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CALCULATION OF THE GAS-DYNAMIC COMPLEX SIZES

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Abstract**—***In the paper exact and approximation analytical expressions for calculation of the gas-dynamic jets parameters for gas-dynamic complex are obtained. The sizes of gas-dynamic complex for providing of the unmanned aerial vehicle takeoff and landing with help of these expressions be defined. In particular, the relationship between the aerodynamic characteristics of the unmanned aerial vehicle and braking distance in artificial airstream is obtained. The mathematical model of the unmanned aerial vehicle motion in artificial airstream is based on kinematics and flight dynamics equations. Peculiarity of this model is that it is used real function of velocity distribution in a transverse cross-section of axisymmetric flooded.*

Index Terms—Gas-dynamic complex; artificial airstream; conditional boundary of airstream.

I. INTRODUCTION

The area of application of unmanned aerial vehicles (UAVs) weighing more than 20 kg can be expanded by using nonaerodrome take-off and landing. In work [1] – [3], a description is given of the nonaerodrome gas-dynamic takeoff and landing (GTL) method of UAV and features of the implementation of this method are considered.

The equations of motion of UAV are considered in work [1], [3], but their numerical solution is not given.

In addition, in previous works on GTL method, the characteristics of artificial airstream (AA) for braking (or acceleration) UAVs were not determined.

II. PROBLEM STATEMENT

One of the unresolved issues for implementing the proposed method is to determine the size of the gas-dynamic complex (GDC), which realizes GTL method. Firstly, such sizes the horizontal and vertical constituents of AA are determined, which must create a GTL for braking (the UAV in the horizontal and ensuring its "soft" landing (take off) in the vertical plane. The UAV dimensions influence on the size of GDC also, but this question does not consider here.

III. PROBLEM SOLUTION

A. The size of the rectangular parallelepiped

The dimensions of the rectangular parallelepiped AA (Fig. 1) depend on the size of the UAV and its runway characteristics.

The flight of the UAV to the conditional boundary of the AA was carried out in a stationary airflow (turbulence is not taken into account). When the UAV enters to the counter airstream from GDD1, which can be considered as a flooded jet of predetermined sizes, the airspeed of the UAV will decrease.

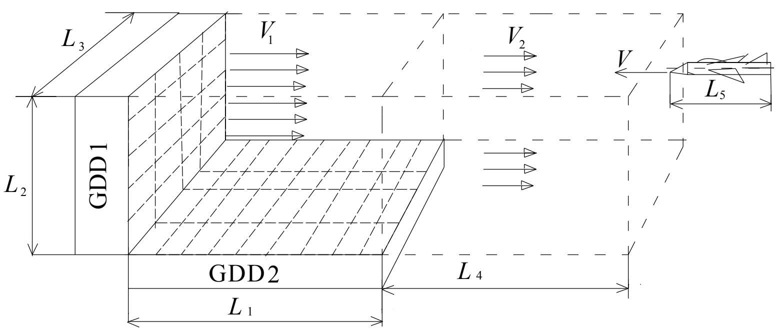

Fig. 1. Conditional boundaries of a rectangular parallelepiped AA: GDD1 is the gas-dynamical device for the creation of AA in the horizontal plane; GDD2 is the gas-dynamical device for creating AA in the vertical plane; L_1 is the length GDD2; L_2 is the height GDD1; L_3 are GDD1 and GDD2 width; L_4 is the distance between the boundary of GDD2 and the conditional boundary with the nonzero speed of the horizontal component of the AA from GDD1; L_5 is the characteristic size of the UAV; V_1 is the an average speed of AA over GDD2; V_2 is the an average speed of the AA in its final part

In what follows we assume that the conditional boundaries of the rectangular parallelepiped AA during take-off and landing of the UAV are approximately the same.

