VERTICAL TAKE-OFF DEVICES WITH JET-VORTEX LIFT GENERATORS

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ABSTRACT

A theoretical and calculational substantiation of a possibility of implementing a qualitatively new design scheme of an aircraft of vertical take-off, in which the lifting force is initiated by a single vortex, artificially created over the aircraft, and the resulting static pressure drop above and below the device is presented. Decisions on vortex flows generated by a rotating disk and tornado-like vortexes arising in the atmosphere are analyzed. Layout schemes of an apparatus for vertical take-off of two types are proposed – with vortex and jet-vortex lift generators. In both schemes, it is supposed to use vertically mounted bi-rotor drive motors, in which both the rotor and the stator rotate, but in mutually opposite directions.

Keywords: *aircraft, vertical take-off, vortex flows in gases, tornado-type vortices, methods of generating vortices, bi-rotor turbojet engines, lifting force.*

Background. *The purpose of the study is to evaluate (analyze) the possibility of implementing design schemes for the aircraft of vertical take-off that differ from the helicopter design, the only one used in practice, when the lifting force is generated by a rotor [1, p. 23].*

The relevance of the topic is due to at least two reasons:

• firstly, the design of a drone aircraft with a rotor, in essence, eliminates significant changes in the mass and size characteristics of the device compared to the traditional helicopter scheme: in particular, the parameter ωl (ω – angular velocity of rotation of the propeller, l – length of the propeller blade) cannot exceed the sound speed in the air [2, p. 866];

• secondly, from the mechanics of continuous media [3, pp. 295–298] it is known that in natural conditions there are relatively stable vortex currents, including single isolated currents of «tornado» type [4, pp. 49–51], in which (throughout the volume of the vortex), reduced static pressure ($\Delta p = 1/2\rho u^2$) is realized.

When artificial generation of such a vortex above the aircraft takes place, the pressure drop under and above the apparatus should lead to the emergence of the lifting force, which increases with the size of the vortex and the air speed in it. That is, a single vortex generator, localized above the aircraft, is promising for vertical take-off conditions. In this case, realization of the idea itself is basically reduced to the problem of generating a stable local vortex, which is comparable in scale with the size of the upper shell of the aircraft.

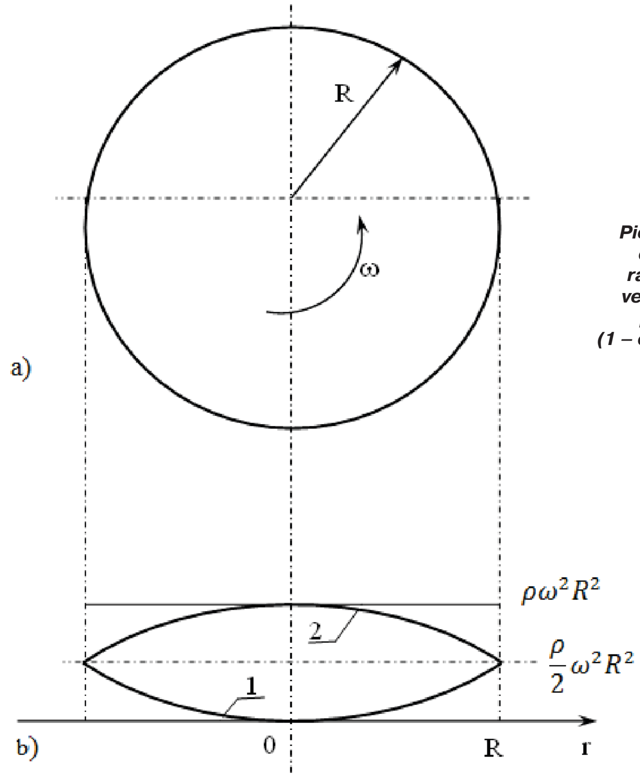
Objective. *The objective of the authors is to consider vertical take-off devices with jet-vortex lift generators.*

Methods. *The authors use general scientific and engineering methods, comparative analysis, mathematical and physics methods.*

