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EXPERIMENTAL RESEARCH OF SINGLE - ROTOR HELICOPTER UNINTENTIONAL YAW ROTATION

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Aviation accidents related to unintentional rotation may periodically occur while flying single-rotor helicopters. On-time and correct actions may help the pilot to find the way out of this hazardous situation. But it is also important to understand the situation which contributes to the unanticipated yaw occurrence, and whether there are any factors which can stop the pilot from preventing such unintentional rotation, in order to avoid these conditions. Literature analysis shows that researchers studying this phenomenon don't have the shared vision on unanticipated yaw occurrence conditions. In regards to this fact the decision to carry out a series of wind tunnel experiments using helicopter model and propeller was taken. The main object of research was a radio-controlled model of the Blade 130 x helicopter, mounted on a platform rotating around a vertical axis, which was installed on a vertical strut. Research-laboratory aerodynamic complex belonging to the Aerodynamics, Design and Aircraft Strength Chair of Moscow State Technical University of Civil Aviation was used to generate airflow. A set of dynamic experiments was carried out to determine the conditions contributing to unanticipated yaw occurrence. The analysis of the experiments has shown that there is a range of sliding angles at a certain speed of the incoming air flow which makes the helicopter yaw balancing impossible, and if the helicopter occasionally gets into this range, it inevitably leads to the unintended rotation of the helicopter on the yaw occurrence. Helicopter yaw trim inability occurs at negative sideslip angles because of tail rotor thrust decrease due to the incoming airflow blowing which decreases the blades angles of attack and worsens helicopter airframe aerodynamic moment that coincides in direction with main rotor torque if helicopter airframe possesses directional stability. In these conditions the required tail rotor pitch is greater than the available pitch so the pilot is not able to counteract the initiated unanticipated yaw rotation of the helicopter that has begun. The possibility of helicopter unanticipated yaw rotation caused by the impact of the main rotor on the tail rotor was not experimentally confirmed. It was impossible to create the conditions of unanticipated yaw occurrence during the experiments because of the tail rotor vortex ring state.

Key words: helicopter, flight dynamics, unintentional rotation of the helicopter, tail rotor, efficiency loss, vortex ring.

INTRODUCTION

Aviation accidents related to unintentional rotation may periodically occur while flying single-rotor helicopters. Most often, these accidents occur when the wind affects the take-off and landing modes, and the distance to the ground is small so there is not enough time to parry the dangerous situation that has occurred. However, unintended rotation may also happen while flying at relatively high altitudes, for example, in mountainous areas where high-intensity atmospheric turbulence exists. On-time and correct actions may help the pilot to find the way out of this hazardous situation. It is also important to realize the conditions that lead to the unintentional rotation emerging in order to avoid such a dangerous situation. Unfortunately the researchers studying this phenomenon don't have the shared vision on this problem. In this regards it was confirmed to carry out a set of experiments with helicopter models and propeller in the wind-tunnel which created the air flow modeling the impact of wind. The results of these experiments are reflected in this article.

ANALYSIS OF THE PROBLEM

The vast majority of works devoted to this problem^{1,2,3,4} indicates that among the reasons for the helicopter unintended rotation is the loss of the tail rotor efficiency, which function is to balance

¹ Loss of Tail Rotor Effectiveness in Helicopters. (2017). National Transportation Safety Board. Safety Alert SA-062, March, 3 p.

the main rotor reactive moment acting on the helicopter and to ensure the directional control of the helicopter [1–9]. The foreign literature has a fixed phrase and a corresponding abbreviation to the Loss of Tail Rotor Efficiency (LTE). While analyzing this problem we face a question of what effectiveness of the tail rotor is. The authors of the article consider that the effectiveness of the tail rotor is identified by the amount of maximum tail rotor power in specific flight conditions. As a rule, the maximum value of the tail rotor thrust depends primarily on the pitch of the propeller, so it must be clearly understood that changes in the flight conditions (wind speed and direction, roll and pitch of the helicopter) with a constant pitch of the propeller is not a loss of the tail rotor efficiency. It is enough to increase the pitch of the tail rotor and its thrust will also increase, provided that the pitch value was not the maximum. Aviation accidents causes analysis with Mi-8 helicopters which have the modern system of helicopter movement parameters registration (onboard registration device), presented by one of the authors in his report [10], shows that in all cases of helicopter unintentional left rotation which were studied, the maximum tail rotor pitch was not reached. Thus, it is incorrect to talk about the loss of efficiency of the tail rotor in these cases, it is more appropriate to talk about a decrease of the tail rotor thrust due to the changes of flight conditions.

According to the authors' of the mentioned above works opinion the decrease of the tail rotor thrust may occur on different reasons.

