METHOD FOR DETERMINING THE PHENOMENON OF STALL ON HELICOPTER BLADE

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The analysis of dangerous factors leading to the phenomenon of flow stall on the rotor blades of a helicopter has been carried out. The estimated cruising speed of a helicopter without auxiliary propulsion at the current level of technology development lies in the range of 280-370 km/h. The results of flight experiments showed that the stall phenomenon leads to a sharp increase in the load on the blades, which in turn is transferred to the lower fixed plate of the swashplate. This phenomenon is accompanied by the appearance of the n-th harmonic of the main rotor speed. The results of these experiments made it possible to create a subsystem for recognizing the phenomenon of stall with the issuance of visual and audible indication to the pilot to change the flight mode. A block diagram and description of the operation of the subsystem based on the simultaneous use of two features are given: measurement of mechanical stresses on the swashplate and the amplitude of the harmonic component of the signal from the frequency of rotation of the rotor blades of the helicopter. The use of two signs can significantly increase the probability of determining the moment of flow stall. The technical implementation of the proposed method for determining the phenomenon of flow stall on the rotor blades of a helicopter makes it possible to provide a qualitatively new level of flight safety under conditions of complex maneuvers.

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Introduction

In some cases, helicopter flight features are associated with such a phenomenon as flow disruption on the bearing blades. This phenomenon is caused by the simultaneous impact of many flight factors, such as helicopter maximum speed in the horizontal plane, helicopter weight, pitch and roll angles, route height and other factors. The main limitation for many modern helicopters is flow disruption on the lagging blade, leading at high flight speeds to a sharp increase in loads on the bearing rotor and control system and, as a consequence, an increase in vibrations of the entire machine.

Materials and research methods

The rotating bearing rotor discards the surface, that can be represented as a bearing one, that creates thrust (Fig. 1) [1].

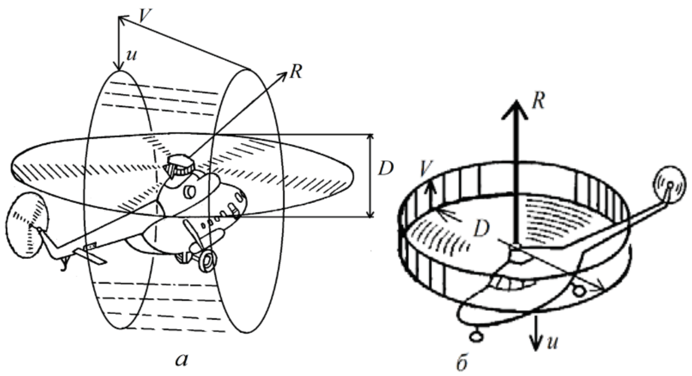

Fig. 1. The volume of air involved in creating the thrust of the bearing rotor of the helicopter:
a – with oblique blowing; b – with «hovering» and vertical lifting

The air, flowing through the surface, discarded by the bearing rotor, as a result of interaction with the rotating blades, is thrown down with an inductive speed *u*. In the case of horizontal or inclined flight, air flows to the surface, discarded by the bearing rotor at a certain angle (oblique blowing) (Fig. 1, a).

The volume of air involved in creating the full aerodynamic force of the bearing rotor can be represented as a cylinder, whose base area is equal to the surface area, discarded by the bearing rotor, and the length – the flight speed expressed in m/s (Fig. 1, b).

During the operation of the bearing rotor in place or in vertical flight (direct blowing), the direction of the airflow coincides with the axis of the bearing rotor. In this case, the air cylinder will be positioned vertically (Fig. 1, b). The total aerodynamic force of the bearing rotor will be expressed as the product of the mass of air flowing through the surface, discarded by the bearing rotor in one second, by the inductive velocity of the outgoing stream (1):

$$R = \pi \frac{D^2}{4} V \rho u \tag{1}$$

where $\pi \frac{D^2}{4}$ – surface area discarded by the bearing rotor;
V – flight speed in m/sec;
ρ – density of air;
u – inductive velocity of the outgoing stream in m/sec.

