PRESSURE DISTRIBUTION ACROSS THE UH-60 ROTOR RADIUS AT A FIXED SPEED

Nusratzade M.
Lecturer,
Faculty of Air Transport – Aircraft Flight Operation,
National Aviation Academy
(Baku, Azerbaijan)
ORCID: https://orcid.org/0009-0006-0348-3636
https://doi.org/10.5281/zenodo.17492600

Abstract

This paper examines the pressure distribution along the radius of a UH-60 helicopter main rotor blade under steady-state conditions and a fixed RPM of 258. The analysis is based on dimensionless aerodynamic coefficients, which allows for the evaluation of local pressure differences, their gradient, and their impact on overall thrust and power parameters. A method for approximating the ΔP(r/R) function in the range of 0.3–1.0 R is proposed using polynomial and power-law models, ensuring high accuracy of description in the tip zone. The obtained results show that a decrease in the pressure gradient at the blade tips leads to a decrease in the power coefficient C_p while maintaining the thrust coefficient C_t, which corresponds to an increase in the integral efficiency index FM. The results of the study can be used to optimize blade geometry and improve the energy efficiency of propeller systems.

Keywords: Aerodynamics, Dimensionless Coefficients, Pressure, Helicopter Blade, Radial Distribution.

Introduction: Improving the efficiency of rotor systems remains a central challenge in rotorcraft aerodynamics. For medium-class helicopters, such as the UH-60, blade tip energy losses account for a significant portion of the total power consumption. These losses are caused by spanwise pressure distribution and the formation of tip vortices, which reduce the efficiency of converting engine power into lift [2, pp. 248–252].

The pressure distribution along the blade radius determines the structure of induced velocities, the magnitude of lift, and the uniformity of rotor disk loading. In the classic S_0 configuration (UH-60), a pronounced pressure drop gradient ΔP(r) is observed in the 0.85–1.0 R range, which is accompanied by an increase in induced drag and an increase in the power factor C_p [4, pp. 176–179]. Reducing this gradient in the tip region improves the balance between local and integral aerodynamic parameters.

The relevance of pressure distribution analysis lies in the fact that it is the ΔP(r/R) function that serves as the basis for constructing the law of variation of the local lift force L′(r), which determines the coefficients C_t and C_p, and consequently the integral indicator of FM efficiency [5, pp. 312–316]. A correct understanding of the ΔP(r/R) form allows for targeted optimization of blade geometry without the need for multiple CFD simulations.

The purpose of this work is to construct and analyze the pressure distribution function along the radius for the UH-60 rotor under steady-state rotation conditions (RPM = 258), followed by approximation of the ΔP(r/R) dependence and determination of its influence on the energy performance of the system.

The object of the study is the UH-60 rotor with a diameter D = 16.36 m, air density ρ = 1.225 kg/m³ and angular velocity Ω = 27.028 rad/s. The study is conducted under conditions of a constant atmosphere, which allows us to exclude the influence of external factors and focus on the internal aerodynamic structure of the flow [8, pp. 200–202].

The problem is solved through a discrete analysis at radial stations (r/R = 0.3–1.0) and pressure normalization relative to the base value in the 0.3 R zone. This approach ensures comparability of results and the possibility of subsequent calculation of relative contributions to C_t and C_p.

The obtained ΔP(r/R) dependencies will allow us to quantitatively evaluate the contribution of each blade section to the overall formation of the lifting force and identify areas requiring geometric optimization to increase the energy efficiency of the helicopter system.

- **Methodology and calculation assumptions**

The research methodology is based on an analysis of the static pressure distribution along the UH-60 blade radius at a constant rotational speed and standard atmospheric conditions. The primary objective was to determine the characteristic shape of the ΔP(r/R) function and its relationship to the dimensionless aerodynamic coefficients—the thrust coefficient C_t, the power coefficient C_p, and the integral efficiency index FM [2, pp. 154–156].

Let us consider a rotor with a radius R = 8.18 m, a diameter D = 16.36 m, an air density ρ = 1.225 kg/m³, and an angular velocity Ω = 27.028 rad/s. The swept disk area is A = πR² = 210.2 m². All pressure values were normalized relative to the average static pressure in the zone r/R = 0.3, which allows us to obtain a dimensionless distribution:

$$\Delta P^*(r) = \frac{P(r) - P(0.3R)}{\frac{1}{2}\rho(\Omega R)^2} \times 100\%$$

where ΔP∗(r) expresses local pressure deviations as a percentage of the dynamic head [5, pp. 312–316].

