1. Introduction

Improving the energy efficiency of helicopter rotor systems requires a quantitative description of the influence of blade pitch angle on the aerodynamic and power characteristics of the rotor. The pitch angle determines the balance between the generated thrust and the required power, shapes the load distribution along the wingspan, and sets the conditions for the occurrence of induced and profile losses. For machines of different sizes and configurations—the Mi-8 and the UH-60—the sensitivity of energy indicators to changes in pitch angle differs due to blade geometry, the swept area of the disk, and the characteristics of the tip zones [5, pp. 151–176; 4, pp. 219–232; 7, pp. 103–118].

The relevance of the study is determined by the fact that adjustment of the installation angle is the basic mechanism for controlling rotor modes, directly related to the operating efficiency and service life of the power plant. An excessive angle causes an accelerated increase in the required power due to the profile component and the strengthening of vortex structures at the blade tips; an insufficient angle reduces the lifting capacity and requires compensation by increasing the rotational speed, which also leads to an increase in energy losses [2, pp. 245–250; 8, pp. 118–126]. The practical problem is to determine the range of angles that ensure maximum integral efficiency under constraints on dynamics, noise, and vibration.

The objective of this study is to conduct a systematic comparative analysis of the influence of the installation angle on the coefficients C_t, C_p, and the FM efficiency index for the Mi-8 and UH-60 rotors in the S_0–S_3 configurations under steady-state conditions. The study is aimed at identifying patterns of energy balance changes with variations in the installation angle and developing criteria for selecting optimal pitch settings depending on the blade configuration and rotor scale.

The methodological basis includes torque theory and rotor theory for estimating the inductive power component, supplemented by a profile loss model and a weakly compressible correction in the zone of elevated local Mach numbers at the wingtip. Normalization by the dimensionless coefficients C_t, C_p, and the FM index allows for comparison of results for rotors of different diameters and blade numbers, eliminating the influence of external scales and capturing atmospheric conditions.

The objects of the study are the rotors of the Mi-8 (D = 21.29 m) and UH-60 (D = 16.36 m) with blade configurations S_0–S_3, where S_0 is interpreted as the basic geometry, S_1 — with moderate twist, S_2 — with a saber-shaped tip, S_3 — with a combined optimization of twist, thickness and chord. For each case, an identical disk load, the same atmospheric conditions and a steady state are assumed, which makes it possible to isolate the influence of the installation angle on the energy characteristics [9, pp. 12–15; 12, pp. 77–84; 15, pp. 211–229].

The scientific novelty lies in the unified approximation of the $C_t(\theta)$, $C_p(\theta)$, and $FM(\theta)$ dependencies for two helicopters and four configurations with physical constraints on the loss parameters to ensure the monotonicity and convexity of the energy curves. This approach ensures comparability of the results and allows for the interpretation of the differences between the Mi-8 and UH-60 through configuration-dependent loss parameters and scale effects.

The practical significance is determined by the possibility of directly using the obtained dependencies when adjusting the collective pitch and selecting operational ranges of installation angles that ensure the maximum FM efficiency indicator with permissible thrust and limited required power. The result of the study is the formation of optimality criteria for the installation angle for each S_0–S_3 configuration, as well as recommendations for expanding the efficiency plateau through geometric optimization of the blade tip zones [10, pp. 145–168; 13, pp. 32–47; 14, pp. 118–126].

2. Methodology and calculation assumptions

The calculation method is based on classical rotor theory in combination with a moment model, which provides a relationship between the blade pitch angle, the thrust coefficients C_t and power coefficients C_p, as well as the integral efficiency index FM. Two helicopters of different classes were selected for comparison: the Mi-8 and UH-60, which have different swept disk areas but comparable disk load values, allowing for accurate standardization without the influence of scale factors [2, pp. 178–185; 5, pp. 207–210].

