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Andrii Zirka PhD,
Central Research Institute of
Armament and Military Equipment of Armed
Forces of Ukraine, Kyiv, Ukraine.
orcid.org/0000-0001-5304-2894
e-mail: alzirka@ukr.net;

Mariia Zirka PhD,
Central Research Institute of
Armament and Military Equipment of Armed
Forces of Ukraine, Kyiv, Ukraine.
orcid.org/0000-0003-2915-3011
e-mail: zirkamaria23@gmail.com;

Natalia Kadet
National Aviation University, Kyiv, Ukraine.
orcid.org/0000-0003-2954-6325
e-mail: kadet-nata@ukr.net

ENSURING SPEED STABILITY OF THE UNMANNED AERIAL VEHICLE IN DIFFERENT FLIGHT MODES

Introduction

Modern UAVs are capable of performing a wide range of specific tasks, while the most common task, regardless of the intended purpose of the UAV, remains remote observation (monitoring) of certain areas of the earth's surface [1]. In this case, as a rule, requirements are put forward for the choice of optimal flight modes in terms of range and duration to ensure the required time and observation area [2]. Under these conditions, the question arises of the correct choice of the flight mode (speed and altitude) and ensuring acceptable stability and controllability, in particular, stability in speed.

Speed stability is understood as the ability of the UAV to maintain a given flight speed in the presence of various disturbances without operator (autopilot) intervention [3]. This property is most in demand when flying along a given route at the most advantageous mode, when maintaining a constant speed provides the greatest range / duration of flight [4].

An unstable/unstable UAV in speed will deviate from the set speed in one direction or another, fuel consumption will increase, and the range and duration of the flight will be reduced.

Sometimes the need for accurate speed control is due to other circumstances: the requirements for using a target load, tactics of UAV combat use, weather conditions, etc.

Two modes of flight are of most interest in the study of stability [5]:

– steady rectilinear horizontal flight along a given route, which is maintained by the operator not only

with the help of the engine thrust control lever, but also with the help of controls in order to ensure a constant altitude ($H = \text{const}$), vertical speed ($V_y = 0$), roll exclusion ($\gamma = 0$) and sliding ($\beta = 0$);

– free flight of the UAV, specified by the operator, without further intervention in the control.

In both cases, the UAV may go beyond the established limits, and it becomes necessary to consider in more detail their physical nature and flight safety issues.

Let's consider the features of each of these cases.

Analysis of the latest research and publications

It should be noted that a large number of publications and research papers are devoted to the development of the theory of evaluation and speed stability of the UAV in different flight modes. Thus, in [3, 5] the main questions of flight dynamics and combat maneuvering of aircraft are presented. The physical interpretation of types of stability, as well as particular criteria of controllability, are given. In [1, 4], special features of the calculation of aerodynamic and flight-technical characteristics of UAVs, including issues of ensuring stability and controllability, are presented.

Formulation of the problem

However, despite the sufficiently developed scientific and methodological apparatus in the field of research of UAV stability at speed, a number of scientific and practical issues remain unresolved. So, in contrast to piloted aircraft when controlling UAV

operator (external pilot) may encounter flight in the second modes much more often than the pilot of the piloted aircraft. It can be connected with peculiarities of requirements to flight mode, long-term flight mode (for maximum duration) on the most advantageous mode and a number of other cases.

Taking into account the above, the **purpose of the article** is:

To determine the features of stability and controllability of an unmanned aerial vehicle in route flight mode. Identify features of UAV piloting in the first and second modes of flight. Demonstrate a method of determining the boundary between the first and second modes of flight.

Presentation of the main research material

1. Static stability of UAV in terms of speed

1.1. First and second flight modes

The condition for the performance of a steady (at constant speed) rectilinear horizontal flight are two