In the considered case, for the bearing rotor of a helicopter, the inductive velocity of the outgoing stream at some distance from the bearing surface is taken as the inductive velocity. The inductive velocity of the air stream, arising on the bearing surface itself, is twice as small [2,3].

If the total aerodynamic force of the bearing rotor is expressed as the product of the mass of air, flowing through the surface, discarded by the bearing rotor, by the inductive velocity, and the volume of this mass is a cylinder, whose base is the surface area, discarded by the main rotor, and the length is the speed of flight, then it is quite clear, that to create a thrust of constant magnitude (for example, equal to the weight of the helicopter) with a higher flight speed, and therefore with a larger volume of air being discarded, a lower inductive speed is required and, consequently, less engine power.

To keep the helicopter in the air while «hovering» in place, more power is required than during a flight with some translational speed, at which there is an oncoming air flow due to the movement of the helicopter.

In other words, with the expense of the same power (for example, the rated power of the engine) in the case of an inclined flight with a sufficiently high speed, it is possible to achieve the most maximum range, than with vertical lifting, when the overall speed of the helicopter is less than in the first case. Therefore, the helicopter has two maximum ranges: static, when the height is dialed in vertical flight, and dynamic, when the height is dialed in inclined flight, and the dynamic range is always higher than static.

Thus, the thrust of the bearing rotor of the helicopter will be proportional to [4,6]:

- he diameter of the rotor in the fourth degree D^4;
- he square of the second rotations of the bearing rotor $n^2 s$;
- he density of air ρ;
- the traction coefficient a_T.

An increase in the diameter or speed of rotation of the rotor entails an increase in the required power. Consequently, the amount of thrust ultimately depends on the engine power.

For the average calculation of the thrust of the bearing rotor in hovering mode, the following formula is used [5]:

$$T = (aND)^{2/3} \tag{2}$$

where T – thrust of the bearing rotor (for hovering mode with no wind $T \approx R$) in kg;
N – engine power in h.p.;
D – diameter of the bearing rotor in m;
a – coefficient, characterizing the aerodynamic quality of the bearing rotor and the influence of the «air cushion» (depending on the characteristics of the bearing rotor, the coefficient value when hovering near the ground can have values of 15-25).

The bearing rotor of the helicopter has an extremely important property – the ability to create lifting force in the self-rotation mode (autorotation) in the case of engine shutdown, which allows the helicopter to make a safe gliding or parachuting descent and landing [7].

There is a significant difference in the operation of the bearing rotor in the case of motor flight, when the power from the engine is transferred to the rotor, and in the case of self-rotation flight, when it receives the energy to rotate the rotor from an oncoming stream of air.

In a motor flight, oncoming air runs into the bearing rotor from above or from above at an angle. When the rotor is operating in self-rotation mode, air flows into the plane of rotation from below or at an angle from below (Fig. 2). The bevel of the flow behind the bearing rotor in both cases will be directed downward, since the inductive velocity according to the theorem on the amount of motion will be directed directly opposite to the thrust, i.e. approximately down the axis of the bearing rotor.

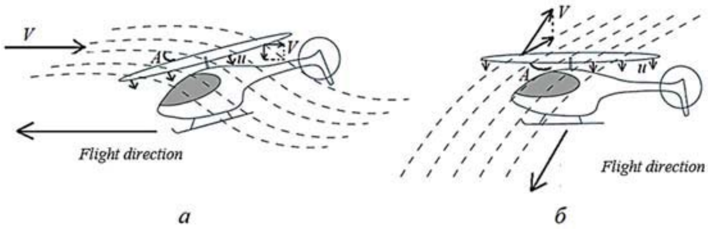

Fig. 2. Interaction of the air flow with the bearing rotor of the helicopter:
a – flow bevel in motor flight; b – flow bevel on the self-rotation mode of the rotor

The flow disruption occurs on the rotor blades, moving along the flow and with a large angle of attack during the forward movement of the helicopter. This is the main factor limiting the maximum speed of helicopters. Just as the disruption of the flow from the wing limits the minimum speed of the aircraft, the disruption of the flow from the helicopter rotor blade limits the maximum speed of the helicopter, since the resulting speed of the lagging blade decreases with increasing helicopter speed.

