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MULTITHREADED CONTINUOUSLY VARIABLE TRANSMISSION SYNTHESIS FOR NEXT-GENERATION HELICOPTERS

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Abstract

The results of analysis of optimal design solutions for helicopter transmission with separate control systems of rotor and pushing blades are discussed. The advantages of mechanical continuously variable transmissions for the implementation of variable gear ratio transmission were shown. Optimal kinematic scheme of variable transmission with integrated CVT drives for high-speed helicopter was designed with using synthesis methods of multi-threaded planetary mechanisms.

1 Introduction

One of priority directions of development of modern helicopters is to increase the speed of horizontal flight. Existing civil and military helicopters have limitations horizontal flight speed at around 300-350 km/h. This speed level flight does not meet the requirements for the implementation of the goals and tasks of the modern helicopter equipment. In this regard, the leading helicopter manufacturing companies began to work on projects of high-speed helicopters having a fundamentally new design and aerodynamic scheme. For example, the Sikorsky is working on the project multipurpose helicopter S-97 Raider with two coaxial bearing blades and one pusher propeller at the tail end. This helicopter, designed primarily for military applications, will have a maximum speed of 444 km/H. It is a development prototype demonstration Sikorsky X2, who in September 2010 exceeded the speed of 460 km/h (fig.1).

Fig. 1. High-speed helicopter Sikorsky X2.

The requirement to increase the horizontal speed of flight of helicopters limited by a number of factors, primarily faces the aerodynamic restrictions for the main rotor, such as disruption of the flow with the backing of the rotor blades in high-speed flight. The solution to this problem is possible by reducing the frequency of rotation of the rotor at high horizontal flight speeds (300 km/h) and add the progressive traction in the horizontal direction. In projects of high-speed helicopters such a source thrust is usually pusher propeller at the rear fuselage of the helicopter. Pusher propeller is driven by the engine helicopter through the transmission scheme, similar to the steering screw in the single-rotor helicopters scheme. However, in the design of high-speed helicopter transmission must perform a number of additional functions, providing independent rotor blades and pushing blades. The transmission speed of the helicopter should provide the possibility of changing the gear ratio from the engine to the bearing blades and redistribution of power to push the blades, which provide extra traction in the horizontal direction.

When developing a new scheme of the

transmission for high-speed helicopter should be solved tasks, providing the following functions:
• control transmission gear ratio from the engine to the rotor blades;
• control gear ratio between main gearbox and system of pushing blades;
• redistribution of engine power between the systems of rotor blades and the pushing blades.
The need for controlled change of frequency of rotation of rotor and pushing blades at a constant speed engines depending on the mode and speed of flight of the helicopter requires the inclusion in the transmission mechanisms of change of gear ratio from between engine and blades. The solution to this problem is also the most difficult, since the need for placement in the transmission the mechanism leads to the growth of the mass of the transmission and average size of a transmission and improving the dynamic loads in general.

In this paper, analysis of optimal alternative design solutions for transmission of helicopters with pushing blades were conducted.

2 Alternative types of helicopter transmissions

In the result of the analysis [4] different kinematic schemes and design solutions for the transmission of high-speed helicopters, the main advantages and disadvantages of each of the schemes was demonstrated with the main technological and structural complexity of the realization of various circuit designs for the transmission of high-speed helicopter with variable gear ratio. Hydrostatic transmissions, electrical, electromechanical (hybrid) (fig. 2), mechanical continuously variable and mechanical stepless transmissions were shown.