The following geometric and physical parameters were adopted in the study: for Mi-8 — rotor diameter D = 21.29 m, radius R = 10.645 m, for UH-60 — D = 16.36 m, R = 8.18 m. Air density ρ = 1.225 kg/m³, number of blades B = 4. The rotor speed is maintained constant (192 rpm for Mi-8 and 258 rpm for UH-60) in order to isolate the influence of the installation angle θ with constant Ω. The range of installation angle variation is θ = 0° – 15°, step — 1°.

The thrust coefficient is determined by the expression

$$C_t = \frac{T}{\rho A(\Omega R)^2} \tag{1}$$

where T is the total rotor thrust, A = πR² is the swept disk area, Ω is the angular velocity, and R is the propeller radius. The power factor is calculated similarly using the consumed power P:

$$C_p = \frac{P}{\rho A(\Omega R)^3} \tag{2}$$

The integral indicator of efficiency (figure of merit) is defined as

$$FM = \frac{{C_t}^{3/2}}{C_p} \tag{3}$$

which makes it possible to estimate the proportion of useful power converted into lift [3, pp. 144–149; 6, pp. 198–203].

To take into account the relationship between the installation angle and aerodynamic forces, a dependence of the lift coefficient of the profile was introduced

$$C_L = \alpha(\alpha_0 + \theta) \tag{4}$$

where a is the lift gradient of the profile, and α_0 is the effective angle of attack at zero lift. Then the rotor thrust is expressed as a spanwise integral:

$$T = \int_0^R \frac{1}{2}\rho\alpha(\alpha_0 + \theta)c(r)(\Omega r)^2 B dr \tag{5}$$

where c(r) is the local chord of the blade. When approximating a uniform chord and a constant pitch angle, we obtain

$$T = \frac{1}{6}\rho\alpha B c R^3 \Omega^2(\alpha_0 + \theta) \tag{6}$$

Accordingly, the coefficient C_t depends linearly on the installation angle θ, and the coefficient C_p includes an additional quadratic component associated with profile losses [4, pp. 229–234]:

$$C_p = C_{p0} + k_1 C_t + k_2 {C_t}^2 \tag{7}$$

where Cp0 is the constant part (profile losses at zero thrust), and k_1 and k_2 are the coefficients of inductive and parasitic losses.

For all S_0–S_3 configurations, numerical normalization of the coefficients is performed according to the nominal mode:

$$\overline{C_t} = \frac{C_t}{C_{t0}}, \quad \overline{C_p} = \frac{C_p}{C_{p0}}, \quad \overline{FM} = \frac{FM}{FM_0} \tag{8}$$

This representation eliminates scale differences and allows one to evaluate the pure influence of the installation angle on aerodynamic efficiency.

3. Theoretical approximation of the dependencies $C_t(\theta)$, $C_p(\theta)$ and $FM(\theta)$

The theoretical approximation was performed based on the dependence of the profile lift on the installation angle and the inductive effects associated with the circulation of the flow around the blades. In a simplified linear formulation, the rotor thrust coefficient is expressed through the installation angle θ as a linear function:

$$C_t(\theta) = k_1\theta + k_2 \tag{9}$$

where k_1 is a proportionality constant determined by the blade geometry (twist, relative chord ratio, and number of blades), and k_2 is a term dependent on the profile and angle α_0 at zero lift [2, pp. 252–257; 5, pp. 211–213]. For the Mi-8 and UH-60 helicopters, the k_1 values differ due to scale effects: the larger radius of the Mi-8 yields a smaller specific change in C_t for the same increment in angle θ, reflecting the more inertial nature of its flow.

The power factor C_p does not increase linearly with angle θ, as it includes nonlinear losses associated with the increase in profile resistance and inductive losses. This dependence is approximated by a quadratic equation:

$$C_p(\theta) = C_{p0} + a\theta^2 + b\theta \tag{10}$$

where Cp0 is the base power required to maintain rotation at zero thrust (profile component), a is the coefficient of quadratic dependence, characterizing the growth of losses with an increase in the installation angle,
b is a linear term that takes into account the influence of inductive power. For the Mi-8, the coefficient a is smaller than for the UH-60, which is due to a more uniform distribution of velocities along the radius and a lower intensity of vortices at the tips of the blades [6, pp. 188–191].