B. Calculation of the vertical dimension of a rectangular parallelepiped

The initial stage of take-off of a UAV is its detachment from a perforated plate and a rise to a given height (Fig. 2) due to the AA's force action from GDD2. Climb of UAV must be made from the perforated walls of the stationary state (position I) to a height $H1$ (position II), which defines an axis of symmetry GDD1, the magnitude of the vertical component of the velocity of the UAV at position II is closely to zero, and acceleration equals zero. Position III in Fig. 2 defines the movement of the UAV with a specified horizontal component of the speed. Similarly, when landing (Fig. 3), the UAV should pull down from the height H_1 (position II) to the perforated baffle (position III), and the speed of the UAV in position II is closely to zero, and in position III must be zero.

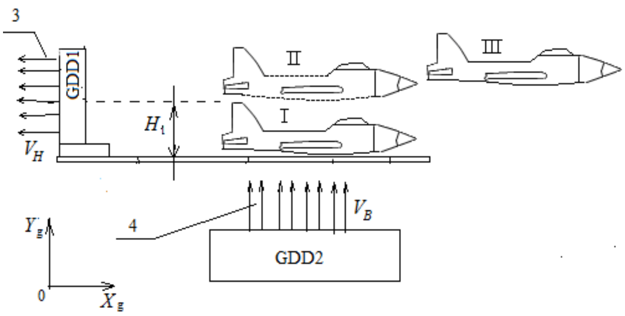

Fig. 2. The functioning of gas-dynamic installation during the take-off phase of a UAV

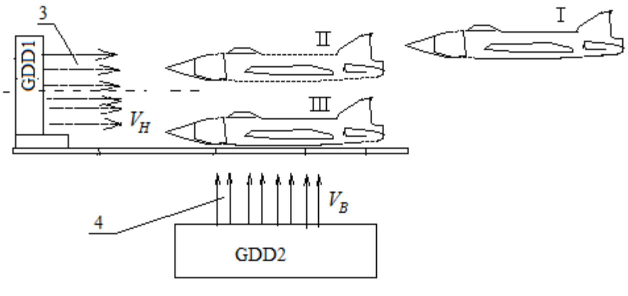

Fig. 3. Functioning of gas-dynamic installation at the landing stage of a UAV

Equation of forces acting on the UAV along the axis OY_g нand the takeoff and landing phase, can be written in the form [1]

$$m\frac{dV_{\text{UAV}}}{dt} = R - G = C_x(\alpha = 90°)\rho\bar{V}_B^2 S/2 - mg, \quad (1)$$

where V'_{UAV} is the acceleration of the UAV along the axis OY_g; m is the mass UAV; $C_x(\alpha = 90°)$ is the aerodynamic drag coefficient of UAV at angle $\alpha = 90°$; ρ is the air density; S is the characteristic UAV area; $\bar{V}_B$ is the speed artificial air flow, created by the GDD2 near the UAV.

It is necessary to solve equation (1) under condition $V_{\text{UAV}}(t = 0)$ and a given restriction by an amount $V_{\text{UAV}}(H = H_1)$ with an unknown function $\bar{V}_B = \bar{V}_B(t)$.

Presenting the speed of the artificial airflow created by GDD2 near the UAV (V'_{B}) in the form of a sum $\bar{V}_B = V_0 + \Delta V$, and ram air with the velocity V_0 = const allows to balance the weight of the UAV (mg), we can be rewritten (1) in the form:

$$\frac{dV_{\text{UAV}}}{dt} = \cancel{\frac{BV_0^2}{2}} + B\Delta V V_0 + \frac{B\Delta V^2}{2} - \cancel{g}, \quad (2)$$

where $B = \left[C_x(\alpha = 90°)\rho S/m\right] = \text{const}$ and the velocity

$$V_0 = \sqrt{2g/B}. \quad (2a)$$

Considering (2), as a quadratic equation with respect to the variable ΔV, we obtain a restriction on the acceleration of the UAV

$$V'_{\text{UAV}} \geq -g. \quad (2b)$$

B.1 An approximate solution of equation (2)