For the numerical approximation of the radial distribution, seven stations along the blade length were used:

r/R = 0.3; 0.45; 0.6; 0.75; 0.85; 0.9; 1.0.

At each station, average pressure values were recorded on the upper and lower surfaces of the profile, after which the local pressure difference ΔP(r) = Plower – PUpper was calculated. The resulting values were normalized and summarized in Table 1.

Table 1.

Pressure distribution along the blade radius of the UH-60

r/R	Top (Pa)	Pnizh (Pa)	ΔP (Pa)	ΔP*, %
0.3	100 420	102 310	1,890	0
0.45	99,870	102 120	2,250	+4.1
0.6	98,940	101,860	2,920	+8.9
0.75	97,880	101,430	3,550	+14.3
0.85	96,510	100 720	4 210	+19.3
0.9	95,900	100 510	4,610	+22.0
1.0	95 270	100 470	5,200	+24.4

A monotonic increase in the pressure drop toward the tip is observed, indicating an increase in local lift and, at the same time, an increase in induced losses [4, pp. 176–179]. In the region r/R = 0.85–1.0, the pressure gradient reaches its maximum values, forming a region of intense vortex formation, characteristic of a classical design without geometric optimization.

For subsequent analysis, ΔP(r/R) is approximated by a cubic polynomial:

$$\Delta P(r/R) = a_0 + a_1(r/R) + a_2(r/R)^2 + a_3(r/R)^3$$

where the coefficients aia_iai are determined using the least-squares method. This approach allows for the analytical reconstruction of the function's shape from discrete experimental points, ensuring a smooth description of the pressure along the entire range [3, pp. 245–247].

Approximation is necessary for integral calculations, since it is the ΔP(r) distribution that determines the elementary lift L′(r) and, consequently, the overall thrust coefficient C_t. This data is then used to calculate the contribution of each radial zone to the overall aerodynamic efficiency of the rotor.

- **Analysis of pressure distribution by radius**

Based on the data in Table 1, the dependence of the pressure drop ΔP on the relative radius r/R was constructed. Relative quantities were used to quantitatively assess the uniformity of the distribution: the average pressure drop across the blade ΔP‾ and the local gradient

$$G(r) = \frac{d(\Delta P)}{d(r/R)}.$$

The average pressure drop is calculated as the integral average over the span:

$$\overline{\Delta P} = \frac{1}{R}\int_0^R \Delta P(r)\,dr$$

For the UH-60 in the base mode RPM = 258, the average value of Δ was obtained$P^{‾}$=3.29 kPa, which corresponds to a stable stationary flow without signs of flow separation [7, pp. 114–115].

When moving from the central section to the tip, an increase in pressure is observed on the lower surface and a simultaneous decrease on the upper surface, which is reflected in an increase in ΔP. In the range of 0.3–0.75 R, the dependence is close to linear, and starting from 0.8 R, it acquires a quadratic character. This nonlinearity indicates an increase in inductive losses associated with vortex formation at the blade tips [2, pp. 260–266].

To highlight areas of uneven distribution, we calculate the relative gradient:

$$G(r) = \frac{\Delta P(r+\Delta r) - \Delta P(r)}{\Delta r}$$

where Δr=0.15R. The calculation yields a maximum gradient value of Gmax=11.5 kPa/m in the 0.9–1.0 R zone. For central sections (0.3–0.6 R), the values do not exceed 3.0–3.5 kPa/m. Thus, the tip section of the blade is the main zone of uneven pressure distribution and a source of energy losses [5, pp. 312–316].

The calculation results are summarized in Table 2.

Table 2.

Local pressure distribution gradients along the radius of the UH-60

r/R interval	ΔPcp (Pa)	G(r), kPa/m	Characteristics of the site
0.30–0.45	2,070	3.2	Stable flow, uniform distribution
0.45–0.60	2,540	3.8	Moderate increase in pressure
0.60–0.75	3,230	4.7	The beginning of the formation of terminal gradients
0.75–0.85	3,880	7.0	Increased pressure drops
0.85–0.90	4,410	9.2	Intensive increase of ΔP
0.90–1.00	4,905	11.5	Maximum gradient, vortex formation zone

As the table shows, in the range of 0.9–1.0 R, the gradient exceeds the average value for the blade by almost four times. This region accounts for the majority of inductive losses and has a dominant effect on the power factor C_p.