The integral indicator of energy efficiency of FM is expressed through the ratio of thrust and power according to the formula

$$FM(\theta) = \frac{C_t(\theta)^{3/2}}{C_p(\theta)} \tag{11}$$

Substituting the previous dependencies, we obtain an analytical approximation:

$$FM(\theta) = \frac{(k_1\theta + k_2)^{3/2}}{C_{p0} + a\theta^2 + b\theta} \tag{12}$$

This function has a clearly defined maximum at a certain angle θ_{opt}, determined from the condition

$$\frac{dFM}{d\theta} = 0 \tag{13}$$

By differentiating and simplifying the expression, we obtain the criterial relationship:

$$\frac{3k_1}{2(k_1\theta_{opt}+k_2)} = \frac{2a\theta_{opt}+b}{C_{p0}+a\theta_{opt}^2+b\theta_{opt}} \tag{14}$$

This equation is solved numerically by selecting θ_{opt} at which the maximum FM is achieved. For the UH-60, with the basic parameters S_0–S_3, $\theta_{opt} \approx 9.3$–$10.1°$ was obtained, for the Mi-8 — $\theta_{opt} \approx 10.5$–$11.2°$. This difference is explained by the fact that the UH-60 has a smaller swept disk area and a higher specific load, as a result of which an increase in the installation angle more quickly causes an increase in C_p and premature saturation of FM [4, pp. 210–214; 8, pp. 178–181].

Visually approximated dependencies have the following structure:

- **C_t(θ)**— linear growth, reflecting the direct dependence of thrust on the increase in the installation angle;
- **C_p(θ)**— parabolic dependence with increased losses at $\theta > 12°$;
- **FM(θ)**— a bell-shaped curve with a maximum in the range $\theta_{opt} \approx 9$–$11°$, after which the efficiency decreases due to an increase in profile and inductive losses.

Thus, the theoretical approximation allows us to analytically describe the behavior of the main coefficients when changing the installation angle and serves as the basis for determining the optimal range of θ, ensuring maximum energy efficiency of the rotor. These dependencies will then be used to construct comparative graphs and analyze the sensitivity of FM to changes in θ depending on the geometric configuration of the blade.

4. Comparative analysis of Mi-8 and UH-60 by the dependencies C_t(θ), C_p(θ) and FM(θ) for S_0–S_3

The comparison is performed under constant external conditions and a fixed rotational speed of each rotor (Mi-8 — 192 rpm, UH-60 — 258 rpm), which makes it possible to isolate the influence of the installation angle θ. For both machines, approximated dependencies from section 2.2 are constructed and their parametric identification is carried out with physical constraints of monotonicity $C_t(\theta)$ and convexity $C_p(\theta)$ [5, pp. 300–318; 2, pp. 252–257; 7, pp. 103–118].

Basic approximation relations:

$$\begin{gathered} C_t(\theta) = k_1\theta + k_2 \\ C_p(\theta) = C_{p0} + a\theta^2 + b\theta \\ FM(\theta) = \frac{C_t(\theta)^{3/2}}{C_p(\theta)} \end{gathered} \tag{15}$$

The optimal angle θ_{opt} is determined from the maximum criterion

$$\frac{dFM}{d\theta} = 0$$

$$\frac{3k_1}{2(k_1\theta_{opt}+k_2)} = \frac{2a\theta_{opt}+b}{C_{p0}+a\theta_{opt}^2+b\theta_{opt}} \tag{16}$$

This equation is solved numerically for each S_i configuration and each helicopter, subject to technological constraints on local Reynolds numbers and permissible angles of attack [4, pp. 219–232; 1, pp. 267–294].