Taking into account that the quantity $\Delta V/2$ can be much smaller than V_0, the summand $B\Delta V^2/2$ we can be neglected and rewrite (2) in the form:

$$\frac{dV_{\text{UAV}}}{dt} = \sqrt{2gB}\Delta V. \quad (3)$$

Magnitude of current height H is defined in the next form

$$dH/dt = V_{\text{UAV}}. \quad (4)$$

The solution of the equations (3), (4) must satisfied four conditions:

$$H(0) = 0, V_{\text{UAV}}(0) = 0, V'_{\text{UAV}}(0) = 0, V'_{\text{UAV}}(H = H_1) = 0. \quad (5)$$

Partial solution of the equations (4), (5) is function $\Delta V = V_1 t - V_2 t^2$, where V_1, V_2 – some constants.

By means of substitution of function ΔV in equation (3) and integrating it under zero initial data it is possible to get

$$V_{\text{UAV}} = \frac{dH}{dt} = \sqrt{2gB}\left[\frac{1}{2}V_1 t^2 - \frac{1}{3}V_2 t^3\right]. \quad (6)$$

After integration of equation (6) under zero initial conditions, we get time dependence climb height

$$H = \sqrt{\frac{gB}{18}}\left[V_1 t^3 - \frac{V_2}{2} t^4\right].$$

Time dependences of climb, velocity and acceleration at $B = 0.0275$ m^{-1}, $V_1 = 5$ m/s^{-2} and $V_2 = 5$ m/s^{-3}, which are calculated by means of MatLab, are shown in Fig. 4.

As it is follows from calculations, maximal magnitudes $H = H(t = 1)$, $V_{\text{UAV}} = V_{\text{UAV}}(t = 1)$, $a = a(t = 0.5)$ depend on values V_1 and V_2 significantly.

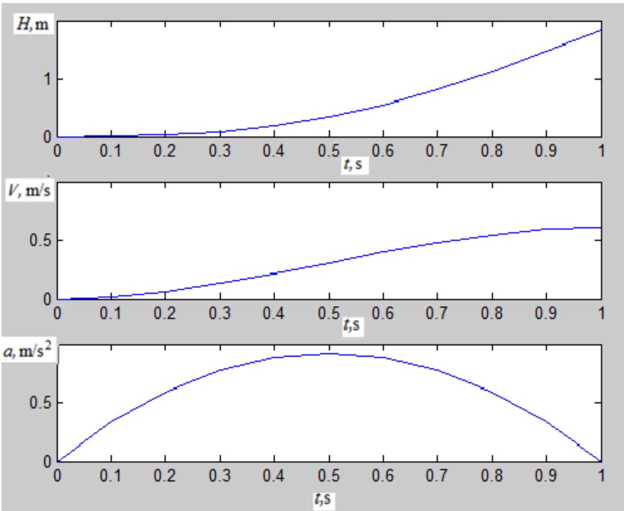

Fig. 4. Time dependences of climb, velocity and acceleration

B.2 Exactly solution of equation (2). Let's rewrite equation (2) with account of (2a)

$$V'_{\text{UAV}} = \sqrt{2gB\Delta V} + B\Delta V^2 / 2. \tag{7}$$

Equations (7) and (4) consist of system, which must satisfy conditions (5).

Introducing designation $V_d = \sqrt{B}\Delta V$ and rewriting (7) in form

$$U'_{\text{UAV}} = \sqrt{2gV_d} + V_d^2 / 2. \tag{8}$$

Expression for function V_d, which is satisfied solution (8) is written down in form

$$V_d = V_p \sin \omega t,$$

where V_p = const, and value $\omega = \text{const}$ defines a frequency of sign chance of the UAV acceleration (Fig. 5). Time dependences of the UAV acceleration is built at $\omega = 1\,\text{s}^{-1}$, V_p = 5 m/s^{-1}. It should be noted that on stage of braking ($a < 0$) at $4 < t$, s < 5 is not fulfilled condition (2b).