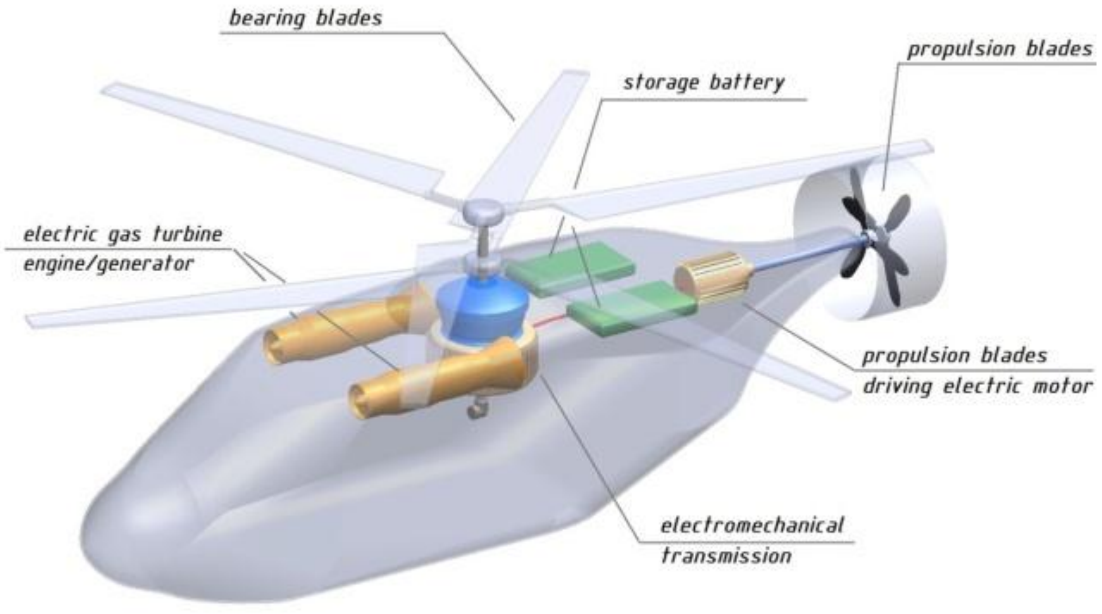


Fig. 2. Model of high-speed helicopter with electromechanical transmission.

From other types of mechanisms with change of transmission gear ratio from the point of view of defining criteria - reliability and stability of the transmission, to minimize the weight and size of the gearbox, and safety and efficiency at the present stage of technological development, one should prefer the mechanical continuously variable transmissions with parallel connection planetary gearbox and mechanical variable-speed drive (Fig. 3).

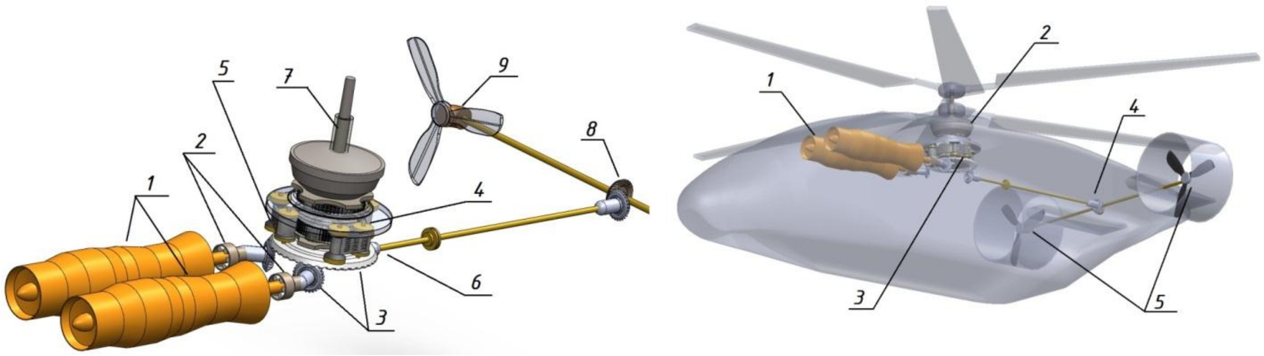


Fig. 3. Model of continuously variable mechanical transmission packaging in the high-speed helicopter with 2 pushing blades: 1-engines (GTE); 2 - freewheel; 3 - bevel gear of first reduction level; 4 - planetary mechanism with two power threaded and CVT; 5 – mechanical CVT variators; 6 - drive of pushing blades (bevel gearbox); 7 - planetary part of the main gearbox with shaft rotor blades; 8 - angled drive (bevel gearbox); 9 - angular gear drive of pushing blades.

This is largely due to the low speed of main rotors (200-400 rpm) in comparison with the value of drive motors rpm that will require integration into the composition of the transmission of additional mechanical gearboxes. Mass of planetary gearboxes, as shown above, depends primarily on the size of torque on the output shaft and to a lesser extent on the value of the reduction ratio of the gearbox. Thus, even in all-electric powertrain helicopter cannot get rid of mechanical reducer, comparable on weight with a main reduction gearbox of helicopter with mechanical transmission.