Comparison of geometrically determined trends. For the Mi-8, the larger radius R and area A provide a lower specific velocity at the tip for the same θ, which leads to a lower intensity of the tip vortices and a smaller coefficient a in the expression for $C_p(\theta)$. For the UH-60, the smaller R and higher power density increase the sensitivity of the profile losses to θ (larger a and b), as a result of which the maximum FM is achieved at a slightly smaller angle θ, and the efficiency plateau is narrower [5, pp. 207–213; 6, pp. 188–191].

Configuration hierarchy S_0–S_3. The loss parameters are ordered physically: $S_3 \rightarrow S_2 \rightarrow S_1 \rightarrow S_0$ with decreasing C_{p0}, a, b and increasing k_1 (improving the aerodynamic quality of the profile and redistributing the load along the span) [2, pp. 255–258; 8, pp. 118–126]. This means a steeper "thrust" increase and a more gradual increase in power with θ for S_2–S_3.

Characteristic optima of θ_{opt} and FM behavior. As a result of identification (in typical takeoff and hover modes), stable ranges of optimal angles were obtained:

$$\text{Mi-8:} \quad \theta_{opt} \approx 10.5^\circ—11.2^\circ \quad (S_0 \rightarrow S_3),$$

$$\text{UH-60:} \quad \theta_{opt} \approx 9.3^\circ—10.1^\circ \quad (S_0 \rightarrow S_3).$$

The downward shift of θ_{opt} for the UH-60 is explained by a more pronounced increase in $C_p(\theta)$ with increasing installation angle. For both machines, the transition from S_0 to S_3 shifts θ_{opt} to lower values and simultaneously increases the maximum FM due to a decrease in C_{p0} and a [5, pp. 312–316; 4, pp. 210–214].

Standardized energy indicators. For comparability, a standardization is introduced based on the maximum efficiency of each helicopter-configuration pair:

$$FM(\theta) = \frac{(k_1\theta + k_2)^{3/2}}{C_{p0} + a\theta^2 + b\theta} \quad (17)$$

For S_3, the plateau $FM_{rel}(\theta) \geq 0.95$ is wider (≈ ±1.0–1.2° around θ_{opt}) compared to S_0 (≈ ±0.6–0.8°). This indicates the technological stability of the angle setting for configurations with optimized tip and twist [7, pp. 115–118].

Interpretation of curves $C_t(\theta)$, $C_p(\theta)$, FM(θ).

1. At small angles θ, the growth of C_t is close to linear, and C_p is dominated by the constant C_{p0}; therefore, FM increases rapidly.
2. In the vicinity of θ_{opt}, the contribution of $a\theta^2$ and $b\theta$ to C_p becomes comparable to the inductive power, which gives the maximum FM according to the criterion relation above.
3. At $\theta > \theta_{opt}$, an accelerated increase in C_p (profile + inductive losses) is observed, while C_t remains quasi-linear; FM decreases. For UH-60, the decline is steeper due to higher a and b.

These patterns are consistent with the classical results of rotor theory and experimental trends in the growth of profile losses with an increase in the angle of attack of the blade profile [3, pp. 144–149; 5, pp. 211–213].

For θ close to the boundary of subcritical angles for the applied profiles, the following should be taken into account: (a) local pre-breakaway non-stationarity and drop in the lift gradient a; (b) enhancement of tip vortices in the 0.85–1.0R zone; (c) potential growth of local $M_{tip,loc}$ due to a combination of rotation and induced velocity. In our approximation, this is reflected by limiting the range of θ to a region where the monotonicity of $C_t(\theta)$ and the convexity of $C_p(\theta)$ are satisfied, and the subsonic regime at the wingtip is maintained [1, pp. 267–294; 4, pp. 229–234]. — For Mi-8, the optimal range of θ is somewhat higher (≈ 10.5–11.2°), the width of the plateau FM is larger; the system is less sensitive to angle tuning errors.— For the UH-60, the optimal θ range is lower (≈ 9.3–10.1°), the plateau is narrower; tuning accuracy is critical, especially for S_0–S_1.— Moving from S_0 to S_3 reduces C_{p0}, a, and b, which widens the plateau FM_{rel} and shifts θ_{opt} down by ~0.5–0.8°, providing a larger efficiency margin for the same thrust constraints.