Ideally, the lagging blade should create a lifting force, equal to the lifting force, generated by the advancing blade. Since the speed of the lagging blade is less than that of the advancing one, the angle of attack of the lagging blade must be increased in order to equalize the lifting force over the entire area of the bearing rotor. As the speed of the helicopter increases, the angle of attack of the lagging blade increases more and more, and its speed decreases until the flow disruption occurs [8,9].

An explanation of the phenomenon of flow disruption is given in Figure 3.

In the first case, the first manifestations of vibration and rocking are observed, in the second – the helicopter increases pitch and rolls to the right. The effect of disrupting the flow from the blades is generally manifested as increased vibration of the helicopter, nose lifting and roll. If the control knob (cyclic step) continues to be held in front and the overall step is not reduced, the phenomena of flow disruption are aggravated, and vibration increases noticeably. In such a situation, control of the helicopter may be lost. The procedure for exiting the roll to the right [10]:

– reduce he overall step;
– put the control knob to the neutral position;
– reduce he speed;
– in rease the speed of the bearing rotor.

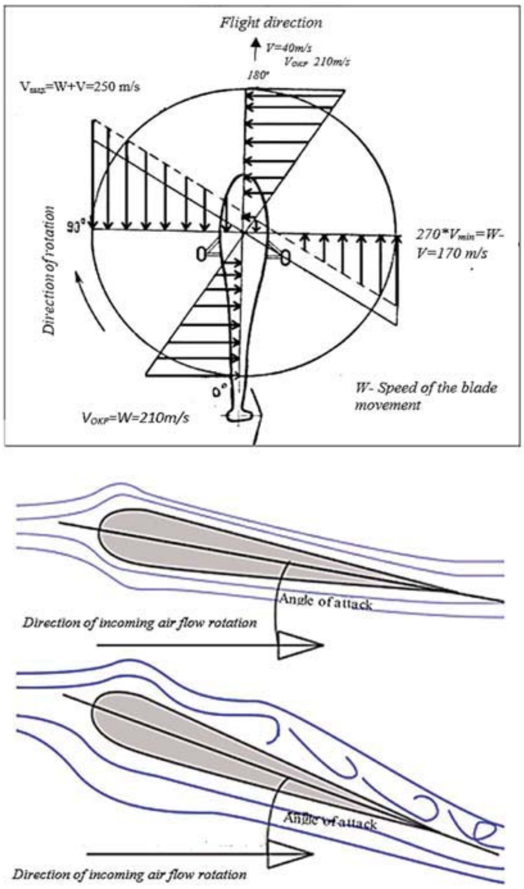

Fig. 3. Scheme of explanation of the complex movement of the bearing blades in horizontal flight, leading to the flow disruption

For this reason, the estimated cruising speed of a helicopter without auxiliary propellers at the current level of technology development lies in the range of 280–370 km/h (Fig. 4). Exceeding this speed can also lead to the phenomenon of flow disruption.

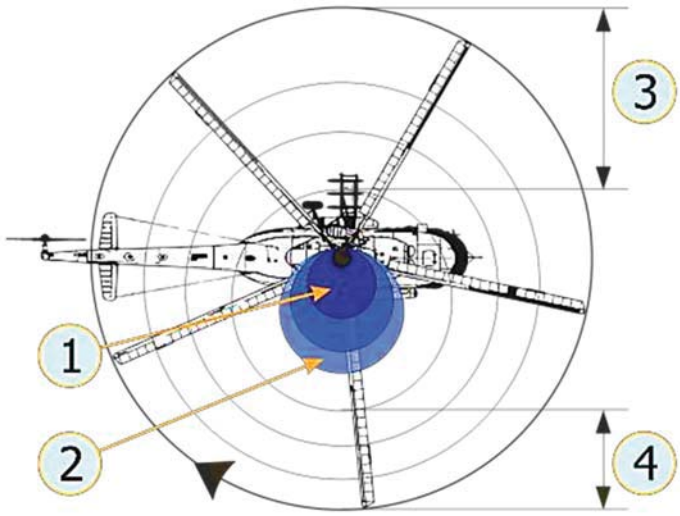

Fig. 4. Distribution of lifting forse in normal flight:
1 – reverse flow zone; 2 – zone of absence of lifting force; 3 – the lifting force in this zone is created by the blades at a low angle of attack;
4 – the lifting force in this zone is created by the blades at a large angle of attack (should be equal to the lifting force created in zone 3)

