Rotating blade propellers in prospective aviation technology

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Abstract. The study proposes the use of a new generation of aircraft based on the use of cylindrical rotating blade propellers as a means of transportation. The results of research and development work carried out on several dimensions of cylindrical rotating blade propellers are considered. The results obtained allow us to lay down a certain basis for the theory and practice of the operation of cylindrical rotating blade propellers. In the process of scientific research, an understanding of the role of geometric ratios of rotor elements and the number of blades is obtained. The limits of the angle of attack and thrust vector deflection are defined. The requirements for structural strength and stiffness of the rotating blade propeller parts are formed. The solution of the kinematic mechanisms for controlling the angles of attack of the blades and flaps, and the thrust vector in general, etc., was formed. A conceptual image of a two-seat aircraft using cylindrical rotating blade propellers is proposed. Bench tests of the cylindrical rotating blade propellers allowed the formation of tactical and technical requirements for the two-seat aircraft. It is suggested that further research be considered to determine design solutions for promising aircraft of greater payload and capacity.

1 Introduction

In the normative documents of the Russian state, including “On National Development Goals of the Russian Federation until 2030”, “On National Security Strategy of the Russian Federation”, “Transport Strategy of the Russian Federation until 2030 with the forecast for the period up to 2035”, as well as in a number of other legal acts, tasks related to the development of the transport industry in the Russian Federation were set, including increasing access to safe and quality transport services with minimal impact on the

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environment and the climate; increasing spatial connectivity and transport accessibility of territories and mobility of the population; strengthening the leading positions and competitive advantages achieved by the Russian Federation in the aviation industry; and some other important tasks [1-4].

The solution to these tasks will require the use of new and latest advances in technology, including aviation. Developing a new generation of vertical takeoff and landing aviation technology based on the use of cylindrical rotating blade propellers is of particular interest.

In this connection, it should be specified that all known aerodynamic propellers can be conditionally divided into two groups, including disk and cylindrical ones. In disk aerodynamic propellers, the working elements (blades) move in a plane perpendicular to the axis of rotation, and in the cylindrical – working elements describe a cylindrical trajectory parallel to the rotation axis. The first group includes the propeller (used in airplanes), the main rotor (helicopters), and the axial turbine (turbojet engines). The best-known cylindrical propellers are the Savonius rotor (which uses the Magnus effect), the Darrier rotor (a type of low-pressure turbine), and also rotating blade propellers [5, 6].

2 Materials and methods

In general, a rotating blade propeller is a device for generating the lifting and traction forces of an aircraft. It structurally looks like a cylindrical rotor, around the circumference of which wing-shaped blades are arranged at equal angular distances, which make circular movements together with the rotor and oscillatory movements around their axes, which lie on the cylindrical surface of the rotor. The oscillating movements of the blades on the rotor rotation cycle, are set by the eccentric mechanism, which are transmitted by the control system (Fig. 1). The rotation of the rotor is driven by an external motor [6, 7].

The most famous aircraft using cylindrical rotating blade propeller are such aviation constructions as engineer Strandgren’s aircraft; Cyclogyro flying machine (by E. A. Schroeder); Haviland Platt’s cyclogyro; John B. Whitley’s cyclogyro; John B. Wheatley’s cyclogyro; A. Rohrbach’s cyclogyro; Frederick K. Kirsten’s cyclogyro; and several other aircraft [6, 8, 9].

At present, the Austrian company IAT21 has achieved some success in the use of rotating blade propellers in aircraft technology. In 2012, it tested an aircraft with a diesel engine with a total mass of 200 kilograms and a payload capacity of 100 kilograms [10].

In the Russian Federation, work on the creation of an aircraft based on the use of a cylindrical rotating blade propeller is being carried out by the “Arey” research group on an initiative basis (started in 2002). It conducts R&D on the design of an air transport vehicle for use in urban environments without reference to an airfield location [11].

In the process of ongoing research, the task of creating a new type of urban transport infrastructure. It can be conventionally called a 3D transport environment. It will include air, ground, and underground transport components.

