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Research of the crosswind effect on the single-rotor helicopter unintentional yaw rotation

V.V. Efimov[1], V.A. Ivchin[2], K.O. Chernigin[1]
[1]Moscow State Technical University of Civil Aviation, Moscow, Russia
[2] JSC "HELIBURO", Moscow, Russia

Abstract: During the operation of single-rotor helicopters, aviation accidents quite frequently occur in the form of an unintentional turn or even a yaw rotation, causing, as a rule, a ground collision. Numerous researchers of this problem consider the loss of helicopter tail-rotor effectiveness due to wind effects as one of its possible causes. There is even a special term – the Loss of Tail Rotor Effectiveness (LTE) in the foreign literature. Hence, this paper deals with an attempt to determine the capacity of an unintentional single-rotor helicopter yaw rotation occurrence due to wind effects (the impact of the main rotor on the tail rotor was not considered in this paper). To solve this issue, theoretical methods (analytical calculations and computational experiments) were used. To carry out analytical calculations and computational experiments, a mathematical model of the Mi-8MTV helicopter yaw rotation dynamics was developed, on the basis of which a software package integrating the LTE module (for modeling the dynamics of rotational yaw motion of the helicopter) and OGL (for helicopter motion visualization) was created. Analytical calculations revealed that the yaw angular acceleration value monitored in-flight during an unintentional rotation can manifest itself due to the tail rotor thrust loss in the vortex-ring state. But for the development of an unintentional rotation to angles and angular velocities recorded in real flights, that kind of tail rotor thrust loss should occur during the entire turn. In computational experiments using the mentioned above software package, conditions failed to be created for that kind of thrust loss during the entire turn. Consequently, those yaw angles and angular velocities, that occurred in flights, could not be reached. The tail rotor, when blown by the wind in the investigated range of wind velocities (from 1 to 20 m/s) does not lose its effectiveness to such an extent that an unintentional rotation cannot be stopped by means of the tail rotor.

Key words: helicopter, flight dynamics, unintentional helicopter rotation, loss of tail rotor effectiveness, vortex-ring state.

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Исследование влияния бокового ветра на непреднамеренное вращение одновинтовых вертолетов по рысканию

В.В. Ефимов[1], В.А. Ивчин[2], К.О. Чернигин[1]
[1]Московский государственный технический университет гражданской авиации, г. Москва, Россия
[2]АО «Хелибюро», г. Москва, Россия

Аннотация: При эксплуатации одновинтовых вертолетов нередко возникают авиационные происшествия, заключающиеся в возникновении непреднамеренного разворота или даже вращения по рысканию, заканчивающегося, как правило, столкновением с землей. Многочисленные исследователи этой проблемы считают одной из ее возможных причин потерю эффективности рулевого винта вертолета вследствие ветровых воздействий. В иностранной литературе имеется даже специальный термин – Loss of Tail Rotor Effectiveness (LTE). В связи с этим в настоящей работе сделана попытка определения возможности возникновения непреднамеренного вращения одновинтовых вертолетов по рысканию из-за ветровых воздействий (влияние несущего винта на рулевой винт в данной работе не учитывалось). Для решения этой задачи использовались теоретические методы (аналитические расчеты и вычислительные эксперименты). Для проведения аналитических расчетов и вычислительных экспериментов была создана математическая модель динамики вращения вертолета Ми-8МТВ по рысканию, на основе которой был создан программный комплекс, состоящий из модуля LTE (для моделирования динамики вращательного движения вертолета по рысканию) и OGL (для визуализации движения вертолета). Аналитические расчеты показали, что величина углового ускорения рыскания, наблюдаемая в полете при непреднамеренном вращении, может быть достигнута вследствие падения тяги рулевого винта на режиме вихревого кольца. Но для развития непреднамеренного вращения до углов и угловых скоростей, зафиксированных в реальных полетах, необходимо, чтобы такое падение тяги рулевого винта имело место в течение всего разворота. При вычислительных экспериментах с помощью вышеупомянутого программного комплекса не удалось создать условия для такого падения тяги в течение всего разворота и, соответственно, не удалось достичь тех углов и угловых скоростей рыскания, которые возникали в полетах. Рулевой винт при обдувке ветром в исследуемом диапазоне скоростей ветра (от 1 до 20 м/с) не теряет своей эффективности до такой степени, что с его помощью нельзя остановить непреднамеренное вращение.

Ключевые слова: вертолет, динамика полета, непреднамеренное вращение вертолета, потеря эффективности рулевого винта, вихревое кольцо.

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Introduction

In the practice of single-rotor helicopter flight operation, aviation events of an unintentional turn and a yaw rotation occur quite frequently. This phenomenon has been known for a long time, which is confirmed by a large number of various publications on this subject, for example, [1–16]. Under certain conditions, an unintentional turn can lead to an aviation incident, including an accident. Most frequently, it occurs at takeoff and landing modes at flight mass of the helicopter close to maximum when the helicopter main rotor (MR) generates the high thrust and the considerable reaction torque accordingly, which is compensated by the torque from the tail rotor (TR) in this scheme. In this regard, many researchers consider the Loss of Tail Rotor Effectiveness (LTE) in foreign literature)), as the cause of an unintentional turn and yaw rotation occurrence since an unintentional rotation occurs exactly in the direction to which the MR reaction torque turns the helicopter, and the TR fails to respond.

An unintentional yaw rotation of the helicopter may occur due to the LTE caused by all possible kinds of failures and inadequate pilot actions, but it is very important to understand if there are conditions under which the unintentional rotation occurrence cannot be prevented by timely competent crew actions, i.e., if an unintentional rotation is a certain property of single-rotor helicopters, which manifests itself under specific external influencing factors that do not lead to damage to their design as well as failures. Atmospheric turbulence, i.e., a wind gust or a constantly blowing wind (flow) can be such environment.