Firstly, a decrease in the tail rotor thrust is possible when it enters the vortex bundle that comes from the main rotor, in the direction of the tail rotor rotation, when its blade, located in the upper position, moves forward (upward-forward) [4]. When the upper position blade moves rearwards (upwards - rearwards), the tail rotor thrust, when it hits the vortex bundle, increases. Modern helicopters have mostly upward - rearward tail rotor rotation scheme, so the interference of the main rotor and the tail rotor, in this case, does not lead to a decrease in the tail rotor thrust, but is unfavorable, since it changes the yaw control of the helicopter, and the pilot must be prepared for it⁵.

Secondly, the authors of the above mentioned works associate the tail rotor thrust decrease with side wind blowing on it. Left and right winds affect the tail rotor in different ways. It is important to take into account the tail rotor thrust direction which depends on the direction of the main rotor rotation and consequently, on the direction of the jet moment which comes from the main rotor and affects the helicopter. Domestic helicopters have the clockwise main rotor rotation if you look at the helicopter from above. On foreign-made helicopters, for example, on the US-made ones, the tail rotor can rotate in the opposite direction. In order to compensate the main rotor jet moment looking along the flight path, the main rotor should rotate clockwise and the thrust of the tail rotor should be directed to the left and in the opposite case, it should be directed to the right.

According to the classical rotor theory, tail rotor thrust, as well as the main rotor thrust, is created mostly due to the blades rotational motion set at the angle of attack to the velocity vector of air flow. At the same time, some aerodynamic forces which sum up on the bushing and produce the actual thrust are created on the blades. When the wind blows at the tail rotor in the opposite direction to the tail rotor thrust vector its blades' angles of attack decrease which leads to a decrease in thrust. When being blown in the opposite direction, the blades' angles of attack increase and the thrust increases accordingly. But, as it is known, the aerodynamic lift dependence on the angle of attack stops to be linear at the beginning of the profile flow separation. When the angle of attack continues to grow the aerodynamic lift reaches its maximum (at a critical angle of attack), which follows with

² FAA-H-8083-21B. Helicopter Flying Handbook. (2019). U.S. Department of Transportation. Federal Aviation Administration. Flight Standards Service. Chapter 11: Helicopter Emergencies and Hazards, pp. 11-18 - 11-21.

³ RAAF Aircraft Research and Development Unit. Bell 206B-1 Directional Control in Low Airspeed Flight. (1981). ARDU-TI-721, May, 57 p.

⁴ How to crash by the book. (1977). US Army Aviation Digest. September, pp. 43–45.

⁵ Unanticipated Right Yaw in Helicopters. (1995). U.S. Department of Transportation. Federal Aviation Administration. Advisory Circular AC 90-95, December, 8 p.

its decrease. That means that when the wind direction is opposite to the thrust vector, and when the wind direction coincides with the thrust vector direction the tail rotor thrust decreases under certain conditions.

In the literature, which studies the helicopter unintended yaw rotation, special attention is paid to the tail rotor wind blowing that coincides with the direction of the thrust vector. This is due to the fact that at such direction of the wind, the main rotor thrust allegedly decreases more [6]. This can be explained by the fact that according to the airscrew pulse theory at a certain speed of axial screw air-flow which has the direction coinciding with the direction of the thrust vector, which means against the direction of air flow thrown by the screw, the screw works in the mode of so called “vortex ring”. In this mode, the screw sucks back all the air thrown from the screw and vortex movement appears – the air circulates in the closed area around the screw without being thrown from it. Thus, the momentum is not created, the thrust is lost. But this phenomenon is actually much more complex, and according to its author B. N. Yuriev the impulse theory is just arbitrary applied [11].

The tail rotor side blowing with regards to the main rotor interference has been recently studied in many works [12–16]. These works are devoted to computational experiments with the use of a software package [18] based on a nonlinear blade vortex model of a screw with a free diffusing trace [18]. The results of the computational experiments have shown that tail rotor thrust decrease and increase can occur depending on the sliding angles and the speeds of the side blowing at the main rotor and tail rotor interference.

The title of the work [19], written by a specialist of Airbus Helicopters, can be translated as “Tail rotor efficiency loss myth”. It states that the Bell 206-B1 helicopter, having the tail rotor being blown by the wind coinciding in the direction with the main rotor thrust vector, which means the blades angles of attack increase and the “vortex ring” mode occurrence, does not lose the tail rotor efficiency. The helicopter is balanced at wind speeds of up to 40 knots (20.6 m/s) with a significant margin of directional control. In addition, the author notes that according to the recommendations for the helicopter unintentional rotation avoidance, which are included into different documents there is a requirement to push the pedal, which increases the pitch of the tail rotor, forward as quickly as possible until it stops. At the same time, if the tail rotor were not effective due to the “vortex ring” mode, such a recommendation would be meaningless or even harmful, since it would only make the situation worse. We can face the apparent contradiction.