Results and its discussion

The results of flight experiments have shown that the phenomenon of flow disruption leads to a sharp load increase on the blades, which in turn is transmitted to the lower fixed swashplate. This phenomenon is accompanied by the appearance of the *n*-th harmonic of the bearing rotor speed. The diagrams of this phenomenon processes are shown in Figure 5.

These diagrams clearly show that in the absence of the flow disruption the RMS (root-mean-square) value of the force does not exceed 20 kgf, and the vibration level of the harmonics of the main rotation frequency of the blade and the fifth harmonic are approximately the same. At the same time, the load on the lower swashplate increases sharply, and the level of the fifth harmonic of the vibration frequency increases significantly. Diagrams of these phenomena processes are shown in Figure 6 [11,14].

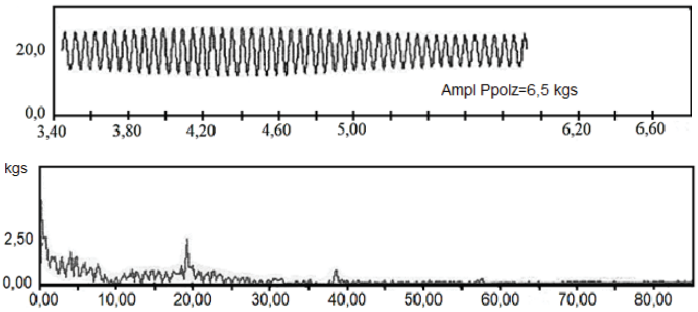

Fig. 5. Diagrams of force changes on the lower swashplate and oscillation harmonics without the flow disruption phenomenon on the helicopter blades

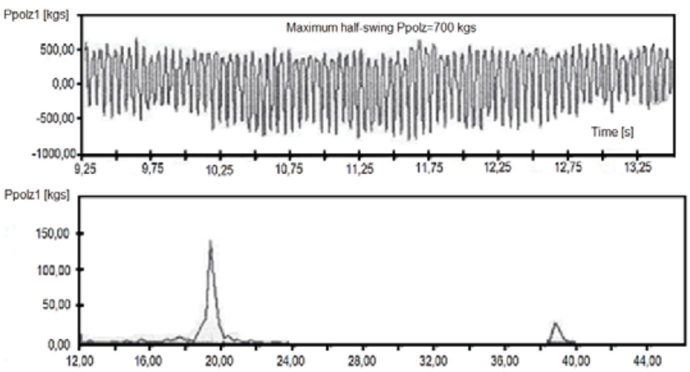

Fig. 6. Diagrams of force changes on the lower swashplate and oscillation harmonics with the flow disruption phenomenon on the helicopter blades

The results of these experiments made it possible to create a subsystem for recognizing the phenomenon of flow disruption with the issuance of visual and audio indications to the pilot to change the flight mode. The operation of the subsystem is based on the simultaneous use of two features: measurement of mechanical stresses on the swashplate and the amplitude of the harmonic component of the signal from the rotational speed of the bearing helicopter blades [12,13].

In flight modes, due to periodic changes in the flow conditions of the blades, the flow disruption occurs on the lagging blade, which in turn leads to the appearance of blade-twisting loads and the occurrence of vibrations.

The main frequency of the blade load change is equal to the frequency of the blades passing, which corresponds to the period $T = 2 \cdot \pi / (N \cdot \omega)$, where N – the number of the bearing helicopter blades. Thus, in the helicopter operation mode without the flow disruption on the blades, the oscillation with vibration frequency ω – the angular velocity of rotation of the rotor axis has the greatest amplitude. When the flow disruption phenomenon occurs, there is a significant increase in the oscillation amplitude with the frequency of the blades passage $N \cdot \omega$, since through each angle of movement of a separate blade by the value $\Theta = 2 \cdot \pi / N$ one of the blades, which is a retreating one along the course of the helicopter, enters the process of flow disruption.