Therefore, the present work deals with an attempt to determine the capacity of the unintentional yaw rotation occurrence of single-rotor helicopters due to wind effects. Theoretical methods (analytical calculations and computational experiments) were used to solve this problem.

Analysis of the problem

The following wind-induced phenomena are considered in the literature devoted to the problem of an unintentional yaw rotation of a single-rotor helicopter[1]:

1) the TR entering the vortex-ring state (VRS) due to wind blowing in the direction of the TR thrust vector (against the direction of air throwing by the helicopter rotor, on increasing the angles of attack of the blades), consequently, significant TR thrust pulsations, which disorients

[1] Loss of tail rotor effectiveness in helicopters. National transportation safety board. Safety alert SA-062. (2017). *NTSB*. March, 3 p. Available at: https://vast.aero/archives/Repository/NTSB%20Bulletin% 20tail%20 rotor.pdf (accessed: 12.01.2024).

the pilot [2]. Some sources also indicate a significant thrust loss in this case, e.g., [4, 9];

2) the vortex effect on the TR trailing from the MR, leading to a decrease in the TR thrust when blowing its blades on increasing the angles of attack, i.e., on generating a vortex ring. At the same time, the TR thrust can be affected by the terrain proximity due to the impact of inductive flux from the MR, flowing along the ground and interacting with the TR blades, if the TR rotates so that its blades, being in the upper position, move forward (direction of rotation F-F) [4];

3) helicopter nose-turn against the wind when blown from the rear hemisphere due to its longitudinal (vane) stability.

Let us note that, in accordance with work [4], the TR effectiveness at its interference with the MR is powerfully influenced by the TR rotation direction (the blades in the upper position can move forward – F-F or backward – F-B). If the direction of rotation is F-F, the TR thrust at interference with the MR loses significantly, and if the rotation direction is F-B, the TR thrust loses, but insignificantly. In addition to changing the angles of attack of the blades, the reduction of the total flow velocity blowing over the blade cross-sections in the case of rotation direction F-F is crucial. According to the results of the analysis of works [17, 18], we can conclude that both in the direction of rotation F-F and in the direction of rotation F-B, the TR thrust under the flow impact from the MR on increasing the angles of attack of the blades does not decrease but increases. A decrease in the TR thrust occurs when it is blown by the flow from the MR on reducing the angles of attack of the blades. Therefore, the results of the works of different researchers of the MR and TR interference contradict each other. Moreover, in any case, the MR impact on the TR is manifested in a narrow range of angles of helicopter slip due to the fact, a possible TR thrust loss will be short-term during a helicopter yaw rotation. This phenomenon in this paper will not be taken into account. In this respect, it should be noted that this phenomenon should not be neglected in the study of an unintentional yaw rotation of the helicopter, because when a vortex, trailing from the MR, hits the TR, significant pulsations of the TR thrust occur, which can disorient the pilot and cause him to make inadequate actions with pedals, which can lead to an unintentional rotation. But in this paper, as stated above, only specific wind effects are considered, which themselves can directly cause an unintentional rotation.

Previously, the authors of this paper have conducted a study of the conditions for the unintentional yaw rotation occurrence of a single-rotor helicopter by conducting experiments with a helicopter model in a wind tunnel. In the present work, analytical calculations and computational experiments will be mainly used.

Research methods and methodology

To carry out analytical calculations and computational experiments, a mathematical model of the yaw rotation dynamics of a single-rotor helicopter was created. This mathematical model was based on the full mathematical model of flight dynamics of a single-rotor helicopter with six degrees of freedom, developed by one of the authors of this paper – V.A. Ivchin [19]. The full mathematical model of helicopter dynamics was evaluated for adequacy in the previous works of the authors of this article, and on its basis the software was created for the flight simulation facility, which is successfully used for scientific research at the M.L. Mil and N.I. Kamov National Helicopter Center.

To achieve the purpose of this paper, the full model was simplified to a model with one degree of freedom – yaw rotation. The description of this mathematical model is presented below.

Let us assume that the helicopter rotation occurs around the normal axis OY of the body axis coordinate system (neutral point is considered). Then

$$I_y \dot{\omega}_y = M_y, \quad (1)$$

where I_y – the moment of inertia of the helicopter around the normal axis OY of the body axis coordinate system;

$\dot{\omega}_y$ – the angular yaw acceleration of the helicopter;

M_y – the total moment acting on the helicopter around the normal axis OY of the body axis coordinate system.

The total momentum is made up of several components:

$$M_y = M_{MR} + M_{TR} + M_a, \tag{2}$$

where M_{MR} – the MR reaction torque;

M_{TR} – the torque generated by the TR thrust;

M_a – the aerodynamic moment of the helicopter airframe.

In the general case, the MR reaction torque can be written as follows:

$$M_{MR} = M_{\text{кр}MR} + I_{TR}\dot{\omega}_{TR}, \tag{3}$$

where $M_{\text{кр}MR}$ – the MR torque;

I_{MR} – the MR moment of inertia;

$\dot{\omega}_{MR}$ – the angular MR acceleration.