Thus, the comparative analysis confirms that the geometric optimization of the blade (S_2–S_3) simultaneously increases the maximum FM efficiency and expands the permissible range of installation angles within which high energy efficiency is maintained. For operation, this means the ability to maintain the required thrust with lower energy consumption and with lower sensitivity to θ variations, which is consistent with the goals of rational design and tuning of the Mi-8 and UH-60 rotors [5, pp. 312–316; 2, pp. 255–258; 7, pp. 115–118].

5. Analysis of FM sensitivity to changes in installation angle θ

To quantitatively assess the influence of the installation angle on the rotor's energy efficiency, the sensitivity index $S_{FM\theta}$ was introduced, reflecting the relative change in the efficiency coefficient FM with a small increment of the angle θ. It is defined as the ratio of the partial derivative of FM with respect to θ, normalized by the current value of the angle, to FM itself [4, pp. 229–234; 5, pp. 300–318]:

$$S_{FM\theta} = \frac{\partial FM}{\partial \theta} \times \frac{\theta}{FM} \tag{18}$$

This value allows us to determine the ranges of angles in which the rotor efficiency is most sensitive to changes in blade pitch.$|S_{FM\theta}|<0.2$ the system is considered energetically stable - small changes in θ do not cause a significant deviation of FM. At$|S_{FM\theta}|>0.5$ high sensitivity is observed, requiring precise step adjustment.

From the approximated dependence

$$FM(\theta) = \frac{(k_1\theta+k_2)^{3/2}}{C_{p0}+a\theta^2+b\theta} \tag{19}$$

we take the derivative with respect to θ and substitute it into the expression for sensitivity:

$$S_{FM\theta} = \frac{\theta}{FM} \times \frac{\partial}{\partial \theta}\left(\frac{(k_1\theta+k_2)^{3/2}}{C_{p0}+a\theta^2+b\theta}\right) \tag{20}$$

After differentiation, we obtain a decomposition into two components - “traction” and “power”:

$$S_{FM\theta} = \frac{3k_1\theta}{2(k_1\theta+k_2)} - \frac{\theta(2a\theta+b)}{C_{p0}+a\theta^2+b\theta} \tag{21}$$

The first term characterizes the increase in efficiency due to increased thrust with increasing pitch angle, while the second represents the power loss due to increased drag. The balance between these two components determines the sign and magnitude of the sensitivity.

Calculation results for Mi-8 and UH-60.

For each helicopter, the SFMθ values were calculated in the range θ = 6°–14° for all S_0–S_3 configurations. General patterns were observed:

Table 1

Helicopter	Configuration	θ_{opt} (°)	$S(FM\theta)_{max}$	The nature of the system response
Mi-8	S_0	11.2	0.46	Medium sensitivity, wide plateau of effectiveness
Mi-8	S_3	10.5	0.33	Stable efficiency zone, minimal dependence of FM on θ
UH-60	S_0	9.8	0.62	High sensitivity, narrow plateau of efficiency
UH-60	S_3	9.3	0.41	Decreased sensitivity, increased energy stability

For the UH-60, in the S_0–S_1 configurations, the SFMθ value exceeds 0.6 near θ_{opt}, indicating a sharp dependence of the FM on the slightest angular variations. For the Mi-8, on the contrary, the stability plateau is wider, and the sensitivity does not exceed 0.46 even for the basic configuration. This confirms the more "inertial" nature of the Mi-8 rotor, due to its larger radius and more uniform speed distribution across the span [2, pp. 255–258; 6, pp. 188–191].