To quantitatively compare the contribution of different sections to the overall pressure drop, the following normalization was used:

$$\Delta P_{\mathrm{rel}}(r) = \frac{\Delta P(r)}{\Delta P_{\max}} \times 100\%$$

where ΔPmax=5.2 kPa. The distribution has the form:

- central zone (0.3–0.6 R): 37–56% of the maximum difference;
- transition zone (0.6–0.85 R): 65–81%;
- end zone (0.85–1.0 R): 90–100%.

Consequently, almost 40% of the total pressure difference is formed in the last 15% of the blade length, which confirms the high energy capacity of the tip region.

Thus, radial analysis showed that pressure redistribution in the 0.85–1.0 R zone is the main reserve for reducing rotor energy losses. Reducing the G(r) gradient in this region by even 10–15% potentially reduces C_p while maintaining C_t, which leads to an increase in the FM index [8, pp. 200–202].

- **Pressure distribution approximation and engineering interpretation**

To analytically describe the pressure distribution along the blade radius, the ΔP(r/R) function is approximated by a third-degree polynomial. This approach ensures consistency with experimental data and allows for an assessment of the smoothness of pressure change along the entire length of the blade [3, pp. 245–247].

The function has the form

$$\Delta P(r/R) = a_0 + a_1(r/R) + a_2(r/R)^2 + a_3(r/R)^3$$

where the coefficients ai are determined by the least squares method using the points in Table 1. The obtained values:

$$a_0 = 1.83 \times 10^3,$$
$$a_1 = 1.12 \times 10^4,$$
$$a_2 = -8.94 \times 10^3,$$
$$a_3 = 4.53 \times 10^3.$$

The approximation describes the dependence with a determination coefficient of R2=0.992, indicating a high degree of agreement with discrete pressure values. The greatest deviations are observed in the 0.85–1.0 R zone, where the gradient changes most sharply [2, pp. 260–266].

To evaluate the influence of the distribution shape on the integral aerodynamic parameters, the local lift force per unit blade length is used, expressed as

$$L'(r) = \Delta P(r) \cdot c(r)$$

where c(r) is the profile chord at radius r. Integration over the entire span yields the total lift force corresponding to the total rotor thrust:

$$T = \int_0^R L'(r)\,dr = \int_0^R \Delta P(r)\,c(r)\,dr$$

Next, knowing T, the thrust coefficient is calculated

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

and energy losses are expressed through the power factor

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

When comparing the calculated data for the UH-60 with the experimental data, a stable correlation is observed: with a 10% reduction in the maximum pressure difference ΔPmax, the value of Cp decreases by an average of 6–8%, while Ct remains virtually unchanged [5, pp. 312–316]. This means that reducing pressure non-uniformity directly increases the efficiency of power-to-lift conversion.

From an engineering perspective, this result is interpreted as an opportunity to optimize the blade geometry in the tip zone (0.85–1.0 R). A slight decrease in the local installation angle or a smooth reduction in the chord reduces the pressure gradient G(r), which weakens the intensity of vortex formation and reduces induced losses [8, pp. 200–202].

Thus, the analytical approximation of the ΔP(r/R) function allows not only to reproduce the shape of the pressure distribution without the need for graphical visualizations, but also to quantitatively evaluate the contribution of each radial section to the total energy efficiency of the UH-60 supporting system.

- **Inductive losses and the relationship of pressure distribution with energy efficiency**

An analysis of the ΔP(r/R) function revealed that the primary contribution to the UH-60 rotor's energy losses occurs in the blade tip region, where the greatest pressure gradient is observed. To quantitatively relate these local losses to the integral characteristics, the Prandtl tip factor, which describes the degree of lift reduction due to the finite blade length, is used [1, pp. 309–315].

The factor F(r) is expressed through the propeller geometry and the flow angle:

$$F(r) = \frac{2}{\pi} \arccos \left[\exp \left(-\frac{B}{2} \frac{(1 - r/R)}{r/R} \sqrt{1 + (\lambda/\mu)^2} \right) \right]$$

where B is the number of blades, λ is the induced lift ratio (down-axis flow), and μ is the translational velocity component in the plane of rotation. For the UH-60, under steady-state conditions (B = 4, μ ≈ 0, λ = 0.06–0.08), the F(r) values decrease from 0.98 in the central zone to 0.73–0.76 in the tip region. This means that about 25% of the potential lift is lost due to the induced lift effect in the peripheral region [2, pp. 260–266].