3 Synthesis of multithreaded planetary transmissions

The main task of planetary mechanism synthesis for continuously variable transmission will consider the search of optimal kinematic scheme, which will allow to minimize the load of the branches of the mechanism, containing a CVT. This requirement is defined as existing characteristics of variable-speed drives, and requirements to the reliability and the weight of the construction of the transmission. To solve this problem at the planetary mechanism synthesis produces some criteria based on which a search for the optimal solution for variable transmission.

According to minimize the weight and size of the transmission, reliability and simplicity of the scheme, two line planetary gear with built-in variable-speed drive can consist of either one or two planetary alignments. More simple scheme with one planetary set unable to enforce a constant value of parallel power flow going through a variable speed drive on a range of change of transmission gear ratio. In addition, the one planetary set more likely the occurrence of the circulation of power.

The main advantage of planetary mechanism with two sets is the possibility of implementing a wider number of variants of division of the power flows with the exception of circulation due to the combination of ratios of each set. Therefore we conduct synthesis for this planetary mechanism design.

The planetary mechanism, consisting of two sets has 6 sections and 4 degrees of freedom, contain leading, slave, and supporting units. This transmission is divided into acyclic and single-circuit. The circuit is called a closed path, passing over two or more serially connected among themselves the main moving parts. Therefore, it is necessary to exclude 3 degrees of freedom - one of the links must be retarded, and two pairs of links from each row is a tight connection between them. We can have 6 variants for building such mechanism.

Kinematic based in the mechanism of change of transmission gear ratio with built-in variable element will be defined also by the value of gear ratio of the variable-speed drive. Therefore, to change the value of power flux passing through the variator, when his change of gear ratio. So after selecting a scheme of a mechanism of the next stage of synthesis is the calculation of kinematic parameters of the mechanism with integrated variable-speed drive. According to the accepted classification on the basis of reference [2] such mechanisms have the designation RP4 and refer to the planetary mechanisms of the second class. Define the mechanism for this class, with one of the branches of mechanical variable-speed drive, kinematic dependence and dependence of the power flux from the value of CVT gear ratio. The two-row diagram of the planetary mechanism with integrated variable-speed drive and a scheme of distribution capacities are presented in fig. 4.

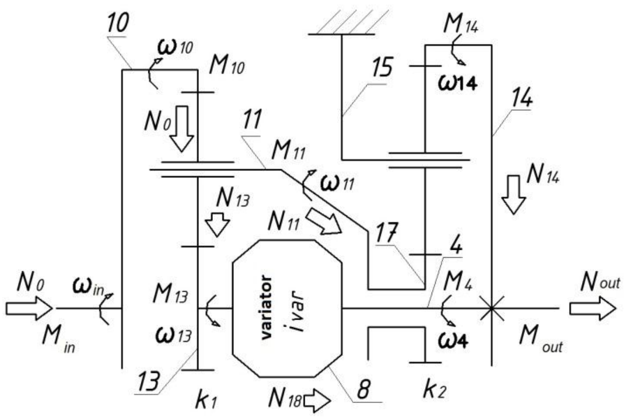


Fig. 4. Power split in planetary mechanism with CVT.

At the conclusion of the kinematic dependencies mechanism with integrated variable-speed drive will mean that the level 3 consists of two parts: level 3' and element 3", in speed of which will be determined by the ratio of the variable-speed drive:

$$\omega'_3 = i_{var} \cdot \omega"_3 \qquad (1)$$

Then equation by Willis for planetary alignments mechanism will be show as:

$$\omega_2 \cdot (1 - i_I) = \omega'_3 - i_I \cdot \omega_1 \qquad (2)$$
$$\omega_4 \cdot (1 - i_{II}) = \omega_2 - i_{II} \cdot \omega"_3$$

where $i_I = -k_I$ и $i_{II} = -k_{II}$ - gear ratio respectively the first and second planetary sets.

