AVIATION AND KOSMICHESKAYA TECHNIKA
05.07.01 – Aerodynamics and processes of heat exchange of aircraft;
05.07.02 – Projecting and construction of aircraft manufacturing;
05.07.03 – Aerodynamics and thermodynamic of aircraft;
05.07.05 – Thermal-electric rocket engines and their installations of aircraft;
05.07.07 – Control and testing of aircraft and their systems;
05.07.09 – Dynamics, ballistics, control of movement of aircraft;
05.07.10 – Innovative technologies in aerospace activity

УДК 629.735.45
DOI: 10.26467/2079-0619-2020-23-4-96-104

THrust PulSation of COAxial Main Rotor, CAUsED By the BlADEs RelATIVE PoSIton

B.S. KRiTSKY1,3, R.M. MIRGAZOv1,3, V.A. ANiKIN2,3, O.V. GErASIMOV3
1 Central Aerohydrodynamic Institute, Zhukovsky, Russia
2 National Helicopter Center Mil & Kamov, Tomilino, Moscow Region, Russia
3 Helicopters of Russia – Technology LLC, Moscow, Russia

The influence of reciprocal position of the upper rotor blades in respect to the lower rotor blades is characteristic for coaxial main rotor. It is established that the initial azimuth of the blade, for example, of the upper rotor’s which does not coincide with the initial azimuth of the lower rotor blades, affects the level of vibrations caused by the rotors thrust pulsations, the level of noise, generated mainly by coaxial rotor. This paper presents numerical studies which assess the effect of the initial azimuth of the upper rotor blades (“phas ing”) on the helicopter coaxial rotor thrust force pulsation. The research was carried out applying the calculation method based on the nonlinear vortex theory in a non-stationary formulation. The results of the helicopter coaxial rotor with different initial azimuths of the upper rotor blade relatively to the azimuth of the lower rotor blade flow around numerical simulation are presented. The influence of the blades “phas ing” on the rotor thrust coefficient change and thrust force pulsation magnitude is shown. The flow of a six-bladed coaxial main rotor (two rotors with 3 blades) was simulated in the oblique flow mode at speeds of 51.25 m/s and 71.75 m/s at the rotor angles of attack – 5° and – 12°, respectively. The change in the coefficient of the main rotor thrust per revolution at different values of “phas ing” was studied. The coaxial rotor thrust coefficient is determined by summing the lower and upper rotors thrust coefficients respectively. Thus, at some “phas ing” the thrust coefficient of the lower and upper rotors increase intensifies the thrust pulsations, and at others, the peaks of the upper and lower rotors pulsations are displaced and the total coaxial rotor thrust coefficient changes per one revolution with smaller amplitude. It is established what “phas ing” produce the maximum values of thrust pulsation, and at which–a minimum of thrust pulsation.

Key words: coaxial rotor, thrust pulsation, blades relative position.

INTRODUCTION

The area where coaxial helicopters are applied is determined by their characteristic features – small overall dimension, high thrust-to-weight ratio and maneuverability, as well as aerodynamic symmetry (fig. 1). These features have provided them with a convenient base on small-sized take-off and landing sites of ships which are designed for various purposes. Features of coaxial helicopters are associated with the main rotors reactive moment compensating new method implementation compared to single-rotor helicopters. The coaxial helicopter propellers reactive moments are mutually balanced right on their axis of rotation. Due to the coaxial helicopter aerodynamic symmetry, there are almost no connections between longitudinal and lateral movement, independence of control channels and simplicity of piloting are provided [1].

96
At the same time, the helicopter with a coaxial design is made a demand to eliminate the upper and lower rotor blades collision during flight operation, reduce vibrations caused by the propeller thrust pulsations, and reduce noise generated mainly by the coaxial main rotor. It was determined that the blade initial azimuth of the upper propeller, for example, which does not coincide with the initial azimuth of the lower propeller blade, affects the above-mentioned features of the coaxial helicopter.