It was decided to initiate this phenomenon study in order to ensure flight safety and understand whether there are conditions for the helicopter unintentional yaw rotation occurrence which are unaffected by the pilot even with timely and correct intervention in the helicopter control. Some results of this study are given below.

RESEARCH METHODS AND METHODOLOGY

While carrying out this research experimental laboratory research methods were used. The research object was a radio controlled model of the Blade 130 X helicopter with the following characteristics:

- airframe length.....305mm;
- airframe height.....122 mm;
- main rotor diameter.....325 mm;
- tail rotor diameter.....76 mm;
- weight.....107 g.

This model’s main rotor rotation direction coincides with the rotation direction used on domestic helicopters, i.e. the screw rotates clockwise if you look at the helicopter from above. So, under certain conditions, this helicopter must have left side unintentional rotation.

The amount of this model tail rotor thrust can be controlled by changing its pitch, as it usually happens on full-sized helicopters.

In order to expand the speed range at which the helicopter model side-blown balancing is available its directional (weathercock) stability was reduced by removing the fin.

The helicopter model was mounted on a special holder in the form of a vertical rod with the lower end fixed on a massive base, and at its upper end with a platform that could freely rotate on a ball-bearing around the vertical axis of the rod. The model of the helicopter was firmly fixed to the platform. So, the model together with the platform could easily rotate around the vertical axis whereby it was possible to change the model slip angle relatively to the incoming flow speed vector, which was created by the wind tunnel. The general views of the helicopter model on the holder and in the working section of the wind tunnel are shown in Figure 1 and Figure 2 respectively.



Fig. 1. Helicopter model on vertical strut support



Fig. 2. Helicopter model in the wind tunnel test chamber

In order to generate the airflow research-laboratory aerodynamic complex belonging to the Aerodynamics, Design and Aircraft Strength Chair of Moscow State Technical University of Civil Aviation was used. The helicopter model was controlled remotely using a remote control. A series of dynamic experiments was carried out in order to identify the conditions when even timely helicopter control intervention is unable to prevent the occurrence of its unintended rotation.

The wind tunnel flow speed varied from 2 to 22 m/s with 1 m/s. pitch. The operator made a 360° low angular speed yaw turn of the helicopter model at each mode of the flow speed. It was made from the initial position (sliding angle is $\beta = 0$) as it is shown in Figure 3, counterclockwise when looking at the helicopter from above. The gliding angle and its sign were determined in accordance with the State Standards 20058-80 "Dynamics of aircraft in the atmosphere. Terms, definitions and designations".

Video recording was also produced.

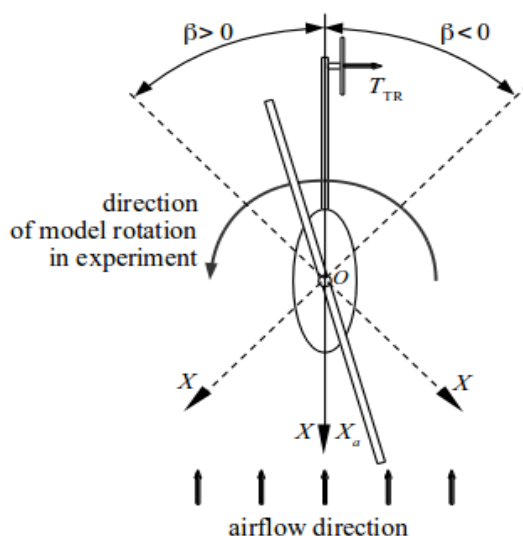


Fig. 3. The model initial position

THE RESEARCH RESULTS

At the rate of air flow speed from 2 to 5 m/s inclusively, the model was balanced at all sliding angles, it retained yaw control with sufficient control margin to allow both reducing and increasing the sliding angle. However, when the sliding angles were equal to $\beta \approx 90^\circ$ and $\beta \approx -90^\circ$ the helicopter slight yaw oscillation was observed, which was obviously associated with the tail rotor “vortex ring” mode and the tail rotor and the tail boom stall.

It should be noted that according to [11], the “vortex ring” mode occurs when the speed of the incoming air flow is equal in magnitude and is opposite in the direction to the double inductive speed of the propeller, it is equal in magnitude and is opposite in the direction to the ejection speed. The helicopter model under study had the tail rotor rate of ejection measured by an anemometer and it was approximately equal to 5 m/s. So, when the model was in the position shown in Figure 4 ($\beta = 90^\circ$), and the speed of the incoming flow was equal to 5 m/s, the “vortex ring” mode is to be implemented on its tail rotor. However, as it is pointed above, the model's balancing under these conditions was not disrupted and unintentional rotation did not occur.

At the flow rate in the range of 6 m/s to 11 m/s inclusively, there was a number of sliding angles blowing the helicopter model on the left, where the model balancing is impossible (Table 1, Figure 5). The higher is the flow speed, the wider is this range. The minimum flow velocity which has a range of sliding angles and where the yaw balancing is impossible is called *critical*.