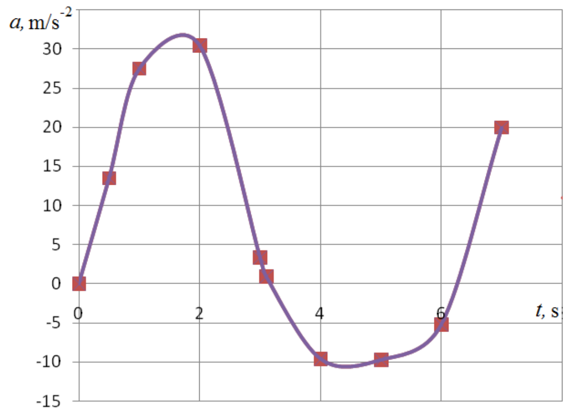

Fig. 5. Time dependences of the UAV acceleration

Comparison of exact (curve 1) and approximate (curve 2) solution (2) is shown in Fig. 6.

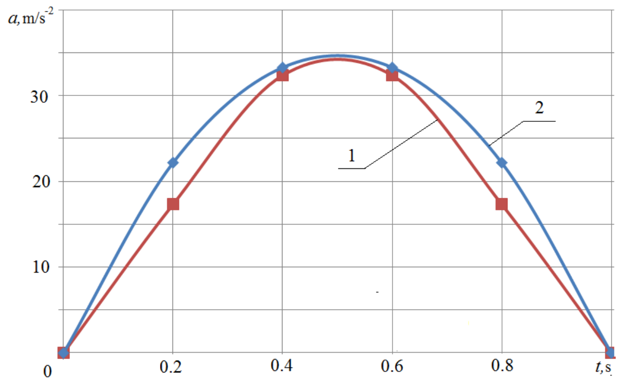

Fig. 6. Comparison of exact (curve 1) and approximate (curve 2) solution (2)

Thus, the equations obtained allow us to calculate the vertical size of AA L_2, which is determined by the value of H_1 multiplied by the safety factor, taking into account the vertical dimensions of the UAV. The wing span of a UAV determines the magnitude L_3.

C. Calculating the length of a rectangular parallelepiped

Calculation of the length of the rectangular parallelepiped AA, which is necessary for the complete deceleration of the UAV in the horizontal plane, we shall make with help of two different methods: an approximate and exact. This length is equal the sum of magnitudes $(L_1 + L_4)$.

C1. Approximate calculation

Let us find the length estimate $(L_1 + L_4)$ under the following conditions: 1) the horizontal flow velocity throughout the parallelepiped is the same $V_1 = V_2 = V_f = \text{const}$; 2) when the AA boundary is reached, the thrust of the engine P is reset; 3) UAV airspeed is equal to $V_{\text{UAV}} = \text{const}$.

Let's also assume that the landing speed of various types of UAVs V_{UAV} can vary in the range from 20 to 50 m/s. Further, we assume that the length of the UAV, as well as the its wingspan, can vary in the range $L_{\mathrm{UAV}} = L_5 \simeq 2...5$ (m).

For preliminary calculations, we assume that the quantity $L_5 = 3\,\mathrm{m}$, and the restriction of UAV braking distance is 10 m, i.e. $L_{br} \le 10$ m.

Further, we assume that the drag coefficient of the UAV $C_x = 1.1$, the mass of the UAV $m = 50\,(\mathrm{kg})$, and the reference area $S \simeq 0.2\,\mathrm{m}^2$.

According to the formula for calculating the resistance force [2]

$$X = C_x \frac{\rho V_f^2}{2} S, \tag{9}$$

where ρ is the air density (near the ground under normal conditions $\rho \simeq 1.25$ kg/m^3).

Substituting the initial data into (9), we obtain the resistance force $X = F_{br} \simeq 124$ (H). According to Newton's 2nd law, in the absence of other forces acting in the horizontal plane, one can write down

$$F_{br} = m a_h, \tag{10}$$

where a_h is the UAV braking acceleration relative to the Earth in the horizontal plane.