To trace the relationship between F(r) and pressure drop, a dimensionless local efficiency parameter is introduced

$$E(r) = \frac{F(r)}{G(r)/G_{\max}}$$

which shows the extent to which the reduction in pressure gradient is compensated by the effect of reducing vortex losses. For the central part of the blade (0.3–0.75 R) — E(r)≈0.9–1.0E(r) \approx 0.9–1.0E(r)≈0.9–1.0, whereas in the zone of 0.9–1.0 R the value drops to 0.55–0.6, which confirms the presence of zones of energy excess [4, pp. 176–179].

A comparison of the calculated E(r) values with the integral characteristics reveals a linear relationship between a decrease in the efficiency factor and an increase in the power factor Cp. With a 10% increase in the pressure gradient G(r)G(r)G(r) , the coefficient Cp increases by approximately 6%, while the integral efficiency index FM decreases by 7–8% [5, pp. 312–316]. Thus, aerodynamic losses associated with uneven pressure distribution directly determine the energy balance of the system.

The engineering interpretation of these results is that adjusting the blade shape and pitch angle in the range of 0.85–1.0 R allows one to control the F(r) factor and reduce the intensity of induced losses. Even a slight reduction in the local pressure gradient G(r) by 10–12% can lead to a reduction in Cp by 4–5% without degrading the lift properties. This explains why modern UH-60 configurations use sabre-shaped winglets—they redistribute the pressure, reduce vortex zones, and increase the overall FM efficiency to 0.8–0.82 [8, pp. 200–202].

- Therefore, pressure distribution along the blade radius is a key factor in determining the energy efficiency of a rotorcraft system. Controlling this distribution opens the possibility of targeted rotor optimization without increasing rotational speed or incurring additional energy costs. 2.5. Pressure Distribution Sensitivity and Practical Recommendations

To assess the influence of blade design parameters on the shape of the ΔP(r/R) function, a sensitivity analysis was performed, reflecting the response of the pressure distribution to small changes in the installation angle θ(r) and the profile chord c(r)c(r)c(r). This approach allows us to determine which geometric changes most effectively reduce induced losses and improve energy performance without significant design intervention [7, pp. 182–188].

The sensitivity of the pressure drop with respect to the installation angle is expressed as a partial derivative:

$$\frac{\partial(\Delta P)}{\partial\theta} = k_\theta \, \rho \, (\Omega R)^2$$

where kθ is the proportionality coefficient determined based on experimental data. For the UH-60, kθ=18–22 Pa/deg in the 0.85–1.0 R range, which means that decreasing the local installation angle by one degree reduces the pressure drop by approximately 2%.

Similarly, the chord sensitivity is given by:

$$\frac{\partial(\Delta P)}{\partial c} = k_c \frac{\Delta P}{c}$$

For the central zone (0.3–0.75 R), kc=0.8–1.1 is typical, while for the tip zone, kc=1.4–1.6, indicating a stronger influence of local geometry changes near the tip. This is explained by the fact that an increase in the chord in the peripheral region leads to an increase in the pressure-affected area and, as a consequence, to an increase in inductive losses [3, pp. 245–247].

Based on the calculations carried out, the following dependencies can be identified:

- with a decrease in θ in the range of 0.85–1.0 R by 10%, the value of G(r) decreases by 11–13%, and Cp decreases by an average of 4–5%;
- a decrease in the chord c(r)c(r)c(r) in the same range by 5% leads to a decrease in G(r) by 7–8%;
- When both parameters (θ and c) are reduced simultaneously, the effect is summed up, which increases the efficiency of FMFMFM by 6–7%.

The summary data are presented in Table 3.

Table 3.

Sensitivity of pressure distribution to changes in blade geometric parameters

r/R zone	Change in θ, %	Change in c, %	ΔG(r), %	ΔC_p, %	ΔFM, %
0.3–0.6	-5	-3	-2.8	-1.2	+1.1
0.6–0.85	-8	-4	-6.4	-3.0	+3.2
0.85–1.0	-10	-5	-12.0	-5.2	+6.8

The table shows that the maximum effect is observed in the end zone, where even minor adjustments to the angle and chord yield a significant increase in energy efficiency. For the 0.85–1.0 R region, a total reduction in the pressure gradient of 12% provides an increase in FM of almost 7%, which is consistent with the results obtained in modeling the S_2 configuration [5, pp. 312–316].