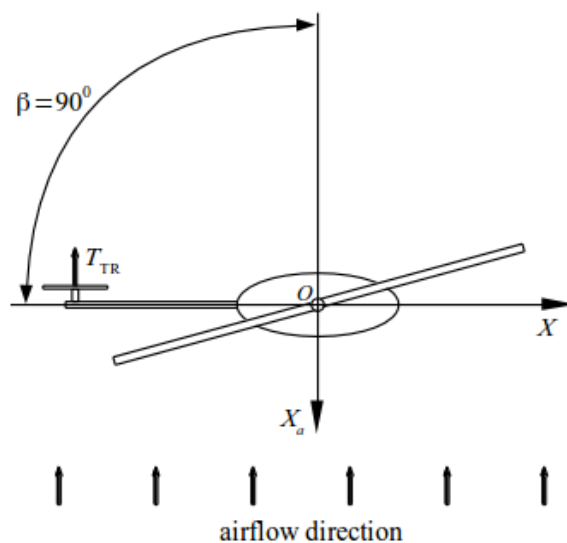


Fig. 4. The position of the model with the tail rotor “vortex ring” mode

Table 1

Airflow velocity and corresponding ranges of side blowing sliding angles which make the helicopter model yaw balancing impossible

Air flow velocity, m/s	Sliding angles range, degrees
6	– 122 ... – 60
7	– 129 ... – 62
8	– 136 ... – 55
9	– 143 ... – 54
10	– 148 ... – 59
11	– 169 ... – 39

The helicopter model makes a controlled rotation from its initial position to the left, which means counterclockwise, and it is viewed from above (Figure 3). Reaching the angle of the range start, with the impossible balancing (in Figure 5 this angle equals to $\beta = -148^\circ$), the model makes a sharp uncontrolled left turn up to the opposite border of the range (Figure 5 this angle is $\beta = -59^\circ$) and it turns by inertia afterwards. The higher the flow rate is, the greater is the inertia throw, which the model experiences.

It was possible to rotate the helicopter model to the right from the initial position only up to the edge of the sliding angles range, where balancing was impossible (Figure 5 this corner equals to $\beta = -59^\circ$).

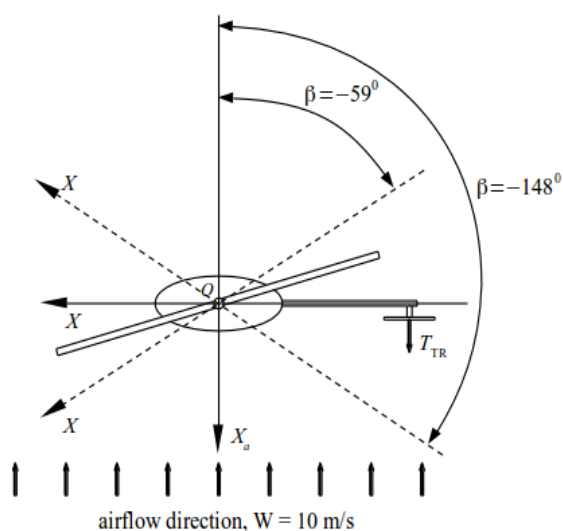


Fig.5. Boundaries of helicopter model yaw trim range being blowing from the left with airflow speed of 10 m/s

It should be noted that in the area of the slip angle $\beta = 90^\circ$ (Figure 4) at the flow speeds ranging from 6 to 11 m/s, which exceeds the speed of the tail rotor "vortex ring" formation, the helicopter model was balanced with a yaw control margin, which allowed both to increase and decrease this position model sliding angle.

At the flow rates ranging from 12 m/s to 22 m/s inclusively, with the controlled helicopter model left rotation from its initial position, it was only possible to balance the helicopter model in the following range of sliding angles: $0 \leq \beta \leq 90^\circ$. It was only possible to increase the sliding angle for more than $\beta = 90^\circ$ in dynamics by reducing sharply the pitch of the tail rotor that was followed by the throw to negative sliding angles with an unintentional left turn, which forces the model to make several finished turns around the axis of rotation.

THE OBTAINED RESULTS DISCUSSION

Having based on the analysis of literary sources we expected the mode of unintentional rotation should have begun at a certain speed of the incoming airflow in the area of the sliding angles equal to $\beta \approx 90^\circ$ when the "vortex ring" mode is possible (Figure 4). For example, as it is noted⁶ that the most likely "trigger" of the helicopter yaw unintentional rotation is the hit of the tail rotor in the "vortex

⁶ RAAF Aircraft Research and Development Unit. Bell 206B-1 Directional Control in Low Airspeed Flight, ARDU-TI-721, May 1981. 57 p.

ring” mode. However, it was not possible to achieve the unintentional helicopter-model rotation mode from this position at any flow rate in the experiment described above. In the area of sliding angles of $\beta \approx 90^\circ$ the model was always balanced; it did not tend to demonstrate unintentional left-side rotation. This means that at sliding angles of $\beta \approx 90^\circ$ the tail rotor does not lose efficiency, and the ”vortex ring” mode does not lead to a noticeable drop in thrust. We can find confirmation of this in [11], which gives the air screw experiments results with the axially blown by the incoming air flow (Figure 6, where c_T is the propeller thrust coefficient; $\bar{V}_0 = \frac{V_0}{\omega R}$ – relative axial wind-stream velocity, $\bar{V}_0 > 0$ if it coincides with inductive speed direction; ω the angular velocity of the screw rotation; R – the screw radius; φ – pitch).