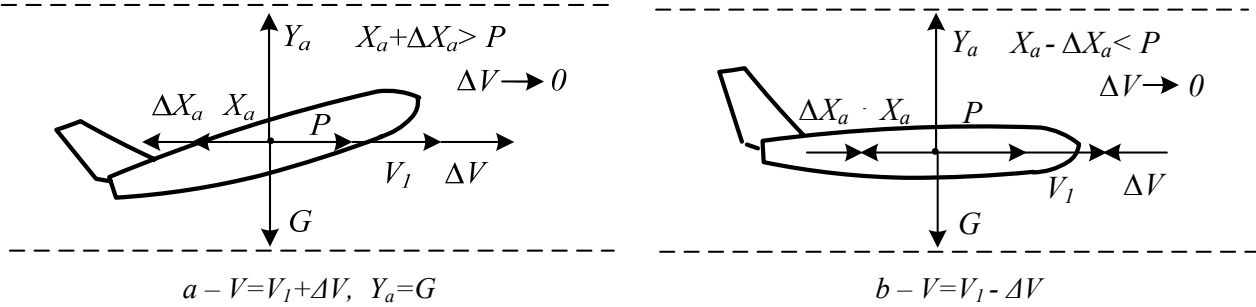


Fig. 1 Diagram of forces and their change in stable flight at speed V_1

In case of an accidental deviation of the speed by ΔV from a given V_1 the operator must comply with the condition $Y_a = G$ a corresponding change in the angle of attack, and then the drag will change as shown in Fig. 1. So, if the speed has increased by an amount $\Delta V > 0$ (fig. 1, a), then the frontal resistance will also increase and become more than the available thrust by an amount ΔX_a . The excess thrust will turn negative $\Delta P_{px} = (P - X_a) < 0$, that is, there will be an unbalanced force directed backward to braking the UAV. It can be seen that with a random decrease in speed by $\Delta V < 0$ (fig. 1, b), excess force

will be $\Delta P_{px} > 0$, which will strive to accelerate the UAV to its original speed V_1 .

Thus, the balance of power at speed V_1 sustainable – UAV independently, without operator intervention in the operation of the power plant, it maintains a given speed. The stability condition can be written as a relation:

$$\frac{\Delta P_{px}}{\Delta V} < 0 \quad \text{or} \quad \frac{dX_a}{dV} > \frac{dP}{dV}$$

Now, let's show that the flight at speed V_2 will be unstable (fig. 2).

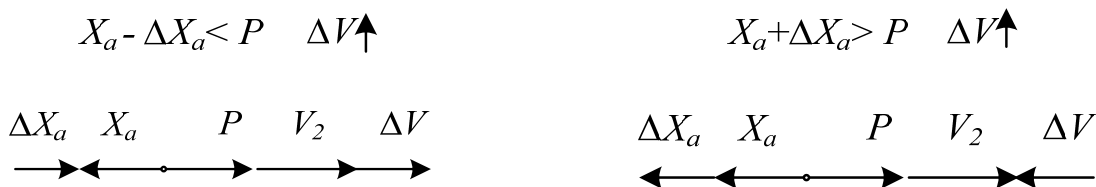


Fig. 2. Diagram of forces and their change in unstable flight at speed V_2

So, if for any reason the speed increases by $\Delta V > 0$, then at the new speed the excess thrust will be positive ($\Delta P_{px} > 0$) and UAV will strive to

increase the speed even more. If the speed decreases ($\Delta V < 0$), then the excess of thrust $\Delta P_{px} < 0$ and UAV will continue to slow down. In both cases

$$\frac{\Delta P_{px}}{\Delta V} > 0 \quad \text{or} \quad \frac{dX_a}{dV} < \frac{dP}{dV}.$$

Thus, two UAV flight modes should be distinguished: stable (first) and unstable (second). It can be shown that the boundary of the modes is the most advantageous flight speed V_{HB} , when the aerodynamic quality of the UAV is maximal and the drag is minimal [6]. At speeds great V_{HB} , the first flight modes are located, and at speeds less than the most advantageous - the second modes.

With an increase in flight altitude, the minimum drag while maintaining a constant indicated (indicated) speed remains unchanged, and the true speed increases. As a result of a decrease in air density with increasing altitude, it will be necessary to increase the propeller speed. But for this it is necessary to increase the engine speed. At the same time, the ratio of the propeller thrust to the speed P/V are decreasing.

Flap extension increases the most advantageous lift coefficient $C_{y_{HB}}$, shifts the mode boundary to lower speeds and UAV, for example, in the pre-landing planning mode, may be in the second modes.

1.2. Features of UAV piloting in the first and second flight modes

When flying in the first modes, the operator brings the UAV to the set speed and subsequently does not interfere with the engine operation without the need for the engine, maintaining only the altitude, the required course and controlling the flight mode according to the readings of the altimeter, accelerometer, variometer.