To simplify the calculations, we assume that the UAV during deceleration moves with a constant negative acceleration a_h = const, the mass of the UAV does not change also m = const.

In this case, the acceleration value $a = 2.47$ m/s^2 and, according to the equations of uniformly retarded motion, the braking distance L_{br} is 182.2 m instead of given 10 m.

As follows from the analysis of formulas (9) and (10), for a constant UAV mass, the acceleration value is directly proportional to the values C_x, ρ and S.

However, the air density near the Earth's has the maximum value; the magnitude C_x is close to the maximum. With an increase in the reference area of the UAV in 2 times, the stopping distance is also reduced by a factor of 2 and consists of 91.1 m. Since the value of acceleration a_h is proportional to the square of the AA velocity, then an increase in the value V_f affects more effectively by reducing the value of L_{br} (Table I).

TABLE I

THE CALCULATED VALUES OF DISTANCE AND TIME OF BRAKING, ACCELERATION AND OVERLOAD

V_f, m/s	60	90	120
L_{br}, m	22.73	10.1	5.68
t, s	1.52	0.67	0.379
a, m/s^2	19,8	44,55	79,2
n	2,02	4,54	8,07

As follows from the calculations, for velocity of AA greater, then 100 m/s the braking distance satisfies given requirement, i.e. the meaning L_{br} < 10 m and the overload of UAV isn't exceed 9 units at value $V_f = 120$ m/s.

C2. Refined calculation

As an artificial airstream, let us consider an axisymmetric flooded jet [4].

As in the case of *C1* we assume that: 1) when the AA boundary is reached, the air speed of the UAV is equal to V_{UAV}, and the thrust of the UAV engine P is equal zero; 2) the airspeed of the UAV in AA varies linearly relatively time

$$V(t) = V_{\mathrm{UAV}} + a_1 t = V_f, \tag{11}$$

where a_1 = const<0.

The second assumption is based on the fact that the air outside the AA boundaries is stationary, but by the reversibility theorem it can be considered that the UAV is stationary, and the oncoming airflow has a speed V_{UAV}. Thus, the first term in (11) is obtained. At first approximation, the second term in (11) is proportional to time.

For further calculations, let's introduce the following notations:

$$B_1 = \frac{C_X \rho S}{2}; \quad K_1 = B_1 V_{\mathrm{UAV}}^2; \quad \xi = \frac{a_1}{V_{\mathrm{UAV}}}.$$

Now (9) can be written in the form

$$X = B_1 V^2 = K_1 (1 + \xi t)^2. \tag{12}$$

Equation (10) for the acceleration of UAVs in the Earth's coordinate system V_e, with allowance for (12), is written in the form

$$m \dot{V}_e = -X = -K_1 (1 + \xi t)^2. \tag{13}$$

Transforming (13) to the form convenient for integration, we obtain

$$dV_e = -K_0 (1 + \xi t)^2 dt. \tag{14}$$

where $K_0 = \dfrac{K_1}{m} = \mathrm{const}$.

Integrating both parts (14) from the moment when the UAV reaches the AA boundary (t = 0) until the moment of its complete deceleration, when the ground speed of the UAV becomes zero (t = T)

$$I = \int_0^T dV_e = -K_0 \int_0^T (1+\xi t)^2 dt, \qquad (15)$$

and $\begin{cases} V_e(0) = V_{\text{UAV}}, \\ V_e(T) = 0. \end{cases}$

After integrating (15), we obtain

$$0 - V_{\text{UAV}} = -K_0 \int_0^T (1+\xi t)^2 dt .$$

Let's make the change of variable $1+\xi t = z$ and replace the limits of integration in (16), instead of $\begin{cases} t=0, \\ t=T, \end{cases}$ write $\begin{cases} z=1; \\ z=1+\xi T. \end{cases}$