The graph analysis in Figure 6 shows when the propeller is blown against the direction of the inductive speed ($\bar{V}_0 < 0$), which increases the angles of attack of the tail rotor blades and the ”vortex ring” mode is implemented, the drop in the thrust coefficient c_T at a fixed screw step is not observed. In addition, you can see when the pitch of the screw φ at a fixed blowing speed increases the thrust coefficient c_T also slightly increases. Thus, we can conclude that the screw efficiency is not completely lost at the occurrence of the ”vortex ring”, but the yaw control can still deteriorate. But the curves in Figure 6 were probably the approximations of experimental results and could be unduly smoothed.

In order to test this, the authors of this research carried out a similar experiment with a constant-pitch propeller for a cord model aircraft and Figure 7 demonstrates the obtained results.

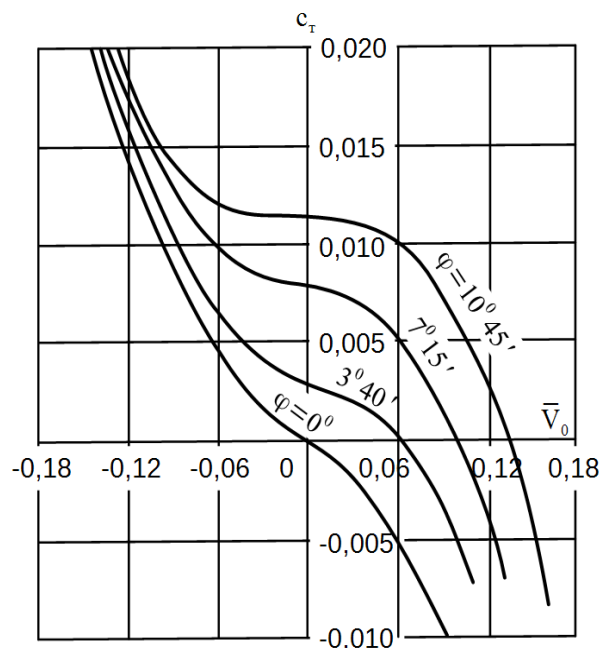


Fig. 6. Propeller thrust coefficient on the incoming flow axial speed and propeller pitch dependence

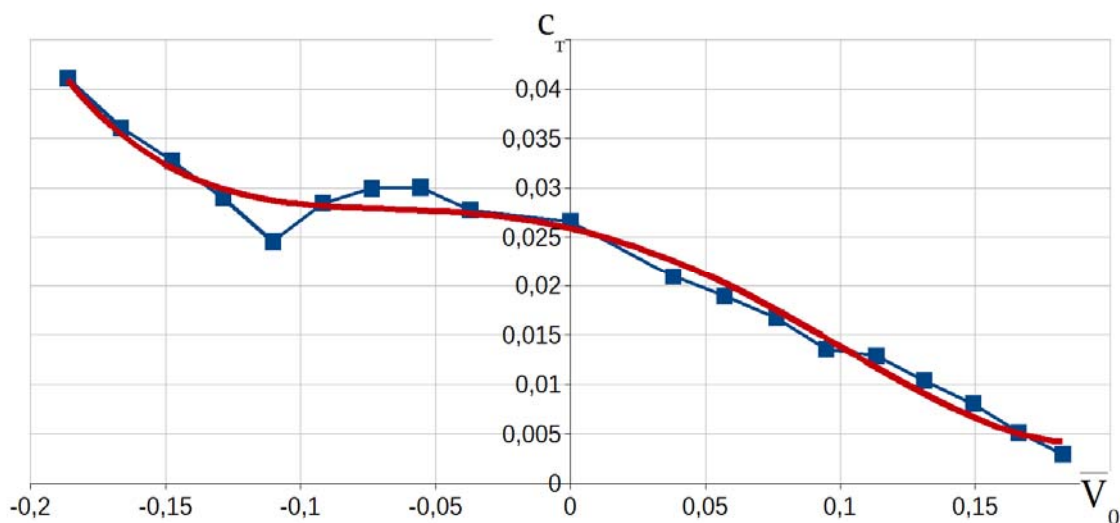


Fig. 7. The propeller thrust coefficient on the axial speed incoming flow dependence based on the results of the experiments

The experimental points that are connected with straight lines are pointed out with markers, and the approximating curve is shown by a smooth line in Figure 7. It is clear that the approximating curve has the same nature as the curves shown in Figure 6. Meanwhile, the graph connecting the experimental points has a vivid local minimum at $\bar{V}_0 \approx -0,11$, corresponding to the "vortex ring" mode. By the absolute value, this axial velocity of the incoming flow is equal to $V_0 = 6$ m/s, which corresponds to the rejection rate measured by the anemometer.