6. Interpretation of sensitivity behavior

1. In the region θ < 8°, an increase in the installation angle leads to a linear increase in C_t with a slow increase in C_p, which gives a positive SFMθ—an increase in efficiency.
2. At $\theta \approx \theta_{opt}$, compensation occurs between the increase in thrust and the increase in required power, and the sensitivity tends to zero (SFMθ→0).
3. At θ > 12° the growth of profile losses accelerates, $\partial C\ p/\ \partial\theta$becomes dominant, and SFMθ becomes negative—further increase in the angle reduces the efficiency of FM.

Thus, the optimal range of installation angles is determined not only by the maximum FM, but also by the low-sensitivity zone in which the system maintains high efficiency with minor deviations of θ.

For the UH-60, the critical zone θ = 8.5–10.5° requires high accuracy of collective pitch control, since a change in angle of only ±0.3° can change FM by 2–3%. For the Mi-8, the stability zone is wider: when θ changes within ±0.5° of θ_{opt}, the efficiency remains at 95% of the maximum. Therefore, when designing pitch control systems, it is preferable to focus not only on maximum FM, but also on minimizing the sensitivity of SFMθ. Configurations S_2 and S_3 provide the best compromise between energy efficiency and stability, which makes them optimal for operation in variable atmospheric conditions [7, pp. 115–118; 12, pp. 77–84].

Overall, the SFMθ sensitivity analysis demonstrates that geometric blade optimization reduces the dependence of efficiency on the precise pitch angle. For the UH-60, the upgraded S_2–S_3 profiles reduce sensitivity by almost a third, while for the Mi-8, they stabilize the SFMθ while maintaining thrust performance. This effect confirms the importance of integrated blade design, focused not only on maximizing SFMθ but also on expanding the rotor's energy stability range.

7. Energy interpretation and optimization of the installation angle

To summarize the results of the study, the relationship between the coefficients C_t, C_p and the integral indicator of FM efficiency at optimal and near-limit values of the installation angle θ was analyzed. The main relationship of the energy balance can be represented as:

$$FM = \frac{{C_t}^{3/2}}{p} \tag{22}$$

This expression shows that efficiency increases as thrust increases faster than power increases, that is, when $C_t3/2$ increases faster than C_p. However, increasing the installation angle θ has opposite effects:

- On the one hand, increasing θ increases C_t almost linearly;
- On the other hand, an increase in θ increases the resistance, which leads to a quadratic increase in C_p.

Optimizing the thrust angle involves finding a compromise between these processes—a region where additional thrust still compensates for increasing power losses. For both machines, a clearly defined energy plateau is observed—a range of angles in which the FM remains virtually unchanged with small fluctuations in θ.

- For Mi-8, the stability range is 10°–12°, with FM ≈ 0.80–0.83.

For the UH-60, the range is narrower: 8.8°–10.0°, FM ≈ 0.78–0.82. Within these ranges, changes in C_t and C_p compensate each other, ensuring stable aerodynamic and energetic performance of the rotor. Configurations with optimized winglets (S_2, S_3) demonstrate a reduction in parasitic power losses C_p due to the weakening of vortex structures in the 0.85–1.0R zone. This leads to an increase in FM up to 8–12% compared to S_0 at equal θ angles. For the Mi-8, this effect is more pronounced, since its larger disk area reduces the influence of peripheral losses.
The UH-60, having a more compact rotor, demonstrates a significant dependence on the shape of the blade tip - the transition $S_0 \rightarrow S_3$ gives up to 10.5% increase in FM at the same installation angle [5, pp. 312–316; 7, pp. 115–118]. Based on the data obtained, it is possible to determine the installation angle ranges that provide the minimum required power while maintaining nominal thrust:

- Mi-8: $\theta_{opt} = 10.5° \pm 0.7°$, at $FM_{max} \approx 0.83$;
- UH-60: $\theta_{opt} = 9.4° \pm 0.5°$, with $FM_{max} \approx 0.82$.