If it is necessary to change the speed, the operator moves the engine control lever to the desired direction. For example, to increase the speed from V_2 to V'_2 the engine control lever moves forward (fig. 3), the available thrust curve moves up to position P' . At speed V_2 a positive excess of thrust appears, the speed begins to increase. When speed is reached V'_2 excess thrust will be zero and the UAV will move at that speed.

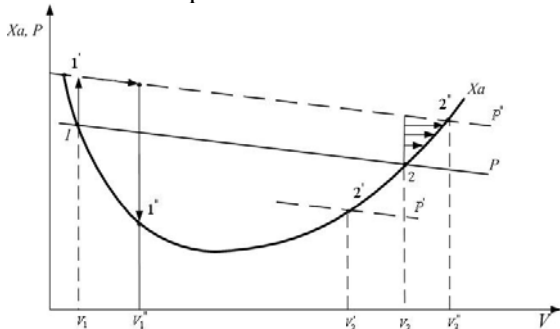


Fig. 3. Features of motor control in the first and second modes

If it is necessary to reduce the speed, the thrust is reduced to the position P' and UAV goes to speed V''_2 . In both cases, only one movement is required from the operator of engine control knob.

In the second modes, double movements are required to change the speed of engine control knob. For example, to increase the speed from V_1 to V'_1 the operator must first move engine control knob at least a small amount away from himself (otherwise the UAV will not accelerate). The available thrust will take the position 1', there will be more drag and the speed will begin to increase. However, upon reaching the required speed V'_1 available thrust will be more required and to ensure equality $P = X_a$ engine control knob it is necessary to translate into position 1''.

To decrease the speed of engine control knob first, they move backward, and when the required speed is reached, forward. As it is difficult for the operator to determine the position required for a given speed of engine control knob, and UAV is unstable in speed, then when flying in the second modes, continuous operation is required for engine control knob. This makes the operator tired and distracts from the main task.

The danger of flying in the second modes is that if for any reason the speed has decreased relative to the target speed, the UAV will decelerate without the operator interfering with the engine operation, and the more intense the lower the speed becomes (due to an increase in negative excess thrust), the UAV will be in danger of stalling [6]. To prevent stall, the operator must first reduce the angle of attack and then bring the engine to maximum operation.

In the second modes, the main drag is inductive drag, which is proportional to the square of the angle of attack. Consequently, reducing the angle of attack is the most effective means of reducing the overall drag. The engine thrust, due to its low infectivity, cannot increase fast enough to prevent the UAV from braking.

Because of the danger of stalling, cruising flights in the second modes are undesirable. In this case, the speed exceeding the most advantageous is taken as the minimum.

2. Long-period movement of UAV and its characteristics

2.1. Long-period equations of UAV motion

In the dynamics of flight, it is generally accepted to divide the general motion into longitudinal and lateral [3]. Longitudinal movement is carried out in the plane coinciding with the plane of symmetry UAV. It consists of two translational (along the speed axes OX_a and OY_a) and one rotational – around the associated axis OZ and, therefore, it is described by three equations:

$$\begin{aligned}
 m\dot{V} &= P - X_a - gm \sin \theta, \\
 mV\dot{\theta} &= Y_a - gm \cos \theta, \\
 J_z\dot{\omega}_z &= M_z.
 \end{aligned}$$

In these equations m – weight of UAV, V – its flying speed, P – engine thrust, X_a – drag, Y_a – lifting

force, $G = gm$ – the force of gravity, J_z – moment of inertia, M_z – cumulative moment of external forces, θ – the angle of inclination of the trajectory (the angle between the velocity vector and the plane of the horizon). A diagram of these forces and moments is shown in Fig. 4.