In general, it should be noted that at the growing speed of the screw axial blow-off by increasing the angles of attack of its blades, there is a moment when the thrust stops growing and even decreases slightly (in the "vortex ring" mode), and then begins to grow again. At increasing the rotor axial blowing speed to reduce its blades angles of attack, the thrust coefficient monotonously decreases. If we compare the thrust value coefficients at $\bar{V}_0 < 0$ and at $\bar{V}_0 > 0$, the equal flow speed in the second case will show a significantly reduced value of the thrust coefficient. Moreover, even the "vortex ring" mode does not lead to such a drop in the thrust coefficient relatively to its value at $\bar{V}_0 = 0$, as the blowing to reduce the blades angles of attack.

Taking into consideration the experimental data obtained, we will try to give a theoretical justification for the helicopter dynamics during side blowing, and in particular the conditions for the helicopter unintentional yaw rotation occurrence. Let us write the helicopter yaw balancing general equation in the vector form:

$$\mathbf{M}_y = \mathbf{M}_{p \text{ main rotor}} + \mathbf{M}_{y \text{ tail rotor}} + \mathbf{M}_{y \text{ airframe}} = 0, \quad (1)$$

where $\mathbf{M}_{p \text{ main rotor}}$ is the reactive torque of the main rotor;

$\mathbf{M}_{y \text{ tail rotor}}$ is the moment created by the tail rotor relatively to the normal axis of the helicopter associated coordinate system;

$\mathbf{M}_{y \text{ airframe}}$ is the helicopter airframe aerodynamic moment relatively to the normal axis of the associated helicopter coordinate system.

Let us study the characteristic ranges of sliding angles.

1. $\beta = 0$ (is the initial position, Figure 3)

In this case $\mathbf{M}_{y \text{ airframe}} = 0$ and the balancing equation in scalar form will look like

$$M_y = M_{p \text{ main rotor}} - M_{y0 \text{ tail rotor}} = 0. \quad (2)$$

That means that the moment created by the tail rotor thrust is only balanced by the reactive moment of the main rotor

2. $0 < \beta < 90^\circ$

The pilot, pushing forward the left pedal, starts making a left turn from the initial position by means of reducing the tail rotor thrust, i.e. reducing the tail rotor torque by the amount of $\Delta M_{y \text{ tail rotor}}$. But at the same time, the helicopter airframe $M_{y \text{ airframe}}$ aerodynamic moment appears. As a result, in order to make a yaw turn to increase the sliding angle with a constant angular yaw rate, you need to meet the requirement:

$$M_y = M_{p \text{ main rotor}} - (M_{y0 \text{ tail rotor}} - \Delta M_{y \text{ tail rotor}}) - M_{y \text{ airframe}} = 0, \quad (3)$$

where $\Delta M_{y \text{ tail rotor}} = M_{y \text{ airframe}}$.

With the growth of the sliding angle, $M_{y \text{ airframe}}$ will also increase, "helping" the tail rotor to compensate the main rotor reactive moment. Therefore, in order to provide a left turn in this range of sliding angles there should be constant reduction of the tail rotor thrust (increase of $\Delta M_{y \text{ tail rotor}}$), reducing its pitch in an expedited manner, because due to the tail rotor blowing its blades angles of attack will grow, which will lead to the unnecessary tail rotor thrust growth.

3. $\beta = 90^\circ$

The balancing condition in this case is described by the equation (3). Thus, the aerodynamic moment of the airframe $M_{y \text{ airframe}}$ will be maximal and the tail rotor pitch will be minimal. At a certain speed of blowing $\bar{V}_0 = \bar{V}_{0 \text{ vortex ring}}$, the tail rotor "vortex ring" mode is possible. At the same time if the helicopter was balanced at the speed of $\bar{V}_0 < \bar{V}_{0 \text{ vortex ring}}$ the unintentional increase of \bar{V}_0 up to $\bar{V}_{0 \text{ vortex ring}}$ will cause the loss of the tail rotor thrust and as a result to the accelerated helicopter

left turn. However, as the experiments with the constant pitch propeller carried out by the authors of this research revealed, the "vortex ring" thrust loss, if there is one, is very small. It coordinates with the results of the experiments performed by the other researchers, described in [11] which affirms, that they are typical for all researches of this type. The experiments which were performed by the authors of this work with the helicopter model in the wind tunnel prove the tail rotor continued effectiveness at the mode of "vortex ring" and as it was mentioned above, revealed that the helicopter model at the sliding angles equal to $\beta \approx 90^\circ$ was balanced at all wind stream speed modes which were set in the experiments.