We write for the convenience of the equation jeep using the design parameters k and expressing the angular velocity of output variator through his gear ratio:

$$\omega_2 \cdot (1 + k_I) = i_{var} \cdot \omega"_3 + k_I \cdot \omega_1 \qquad (3)$$
$$\omega_4 \cdot (1 + k_{II}) = \omega_2 + k_{II} \cdot \omega"_3$$

Because drove the second planetary some retarded, i.e. ω_4=0, we have:

$$\omega_2 = -k_{II} \cdot \omega"_3 \qquad (4)$$
$$\omega_1 = \frac{\omega_2 \cdot (1 + k_I) - i_{var} \cdot \omega"_3}{k_I} = \frac{-k_{II} \cdot \omega"_3 \cdot (1 + k_I) - i_{var} \cdot \omega"_3}{k_I}$$

Gear ratio of the basic mechanism will be determined by the ratio:

$$i_{13} = \frac{\omega_1}{\omega_3} = \frac{-k_{II} - k_{II} \cdot k_I - i_{var}}{k_I} \qquad (5)$$

The condition of the power equilibrium parts of the mechanism is determined by the relations:

$$M'_3 = \frac{M_1}{k_1} \qquad (6)$$
$$M'_2 = \frac{M_1 \cdot (1 + k_I)}{k_I}$$

$$M_3 = M'_3 + M"_3 = \frac{M_1}{k_1} - \frac{M_1 \cdot (1 + k_I) \cdot k_{II}}{k_I} \qquad (7)$$

Power, held in each of the streams depending on the design parameters:

$$N_2 = M'_2 \cdot \omega_2 = \frac{M_1 \cdot (k_I + 1)}{k_I} \cdot \frac{\omega_1 \cdot k_I \cdot (-k_{II})}{-k_{II} - k_{II} \cdot k_I - i_{var}} = N_0 \cdot \left(\frac{(k_I + 1) \cdot k_{II}}{k_{II} + k_{II} \cdot k_I + i_{var}}\right) \qquad (8)$$

$$N_3 = M'_3 \cdot \omega_3 = \frac{M_1}{k_I} \cdot \frac{\omega_1 \cdot k_I}{-k_{II} - k_{II} \cdot k_I - i_{var}} = N_0 \cdot \left(\frac{1}{-k_{II} - k_{II} \cdot k_I - i_{var}}\right) \qquad (9)$$

I.e. the ratio between the first and the second thread will depend on the ratios of each of the planetary sets in proportion:

$$\frac{N_2}{N_3} = (k_I + 1) \cdot k_{II} \qquad (10)$$

This ratio of power values on parallel links is the most advantageous and convenient because it does not depends on the ratio of the variable-speed drive and remains constant change of frequency of rotation of main rotors. This allows you to select the size of the structural parameters of the planetary series exclusively with the minimum load of links parallel branches.

As you can see from the expression for the ratio of capacity in the branches of the planetary mechanism, minimum power values in the branch containing the variable speed drive can be achieved with maximum values of the structural parameters of the series. Their maximum values are limited constructive thoughts on condition $\frac{4}{3} \leq i_{AB} \leq 4$. Therefore, if the value $k_I = 4$ and $k_{II} = 4$ will have a minimum value $N_{3min} = 0{,}05 \cdot N_0$, where N_0 is input power. However, on the condition of a minimum loading of parts of the variator is imposed additional restrictions associated with the range of gear ratio. According to established performance requirements and functioning of the transmission speed of the helicopter with adjustable rotation of main rotors, the rotational speed of main rotors with increase of speed of horizontal flight should change not less than 30-40%. Therefore, from the adjustable part variable transmission requires a range of change of gear ratio not already than $i_{cvt} = 1 \ldots 1{,}4$. Because, optimal mode of operation for variable of any type is a direct transmission from value of $i_{var} = 1$, and the total ratio of the transmission directly proportional ratio is infinitely adjustable parts, let range $i_{13} = i_{cvt} = 1 \ldots 1{,}4$ at which $i_{13} = i_{cvt} = 1$ variable works as direct transmission - $i_{var} = 1$. The range of the variable, i.e. the ratio of the maximum value of gear ratio to the minimum determined by the design parameters of the planetary alignments. Define the relationship between the range of change of gear ratio of continuously variable transmission and a range of mechanical variable-speed drive built into its branch for the selected scheme RP4-56. For that express the ratio of the variable-speed drive through the gear ratio the transfer:

$$i_{var} = k_{II} + k_{II} \cdot k_I + i_{13} \cdot k_I \qquad (11)$$

Then the range of variable-speed drive D_{var} can be expressed as:

$$D_{var} = \frac{i_{var}^{max}}{i_{var}^{min}} = \frac{k_{II} + k_{II} \cdot k_I + {i_{13}}^{max} \cdot k_I}{k_{II} + k_{II} \cdot k_I + {i_{13}}^{min} \cdot k_I} \qquad (12)$$

where ${i_{13}}^{min}$ corresponds to the direct transmission in the variable-speed drive, i.e.:

$${i_{13}}^{min} = \frac{\omega_1}{\omega_3} = \frac{-k_{II} - k_{II} \cdot k_I - 1}{k_I} \qquad (13)$$

According to the requirements modes of rotors and pushing blades high-speed helicopter rotation speed of the rotor in the transition from hanging to horizontal flight with a maximum speed varies from 220 rpm 160 rpm, i.e.:

$${i_{13}}^{max} = {i_{13}}^{min} \cdot \frac{n_{\mathrm{HB}}^{max}}{n_{\mathrm{HB}}^{min}} = 1{,}375 \qquad (14)$$

Then:

$$D_{var} = -k_{II} - k_{II} \cdot k_I + D_{13} \cdot (k_{II} + k_{II} \cdot k_I + 1) \qquad (15)$$

where $D_{13} = 1{,}375$ - the range of transmission gear ratio.

The technique of synthesis of infinitely planetary transmission with a manual choice can be described by the following main stages:

- select the class and type of the planetary mechanism on the basis of the required values in the number of parts of the mechanism and degrees of freedom, the number of controlled items;
- synthesis of the planetary mechanism, or select an existing directories based on the criteria optimal performance and minimal loading of managed links by calculating noise power along

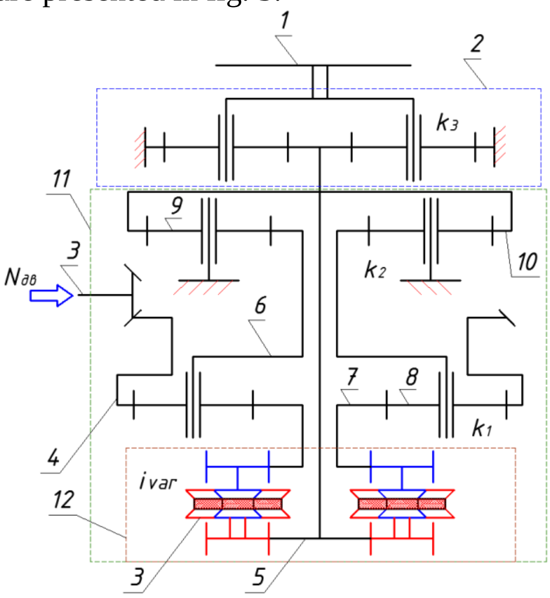
the branches multithreaded mechanism;
- selection of design parameters of the planetary sets based optimization the criteria of a minimum load and range of mechanical variable-speed drive.

4 Optimal scheme of planetary transmission with integrated variable-speed drive

The most advanced design of mechanical variable-speed drive at the moment is the construction of CVT multitronic by Audi company with flexible metal chain, which applied a new technology for joining metal parts. The variable of this type allows conduct a power of 300 kW limit the maximum torque of 400 Nm. Forecast further development of this technology that should allow to transmit power up to 400 kW. The main distinctive feature of this type of CVT is the high reliability and durability, allowing to consider its application in the structure of the transmission of the helicopter.

Therefore, the choice of the values of the structural parameters of the planetary sets need to restrict the maximum value of the range of mechanical variable-speed drives. For the selected scheme of optimal two-row mechanism, in accordance with the above conditions and limitations is the most rational choice of design parameters with value $k_I = 3$ and $k_{II} = 3{,}8$.