The use of two features to detect the moment of the flow disruption occurrence gives a significant increase in the probability of detecting this phenomenon. Since events *A* of the appearance of excessive mechanical stress on non-rotating parts of the swashplate and event *B* of the appearance of the *N*-th harmonic of the rotation frequency ω of the helicopter blades in the case of the flow disruption are joint (appear simultaneously), for the probability of a joint event the following formula is valid [15]:

$$P(A+B) = P(A) + P(B) - P(A,B) \tag{3}$$

If the probability of detecting the flow disruption when using a feature of excessive mechanical stress on non-rotating parts of the swashplate is equal to $P_1 = 0{,}8$ and the probability of detecting the flow disruption when using an additional feature of the appearance of the *N*-th harmonic of the rotation frequency of the helicopter blades is equal to $P_2 = 0{,}8$, then the resulting probability of detecting the phenomenon of flow disruption when using two features will be:

$$P_{1,2} = 0{,}8 + 0{,}8 - 0{,}8 \cdot 0{,}8 = 0{,}96$$

i.e. $P_{1,2} > P_1$ and $P_{1,2} > P_2$.

Thus, the use of the two features makes it possible to significantly increase the probability of determining the moment of flow disruption, therefore there is a possibility to transfer the helicopter flight to a qualitatively new level of safety. Structurally, the sensors for measuring the force and frequency of harmonics on the swashplate can be manufactured on the basis of fiber-optic technology with distributed Bragg cells. The block diagram of the subsystem for detecting the phenomenon of flow disruption, which allows implementing the proposed method, is shown in Figure 7 [16,19].

The power supply unit is switched on, while the power supply is supplied to the blocks of the light source, information storage, information analysis, spectral analysis, digital-to-analog signal converter, the first threshold device, the second threshold device.

When exposed to external mechanical loads on parts of a helicopter with strain-gauge sensors, the spectrum of optical radiation reflected from them changes. The change in the spectrum of reflected radiation carries the information about the mechanical loads experienced by the parts of the helicopter on which the fiber-optic sensors are installed, and each fiber-optic sensor corresponds to a certain band of the radiation spectrum of the light source unit.

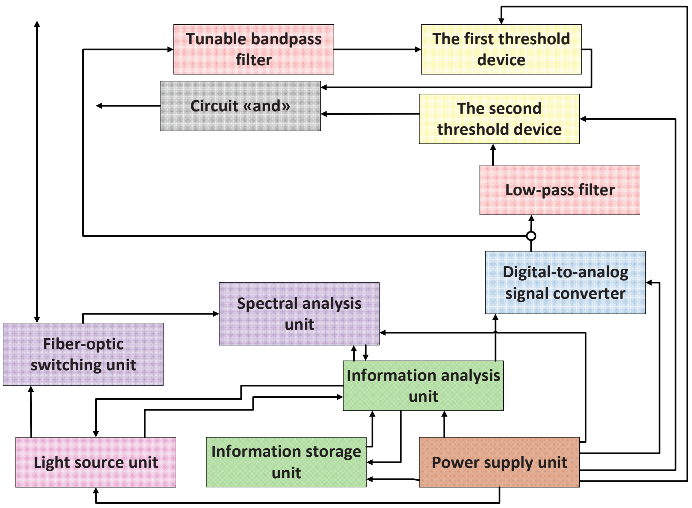

Fig. 7. Block diagram of the subsystem for detecting the flow disruption

The signals of all fiber-optic sensors are summed up, in terms of power, in a fiber-optic connector and transmitted via a fiber-optic cable. In the spectral analysis unit, the optical radiation reflection spectra from each strain-gauge sensor are converted into a digital signal and are also received at the first input of the information analysis unit, where the signal is analyzed by recalculating the changes in the optical signal spectrum from each strain-gauge sensor into the load acting on the parts of the skew machine according to the previously known dependencies obtained during calibration of the strain-gauge sensors, converted into a digital electrical signal and transmitted to the digital-to-analog converter (DAC) block [20].