The upper rotor blades initial azimuth on the helicopter coaxial rotor thrust pulsation effect evaluation by means of computational methods seems to be rational. Currently, there are many methods for numerical study of helicopter main rotor aerodynamic characteristics. Calculation methods based on the non-stationary setting of nonlinear vortex theory both on the basis of a thin carrier surface [2–4] and on the basis of a carrier line (thread) [5] are distinguished among them. The first method allows you to determine the non–stationary aerodynamic characteristics of the main rotor with arbitrary shaped blades as planned, and the second – with the use of stationary results of helicopter profiles blowouts adjusted for non-stationarity.

Fig. 1. A coaxial helicopter Ka-226T

A more detailed description of the main rotor blowout process is given by grid methods, both with and without taking into account viscosity. However, their application to main rotor aerodynamic characteristics determination is associated with a number of difficulties. Firstly, methods of this type require large computational resources, secondly, the calculation flapping movement of the blades and cyclic control for the forward flight mode (oblique flow mode) is associated with the solution of a number of special problems on calculated grids deformation. The main rotor operation on axial flow modes (hovering modes) [6–8] was mainly modeled applying grid methods.

The oblique flow mode of the helicopter main rotor is characterized by the flapping movement of the blades, swinging in the rotation plane, the blades elastic deformation and cyclic change in the angle of installation for one revolution of the propeller. The record of these features is demonstrated in [9]. However, this approach, which requires very large computational resources, is not appropriate for parametric exploratory research. Paper [10] demonstrating the example of hard main rotor modeling shows the application areas of different methods in various software packages. It is shown that the method based on the vortex theory demonstrates good results of the main rotor traction characteristics, especially, for calculating the main rotor vibration loads caused by thrust pulsation [11].

Therefore, this paper produces numerical studies on assessing the effect of the upper propeller blades initial azimuth on the helicopter coaxial main rotor thrust pulsation. The research was carried out using the calculation method based on the nonlinear vortex theory in a non-stationary setting.
ABOUT THE METHOD OF CALCULATION

This paper produces a numerical study on the basis of a nonlinear blade propeller theory in a non-stationary setting based on a thin bearing surface [2, 3]. According to this theory propeller blades are replaced by extremely thin base surfaces in the form of $S_i$ as planned coinciding with the shape of the blades themselves and curved according to the law of curvature of their median surfaces. An ideal incompressible medium is considered. The flow outside the propeller blades and their traces is considered to be vortex-free $\Delta \Phi = 0$.

The following boundary conditions are met (fig. 2):

1. non-flow condition on bearing surfaces

\[(\nabla \Phi - \vec{W}^*) \hat{n} = 0 \ (x, y, z) \in S_i;\]

2. when passing through the surface of the vortex trace $\sigma_i$, the conditions of pressure continuity and the normal velocity component are observed

\[p_\pm = p_\pm (\nabla \Phi \vec{n}) = (\nabla \Phi \vec{n}) \ (x, y, z) \in \sigma_i;\]

3. the Chaplygin-Zhukovsky hypothesis on the speed finiteness is fulfilled on the trailing edges of the bearing surfaces $L_i$, which the vortex surfaces flow down from

\[(\nabla \Phi \vec{n}) = (\nabla \Phi \vec{n}) \ (x, y, z) \in L_i;\]

4. at an infinite distance from the propeller, as well as its trace, the disturbances fade away

\[\lim_{R \to \infty} \nabla \Phi = 0, \text{ where } R = \sqrt{x^2 + y^2 + z^2}.\]

Fig. 2. The boundary conditions at the blades and their vortex wakes

The numerical method for main rotor problem solution in a nonlinear non-stationary setting according to the method of discrete vortices consists in discretization over space and time. Confluent vortex layers, which model the base surfaces of the propeller blades and their vortex wakes, are replaced by the systems of discrete vortex frames, and the time-continuous process of changing boundary conditions and flow parameters is replaced by a stepped process. The values of kinematic parameters remain unchanged within a single time step. At each time period, starting with the first one, after having solved the system of equations for determining the circulations, there are some tensions of all vortex frames of blade systems and their trace. Distributed and total propeller characteristics are
determined by summing the aerodynamic load on the panels. The wake form is drawn up as a result of calculation (fig. 3). The numerical method for the helicopter main rotor aerodynamic characteristics determination, which is under consideration, has been carefully approbated and the approbation justified the reliability of the results obtained [2 – 5].