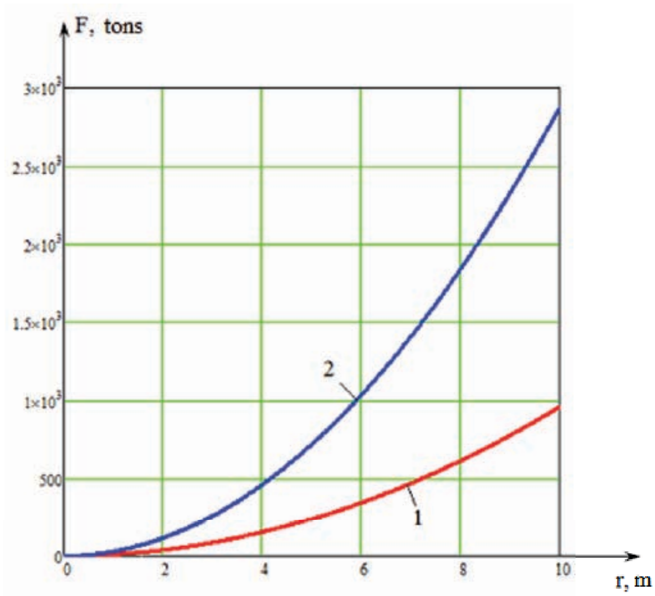
Results.

1. The flow of gas carried by a rotating disk

In the scientific literature [5, pp. 97–100], an analytical solution is given to the problem of the flow



Pic. 1. Illustration to the problems of vortex currents: a) a disk of radius R rotating with an angular velocity ω, b) distribution of static pressure drop over the radius (1 – on the surface of the rotating disk, 2 – in a tornado-type vortex).



Pic. 2. The dependence of the upper limit of the lifting force on the radius of the disk (1 – the upper limit of the lifting force during the initiation of a vortex by a rotating disk, 2 – the vortex component of the lifting force, initiated by a tornado vortex).

of gas carried by a rotating disk. A schematic illustration of the task is presented in Pic. 1.

A disk of radius R and thickness $t << R$ rotates at an angular velocity of ω (rad/s). Due to viscosity, the disk entrains motion of adjacent gas layers, so that in both half-spaces separated by a disk, two three-dimensional flows with non-zero (in cylindrical coordinates) velocity components – radial v_r, circular v_ϕ and axial v_z and boundary conditions – are formed:

- *on the disk surface $z = 0$, $v_\phi = \omega r$, the rest are 0;*
- *at infinity $z = \infty$, $v_z = v_r = v_\phi = 0$.*

In the above mentioned scientific sources, the Navier–Stokes equations for the velocity components v_z, v_r, v_ϕ and static pressure p are numerically solved.

The boundary conditions on the disk surface allow us to estimate the upper limit of the lifting force created by the vortex, namely, the static pressure at the points of a circle of radius r according to the Bernoulli equation:

$$p = p_0 - \frac{\rho}{2}\mathrm{v}^2 = p_0 - \frac{\rho}{2}\omega^2 r^2,$$

so that, $\Delta p = p_0 - p = \frac{\rho}{2}\omega^2 r,$

where p_0 – total pressure (rest).

If a vortex is created only on one side of the disk, then the total force due to the differential static pressure between the surfaces of the disk is:

$$F = \int_0^R \Delta p(r) ds = \pi\rho \int_0^R \omega^2 r^3 dr = \frac{\pi\rho\omega^2}{4} R^4, \qquad (1)$$

where $ds = 2\varpi r dr$ – ring element of the area.

When implemented, the linear velocity at the periphery of the disk should not exceed the speed of sound, i.e. $\omega R \le v_{sound} \cong 300$ m/s, and in this case

$$F_{max} = \frac{\pi\rho \mathrm{v}_{sound}^2}{4} R^2. \qquad (2)$$

Pic. 2 shows the dependence of the upper boundary F on the radius R, calculated from (2). The upper limit of the lifting force generated by the disk above the aircraft is at least not inferior to the lifting force of the rotor of the helicopters of the traditional layout of a comparable size. This circumstance alone justifies the analysis performed, especially since the vortex created by the rotating disk is the simplest known.