When the polling frequency of fiber-optic sensors is at least $2N\omega$, in addition to removing quasi-static mechanical stresses in parts of the helicopter with strain-gauge sensors, it becomes possible to isolate the $N\omega$ -th frequency of vibrations of the helicopter blades that occurs with the flow disruption phenomenon. Therefore, at the output of the DAC unit, in addition to the relatively low-frequency component characterizing the change in mechanical load, there will be a signal with a frequency $N\omega$, characterizing the appearance of the *N*-th harmonic of the rotational speed of the helicopter's bearing blades.

The analog electrical signal, carrying the information about the mechanical loads of the controlled parts of the helicopter, enters the low-pass filter from the output of the DAC, and from its output to the input of the second threshold device, in which the voltage threshold, corresponding to the maximum permissible mechanical load, is set. If the specified threshold is exceeded, a «unit» appears at the output of the second threshold device, which enters the first input of the «AND» circuit [21].

From the output of the DAC, the signal also enters the input of a tunable bandpass filter, pre-tuned to the *N*-th harmonic of the rotational speed of the bearing rotors. Depending on the number of the bearing helicopter rotors *N* and the rotational speed of the bearing blades, the tunable bandpass filter is adjusted for a specific type of helicopter. From the output of the tunable bandpass filter, the signal enters the first input of the first threshold device, in which a voltage threshold is set corresponding to the excess of the level of the *N*-th harmonic above the noises. If the specified threshold is exceeded, a «unit» appears at the output of the first threshold device, which enters the first input of the «AND» circuit. With the simultaneous presence of «units» at the input of the circuit «AND», at its output a «unit» signal appears, which enters the electrical data bus and then the panel indicator of the flow disruption stage. The presence of the «unit» signal on the panel indicator of the flow disruption stage warns the pilot about the presence of a flow disruption phenomenon. The «zero» signal reflects the normal flight mode. The combined use of two signs of the flow disruption phenomenon significantly increases the probability of detecting this phenomenon and, accordingly, reduces the probability of a false alarm [22,23].

The received data on the loads on the parts of the helicopter skew machine from the output of the information analysis unit are transmitted to the information storage unit for subsequent analysis of the correctness of the actions of the helicopter pilot.

Conclusion

Thus, the joint use of the two features of the flow disruption phenomenon increases the probability of detecting this phenomenon, and the registration of such a phenomenon in real time ensures timely informing the pilot about the danger of an emergency situation and performing proactive actions. The technical implementation of the proposed method for determining the flow disruption phenomenon on the bearing helicopter blades allows for a qualitatively new level of flight safety in conditions of performing complex maneuvers.

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МЕТОД ОПРЕДЕЛЕНИЯ ЯВЛЕНИЯ СРЫВА ПОТОКА НА НЕСУЩИХ ЛОПАСТЯХ ВЕРТОЛЕТА

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Аннотация

Проведен анализ опасных факторов, приводящих к явлению срыва потока на несущих лопастях вертолета. Расчетная крейсерская скорость вертолета без вспомогательных движителей при современном уровне развития техники лежит в пределах 280-370 км/ч. Результаты летных экспериментов показали, что явление срыва потока приводит к резкому увеличению нагрузки на лопасти, которая в свою очередь передается на нижнюю неподвижную тарелку автомата перекоса. Это явление сопровождается появлением n-ой гармоники основной частоты вращения несущего винта. Результаты этих экспериментов позволили создать подсистему распознавания явления срыва потока с выдачей визуальной и звуковой индикации пилоту для изменения режима полета. Приведены структурная схема и описание работы подсистемы, основанной на одновременном использовании двух признаков: измерения механических напряжений на автомате перекоса и амплитуды гармонической составляющей сигнала от частоты вращения несущих лопастей вертолета. Применение двух признаков позволяет существенно повысить вероятность определения момента срыва потока. Техническая реализация предложенного метода определения явления срыва потока на несущих лопастях вертолета позволяет обеспечить качественно новый уровень обеспечения безопасности полетов в условиях выполнения сложных маневров.

Ключевые слова: *вертолет, несущая лопасть, волоконно-оптический тензодатчик, распределенная ячейка Брэгга.*

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