**Fig. 3.** The wake behind a coaxial rotor vortex structure

**COMPUTATIONAL RESEARCH RESULTS**

We studied the flow of a six-blade coaxial main rotor (two propellers with 3 blades) in the oblique flow mode at speeds of $V_1 = 51.25$ m/s (the angle of attack of the propeller $\alpha_1 = -5^0$) and $V_2 = 71.75$ m/s ($\alpha_2 = -12^0$). Propeller geometric and kinematic parameters are shown in Table 1.

| Parameter                      | Value               |
|--------------------------------|---------------------|
| The main rotor radius          | $R = 4.2$ m        |
| Finned section radius          | $r_0 = 0.42R$      |
| Blade chord                    | $B = 0.206$ m      |
| Distance between the propellers| $h = 0.1D$         |
| Blade mass                     | $m = 10.2$ kg      |
| The angle of blades setting    | $\varphi_0 = 10^0$ |
| Velocity of rotation           | $\omega R = 205$ m/sec |
| Blade mass center              | $l_{ц.м.} = 0.52R$ |
| Horizontal hinge removal       | $l_{г.ш.} = 0.02R$ (0.084 m) |

Modeling of the main rotor non-stationary airflow starts with the moment when the lower propeller blade takes the initial position with the azimuth of $\psi = 0$. The second upper propeller blade can take the position with the azimuth other than zero, for example, with a shift by a certain angle $\Delta \psi$, which is conditionally called "phase" or "phasing" (fig. 4). The first lower propeller rotates counterclockwise when viewed from above, and the second upper propeller – clockwise. Depending on the phase of $\Delta \psi$ while rotating the upper and lower propellers blades intersect at different time moments.
It is determined that the phase of $\Delta \psi$ affects the nature of the coaxial main rotor upper and lower blades convergence character as well as thrust pulsations and noise produced by the propellers load. This paper estimates the upper propeller $\Delta \psi$ phase effect on the helicopter coaxial main rotor thrust pulsation. We studied the change of the main rotor thrust coefficient $C_T$ per one revolution at $\Delta \psi = 0$, $20$, $30$, $40$, $60$, $80$, $100$, $120$ degrees.

The main rotor thrust coefficient $C_T$ is determined by summing the lower $C_{Tl}$ and upper $C_{Tu}$ propellers thrust coefficients respectively. For example, at the speed of $V1=51.25$ m/s with $\Delta \psi = 0$ the upper and lower propeller coefficient increase reinforces thrust pulsation (fig. 5, a), but at $\Delta \psi = -60^0$ the upper and lower propeller pulsation peaks are shifted and the total thrust coefficient $C_T$ of coaxial main rotor changes per one rotation with a smaller amplitude (fig. 5, b).

Fig. 4. The main rotor blades initial azimuth

Fig. 5. Change in the propellers thrust coefficient per one revolution at $\Delta \psi = 0$ (a) and $\Delta \psi = 60^0$ (b)
Figure 6a demonstrates coaxial main rotor thrust coefficient pulsations calculation results \( \Delta C_T = C_{TMAX} - C_{TMIN} \) for two flow velocity values \( V_1 = 51.25 \text{ m/sec} \ (V_1/\omega R = 0.25) \) and \( V_2 = 71.75 \text{ m/sec} \ (V_2/\omega R = 0.35) \), while Figure 6b presents thrust pulsations as percentage of the average \( C_T \) value for the same speed values.

\[ \Delta C_T = C_{TMAX} - C_{TMIN} \]

![Fig. 6. The phase effect on thrust coefficient change \( C_T \) (a) and coaxial main rotor thrust pulsation amplitude in percentage of the average value of \( C_T \) (b)](image)

The analysis of the results obtained makes it possible to assess the effect of the upper propeller blades initial azimuth \( \Delta \psi \) on the helicopter coaxial main rotor thrust pulsation. In particular, when the values of the upper rotor initial azimuth are about zero, we can see the occurrence of the thrust pulsation maximum values, which, for example, when the flow velocity equals to \( V_2 = 71.75 \text{ m/s} \) exceeds the average value of \( C_T \) by 35% but minimum thrust pulsation – at \( \Delta \psi = 60^\circ \).