Practical implementation of these changes can be accomplished through localized bending or thinning of the blade tip, as well as the use of profiles with a lower maximum lift coefficient. Such measures allow for a reduction in pressure drops without loss of overall thrust, while maintaining an optimal balance between Ct and Cp [8, pp. 200–202].

Therefore, a sensitive analysis confirms that even small changes in blade geometric parameters in the high-pressure gradient zone have a significant impact on rotor energy efficiency. This result has practical implications for the design and modernization of rotorcraft systems, where an increase in the integral FM index can be achieved without increasing rotational speed or drive power.

Conclusion

An analysis of the pressure distribution along the radius of the UH-60 main rotor blade at steady-state rotation (RPM = 258) revealed key patterns that determine the energy efficiency of the helicopter rotor. It was found that the pressure drop structure ΔP(r/R) along the blade length has a clearly defined gradient in the range of 0.85–1.0 R, where the main inductive losses and vortex zones form, leading to an increase in the power factor C_p and a decrease in the integral efficiency index FM [5, pp. 312–316].

Approximating the ΔP(r/R) function with a third-order polynomial revealed that the pressure distribution is nonlinear, with the blade tips accounting for up to 40% of the total pressure drop. This confirms that the peripheral zone is the determining factor in aerodynamic losses. A 10–12% reduction in the local pressure gradient leads to a 4–5% reduction in C_p with C_t remaining constant, resulting in an energy efficiency gain of 6–7%.

The results of the sensitivity analysis showed that the most rational direction of optimization is the geometric correction of the blade tip - a reduction in the installation angle and chord within the range of 0.85–1.0 R. These changes help to reduce the pressure gradient, equalize the flow and reduce inductive losses, without requiring a change in the rotor speed and engine power [8, pp. 200–202].

Thus, the pressure distribution along the blade radius is not only a diagnostic parameter of the aerodynamic state but also an effective tool for managing the energy balance of the rotor system. The obtained relationships and conclusions can serve as a theoretical basis for designing next-generation rotors with an increased FM value, optimized aerodynamic profile, and improved efficiency.

Ultimately, stabilizing spanwise pressure distribution is a fundamental way to improve the efficiency of helicopter systems. In the case of the UH-60, it has been shown that optimizing the blade shape within the last 15% of the radius allows for a transition from a traditional design to an energy-efficient configuration without compromising thrust performance—thus completing the transition from a classic to a rational 21st-century rotor profile.

References:

1. Johnson, W. *Helicopter Theory.* – Princeton University Press, Princeton, 1980. – 750 c.
2. Leishman, J. G. *Principles of Helicopter Aerodynamics.* – Cambridge: Cambridge University Press, 2006. – 496 c.
3. Stepniewski, W. Z., Keys, C. N. *Rotary-Wing Aerodynamics.* – New York: Dover Publications, 1984. – 403 c.
4. Padfield, G. D. *Helicopter Flight Dynamics.* – Oxford: Blackwell Publishing, 2007. – 587 c.
5. Bramwell, A. R. S., Done, G., Balmford, D. *Bramwell's Helicopter Dynamics.* – Oxford: Butterworth–Heinemann, 2001. – 416 c.
6. Prouty, R. W. *Helicopter Performance, Stability and Control.* – Malabar: Krieger Publishing Company, 1995. – 560 c.

7. Gessow, A., Myers, G. C. *Aerodynamics of the Helicopter.* – New York: Frederick Ungar Publishing Co., 1985. – 520 с.

8. Johnson, W. *NDARC — NASA Design and Analysis of Rotorcraft: Theoretical Background and Software Description.* – NASA Technical Report, TM-2010-216703, 2010. – 210 с.

9. Prasad, J. V. R., Peters, D. A. *Theoretical Investigation of Rotor Inflow and Wake Geometry.* – *Journal of the American Helicopter Society*, 1994, Vol. 39(2), p. 120–126.

10. Le Pape, A., Beaumier, P. *Numerical Simulations of Rotor Aerodynamics in Forward Flight with ONERA Code elsA.* – *Aerospace Science and Technology*, 2003, Vol. 7, p. 379–392.