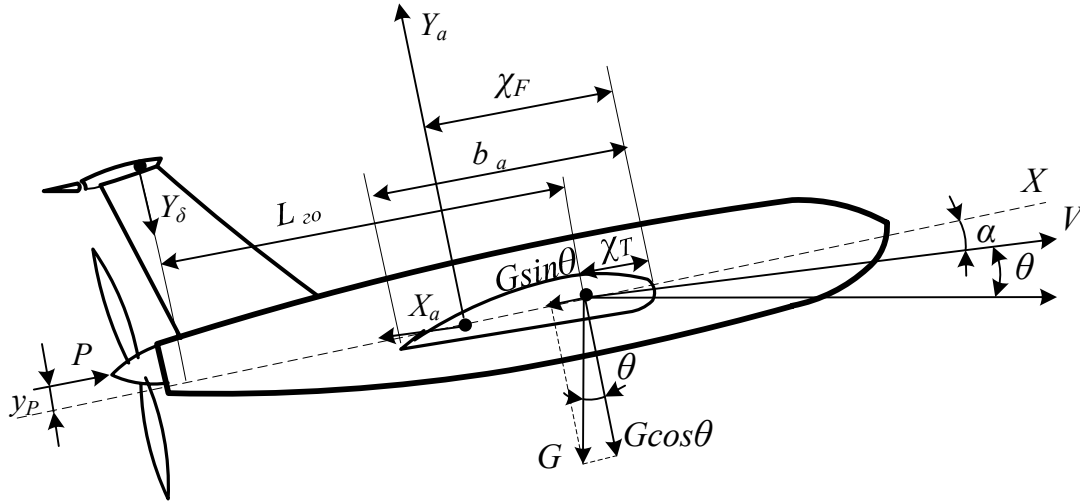


Fig. 4. Diagram of forces and moments in the longitudinal motion of the UAV

We will solve equation (3) according to the traditional scheme [7]: the initial flight will be considered horizontal, rectilinear and steady, when all forces and moments are balanced, that is, when the sum of all forces and moments is zero.

Further, the UAV is affected by some disturbance that disturbs the balance, as a result of which the flight parameters begin to deviate from the initial values (indicated by the index “ Δ ”) by some small amount (denoted by Δ). For example, the true

$$\begin{aligned}
 \Delta P &= P^V \Delta V \\
 \Delta X_a &= X^V \Delta V + X^\alpha \Delta \alpha, \\
 \Delta Y_a &= Y^V \Delta V + Y^\alpha \Delta \alpha, \\
 \Delta M_z &= M_z^V \Delta V + M_z^\alpha \Delta \alpha + M_z^{\dot{\alpha}} \Delta \dot{\alpha} + M_z^{\omega_z} \Delta \omega_z + M_z^{\delta_b} \Delta \delta_b
 \end{aligned}$$

In these equations, the increments are accepted: angle of attack α , the rate of change of the angle of attack $\dot{\alpha}$, the angular rate of rotation of the UAV around the axis ω_z , elevator deflection angle δ_b .

Substituting the increments of forces and moments (4) into equations (3), we obtain a system of linear differential equations of longitudinal motion UAV.

Real UAVs have the ability to quickly change the angle of attack and relatively slow speed. In the first case, within short periods, it is possible to accept the assumption $\Delta V = 0$. This allows us to exclude the first equation from consideration, and the next two equations describe longitudinal short-period motion.

airspeed will be written as $V = V_0 + \Delta V$. Moreover, the increments of the parameters will be found through the derivative of the parameter in the original motion, multiplied by its increment, for example, $\Delta P = (\partial P / \partial V)_0 \Delta V$. To shorten the notation, we will write the derivative as $(\partial P / \partial V)_0 = P^V$.

Then, in accordance with the method of small perturbations, the increments of forces and moments of system (3) in longitudinal disturbed motion can be written in the form:

$$(4)$$

If the flight time is relatively long (measured in tens or hundreds of seconds), then the speed can change by a significant amount. As will be shown below, the change in speed occurs according to a periodic law and, due to the large period of oscillations, is called long-period or fugoid (from the English phugoid mode).

However, in long-period motion, the UAV slowly rotates around the transverse axis, which makes it possible to set the angular velocities equal to zero $\dot{\alpha}$, ω_z and acceleration $\dot{\omega}_z$.

In addition to changing the speed, the altitude will also change, and, therefore, the air density, on which many coefficients depend. However, the

range of UAV heights is significantly less than the range of heights of piloted UAVs, therefore, we will assume the air density in the disturbed movement is commensurate with the density of the initial altitude.