**CONCLUSION**

When adjusting the layout of the coaxial main rotor, it is necessary to take into account the blades relative position at their initial azimuths. It is important both from the position of excluding the coaxial main rotor blades inter collision in oblique flow modes, and reducing vibrations caused by propeller thrust pulsation. Thus, the reduction of helicopter vibrations can be achieved, along with the blade high harmonics individual control application [4], nd taking into account the blades of coaxial main rotor relative position.

**REFERENCES**

1. Petrosyan, E.A. (2004). *Aerodinamika soosnogo vertoleta* [The aerodynamics of the coaxial helicopter]. Moscow: Poligon press, 2004. 820 p. (in Russian)

2. Belotserkovsky, S.M., Loktev, B.E. and Nisht, M.I. (1992). *Issledovaniye na EVM aerodinamicheskikh i uprugikh karakteristik vintov vertoleta* [The computer study of the helicopter rotors aerodynamic and elastic characteristics]. Moscow: Mashinostroyeniye, 219 p. (in Russian)

3. Kritsky, B.S. (2003). *Matematicheskaya model aerodinamiki vintokrylogo letatelnogo apparata* [The mathematical model of a rotorcraft aerodynamics]. Nauchnyy Vestnik MGTU GA, no. 59, pp. 24–31. (in Russian)

4. Golovkin, M.A., Kochish, S.I. and Kritsky, B.S. (2012). *Calculation procedure of aerodynamic characteristics of the combined carrying system of the aircraft*. Trudy MAI, no. 55, 16 p. Available at: [http://trudymai.ru/eng/published.php?ID=30023](http://trudymai.ru/eng/published.php?ID=30023) (accessed 28.05.2020). (in Russian)
5. Ignatkin, Yu.M., Makeev, P.V. and Shomov, A.I. (2015). Aerodynamic interference of helicopters main and tail rotor at horizontal yawed flight. Trudy MAI, no. 82, 23 p. Available at: http://trudymai.ru/eng/published.php?ID=58605 (accessed 28.05.2020). (in Russian)

6. Nik Ahmad Ridhwan Nik Mohd and Barakos, G.N. (2012). Computational aerodynamics of hovering helicopters main and tail rotors at horizontal yawed flight. Jurnal Mekanikal, no 34, pp. 16–46. DOI: https://doi.org/10.1051/epjconf/20159202042

7. Garipova, L.I., Batrakov, A.S., Kusyumov, A.N., Mikhailov, S.A. and Barakos, G.N. (2014). Estimates of hover aerodynamics performance of rotor model. Russian Aeronautics, vol. 57, issue 3, pp. 223–231. DOI: https://doi.org/10.3103/S1068799814030027

8. Kusyumov, A.N., Mikhailov, S.A., Garipova, L.I., Batrakov, A.S. and Barakos, G. (2015). Prediction of helicopter rotor noise in hover. EPJ Web of Conferences, vol. 92, 5 p. DOI: 10.1051/epjconf/20159202042

9. Vershkov, V.A., Kritsky, B.S. and Mirgazov, R.M. (2017). Chislennoye modelirovaniiye obtekaniya nesushchego vinta vertolota s uchetom tsiklicheskogo upravleniya i makhovogo dvizheniya lopastey [Numerical simulation of the flow around the helicopter main rotor taking into account the cyclic blade control and blades flapping]. Materiały XXVII Nauchno-teknicheskoy konferentsii po aerodynamike [Proceedings of XXVII Scientific and Technical Conference on Aerodynamics], p. 78. (in Russian)