We will not consider the transients of the MR rotation, then we can consider that

$$M_{MR} = M_{\text{кр}MR}. \tag{4}$$

The MR torque can be represented as:

$$M_{\text{кр}MR} = m_{\text{кр}MR} const_T R_{MR} k_\omega^2 k_\rho, \tag{5}$$

where $m_{\text{кр}MR}$ – the MR torque coefficient;

$const_T = 0.5\,\rho_0\,\sigma\,MR\,(\omega_{MR}\,R_{MR})_0^2$ – the MR thrust constant;

ρ_0 – air density, at which the calculation of aerodynamic rotor characteristics is performed;

$\sigma = \frac{n\,F_л}{F_{MR}}$ – total rotor-width ratio;

n – the number of blades;

$F_л$ – the area of a single blade;

F_{MR} – the MR rotor disk area;

$(\omega_{MR}\,R_{MR})_0$ – the rotor speed, at which the calculation of aerodynamic rotor characteristics is performed;

ω_{MR} – the angular velocity of the MR rotation;

R_{MR} – the MR radius;

$k_\omega = \frac{(\omega_{MR} - \omega_y)R_{MR}}{(\omega_{MR}\,R_{MR})_0}$;

ω_y – the angular yaw rate of the helicopter;

$k_\rho = \frac{\rho}{\rho_0}$;

ρ – air density at the current flight altitude.

The moment from the TR thrust:

$$M_{TR} = T_{TR} r_{TR}, \tag{6}$$

where T_{TR} – the TR thrust;

r_{TR} – the TR thrust arm relatively the MR axis of rotation.

The TR thrust:

$$T_{TR} = t_{TR} const_{T_{TR}} k_{\omega_{TR}}^2 k_\rho, \tag{7}$$

where t_{TR} – the TR thrust coefficient;

$const_{T_{TR}}$ – the TR thrust constant;

$k_{\omega_{TR}} = \frac{\omega_{TR}}{\omega_{TR.0}}$;

ω_{TR} – the angular velocity of the TR rotation;

$\omega_{TR.0}$ – the angular velocity of the TR rotation, at which the calculation of aerodynamic blade characteristics is performed.

The aerodynamic moment of the helicopter airframe:

$$M_a = M_{f.y} + M_{\text{к}.y}, \tag{8}$$

$M_{f.y}$ – the aerodynamic moment of the fuselage;

$M_{\text{к}.y}$ – the aerodynamic moment of the fin.

The aerodynamic moment of the fuselage:

$$M_{f.y} = 0.5\,m_{f.y}\,\rho\,V^2 S_{con}, \tag{9}$$

where $m_{f.y}$ – the coefficient of the aerodynamic fuselage moment;

$V = \sqrt{V_x^2 + V_y^2 + V_z^2}$ – the helicopter airspeed (V_x, V_y, V_z – projections of the helicopter air speed on the axes of the body axis coordinate system);

S_{con} – the conditional characteristic area of the helicopter (usually the rotor disk area of the MR or a multiple of it is taken);

l_{con} – the conditional characteristic linear dimension of the helicopter (the MR radius is usually taken).

The aerodynamic fin moment:

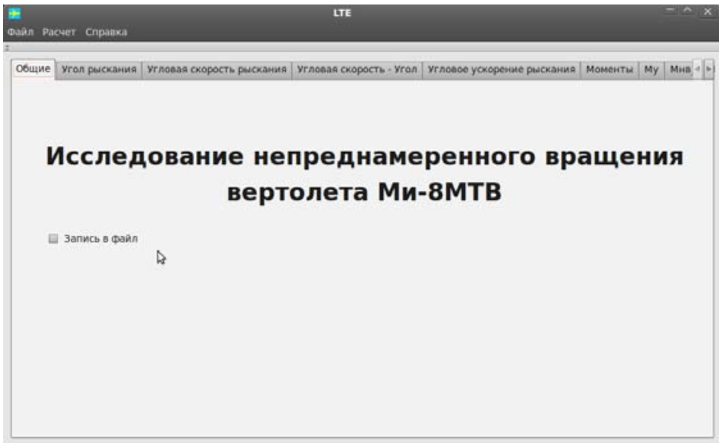

Fig. 1. The start window of the LTE module

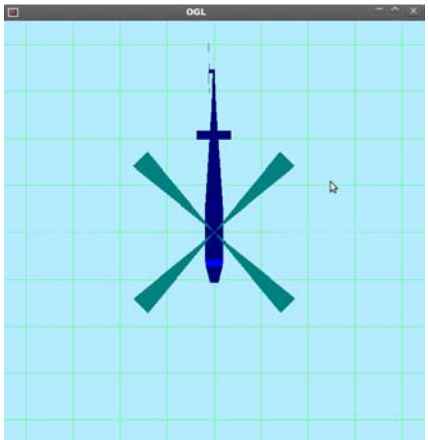

Fig. 2. The OGL module window

$$M_{\text{к}.y} = Z_{\text{к}} r_{\text{к}.y}, \tag{10}$$

where $Z_{\text{к}} = 0.5\, c_{\text{к}.z}\, \rho\, V_{\text{к}}^2 S_{\text{к}}$ – the aerodynamic lateral force of the fin (the effect of blowing over the fin with the flow from the TR is not taken into account);

$c_{\text{к}.z}$ – the coefficient of the aerodynamic lateral fin force;

$V_{\text{к}} = \sqrt{V_x^2 + V_y^2 + V_{\text{к}.z}^2}$ – the air velocity of fin flow (V_x, V_y – projections of the helicopter air speed on the axis of the body axis coordinate system;

$V_{\text{к}.z}$ – the lateral air speed of fin flow taking into account the yaw rotation of the helicopter);

$S_{\text{к}}$ – the fin area;

$r_{\text{к}.y}$ – the arm of the aerodynamic lateral force of the fin relative to the MR rotation axis.

The coefficients of aerodynamic forces and moments are specified discretely with a specific pitch in the form of multidimensional arrays depending on air linear velocities, angular velocities of a rotor and a helicopter rotation, as a whole, rotor pitch, angles of attack and helicopter slip. The intermediate values of coefficients are determined by the linear interpolation method.