The purely rotational movement of air with a peripheral velocity $v_\phi = \omega r$ and the zero radial and axial components ($v_z = v_r = 0$) is realized only on the surface of the rotating disk. As the distance from the surface increases, the circumferential component rapidly decreases, and the other two components become non-zero, but small in absolute values. The characteristic size at which a significant change in velocity occurs is the thickness of the boundary layer

$\delta = \sqrt{\frac{\nu}{\omega}}$ *[6], where ν – coefficient of kinematic viscosity of air, ω – angular velocity of rotation of the disk, with $\omega \cong 10$ rad/s – $\delta \cong 1$–$1{,}5$ mm.*

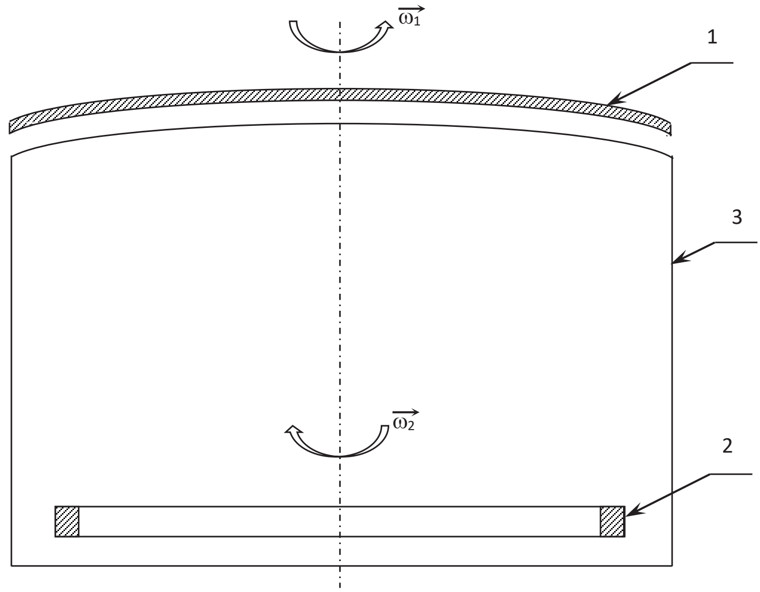
It follows from the solutions given in [5, pp. 97–100; 6, pp. 111–113] that even at distances of 3–5 thicknesses of the boundary layer, the air velocity is several times lower than the peripheral velocities of the corresponding points of the disk, so that the decrease in static pressure becomes negligible.

A rotating disk initiates rotation of gas on both sides (planes), which means that in the case of an isolated disk, no pressure differential occurs on it.

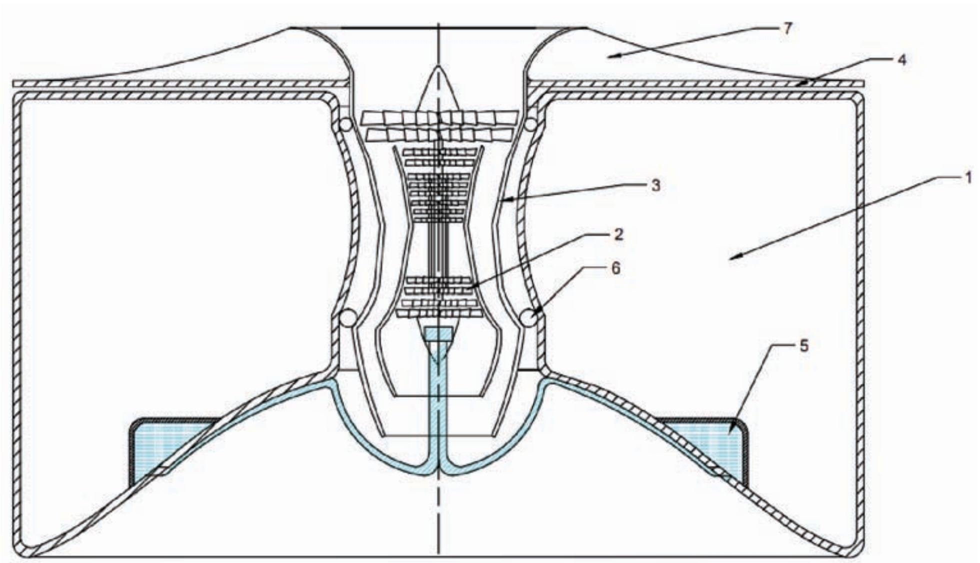
Two circumstances described significantly complicate the technical implementation of the generator (creation) of lifting force only by a rotating disk.