10. Vershkov, V.A., Kritsky, B.S., Makhnev, M.S., Mirgazov, R.M. and Trebunskikh, T.V. (2016). Comparison of the results of numerical simulation of flow around the helicopter rotor in a variety of software. Trudy MAI, no. 89, 17 p. Available at: http://trudymai.ru/eng/published.php?ID=72704&eng=Y (accessed 12.06.2020). (in Russian)

11. Animitsa, V.A., Borisov, E.A., Kritsky, B.S. and Mirgazov, R.M. (2016). Main rotor vibration overload caused by thrust pulsation analytical studies based on vortex theory. Trudy MAI, no. 87, 15 p. Available at: http://trudymai.ru/eng/published.php?ID=69626 (accessed 15.06.2020). (in Russian)

INFORMATION ABOUT THE AUTHORS

Boris S. Kritsky, Doctor of Technical Sciences, Professor, Chief Researcher of the Central Aerohydrodynamic Institute, boris.kritsky@tsagi.ru.

Ruslan M. Mirgazov, Candidate of Technical Sciences, Deputy Head of Scientific and Research Department № 5, Central Aerohydrodynamic Institute, ruslan.mirgazov@tsagi.ru.

Victor A. Anikin, Doctor of Technical Sciences, Chief Designer of the National Helicopter Center Mil & Kamov, v.anikin@kamov.ru.

Oleg V. Gerasimov, Candidate of Technical Sciences, Leading Engineer of LLC “Helicopters of Russia – Technologies”, o.gerasimov@vrtech.aero.

ПУЛЬСАЦИИ ТЯГИ СООСНОГО НЕСУЩЕГО ВИНТА, ОБУСЛОВЛЕННЫЕ ВЗАИМНЫМ РАСПОЛОЖЕНИЕМ ЛОПАСТЕЙ

Б.С. Крицкий1,3, Р.М. Миргазов1,3, В.А. Аникин2,3, О.В. Герасимов3

1Центральный аэрогидродинамический институт им. проф. Н.Е. Жуковского (ЦАГИ), г. Жуковский, Россия
2Национальный центр вертолётостроения имени М. Л. Миля и Н. И. Камова, Московская обл., пос. Томилино, Россия
3ООО «ВР-Технологии», г. Москва, Россия

Для соосного несущего винта характерно влияние взаимного расположения лопастей верхнего винта относительно нижнего. Установлено, что начальный азимут лопасти, например, верхнего винта, не совпадающий с начальным азимутом лопасти нижнего винта, влияет на уровень вибраций, обусловленных пульсациями тяги винтов, на
уровень шума, генерируемого, главным образом, соосным несущим винтом. В данной работе выполнены численные исследования по оценке влияния начального азимута лопастей верхнего винта («фазировки») на пульсацию силы тяги соосного несущего винта вертолета. Исследования проводились с помощью метода расчета, основанного на нелинейной вихревой теории в нестационарной постановке. Приводятся результаты численного моделирования обтекания соосного несущего винта вертолета с разными начальными азимутами лопасти верхнего винта относительно азимута лопасти нижнего винта. Показано влияние «фазировки» лопастей на изменение коэффициента силы тяги и величину пульсации силы тяги. Моделировалось обтекание шестилопастного соосного несущего винта вертолета на режиме косого обтекания на скоростях 51.25 м/с и 71.75 м/с при углах атаки винта – 5° и – 12° соответственно. Изучалось изменение коэффициента тяги несущего винта за один оборот при различных значениях «фазировки». Коэффициент тяги соосного несущего винта определяется суммированием коэффициентов тяги соосного винта соответственно нижнего и верхнего винтов. Таким образом, при некоторых «фазировках» приращения коэффициента тяги нижнего и верхнего винтов усиливают пульсацию тяги, а при других – пики пульсаций верхнего и нижнего винтов смешены и суммарный коэффициент тяги соосного несущего винта изменяется за один оборот с меньшей амплитудой. Установлено, при каких «фазировках» имеют место максимальные величины пульсации тяги, и при которых – мнимум пульсации тяги.

Ключевые слова: соосный несущий винт, пульсация тяги, взаимное расположение лопастей.