Based on this mathematical model, a software package consisting of two modules was created:

- LTE – for modeling the dynamics of rotational yaw motion of the helicopter. The results of calculations are presented in the graphical and test form (fig. 1);
- OGL – to visualize helicopter movement (fig. 2).

Initial data for the calculation are assigned in the form of text files containing geometric, mass-inertial characteristics of the helicopter, arrays of aerodynamic coefficients, as well as in the form of the "flight" program, where the control actions, transmission ratios of the pilot's model and autopilot are set. In a separate file, wind effects in the form of a constantly blowing wind or a gust are assigned.

Research results and discussion

According to some data[2], angular yaw velocities at an unintentional rotation can reach 165 °/s (SA341G Gazelle helicopter). Helicopter Mi-8MTV at an unintentional rotation, according to the data of one of the authors of this article, at the end of the turn, the angular velocity of about 100 °/s at an angular acceleration of 10 $°/s^2$ was recorded. It means the turn lasted approximately 10 seconds. The helicopter turned approximately 390°, i.e., made a full turn during this time.

Let us consider an abstract model case. We determine by how much the TR thrust must decrease for such a turn. We will not be interested in the cause of the thrust loss. Let us make this calculation analytically using the above-described mathematical model.

[2] SA341G Gazelle 1, G-HAVA. (1998). AAIB Bulletin, no: 2/98, 7 p. Available at: https://assets.publishing.service.gov.uk/media/5422f61440f0b61346000617/dft_avsafety_pdf_500862.pdf (accessed: 12.01.2024).

We will consider the steady-state mode of MR operation when $M_{mr} = M_{\text{кр}mr}$. We will not take into account the aerodynamic moment of the airframe ($M_a = 0$). In this case, the condition must be satisfied:

$$I_y \dot{\omega}_y = M_{\text{кр}MR} + T_{TR} r_{TR}, \quad (11)$$

Where

$$T_{\text{TR}} = (I_{\text{y}} \dot{\omega}_{\text{y}} - M_{\text{кр}\text{M}R})/r_{TR}. \quad (12)$$

The MR torque is found by formula (5). At the same time, we will assume that the total pitch of the MR is maximum. Then, for the Mi-8MTV helicopter, the torque will be $M_{\text{кр}MR} \approx 15000$ kgf · m. Let us take the moment of inertia of the helicopter at its normal takeoff weight: $I_y = 8280$ kgf · m · s^2. The TR thrust arm relative to the MR rotation axis is $r_{TR} = 12{,}7$ m. Then, at angular acceleration $\dot{\omega}_y = 10^{\circ}/_{s^2} = 0{,}18\, s^{-2}$ we obtain $T_{TR} \approx 1064$ kgf. Considering that the TR required thrust for balancing at the same MR reaction torque $T_{TR} = \frac{M_{\text{кр}\text{M}R}}{r_{TR}} \approx 1181$ kgf, we obtain the thrust loss leading to a rotation with the given angular acceleration $\Delta T_{TR} = 117\, kgf$, which is approximately 10%. Such TR thrust loss due to wind blowing on increasing the angles of attack of the blades, i.e., creating a vortex ring is quite practical, according to the results of [20]. Thus, it can be assumed that a wind gust on the right can cause commencing an unintentional yaw rotation of the helicopter. However, the question arises, if such a rotation can only result from the TR wind blowing?

It should be considered that at the very beginning of a rotation, the pilot can apply the right pedal and prevent a rotation, which is proved by the flight experiments[3]. As a rule, even at the maximum steady-state MR reaction torque, the balancing position of the pedals ensures a sufficient forward range of the right pedal. The authors of the article have no objective data about the fact that the balancing position of the right pedal was in the manner that it was pushed to the metal in flight experiments with the wind on the right side of the flight. The computational experiments, conducted by the authors of this paper using the above-mentioned software, prove it.

At the initial stage of the computational experiment (from 0 to the 20th second), the balancing position of the helicopter with zero yaw angle is established, from the 20th second the wind begins blowing, its speed reaches the maximum value instantly and does not change until the end of the computational experiment. The cases of wind calming down when the maximum angular velocity was reached were also considered, but the angular velocity, meanwhile, abruptly decreases, and these cases were not of interest.

When conducting computational experiments, the helicopter failed to rotate to the left under any wind conditions from the right in the range from 1 to 20 m/s in increments of 1 m/s at timely actions of the pilot. The authors of the present work did not manage to do this previously with a helicopter model in a wind tunnel.

A number of computational experiments were also conducted under the condition that when the wind impact begins, the pilot does not interfere with the control, maintaining the pedal position. In this case, in a certain range of wind speeds on the right side of the flight (from 10 to 16 m/s inclusively), a turn to the left was monitored due to a decrease in the TR thrust in the VRS. Moreover, in the range of wind speeds from 10 to 12 m/s inclusively for some time after the onset of the wind effect on the right side of the flight, the helicopter turned to the left, and then turned to the right and found the equilibrium position, as in Figure 3, which shows the graph of yaw angle variation during the time under the impact of wind at a speed of 10 m/s. The yaw angle of the helicopter is positive if it turns to the left and negative if it turns to the right.

At this wind speed, the yaw to the left was maximum and amounted to more than 50°. In the range of wind speeds from 13 to 16 m/s inclusively, the helicopter turned only to the left, where it found its equilibrium position (fig. 4).

[3] SA341G Gazelle 1, G-HAVA. (1998). AAIB Bulletin, no: 2/98, 7 p. Available at: https://assets.publishing.service.gov.uk/media/5422f61440f0b61346000617/dft_avsafety_pdf_500862.pdf (accessed: 12.01.2024).