4. $90^\circ < \beta < 180^\circ$

In the given sliding angles range, when the helicopter rotates to the left, the airframe aerodynamic moment $M_{y \text{ airframe}}$ decreases, i.e. its role in the main rotor jet moment compensation decreases. So in order to provide the constant angular yaw speed balancing, it is necessary to reduce $\Delta M_{y \text{ tail rotor}}$ (equation (3)), by means of increasing the tail rotor thrust increasing its pitch.

5. $\beta = 180^\circ (-180^\circ)$

In this position, as well as at $\beta = 0$ the helicopter balancing is described by equation (2).

6. $-180^\circ < \beta < -90^\circ$

In the given sliding angles range balancing is described by the following equation:

$$M_y = M_{p \text{ main rotor}} - (M_{y0 \text{ tail rotor}} + \Delta M_{y \text{ tail rotor}}) + M_{y \text{ airframe}} = 0. \quad (4)$$

In this case, the helicopter airframe aerodynamic moment $M_{y \text{ airframe}}$, changes its mathematical character into opposite compared to equation (3) and now it doesn't oppose the main rotor jet moment $M_{p \text{ main rotor}}$ but assists it. As a result of this in order to balance the helicopter it is necessary to increase the tail rotor moment by the amount of $\Delta M_{y \text{ tail rotor}}$ at the expense of tail rotor thrust increase, having improved its pitch (by pushing forward the right pedal).

It should be taken into account that the tail rotor is blown up by the airstream at its blades angles attack decrease, in this connection the required tail rotor balancing pitch at a certain sliding angle and certain speed can exceed the maximum possible. The right pedal will be positioned up to the stop. The continued left turn will lead to the further airframe aerodynamic moment increase $M_{y \text{ airframe}}$ and it means that

$$M_y = M_{p \text{ main rotor}} - M_{y \text{ tail rotor}} + M_{y \text{ airframe}} > 0. \quad (5)$$

In other words there is an unbalanced yaw moment which leads to the accelerated helicopter left turning, which can't be aborted by pilot as far as the right pedal is on the stop. In this case we can speak about tail rotor efficiency loss. Even considering the fact, that performing the left turn the tail rotor blades angles of attack increase because of its blowing due to the turning increasing the tail rotor thrust, the helicopter can reach high angular speed and perform several complete rotations around the normal axis.

7. $\beta = -90^\circ$

If the balancing is possible at the given sliding angle it is described by equation (4). If the incoming flow speed is high enough and balancing is impossible, the helicopter will be effected by the maximum yaw moment $M_y > 0$, which causes the accelerated helicopter left rotation around its normal axis.

8. $-90^\circ < \beta < 0$

In the given range of sliding angles, similar to the previous case, balancing if possible is described by equation (4). If the speed of the incoming airflow is high enough and balancing is impossible, the yaw moment will be defined in accordance with mathematical expression (5). In this case the helicopter rotation is accelerated and as a rule mechanically passes the second verge of the angles range where balancing is impossible (in Figure 5 this verge corresponds to $\beta = -59^\circ$). As it was pointed out, the helicopter, at the same time, can make several complete rotations around normal axis.

CONCLUSION

This paper presents the results of the helicopter models and propeller models experiments in a wind tunnel aiming to study the conditions for the helicopter unintentional yaw rotation occurrence. The impact of crosswind and the axial blowing of the isolated air rotor on the helicopter was simulated in the wind tunnel.

The experimental analysis revealed the range of sliding angles which makes the helicopter yaw balancing at a certain speed of incoming flow impossible. The helicopter unintentional yaw rotation inevitably occurs when the helicopter falls into this range.

The helicopter yaw balancing is impossible at the negative sliding angles because of the tail rotor reduced thrust due to the blades angles of attack incoming flow reduction. It also happens because of the helicopter airframe aerodynamic moment impact aimed in the main rotor jet moment direction in case the helicopter airframe is directionally stable. In these conditions, the tail rotor required pitch is greater than the available one, so the pilot is not able to parry the helicopter unintentional yaw rotation that has begun. In this case we can speak about the tail rotor efficiency loss.

It should also be noted that non-compensated yaw moment will continue the helicopter rotation within the whole range of sliding angles where the helicopter yaw balancing is impossible. The increased incoming flow speed leads to the increase of both the yaw moment and the angle range where balancing is impossible, if summed up it leads to the yaw moment effect increase. As a result the helicopter obtains a greater energy of rotation, the angular acceleration increases as well as the total helicopter yaw angular rate.