In the process of ongoing research, certain requirements were formed for a promising air transport vehicle based on rotating blade propellers, which will be massively operated in urban areas. These requirements include.

The presence of an aircraft with vertical take-off and landing. This will allow the hover mode to be obtained, as well as the desired level of horizontal and vertical maneuvering. This requirement is important for urban conditions.
Fig. 1. Design of the rotating blade propeller (a) and scheme of its operation (b) [5].

The acceptable noise level during operation. The low noise level will allow, without violating medical requirements, the operation of a significant number of aircraft in urban areas. All this will allow forming stable passenger flows not only in the city but also in the nearest suburbs.

Small dimensions of the aircraft. Its small dimensions will allow organizing a significant number of locations for its deployment. In turn, this will make takeoff and landing sites practically within walking distance access to the urban population, and thus allow for more mass use of the aircraft in urban areas.

The prospective aircraft must have a high level of safety. This implies a minimum number of hazardous rotating parts in the design. The aircraft must have an emergency automatic rescue system. At the same time, the aircraft itself must have a high level of operational reliability.

Not unimportant is the possibility of partial or complete unmanned aircraft. Such a requirement will reduce operating costs, which is significant. In addition, it will allow the aircraft to be built into the current urban passenger traffic on the principles of an automated control system. All of this will combine to reduce the overall cost of operating these aircraft.

We must not forget about the environmental friendliness of the operation, as well as the production and disposal of promising aircraft. Only materials that are not harmful to the environment should be used in its construction.

Of course, there may be other requirements for the prospective aircraft, including design, performance, further utilization, etc. However, the listed requirements are still basic in existing conditions.

3 Results

To determine the optimal dimensionality of both the cylindrical rotating blade propeller and the aircraft itself, the R&D was conducted on the conditions of a gradual increase in the dimensionality of the rotating blade propeller. Initially, a cylindrical rotating blade propeller with a diameter of 0.15 m and a length of 0.18 m was considered. In the process of research, different profiles were considered, including a vortex stepped profile, combinations of different numbers of blades, angles of attack, and rotation speeds [6, 12].

At the next stage of the design of the cylindrical rotating blade propeller, its diameter was increased to 0.5 m. During the R&D process, blades with variable profile curvature
were considered. These studies laid the foundation for the theory and practice of rotating blade propellers. These include understanding the role of geometric ratios of rotor elements and the number of blades. Attack and thrust vector deflection adjustment limits were determined. There is an understanding of the strength requirements for the construction and the stiffness of its parts. A vision of the kinematic mechanisms for controlling the angles of attack of the blades and flaps, the thrust vector as a whole, etc., was formed. All this in general has given a certain opportunity to design aircraft of different sizes, using the rotating blade propeller, including from the unmanned version to the transportation of several dozens of passengers over significant distances [6, 12].

A definite milestone in the design of the cylindrical rotating blade propeller was the propeller with a diameter of 0.78 m with six blades and their length of 0.85 m. The surface area of the cylinder was 2 m² with a total rotor weight of 15 kg and a power of 9 kW. The speed of the rotating blade propeller was 1,400 rpm. The calculated thrust from the rotor reached 50 kg, and the specific thrust from the power was 6 kg/kW. The chord of the blade was 0.12 m. Profile – 18%. The thrust per unit cross-sectional area was 75 kg/m². The dimensionless $C_t$ coefficient, reduced to the rotor cylinder area, was 0.13 (Fig. 2) [12].

The following control elements and mechanisms are provided in a cylindrical rotating blade propeller with a diameter of 0.78 m, including a built-in machine for cyclic change of geometric angles of attack of blades; control of the drive for changing the total angle of attack of blades; thrust vector control; automatic blade profile curvature control [6, 12].