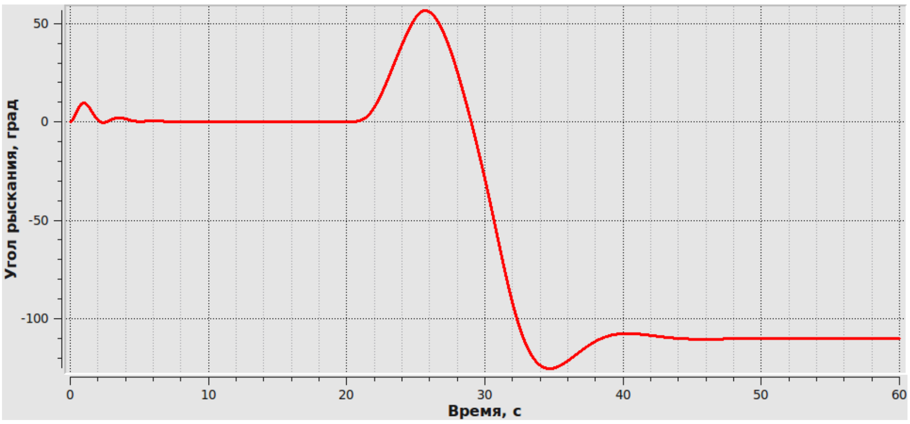

Fig. 3. Yaw angle variation under the wind impact from the right in the flight direction (wind velocity 10 m/s)

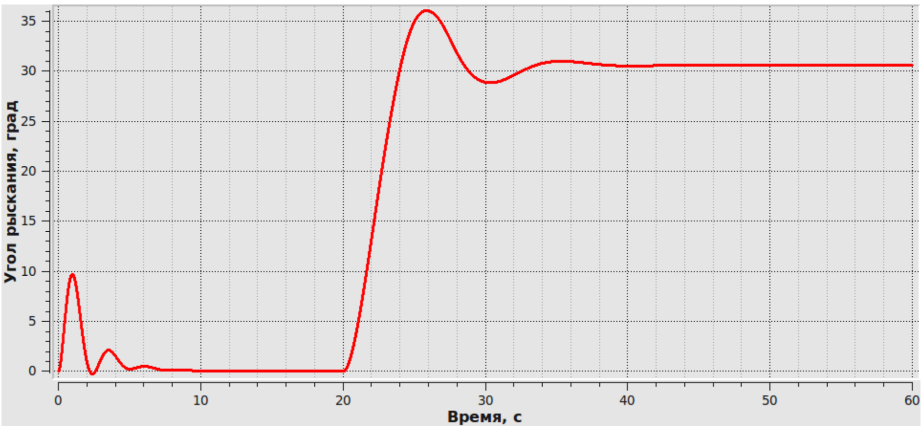

Fig. 4. Yaw angle variation under the wind impact from the right in the flight direction (wind velocity 13 m/s)

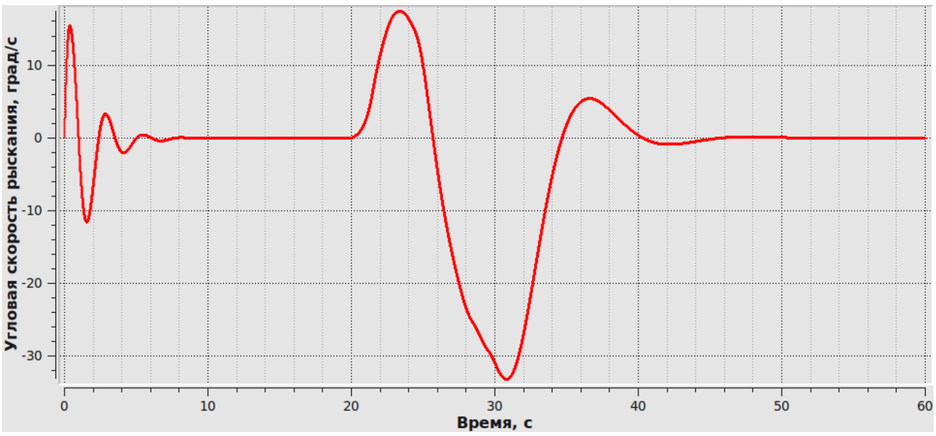

Fig. 5. Yaw rate variation under the wind impact from the right in the flight direction (wind velocity 10 m/s)

Judging by angular velocities and accelerations, their highest values at the beginning of the turn to the left occurred at wind speeds of 10 and 11 m/s, respectively (figs. 5 and 6). Moreover, the maximum yaw rate was approximately 16 °/s, and the angular acceleration was approximately 11,5 °/c^2.

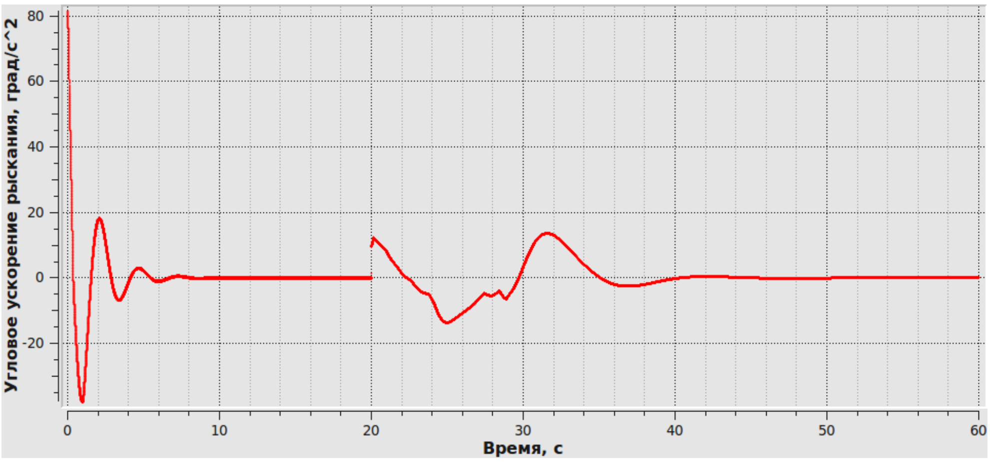

Fig. 6. Yaw angular acceleration variation under the wind impact from the right in the flight direction (wind velocity 11 m/s)