Let us exclude from consideration in (4) the terms related to the parameters $\dot{\alpha}$, ω_z , and $\dot{\omega}_z$, we

$$\begin{aligned}\Delta\dot{V} &= (\bar{P}^V - \bar{X}_a^V)\Delta V - (g - \bar{X}_a^\alpha)\Delta\alpha - g\Delta\theta + \bar{P}^{\delta_p}\Delta\delta_p, \\ \Delta\dot{\theta} &= \bar{Y}_\alpha^V\Delta V + \bar{Y}_\alpha^\alpha\Delta\alpha, \\ 0 &= M_z^V\Delta V + M_z^\alpha\Delta\alpha + \bar{M}_z^{\delta_\theta}\Delta\delta_\theta,\end{aligned}\quad (5)$$

where:

$$\begin{aligned}\bar{P}^V &= \frac{P^V}{m}, \bar{P}^{\delta_p} = \frac{P^{\delta_p}}{m}, \\ \bar{X}_a^V &= \frac{X_a^V}{m} = \frac{2C_{x0}}{\tau} - \frac{2g^2 A\tau}{V^2}, \quad \bar{X}_a^\alpha = \frac{X_a^\alpha}{m} = \frac{2C_x^\alpha \rho V S}{2m} = \frac{C_x^\alpha C_y^\alpha V}{\tau}, \\ \bar{Y}_\alpha^V &= \frac{Y_\alpha^V}{mV} = \frac{2C_{ya} \rho V S}{2mV} = \frac{2C_{ya}}{V\tau}, \quad \bar{Y}_\alpha^\alpha = \frac{Y_\alpha^\alpha}{mV} = \frac{C_y^\alpha}{\tau}, \\ \bar{M}_z^V &= \frac{M_z^V}{J_z} = \frac{m_{zp}^V q S b_A}{J_z}, \quad \bar{M}_z^\alpha = \frac{M_z^\alpha}{J_z} = \frac{m_z^\alpha q S b_A}{J_z}, \quad m_{zp}^V = \frac{P y_P}{q S b_A}, \quad \bar{M}_z^{\delta_\theta} = \frac{M_z^{\delta_\theta}}{J_z}, \\ C_{xa} &= C_{x0} + AC_{ya}^2\end{aligned}$$

In these equations, the partial derivatives X_a^V , X_a^α are obtained by differentiating the dependence of drag on speed $X_a = (C_{x0} + AC_y^2)\rho V^2 S / 2$ accordingly at a constant angle of attack and at a constant speed. The derivative P^V can be obtained by differentiating the propeller thrust from the speed $P(V)$. Polar C_{xa} (C_{ya}) in the working range of angles of attack will be considered as a quadratic dependence with parameters C_{x0} and A .

To determine the intrinsic properties of the UAV in long-period motion, we will assume that the control moments created by the elevator and the thrust of the propulsion system are equal to zero

$$M_z^{\delta_\theta} \delta_\theta = M_{zp} = 0.$$

We also assume that the UAV has sufficient stability on the angle of attack and is able to quickly turn the UAV by a given angle of attack when it is randomly deflected because of atmospheric disturbances.

With these assumptions the system of equations (5) becomes linear. To solve system (5) we reduce it to a single differential equation of the second order:

$$\Delta\ddot{V} + 2n_V\Delta\dot{V} + \Omega_V^2\Delta V = 0, \quad (6)$$

where

$$n_V = -\frac{1}{2}(\bar{P}^V - \bar{X}_a^V + \bar{X}_a^\alpha \frac{m_z^V}{m_z^\alpha}), \quad (7)$$

substitute dependencies (4) into (3), and then divide the first equation by m , second – on mV , third on – J_z . The last procedure will be marked with a dash above each parameter. As a result, we obtain the system of equations (5), which describes the longitudinal long-period motion.

$$\Omega_V^2 = g \left(\bar{Y}_\alpha^V - \bar{Y}_\alpha^\alpha \frac{m_z^V}{m_z^\alpha} \right). \quad (8)$$

In these equations n_V – damping characteristic, Ω_V – stability characteristic. In most practical cases $\Omega_V \geq n_V$, therefore, the flight speed changes according to the periodic law

$$\Delta V = V_0 e^{-n_V t} \sin(\omega_V t + \phi), \quad (9)$$

where

$$\omega_V = \sqrt{\Omega_V^2 - n_V^2}, \quad (10)$$

actual frequency of speed fluctuations.

The period of oscillation is uniquely related to the frequency

$$T_V = \frac{2\pi}{\omega_V}, \quad (11)$$

and the relative degree of damping of oscillations is equal

$$\xi_V = \frac{n_V}{\Omega_V}. \quad (12)$$

Other characteristics of the oscillatory motion in shape are the same as in the short-period motion.

For a better perception of the specifics of the long-period movement of the UAV, let us consider the characteristics of one of the real vehicles and select the flight mode (speed and altitude). The most important of them are shown in Table. 1.