Thus,

$$I = \frac{-K_0}{\xi}\int_1^{1+\xi t} z^2 dz = \frac{K_2}{3} z^3 \Big|_1^{1+\xi T},$$

where $K_2 = -K_0 / \xi$, and correspondingly,

$$I = \frac{K_2}{3}\left[\cancel{1} + 3\xi T + 3\xi^2 T^2 + \xi^3 T^3 - \cancel{1}\right] = -V_{\text{UAV}}. \qquad (16)$$

After the transformation (16), a cubic equation with respect to T is obtained

$$3\xi T + 3\xi^2 T^2 + \xi^3 T^3 - \eta_0 = 0, \qquad (17)$$

where $\eta_0 = 3\xi m / (K V_{\text{UAV}})$.

Dividing (17) by ξ^3 obtain

$$T^3 + \frac{3}{\xi} T^2 + \frac{3}{\xi^2} T - \frac{\eta}{\xi^2} = 0, \qquad (18)$$

where $\eta = 3m / K V_{\text{UAV}}$.

To solve (18) let's make the substitution

$$T = \tau - 1/\xi,$$

after which it will take the form

$$\tau^3 - \cancel{\frac{3\tau^2}{\xi}} + \cancel{\frac{3\tau}{\xi^2}} - \frac{1}{\xi^3} + \cancel{\frac{3\tau^2}{\xi}} - \cancel{\frac{6\tau}{\xi^2}} + \cancel{\frac{3}{\xi^3}} + \cancel{\frac{3\tau}{\xi^2}} - \cancel{\frac{3}{\xi^3}} - \frac{\eta}{\xi^2} = 0,$$

or, after conversion, $\tau^3 = \dfrac{1+\xi\eta}{\xi^3}$, i.e.

$$\tau = \frac{\sqrt[3]{1+\xi\eta}}{\xi}. \qquad (19)$$

Taking for the initial data (ID) the values $C_x = 1.1$, $S \simeq 0.4$ m^2, $m = 50$ kg, $V_{\text{UAV}} = 30$ m/s, $\rho \simeq 1.25$ kg/m^3, according to (19), obtain the dependence of the deceleration time of the UAV from the value a_1 (Table II).

TABLE II

THE CALCULATED VALUES TIME OF BRAKING FROM ACCELERATION

a_1, m/s^2	20	25	30	35	40
T, s	2.04	1.83	1.68	1.55	1.45
L_{br}, m	43.38	32.52	23.07	14.557	6.69

However, this model of calculating the movement of the UAV in the AA requires refinement, because it is possible to perform calculations only with limited ID, in particular, with the selected ID for $a_1 \geq 45$ m/s^{-2} calculated values of L_{br} are negative.

C3. Exactly calculation of braking distance

When studying jets (changes occurring along the jet, velocities, flow rates, temperatures, concentrations), results [3] – [5] are obtained showing that when approaching to the nozzle exit section, the velocity of AA increases in proportion to the distance traveled of the UAV, i.e. can be written

$$V(x) = V_{\text{UAV}} + bx, \qquad (20)$$

where x is the distance traveled by the UAV, and, as in the case of *C1*, we assume that x = 0 at t = 0; b = const –speed increasing coefficient of AA.

In this case, similar to the equation (12) can be written

$$X = B_1 V^2(x) = K_1 (1+\xi_1 x)^2,$$

where $\xi_1 = b / V_{\text{UAV}}$.

Instead of (13), let's write equation

$$m dV_e / dt = -K_1 (1+\xi_1 x)^2, \qquad (21)$$

which together with the kinematic relation

$$dx / dt = V_e, \qquad (22)$$

will make up the system of equations.