However it can't be rejected that the helicopter unintentional rotation can start as a result of the tail rotor "vortex ring" occurrence, if the tail rotor thrust moment reduction will not be compensated by the helicopter airframe aerodynamic moment and if the pilot doesn't push the pedal forward to increase the tail rotor pitch. In this case the possible tail rotor thrust loss, as the experiments proved, under equal conditions will be much less than at the tail rotor angles of attack reduction blowing. It should also be noted that the helicopter airframe aerodynamic moment, in this case, is directed against the main rotor jet moment effect which contributes to its compensation. Generally the helicopter rotation yaw moment effect will be comparatively small what means that the angular acceleration, in this

case, will also be small. It enables the pilot to make a timely response to the unintentional rotation. It should be noted that during the helicopter model dynamic experiments in the wind tunnel performed by the authors of this research, it was impossible to trigger the model's unintentional rotation at the tail rotor blades blowing aimed to increase the angles of attack so to say it was impossible to reach the tail rotor effectiveness loss at the "vortex ring" mode.

It is also possible that main rotor and tail rotor interference may cause unintended rotation. But the authors don't have at their disposal any experimental evidence of the negative effect produced by the main rotor on the tail rotor thrust. In the course of the experiments they didn't manage to detect any noticeable main rotor to tail rotor impact. Perhaps this is due to the small-scale of the helicopter which participated in the experiment.

Thus, it can be assumed that if a given wind speed has a range of sliding angles where helicopter yaw balancing is impossible in case the helicopter falls into this range, unintended rotation will inevitably begin due to the tail rotor efficiency loss. But as soon as the helicopter leaves this range this rotation can be stopped as the tail rotor will restore its efficiency, in case the helicopter doesn't fall into this range at the following cycle. The unintentional rotation which happened because of the tail rotor "vortex ring" mode can easily be stopped if there is no such range and the tail rotor doesn't lose its efficiency at any sliding angle.

It should be understood that the results presented in this paper are obtained for a smaller-scale helicopter model. The further investigation of the single-rotor helicopter unintentional yaw rotation requires the full-scale flight tests or experiments with large-scale helicopter models. The results presented in this research should also be taken into account. It is also possible to implement computational experiments, provided that a sufficiently adequate mathematical model of the phenomenon under consideration and appropriate software are developed.

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ НЕПРЕДНАМЕРЕННОГО ВРАЩЕНИЯ ОДНОВИНТОВЫХ ВЕРТОЛЕТОВ ПО РЫСКАНИЮ

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При выполнении полетов на одновинтовых вертолетах периодически происходят авиационные происшествия, связанные с возникновением непреднамеренного вращения вертолета по рысканию. Своевременные и правильные действия летчика могут привести к выходу из данной опасной ситуации. Но важно также понимать, при каких условиях возникает непреднамеренное вращение, и существуют ли такие условия, при которых летчик не может повлиять на непреднамеренное вращение, чтобы по возможности избежать попадания в эти условия. Как показывает анализ литературы, у исследователей, изучающих данное явление, нет единого мнения об условиях возникновения непреднамеренного вращения. В связи с этим было решено провести ряд экспериментов с моделями вертолета и воздушного винта в аэродинамической трубе. В качестве основного объекта исследования использовалась радиоуправляемая модель вертолета Blade 130 X, закрепленная на вращающейся вокруг вертикальной оси платформе, которая была установлена на вертикальной державке. Для создания воздушного потока использовался учебно-лабораторный аэродинамический комплекс кафедры «Аэродинамика, конструкция и прочность летательных аппаратов» Московского государственного технического университета гражданской авиации (МГТУ ГА). Была произведена серия динамических экспериментов с целью определения условий, при которых может возникнуть режим непреднамеренного вращения. Анализ экспериментов показал, что существует диапазон углов скольжения, в котором при определенной скорости набегающего потока воздуха балансировка вертолета по рысканию невозможна, и при попадании вертолета в данный диапазон это неминуемо приводит к возникновению непреднамеренного вращения вертолета по рысканию. Невозможность балансировки вертолета по рысканию возникает при отрицательных углах скольжения из-за снижения тяги рулевого винта вследствие обдувки его набегающим потоком воздуха на уменьшение углов атаки лопастей, что усугубляется воздействием аэродинамического момента планера вертолета, направленного в сторону действия реактивного момента несущего винта, если планер вертолета обладает путевой устойчивостью. В этих условиях требуемый шаг рулевого винта больше, чем располагаемый, в связи с чем летчик не в состоянии парировать начавшееся непреднамеренное вращение вертолета по рысканию. Возможность начала непреднамеренного вращения вертолета по рысканию из-за влияния несущего винта на рулевой винт в экспериментах не подтвердилась. В экспериментах также не удалось создать условия, при которых возникло бы непреднамеренное вращение из-за появления режима «вихревого кольца» на рулевом винте.

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

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