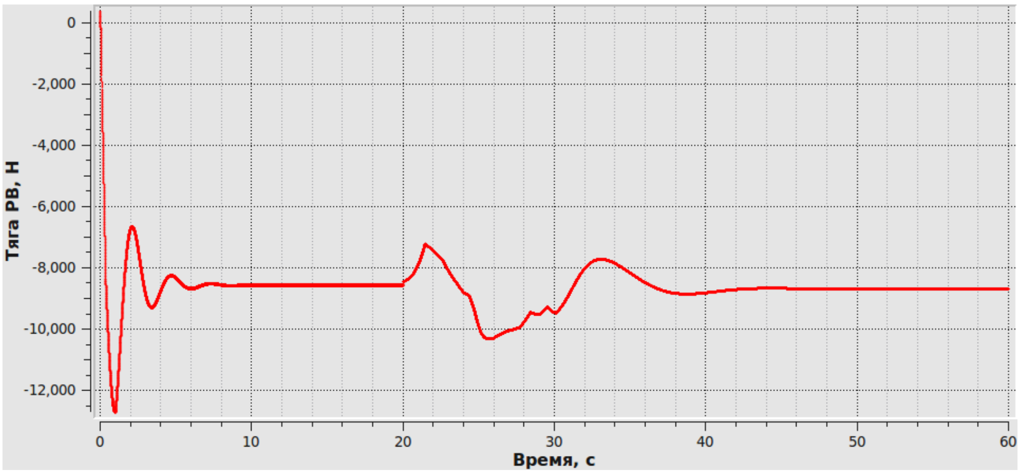

Fig. 7. Tail rotor thrust variation under the wind impact from the right in the flight direction (wind velocity 10 m/s)

As it can be seen from the results of computational experiments, when there is no pilot's intervention after the onset of the wind impact from the right side of the flight, the helicopter failed to make a full turn to the left, which was monitored in real flights supposedly due to the LTE in the VRS. However, at some values of wind speed, the helicopter turned to the left by a significant angle at a considerable angular acceleration corresponding to the acceleration in magnitude recorded in the real flight. For the development of an unintentional rotation with reaching angles and angular velocities of yaw, which are recorded in flights, the appropriate TR thrust loss is required during the entire rotation. In the conducted computational experiments, only a short-term TR thrust loss was recorded, because the orientation of the TR relative to the vector of wind speed in the process of rotation is continuously changing, and the total blowing TR by the wind and ram air, arising from the helicopter rotation, is sufficient for the TR thrust loss only in a narrow range of yaw angles. The dependence of the TR thrust value on time under the above conditions when there is no pilot's intervention in the control during a rotation at a wind speed of 10 m/s is shown in Figure 7.

The negative value of the TR thrust indicates that it is directed to the left of the flight path. Figure 7 shows that when the wind begins impacting at the 20th second of flight, the TR thrust losses in the absolute value due to wind blowing

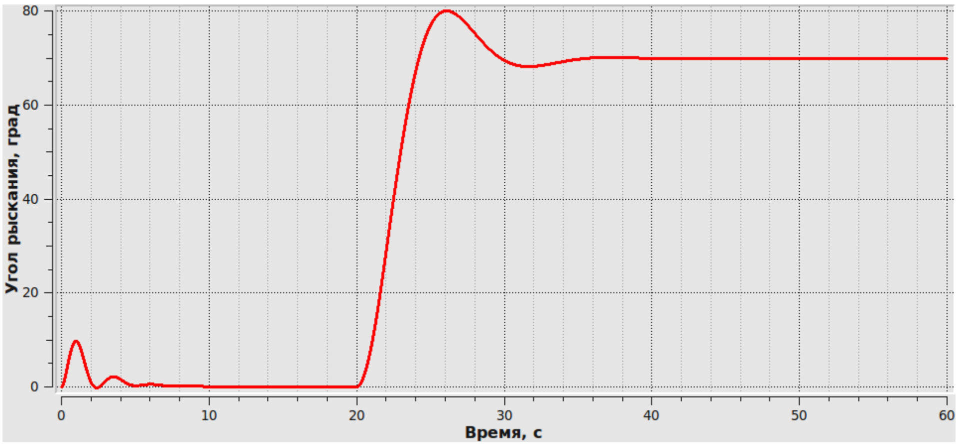

Fig. 8. Yaw angle variation under the wind impact from the left in the flight direction (wind velocity 10 m/s)