For selected values of the structural parameters of the planetary mechanism with continuously variable transmission and a range of progressive transmission gear ratio the transfer will range from i_{13}^{min}=5,4 up to $i_{13}^{max} = 7$. When we have such value of transmission gear ratio then planetary gear cannot be used as the basic level of reduction in transmission helicopters from the engine to the rotor blades, because ratio for the main gearboxes of medium helicopters usually varies in the range of 15 to 60. So in the construction of a main reduction gearbox of helicopter, this transfer can be used as a continuously variable module in combination with an additional degree of reduction, which can be implemented more planetary sets (in combination with bevel gearbox stage at the entrance to main gearbox). This allows to use the transfer as part of the transmission of the helicopter with axial location of the rotor blades and single-rotor helicopters scheme. Furthermore, an additional degree of reduction is also necessary conditions of maximum torque value on the level of variable-speed drive. The amount of torque on the shaft rotor of medium helicopter is 120 000 Nm. When torque limitation on the link variator 400 Nm required total gear ratio from the link variator to rotor blades around 300. This ratio for this scheme continuously variable transmission could not be realised in the transmission of the helicopter, even with an extra degree of reduction. The solution to this problem is the separation of the transmission flow power in the branches of the regulator, i.e. the use of multiple variable-speed drives to change the transmission gear ratio. This decision is an obvious and necessary from the point of view of safety and reliability of transmission, because the variator is the least reliable and critical element in the design of the transmission and requires duplication. In the end, the final version of the CVT transmissions for helicopters with variable speed main rotors are presented in fig. 5.



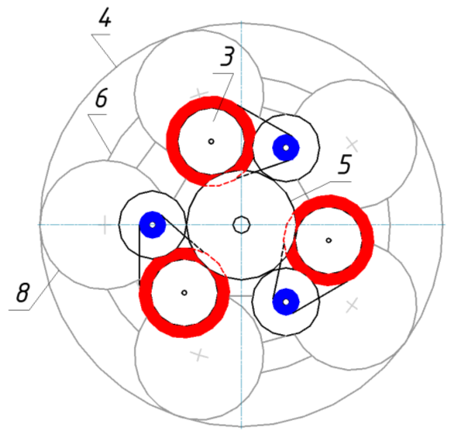


Fig. 5. Scheme of optimal multithreaded planetary transmission design with continuously variable mechanical drive; a - the kinematic scheme, b - arrangement of variable-speed drives.

The diagram presented in fig. 5 identified the following elements: 1 - main rotor; 2 - additional reduction gearbox in transmission; 3 - bevel gear from summarizing gear, transmitting power from two engines to main gearbox; 4 - epicycle gear of first planetary set, combined with bevel gear drive from engines; 5 - the central link of the branches of the variator; 6 - a part of the second branch, which is the planet carrier of the first planetary set and sun gear of the second set; 7 - sun gear of the first planetary set; 8 - satellite of first planetary set; 9 - a satellite of the second planetary set; 10 - epicycle of second gear planetary set; 11 – continuously planetary gearbox; 12 - module system of variable-speed drives. The power from the engine follow through summarizing the transmission enters in bevel gear drive of main gearbox 3, which leads epicycle first planetary set 4. Power in the first planetary set is divided into two streams: through the links, 6, 9 and 10 main branch is held most of the power, as regulated through a branch, consisting of parts 5, 7, and three variable-speed drives held the balance of power. The system of variable-speed drives are arranged according to the scheme, in which three of CVT are situated around the central units, which allows part of the power from level 7 to level 5 is divided into three parts, each of which passes through a variator, thereby decreasing the load. In the variator is a change of gear ratio from level 7 to level 5, which leads to the change in the ratio of frequencies of rotation of all the links in the planetary transmission. In the changing ratio of the entire powertrain, and changing the rotational speed of the main rotor 1. This kinematic scheme of the planetary variable transmission take out patent №142189 (RU) for "Infinitely variable mechanical transmission vehicles".

5 Conclusion

The analysis of optimal design solutions of the high-speed helicopter transmissions identified the basic advantages and disadvantages of each schemes, the main technological and structural problems of the realization of a circuitry for high-speed helicopter transmission with variable gear ratio.
The study shows the inefficiency of electric and electromechanical schemes in the transmission of high-speed helicopter due to the impossibility of avoiding mechanical speed reduction. Problem of transmission mechanism type choice was considered with a view to defining criteria - reliability and stability of transmission; minimize the weight and size of the gearbox, and safety and efficiency at the present stage of technological development. The study demonstrates the preference of mechanical continuously variable transmissions with parallel connection of CVT modules with minimum transmitted power.

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