In the model, the scheme of which is shown in Pic. 3, the simplest way to solve these problems is to minimize the gap between the disk and the body of the aircraft. When reducing this gap to thickness of the boundary layer, there will be no static pressure drop on the disk itself, but the vacuum over the disk, and therefore over the aircraft, will remain. Moreover, the lifting force will occur due to the pressure drop under and above the apparatus.

The ideal limiting case of reducing the gap is the option in which the disk rotates close to the upper



Pic. 3. Model of the device with a vortex disk generator over the top surface (1 – device body, 2 – vortex generator disk, 3 – kinetic moment flywheel-compensator).



Pic. 4. Aircraft layout with a fixed disk arrangement (1 – aircraft body, 2 – turbojet engine, 3 – outer shell, 4 – rotating disk, 5 – fuel capacity, 6 – bearings holding the shell, 7 – edge of disk stiffness).

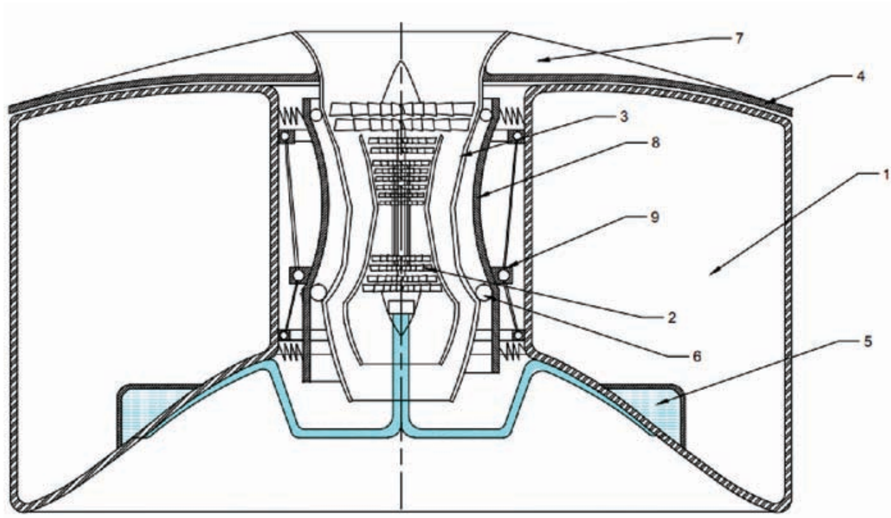
bottom of the body of the aircraft. However, the solution of the problem of eliminating the pressure drop on the disk itself generates a no less complex engineering problem of minimizing friction between the disk and the aircraft body.

Pic. 3 shows a scheme of a model device that implements a vortex flow created by a disk rotating above the device body. The model allows simulating various modes of disk rotation, varying the gap between the disk and the upper shell of the body and allows direct measurements of the lifting force acting on the device.

The model has a hollow hermetic cylindrical body with a flat bottom and flat or slightly convex upper bottoms. A disk is installed above the top head, the radial profile of which repeats the bottom profile. The drive motor (not shown in the picture) is mounted inside the body, its axis of rotation is oriented vertically and it is bi-rotary, as the rotor and the motor stator rotate in opposite directions. The rotation of one of them is transmitted to the disk, the second serves as a compensator of the kinetic moment.

2. Modified bi-rotor «tornado»

From Pic. 1b, it can be seen that in a vortex of the «tornado» type, the decrease in static pressure is much greater than even on the surface of a disk that has the same angular velocity as the vortex. Therefore, the use of «tornado» to create lifting force seems very promising.