Table 1

Initial data for calculating the parameters of long-period motion

№	Name of parameter	Symbol	Dimension	Initial values
1	Flight altitude	H	M	2400
2	Airspeed	V	km/h(m/sec)	170(47.2)
3	UAV weight	m	Kg	160
4	Wing area	S	m^2	3,5
5	Average aerodynamic wing chord	b_A	m	0,547
6	Moment of inertia in relation to the axis OZ	I_z	kgm^2	115,4
7	Radius of inertia	$\bar{r}_z^2 = I_z / mb_A^2$	–	2,41
8	UAV density (longitudinal channel)	$\mu = 2m/\rho S b_A$	–	173
9	Time Scale	$\tau = 2m/\rho S V$	sec	2
10	Static stability degree	$m_z^{C_y}$	–	-0,12
11	Derivative	C_y^α	–	5,2
12	Derivative	m_z^V	sec/m	0,00108
13	Derivative	m_z^α	–	-0,624
14	Derivative	\bar{P}^V	H sec/m kg	-0,0558
15	Derivative	\bar{X}_a^V	H sec/m kg	0,034
16	Derivative	\bar{X}_a^α	H/kg	0,378
17	Derivative	\bar{Y}_a^V		0,009
18	Derivative	\bar{Y}_y^α	1/sec	2,6
19	Derivative	m_z^V	1/m/sec	-0,00108
20	Derivative	m_z^α	–	-0,624

2.2. Simulation of long-period motion

The determining factor for long-period motion is speed.

Although the angle of attack changes during flight, the degree of stability under overload tends to maintain its value all the time.

In order to identify the features of this type of motion and to assess the factors affecting its characteristics, we first calculated the necessary initial data in the speed range of 100...200 km/h

(Table 1). The results of calculating parameters of long-period traffic according to the above formulas are presented in Table 2.

According to formula (7) the damping of UAV motion is carried out mainly by the derivatives of engine thrust and drag on speed (\bar{P}^V, \bar{X}_a^V). To determine them, the dependencies were constructed $P(V)$ и $X_a(V)$, which are shown in Fig. 5.

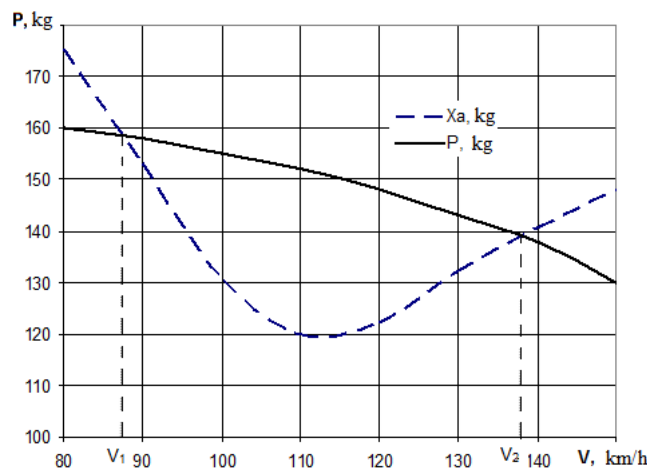


Fig. 5. An example of the dependence of propeller thrust and drag on flight speed

Dependence $P(V)$ was approximated by a second-degree polynomial, which allowed us to find the function $\bar{P}^V(V)$ for any value V . Derivative \bar{X}_a^V is obtained by differentiating the drag force $\bar{X}_a^V = 2C_{x0}/\tau - 2g^2 A\tau/V^2$. The second term of this formula mainly determines the drag at low speeds (in the second flight modes). It is negative in sign and is an anti-damper. Therefore, the total damping UAV in the second modes is small and is determined mainly by the derivative $\bar{P}^V(V)$.

At flight speeds higher than the most advantageous one, the drag coefficient component is the main one $2C_{x0}/\tau$, which is proportional to the speed. So, for example, when the speed increases from 100 to 200 km/h, the indicator n_V is increased by an order of magnitude. The oscillation frequency depends mainly on the lift force through the

derivatives $(\bar{Y}_a^V, \bar{Y}_a^\alpha)$. They are determined by differentiating the lift force formula at a constant angle of attack (\bar{Y}_a^V) or constant speed (\bar{Y}_a^α) .