Equation (22) can be written in the form $dx = V_e dt$ or $dx / V_e = dt$, i.e. $dV_e / dt = V_e dV_e / dx$. Thus, equation (21) can be rewritten in the form

$$V_e dV_e / dx = -K_0 (1+\xi_1 x)^2. \qquad (23)$$

By analogy with integration (14), after integrating (23) from $x = 0$ ($V_e = V_{\text{UAV}}$) until the UAV's full stop $x = L_{br}$. ($V_e = 0$), we obtain a cubic equation with respect to L_{br}

$$L_{br}^3 + \frac{3}{\xi_1} L_{br}^2 T^2 + \frac{3}{\xi_1{}^2} L_{br} T - \frac{B_2}{\xi_1{}^2} = 0, \tag{24}$$

where $B_2 = (3V_{\text{UAV}})/(2K_1)$.

To solve this equation, let's make the substitution

$$L_{br} = L_0 - 1/\xi_1,$$

after which obtain the solution of (24) in the form

$$L_{br} = \frac{\sqrt[3]{1 + B_2\xi_1}}{\xi_1} - 1/\xi_1. \tag{25}$$

The formula obtained (25) for calculating the stopping distance with account of the UAV sizes, makes it possible to calculate the length of the gas-dynamic device.

Dependences of the braking distance from the value b with given ID at different magnitudes of UAV landing velocity is shown in Fig. 7.

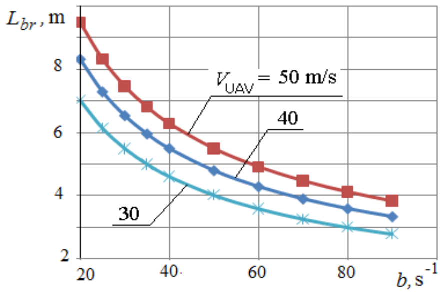

Fig. 7. Dependences of the length of the braking distance from the value b

V. Conclusion

In the paper exact and approximation analytical expressions are obtained, which allow calculate parameters of the gas-dynamic jets for providing of the UAV takeoff and landing. Calculation of these parameters is necessary to determine the dimensions of the gas-dynamic device and to choose the location for its placement. Both length and vertical dimensions of the device depend on parameters of the gas-dynamic jets and the UAV sizes, but width of this device depends on the UAV sizes only, first of all, from wingspan.

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М. Ф. Тупіцин, С. О. Малахов, Е. А. Кримов. Розрахунок розмірів газ-динамічного комплексу

Отримано точні і наближені аналітичні вирази для розрахунку параметрів газодинамічних струменів для газодинамічного комплексу. За допомогою цих виразів визначено розміри газодинамічного комплексу для забезпечення зльоту і посадки безпілотного літального апарату. Зокрема, отримано зв'язок між аеродинамічними характеристиками безпілотного літального апарату і відстанню гальмування в штучному повітряному потоці. Математичну модель руху безпілотного літального апарату в штучному повітряному потоці побудовано на базі рівнянь кінематики і динаміки польоту. Особливість описаної моделі полягає в тому, що вона використовує реальну функцію розподілу швидкості в поперечному перерізі осесиметричного затопленого струменя.

Ключові слова: газодинамічний комплекс; штучний повітряний потік; умовна межа повітряного потока.

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Напрям наукових досліджень: динаміка польоту, експериментальні методи аеродинаміки.
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Н. Ф. Тупицин, С. О. Малахов, Е. А. Крымов. Расчет размеров газодинамического комплекса

Получены точные и приближенные аналитические выражения для расчета параметров газодинамических струй для газодинамического комплекса. С помощью этих выражений определены размеры газодинамического комплекса для обеспечения взлета и посадки беспилотного летательного аппарата. В частности, получена связь между аэродинамическими характеристиками беспилотного летательного аппарата и расстоянием торможения в искусственном воздушном потоке. Математическая модель движения беспилотного летательного аппарата в искусственном воздушном потоке построена на базе уравнений кинематики и динамики полета. Особенность описанной модели заключается в том, что она использует реальную функцию распределения скорости в поперечном сечении осесимметричной затопленной струи.

Ключевые слова: газодинамический комплекс; искусственный воздушный поток; условная граница воздушного потока.

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