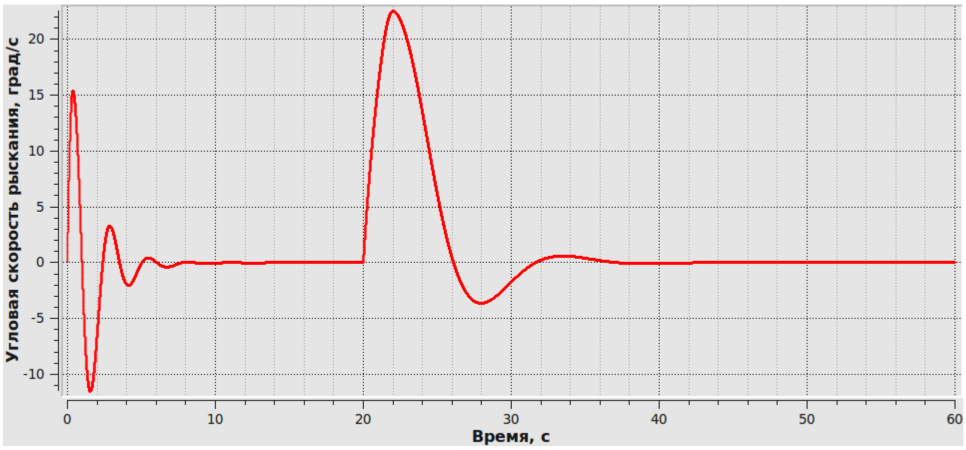

Fig. 9. Yaw rate variation under the wind impact from the left in the flight direction (wind velocity 10 m/s)

and the VRS, which leads to an unintentional turn in the absence of a pilot's reaction.

When the wind impacted on the left side of the flight in the same range of wind speeds (from 1 to 20 m/s inclusively), the helicopter turned only to the left. With timely intervention of the pilot in the control, angles of the turn were insignificant. When the pilot did not intervene in the control after the onset of the wind impact, angles, angular velocities and angular accelerations of yaw reached significant values, although even in this case, it was impractical to make the helicopter turn 360° and more without the pilot's intervention, as noted in real flights. At the same right wind speeds in magnitude (from 10 to 16 m/s inclusively), which cause a turn to the left and, accordingly, are the most dangerous in this wind direction, the left wind led to significantly larger yaw angles to the left at much higher angular velocities and accelerations. For example, as can be seen in the above Figure 3, the right wind at a speed of 10 m/s resulted in a temporary yaw angle to the left at a maximum angle of about 57°, after which the helicopter turned to the right without the pilot's intervention. The maximum angular velocity of the turn to the left was approximately 17 °/s, and the angular acceleration was approximately 11 °/s^2. At the same left wind speed, the helicopter turned to the left at a yaw angle of approximately 80° and then remained in a balancing position at an angle of approximately 70° (fig. 8). In this case, the maximum angular velocity of the left turn was approximately 23 °/s (fig. 9), and the angular ac-

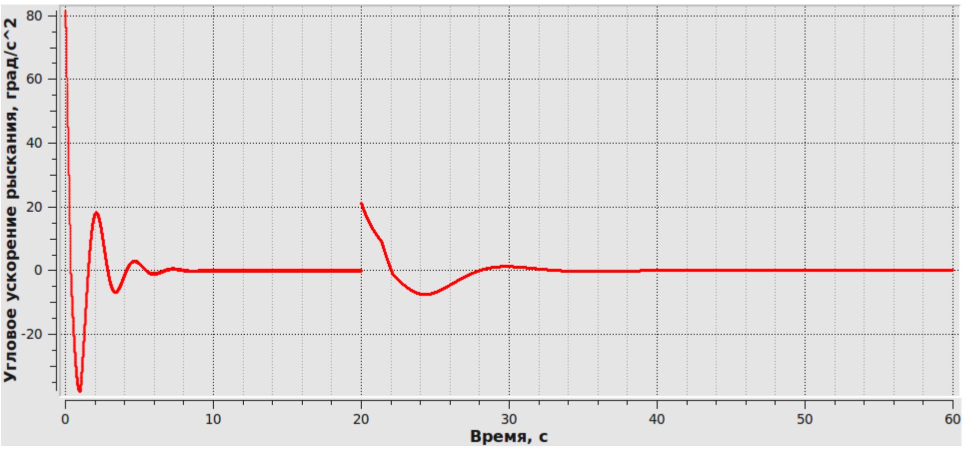

Fig. 10. Yaw angular acceleration variation under the wind impact from the left in the flight direction (wind velocity 10 m/s)

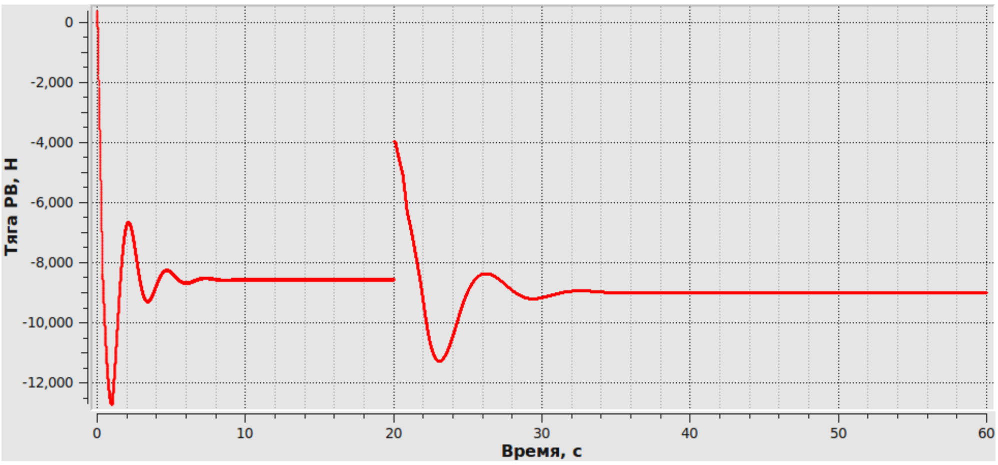

Fig. 11. Tail rotor thrust variation under the wind impact from the left in the flight direction (wind velocity 20 m/s)

celeration amounted to approximately 21 $°/s^2$ (fig. 10). At the maximum left wind speed (20 m/s), considered in the computational experiments, the maximum yaw angle to the left was approximately 90°, the balance angle was approximately 74°, the yaw angular velocity was approximately 38 °/s, and the angular acceleration amounted to approximately 43 $°/s^2$. At the given right wind speed, the helicopter was no longer turning left at all. To be based on these results, the left wind is significantly more dangerous than the right wind from the point of view of initiation of an unintentional yaw rotation of the helicopter, all other conditions being equal.