Pic. 5. Aircraft layout with swivel plate (1 – aircraft body, 2 – turbojet engine, 3 – outer shell, 4 – rotating disk, 5 – fuel capacity, 6 – bearings holding the shell, 7 – edge of disk stiffness, 8 – swinging sleeve, 9 – hinge-rod fastening sleeves).

In nature, tornadoes in the middle latitudes of the Earth are initiated by a local decrease in atmospheric pressure. The resulting radial currents directed into the zone of low pressure under the action of Coriolis force are twisted and as a result a quasi-stable vortex is formed with emission of air through the axial zone. In the case of artificial generation and twisting of the air, it is necessary to forcibly take air from the axial area. To solve this problem, we have proposed a combination of a modified turbojet engine (TJE) and a disk driven in rotation by the outer shell of TJE.

Pic. 4 and 5 show two draft variants of the aircraft with the described scheme.

The aircraft comprises a body 1, made in the form of a hermetic thin-walled shell, having the shape of a rectangular prism, whose axis is oriented vertically.

A turbojet engine 2, the total length of which from the leading edge of the air intake to the nozzle is approximately equal to the length (height) of the aircraft, is mounted coaxially to the body.

The outer shell 3 with two rows of rolling bearings 6 is fixed either in the aircraft body (general case – Pic. 4) or in the sleeve 8 (Pic. 5), which in turn is fixed in the body by means of a hinge-rod assembly 9 with the possibility of deviating TJE from the vertical positions at an angle of up to 15˚ in all directions (azimuths).

Fixing TJE in the aircraft body or in the sleeve with two rows of bearings, on the one hand, rigidly fixes the position of the engine in the axial direction, and on the other, provides the possibility of rotating the shell around the common longitudinal axis of TJE in the direction opposite to rotation of its rotor (fan, compressor and turbine).

On the leading edge of the outer shell of TJE along the perimeter of the air intake device a disk or plate 4 of small curvature with a bulge upward are fixed, which serve as a generator of a single vortex over the entire surface of the aircraft.

The thickness of the disk or plate is 0,5–1 % of their radius; it is chosen to ensure strength at the maximum speed of rotation of TJE shell. In order to avoid loss of stability associated with the possibility of annular elastic oscillations of the disk, its attachment to the shell is made using stiffeners 7.

The width of the gap between the lower surface of the disk (plate) and the upper, equidistant to it, surface of the aircraft body, does not exceed half the thickness of the disk (plate). The smaller is the width of the gap, the less likely is the occurrence of currents in the gap (beyond the boundary layers on the disk and the aircraft body), reducing the lifting force. Optimal option is installation of the device with a minimum width of the gap allowed by the manufacturing technology, in particular with the width that is variable along the radius of the disk with a minimum near the shell of TJE.

With the described layout of the aircraft fuel supply in TJE through the block of nozzles installed on the outer shell of the engine, is impossible. A purely theoretical version of placement of the fuel tank and the fuel supply system in the rotating shell itself (corresponding to the total thickness) is practically unacceptable, since it implies, firstly, construction of a cavity of significant volume in the shell itself, and secondly, the extremely undesirable placement of fuel itself in the rapidly rotating body, complicating fuel injection in the direction opposite to the centrifugal force acting on it. In addition, the mass of fuel in the shell increases the moment of inertia of the «shell-disk» system and, accordingly, reduces the speed of rotation of the disk which is one of the most important parameters. In the application for the invention, the fuel tank 5 in the form of a toroidal cavity is placed on the lower bottom of the aircraft body, and the fuel lines in the form of several tubes are led to the central shaft of TJE.

Optimization of the layout of the blades of the air intake fan and the blades of the compressor and turbine is performed by known methods [7].

When fuel is fed through the radial holes of the main shaft of TJE, the compressor blades and turbines are mounted on the inner surface of the shell, and the blades of the air intake fan (not involved in spinup of TJE rotor) are preferably mounted on the shaft. In general, the optimal layout of the compressor blades, turbine blades, and fan blades is performed not for the sake of creating the maximum jet propulsion of TJE, but taking into account the maximum rotational *speed of the shell (together with the disk or plate) and the maximum air flow through the air intake.*

The aircraft operates as follows. When TJE is started, its rotor, including the main shaft with the fuel supply system and the fan, and the outer shell (formally the stator) with compressor and turbine blades start to rotate in mutually opposite directions. The flow of combustion products and air from the secondary circuit of TJE creates jet thrust, which in the aircraft is a component of the lifting force.