СПИСОК ЛИТЕРАТУРЫ

1. Петросян Э.А. Аэродинамика соосного вертолета. М.: Полигон пресс, 2004. 820 с.
2. Белоцерковский С.М., Локтев Б.Е., Ништ М.И. Исследование на ЭВМ аэродинамических и упругих характеристик винтов вертолета. М.: Машиностроение, 1992. 219 с.
3. Крицкий Б.С. Б.С. Математическое моделирование аэродинамики винтокрылого летательного аппарата // Научный Вестник МГТУ ГА. Серия «Аэромеханика и прочность». 2003. № 59. С. 24–31.
4. Головкин М.А., Кочиш С.И., Крицкий Б.С. Методика расчета аэродинамических характеристик комбинированной несущей системы летательного аппарата [Электронный ресурс] // Труды МАИ. 2012. № 55. 16 с. URL: http://trudymai.ru/published.php?ID=30023 (дата обращения 28.05.2020).
5. Игнаткин Ю.М., Макеев П.В., Шомов А.И. Интерференция несущего и рулевого винтов вертолета при полете со скольжением [Электронный ресурс] // Труды МАИ. 2015. № 82. 23 с. URL: http://trudymai.ru/published.php?ID=58605 (дата обращения 28.05.2020).
6. Nik Ahmad Ridhwan Nik Mohd, Barakos G.N. Computational aerodynamics of hovering helicopter rotors // Jurnal Mekanikal. 2012. № 34. Pp. 16–46.
7. Garipova L.I. Estimates of hover aerodynamics performance of rotor mode / L.I. Garipova, A.S. Bratkov, A.N. Kusyumov, S.A. Mikhailov, G.N. Barakos // Russian Aeronautics. 2014. Vol. 57, iss. 3. Pp. 223–231. DOI: https://doi.org/10.3103/S1068799814030027
8. Kusyumov A.N. Prediction of helicopter rotor noise in hover / A.N. Kusyumov, S.A. Mikhailov, L.I. Garipova, A.S. Batrakov, G. Barakos // EPJ Web of Conferences. 2015. Vol. 92, 5 р. DOI: 10.1051/epjconf/20159202042
9. Вершков В.А., Крицкий Б.С., Миргазов Р.М. Численное моделирование обтекания несущего винта вертолета с учетом циклического управления и махового движения лопастей // Материалы XXVIII научно-технической конференции по аэродинамике, пос. Володарского, 21-22 апреля 2017. Жуковский: ЦАГИ, 2017. С. 78.
10. Вершков В.А. Сравнение результатов численного моделирования обтекания несущего винта в различных пакетах программ [Электронный ресурс] / В.А. Вершков, Б.С. Крицкий, М.С. Макнев, Р.М. Миргазов, Т.В. Требункский // Труды МАИ. 2016. № 89. 17 с. URL: http://trudymai.ru/published.php?ID=72704&eng=N (дата обращения 12.06.2020.)
11. Анимица В.А. Расчетные исследования виброперегрузок несущего винта, вызванных пульсацией силы тяги, на базе вихревой теории [Электронный ресурс] / В.А.
Анимица, Е.А. Борисов, Б.С. Крицкий, Р.М. Миражез // Труды МАИ. 2016. № 87. 15 с. URL: http://trudymai.ru/published.php?ID=69626 (дата обращения 15.06.2020.)

СВЕДЕНИЯ ОБ АВТОРАХ

Крицкий Борис Сергеевич, доктор технических наук, профессор, главный научный сотрудник ЦАГИ, boris.kritsky@tsagi.ru.

Миргазов Руслан Миннхатович, кандидат технических наук, заместитель начальника научно-исследовательского отделения № 5 ЦАГИ; ruslan.mirgazov@tsagi.ru.

Аникин Виктор Андреевич, доктор технических наук, главный конструктор Национального центра вертолётостроения имени М.Л. Миля и Н.И. Камова, v.anikin@kamov.ru.

Герасимов Олег Викторович, кандидат технических наук, ведущий инженер ООО «ВР-Технологии», o.gerasimov@vrtech.aero.

Поступила в редакцию 25.06.2020
Принята в печать 23.07.2020