Apparently, this can be explained by the fact that, firstly, the left wind always leads to a decrease in the TR thrust due to a decrease in the angles of attack of the blades, and this decrease in thrust, other conditions being equal, is more substantial than its decrease in the wind on the right, causing the VRS, which is monitored only in a relatively narrow range of wind speeds. The dependence of the TR thrust value on time in the absence of pilot's intervention in the control during the rotation at a wind speed of 10 m/s on the left is shown in Figure 11. If we compare this graph with the one shown in Figure 7, it can be seen that, in this case, the TR thrust loss is greater than in the right wind, and that led to greater in magnitude angular accelerations and angular velocities in the left wind. At the maximum wind speed on the left, considered in the computational experiments – 20 m/s, the TR thrust loses when the wind begins impacting by more than 50% (fig. 11). Such a loss in the thrust at the vortex ring could not be recorded under any conditions.

Secondly, the vane (longitudinal) stability of the helicopter airframe contributes to the left rotation under the wind conditions on the left, while it prevents the left rotation under the right wind conditions.

The obvious danger of the right wind lies in the fact that with increasing wind speed there is no monotonicity of change in the TR thrust: it, first, increases then decreases in the vortex ring, and then increases again. This thrust behavior disorients the pilot. In addition, at the VRS, the TR thrust pulsations are monitored, which leads to helicopter oscillations and complicates helicopter piloting as well. Unfortunately, the above-described mathematical model of helicopter dynamics does not reproduce thrust oscillations on the VRS and does not simulate the pilot's behavior, so rather obviously, it is impractical to introduce the helicopter into an unintentional left rotation.

There is another aspect that is referred to by the researchers of an unintentional helicopter rotation, which is the impact of the inductive flux of the MR on the TR. However, this effect, to be based on the works of other authors considered above, is reduced mainly to the fact that the VRS is shifted toward lower wind speeds than in the case of the isolated TR wind blowing, and this effect is manifested in a narrow range of helicopter slip angles and wind speeds.

Conclusion

This paper presents the results of analytical calculations and computational experiments using software developed by the authors, aimed at investigating an unintentional yaw rotation of single-rotor helicopters without considering the inductive effect of the MR on the TR.

Analytical calculations have shown that the yaw angular acceleration value monitored in-flight during an unintentional rotation can be reached due to the TR thrust loss in the VRS. However, to develop an unintentional rotation to angles and angular velocities recorded in real flights, such TR thrust loss should occur during the entire turn, which is sometimes performed at 360° and greater. In computational experiments, when the virtual pilot is involved in the control after the onset of the wind impact and when the pilot does not move the pedals, the yaw angles, and angular velocities, that occurred in-flight, could not be reached. The TR, when blown by the wind, does not lose its effectiveness to the extent when an unintentional rotation cannot be prevented.

Apparently, unintentional turns of the helicopter at yaw angles of more than 90° cannot occur without the pilot’s intervention, i.e., without unintentional or intentional (but erroneous, caused, for example, by the TR thrust pulsations or violation of the monotonicity of the thrust value variation by wind speed) pushing the left pedal forward.

The computational experiments, carried out in the present work, have also revealed that the wind on the left can be more dangerous than the wind on the right, leading to the VRS on the TR, because the value of the TR thrust loss in the left wind, other things being equal, is greater than in the right wind, because the left wind is always, in any magnitude, leads to the TR thrust loss due to a decrease in the angles of attack of its blades, and the right wind can lead to the thrust loss only in the VRS, which occurs in a narrow range of speeds and by a value smaller than that of the left wind, which is equal in speed. Moreover, the left wind contributes to the left rotation due to the corresponding action of the aerodynamic moment of the helicopter airframe due to the presence of its vane (longitudinal) stability.

For further and more detailed consideration of the problem concerning an unintentional yaw rotation of a single-rotor helicopter, studies are necessary on a flight simulator with software that adequately simulates all the necessary modes of helicopter operation, its elements and their interaction, or on a turnover stand using a real helicopter and artificial air flow, for example, in a full-scale wind tunnel. Flight experiments can represent a significant hazard and can lead to catastrophic consequences. The tendency to ensure their safety will obviously lead to restrictions that will not allow us to adequately reproduce all the applicable modes and obtain replies to the issues.

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Information about the authors

Vadim V. Efimov, Doctor of Technical Sciences, Associate Professor, Professor of the Aircraft Aerodynamics and Structures Chair, Moscow State Technical University of Civil Aviation, v.efimov@mstuca.aero.

Valeriy A. Ivchin, Candidate of Technical Sciences, Lead Engineer, JSC “HELIBURO”, valivchin@mail.ru.

Konstantin O. Chernigin, Senior Lecturer of the Aircraft Aerodynamics and Structures Chair, Moscow State Technical University of Civil Aviation, k.chernigin@mstuca.aero.

Сведения об авторах

Ефимов Вадим Викторович, доктор технических наук, доцент, профессор кафедры аэродинамики, конструкции и прочности летательных аппаратов МГТУ ГА, v.efimov@mstuca.aero.

Ивчин Валерий Андреевич, кандидат технических наук, ведущий инженер АО «Хелибюро», valivchin@mail.ru.

Чернигин Константин Олегович, старший преподаватель кафедры аэродинамики, конструкции и прочности летательных аппаратов МГТУ ГА, k.chernigin@mstuca.aero.

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