The values of parameters of the investigated cylindrical rotating blade propeller obtained at the test bench exceed the characteristics of products of other research groups by a complex of indicators (Table 1) [6, 12]. The table shows the characteristics and parameters of disk and cylindrical devices, which allows concluding that the cylindrical rotating blade propellers are not inferior to disk devices in terms of the main parameters. At the same time, the tested aircraft model designs with cylindrical rotating blade load-bearing propellers demonstrate the fulfillment of the necessary flight requirements for vertical take-off and landing air vehicles.

Based on the mathematical modeling of the capabilities of the prospective aerial vehicle, we can already conclude that it is superior to similar multicopters in terms of a number of key parameters. In particular, with the same dimensions and takeoff weight, the prospective aircraft requires less engine power with almost twice the payload [6, 12].

In the terms of reference for the design of cylindrical rotating blade propellers and aircraft using them there are certain requirements for materials. It is planned that the main structural material will be aluminum alloys up to 73% of the total weight. Alloy steels will account for up to 11%, composites up to 4%, and other structural materials up to -12%.

Fig. 2. Cylindrical rotating blade propeller with a diameter of 0.78 m Source: [12].
The actual refusal of mass use of composite materials is connected with the problem of their further utilization. Therefore, the most promising material, including in terms of ecology, is the use of aluminum alloys. There are no problems with their disposal. At the same time, the energy input in obtaining the finished metal during the recycling of aluminum structural elements is about 20 GJ/t (the energy input for obtaining primary aluminum is 174 GJ/t) [5].

In general, the energy efficiency of the cylindrical rotating blade propeller will be determined by the selection of geometric and aerodynamic parameters of the blade, including the profiles and their characteristics, dimensionality, ability to adapt the curvature along the rotation cycle, etc. And also the use of the optimum law of blade oscillation, realized through an adequate mechanism, differentially setting the angles of attack of the blades along the rotation cycle.

The rotating blade propellers must be equipped with devices for adjusting the blade oscillation angles to changes in the parameters of the approaching medium. In turn, the control of the aircraft motion will be provided by the eccentric mechanism, which allows changing the direction of the thrust vectors of the rotors.

Structurally, the rotating blade propeller forms a thrust vector across the axis of rotation, which allows creating the thrust force in any required direction, changing it from 0° to 360°. This design feature provides vertical takeoff and landing of the aircraft, as well as the transition to horizontal movement with a smooth climb or descent. And in horizontal flight, it allows the transition from forward motion to reverse motion, as well as hovering and spinning, without turning [6].

<table>
<thead>
<tr>
<th>Device type</th>
<th>Device characteristics</th>
<th>Traction parameters of devices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overall dimensions, m</td>
<td>Power consumption, kW</td>
</tr>
<tr>
<td>Disk devices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main rotor (coaxial)</td>
<td>D 7.2</td>
<td>73.5</td>
</tr>
<tr>
<td>Traction screw</td>
<td>D 1.8</td>
<td>48.0</td>
</tr>
<tr>
<td>Cylindrical devices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotating blade propeller</td>
<td>0.5×0.5</td>
<td>0.55</td>
</tr>
<tr>
<td>(Korea)</td>
<td>1×1.7</td>
<td>23.5</td>
</tr>
<tr>
<td>Rotating blade propeller</td>
<td>1.2×1.2</td>
<td>70.0</td>
</tr>
<tr>
<td>(Austria)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotating blade propeller</td>
<td>0.85x0.78</td>
<td>5.2</td>
</tr>
<tr>
<td>(Russia, Krasnovarsk)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: [5, 12].

### 4 Discussion

In the process of research and development, the Arey research group proposed a conceptual image of a two-seat aircraft using rotating blade propellers. It was called the “Cyclolet”. The aircraft has a three-rotor aerodynamic scheme. There is a cabin capsule between the two front cylindrical rotors. The third cylindrical rotor is located in the aft part of the cockpit capsule. The aircraft has a skid-steer undercarriage. Evolutions control is provided by an eccentric mechanism, changing the direction of thrust vectors of cylindrical rotors (Fig. 3) and the rotation frequency of rotors [6, 13].

| Table 2. Tactical and technical requirements for a 2-seat air transport vehicle of the “Cyclolet” type.