TJE shell rotates in the direction opposite to the rotor rotation and rotates the disk (plate) rigidly connected to it. The rotating disk, due to viscosity, entrains air, as a result a whirling movement of air occurs over the aircraft. An essential feature of this movement is the external exhaust of air from the central (axial) area, due to the air intake of TJE. There is reason to believe that the radial distribution of the static pressure of a tornado-type vortex above the aircraft is described by the relation

$$p = p_0 - \rho\omega^2 R^2 + \frac{\rho\omega^2 r^2}{2} \text{ [3]},$$

which is fundamentally different from the same distribution over a rotating disk without gas from the axial region and small Reynolds numbers

$$p = p_0 - \frac{\rho\omega^2}{2}.$$

The differential static pressure above and below the aircraft leads to the emergence of the second component of the lifting force $F = \int \Delta p ds$, *where*

$\Delta p_{(2)} = \rho\omega^2 R^2 - \frac{\rho}{2}\omega^2 r^2$, *so that the lifting force is:*

$$F = \rho\omega^2 \int_0^R R^2\, 2\pi r\, dr - \frac{\rho\omega^2}{2}\int_0^R 2\pi r^3\, dr = \\ = \pi\rho\omega^2 R^4 - \frac{\pi\rho\omega^2}{4} R^4 = \frac{3}{4}\pi\rho\omega^2 R^4. \quad (3)$$

Taking, as before, $\omega R_{max} = v_{sound}$, *we have*

$$F = \frac{3}{4}\pi\rho v_{sound}^2 R^2,$$

that is three times the upper limit of the lifting force initiated by the rotating disk. The dependence of this component of the lifting force (excluding the reactive component) is shown in Pic. 2 (curve 2). For the calculation, it is possible to use the ratio $F \cong 21R^2$, *where F is in tons.*

This component of the lifting force is estimated to be at least two orders of magnitude greater than the lifting force due to jet propulsion of TJE.

Conclusions.

1. A calculational and technical substantiation has been made for implementation of an aircraft of vertical take-off of a structural scheme that is fundamentally different from a traditional helicopter, namely, an apparatus in which the lifting force arises as a result of a single vortex artificially created over the apparatus; the rationale includes:

- *comparative analysis of the parameters of two vortex flows, formed by a rotating disk and a tornado vortex;*
- *calculation of the lifting force during creation of a tornado-type vortex above the aircraft and the upper limit of the lifting force arising when the rotating disk is created above the aircraft vortex.*

2. A layout scheme of the aircraft model has been developed, in which a vortex is created by a rotating disk, with any type of bi-rotor engine used as a drive motor (despite the fact that its rotor and stator rotate in opposite directions). The use of a bi-rotor engine removes the problem of kinetic moment compensation. It is shown that the calculated upper limit of the lifting force of the aircraft with a rotating disk as a vortex generator, at least, is not inferior to the lifting force of helicopters of the traditional layout of comparable dimensions.

3. An empirical version of the complex solution of the task of creation of a tornado-type vortex (with minimum pressure in the center) over the aircraft is proposed. A modified bi-rotor turbojet engine is used as a drive in such an aircraft, in which a disk initiating a vortex is fixed on the front edge of the outer shell made rotatable relative to the aircraft body, and the air intake of the turbojet engine, by bleeding air from the vortex axis, lowers the pressure in the center.

4. When limiting the maximum peripheral speed at the periphery of the vortex at the speed of sound ($v_{sound} \cong$ *300 m/s) for two considered options, the calculated formulas for the maximum lifting force in tons were obtained:* $F_{max} \cong 7R^2$ *– for the upper limit of the lifting force with a vortex initiated by a rotating disk, and* $F_{max} \cong 21R^2$ *– for a jet-vortex engine.*

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Article received 24.09.2018, accepted 03.11.2018.