Thus, adjusting the installation angle near θ_{opt} allows achieving maximum efficiency of the main rotor without excessive engine power consumption. An important engineering consequence is the possibility of implementing adaptive collective pitch control systems, where the installation angle is automatically adjusted depending on the flight mode to maintain optimal FM. The nature of the change in FM(θ) when moving from S_0 to S_3 can be described by the following parameters:

- reduction of Cp0 by 10–15%;
- reduction of the SFMθ sensitivity coefficient by 25–30%;
- expansion of the range θ, at which $FM \geq 0.95 \cdot FM_{max}$.

These patterns confirm that optimization of the installation angle in combination with modernization of the blade profile is a key direction for increasing the energy efficiency of modern helicopters.

An energy interpretation shows that the effect of blade pitch angle on FM efficiency is nonlinear but predictable. A moderate increase in pitch angle to optimal values increases thrust and efficiency, while exceeding the θ_{opt} threshold causes a sharp increase in losses. Thus, for both the Mi-8 and UH-60 models, optimizing θ in combination with the S_2–S_3 configurations ensures a stable energy balance that maximizes engine power utilization and minimizes losses. This provides the basis for the development of intelligent pitch control systems capable of dynamically maintaining optimal rotor performance under changing flight conditions.

8. Conclusion

The conducted analysis of the dependence of the coefficients C_t, C_p and the integral efficiency indicator FM on the blade installation angle θ for the rotors of the Mi-8 and UH-60 helicopters made it possible to establish general patterns of energy balance and identify optimal pitch setting ranges for various geometric configurations of the blades (S_0–S_3).

The results of theoretical modeling and approximation showed that an increase in the installation angle causes a linear increase in the thrust coefficient C_t and a nonlinear increase in the power coefficient C_p. As a result, the integral FM efficiency has a pronounced maximum at a certain angle θ_{opt}, after which a further increase in the angle leads to an accelerated increase in losses. For the Mi-8, the optimal range of θ_{opt} was 10.5°–11.2°, for the UH-60 — 9.3°–10.1°, which corresponds to the range in which the energy balance between the useful and expended power is achieved.

It has been shown that the geometric modernization of the blade (the transition from S_0 to S_3) ensures not only an increase in the maximum FM value by 8–12%, but also a reduction in the SFMθ sensitivity to 0.3–0.4, which makes the rotor operation more stable with variations in the installation angle. Thus, the efficiency of a modern main rotor is determined not by the absolute value of the θ angle, but by the relationship between its change and the characteristics of the aerodynamic profile and the load distribution along the span.

Comparison of the two systems demonstrated the different nature of energy sustainability:

- **Mi-8**, having a larger rotor radius and a lower specific load, exhibits a wider efficiency plateau and less sensitivity to angle changes;
- **UH-60**, with a smaller swept disk area, achieves higher local efficiency, but requires more precise adjustment of θ.

The practical conclusion is that, in order to maintain an optimal flight regime, one should focus not only on achieving the maximum FM, but also on ensuring a zone of low SFMθ sensitivity. In this context, the S_2–S_3 configurations are the most rational, as they combine a high level of aerodynamic perfection and energy stability of the system.

From an engineering perspective, the results of this work form the basis for the development of adaptive collective pitch systems and intelligent rotor control algorithms that automatically maintain the optimal pitch angle depending on the flight mode, atmospheric conditions, and required thrust. This area holds promise for further research related to the dynamic optimization of blade geometry, the use of active winglets, and the creation of automated, energy-efficient control loops in the design of next-generation rotorcraft.

Thus, this article concludes a series of theoretical studies, demonstrating that balanced control of the θ angle is key to improving the overall aerodynamic efficiency and durability of rotors in both conventional helicopters (Mi-8) and machines with modernized rotor systems (UH-60). This is not just a particular result, but a step toward the formation of a unified energy concept for rotor optimization, linking aerodynamics, mechanics, and control into a single engineering system.

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