<table>
<thead>
<tr>
<th>Device type</th>
<th>Overall dimensions, m</th>
<th>Power consumption, kW</th>
<th>Load on the swept area, kg/m² (consumer properties)</th>
<th>Specific thrust, kg/kW (energy efficiency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main rotor (coaxial)</td>
<td>D 7.2</td>
<td>73.5</td>
<td>17.7</td>
<td>9.7</td>
</tr>
<tr>
<td>Traction screw</td>
<td>D 1.8</td>
<td>48.0</td>
<td>75.0</td>
<td>3.75</td>
</tr>
<tr>
<td>Rotating blade propeller</td>
<td>0.5×0.5</td>
<td>0.55</td>
<td>16.8</td>
<td>7.7</td>
</tr>
<tr>
<td>(Korea)</td>
<td>1×1.7</td>
<td>23.5</td>
<td>16.8</td>
<td>6.3</td>
</tr>
<tr>
<td>Rotating blade propeller</td>
<td>1.2×1.2</td>
<td>70.0</td>
<td>142.0</td>
<td>2.9 (2016)</td>
</tr>
<tr>
<td>(Austria)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotating blade propeller</td>
<td>0.85x0.78</td>
<td>5.2</td>
<td>30.0</td>
<td>5.8</td>
</tr>
<tr>
<td>(Russia, Krasnovarsk)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Indicators</td>
<td>Indicator values</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Takeoff and landing</td>
<td>vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Speed range</td>
<td>from 0 to 200 km/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Rate of climb</td>
<td>up to 10 m/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Necessary movements</td>
<td>forward-backward, up-down, horizontal rotation on the spot in both directions, hover mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Stability and ability to be controlled in wind speeds</td>
<td>up to 20 m/s;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Deviation in any coordinate under external perturbation of the medium</td>
<td>no more than 1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Consumption of fuel and lubricants at maximum takeoff weight;</td>
<td>no more than 12-15 l/h</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Capacity (total)</td>
<td>up to 5000 hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>MTBF of main elements</td>
<td>up to 2000 hours</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: [6, 12].

In the process of R&D on the development of a promising Cyclolet-type aircraft, a number of advantages over classical helicopters were identified, including low noise, low visibility, maneuverability, high specific characteristics, ability to dock to vertical and inclined surfaces, multitasking and multifunctionality, all-weather capability, ability to operate in difficult, mountainous and urban conditions, compactness, safety, security [6, 12].

Fig. 3. Cyclolet-type two-seat aerial vehicle based on cylindrical rotating blade propellers [6, 12].

In addition, during bench tests of the cylindrical rotating blade propeller, technical requirements were formed, which allowed forming the following tactical and technical requirements for the 2-seat aircraft using these propellers (Table 2).

### 5 Conclusion

In general, the preliminary flight characteristics of the Cyclolet vertical takeoff-landing aerial vehicle with a load-bearing and propulsion system based on rotating blade propellers allow us to conclude that the proposed design solution of the promising aerial vehicle can
be taken as a basis for its use in urban agglomerations. Its widespread use under these conditions will allow forming a 3D-type transport environment in cities, not only in the Russian Federation but also beyond its borders.

At the same time, the above basic characteristics of the Cyclolet aircraft are not final. Additional research and development work is required. In particular, the effect of several (3, 4, 6, or more) working rotors on each other has not yet been fully studied. With the increase in the number of rotors in the aircraft, the tactical and technical characteristics will change. In addition, it is necessary to optimize the overall dimensions of the rotors themselves, both in length and diameter, determine their size range, etc. [14, 15].

In general, the obtained tactical and technical characteristics of the vertical take-off-landing Cyclolet-type aircraft with the load-bearing and propulsion system based on rotating blade propellers allows us to conclude that this direction of aviation technology development is quite promising. Work in this direction allows the Russian Federation to develop promising high technologies not only in aviation but also in related industries.

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