As shown in Table 2, the derivative \bar{Y}_a^α significantly larger than the derivative \bar{Y}_a^V and changes linearly in speed, i.e. when the speed changes from 100 to 200 km/h \bar{Y}_a^α doubles, oscillations decay faster. Moreover, its effect depends on the value of longitudinal static stability: with a small degree of stability, the angle of attack, other things being equal, deviates from the set value by a larger value, the trajectory rotates to a larger angle and prevents an increase in the angle of attack. With high stability, a powerful longitudinal moment acts on the UAV, which more energetically turns the UAV to a given angle of attack – the oscillation frequency increases.

Table 2

Characteristics of long-period motion

$V, \text{ km/h}$	100	110	120	130	140	150	160	170	180	190	200
$X_a, \text{ N}$	1300	1200	1220	1320	1410	1480	1670	1940	212	232	253
$P, \text{ N}$	1521	1491	1452	1403	1354	1275	1079	991	912	834	736
$C_{y \text{ III}}$	1,88	1,49	1,20	0,99	0,84	0,71	0,61	0,53	0,47	0,42	0,37
C_{xa}	0,1	0,08	0,065	0,06	0,055	0,051	0,05	0,05	0,050	0,049	0,0484
$\tau, \text{ sek}$	3,41	3,10	2,84	2,62	2,43	2,27	2,13	2,00	1,89	1,79	1,70
$\bar{X}_a^V, \text{ N/m/sek kg}$	-0,02	-0,006	0,005	0,013	0,020	0,025	0,030	0,034	0,038	0,042	0,046
$\bar{X}_a^\alpha, \text{ N/kr}$	0,738	0,738	0,738	0,738	0,738	0,738	0,738	0,738	0,738	0,738	0,738
$\bar{Y}_a^\alpha, \text{ N/m/sek}$	37	1,53	1,68	1,83	1,98	2,14	2,29	2,44	2,59	2,75	2,90
$\bar{Y}_a^V, \text{ N/m/sek kg}$	0,031	0,025	0,021	0,018	0,015	0,013	0,011	0,010	0,009	0,008	0,007
$-P^V, \text{ N/m/sek}$	5,392	5,648	6,72	7,2	7,328	8,336	8,8	8,912	8,928	8,944	8,944
$-\bar{P}^V, \text{ N/m/sek}$	0,034	0,0353	0,042	0,045	0,046	0,052	0,055	0,056	0,0558	0,0559	0,0559
$-m_z^V, \text{ sek/m}$	0,002	0,002	0,002	0,002	0,001	0,001	0,001	0,001	0,0011	0,001	0,0009
$-m_z^\alpha$	0,624	0,624	0,624	0,624	0,624	0,624	0,624	0,624	0,624	0,624	0,624
$n_V, 1/\text{sek}$	0,005	0,0137	0,022	0,028	0,032	0,038	0,047	0,044	0,0464	0,0484	0,0502
$n_V^2, 1/\text{sek}^2$	0,000	0,0002	0,0005	0,0008	0,0010	0,0014	0,0017	0,002	0,0022	0,0023	0,0025
$\Omega_V^2, 1/\text{sek}^2$	0,257	0,2018	0,1546	0,1227	0,1001	0,077	0,0615	0,051	0,04212	0,0352	0,0295
$\omega_v, 1/\text{sek}$	0,507	0,449	0,393	0,349	0,315	0,275	0,244	0,220	0,200	0,181	0,164
$T, \text{ sek}$	12,4	14,0	16,0	18,0	19,9	22,8	25,7	28,5	31,4	34,7	38,2
ζ_V	0,011	0,030	0,057	0,080	0,101	0,136	0,168	0,197	0,226	0,258	0,292

The influence of the value of the initial speed on the frequency of its oscillations has the opposite character, the UAV is more inertial to the change in speed: the greater it is, the more difficult it is to turn the UAV to change the trajectory and the lower will be the frequency of its oscillation. Table 2 also shows

that the oscillation frequency of the UAV at 200 km/h is almost three times less than at 100 km/h. A long period with low attenuation makes long-period oscillations hardly noticeable to an observer from the ground, and it sometimes perceives the UAV's oscillatory transient as a straight flight.

To demonstrate the effect of the flight mode on the character of long-period oscillations, their simulation was performed. The results are presented in Fig. 6, 7.

Numerical solution of equations (5) was performed in MATLAB for two versions of the initial data (see Table 3).

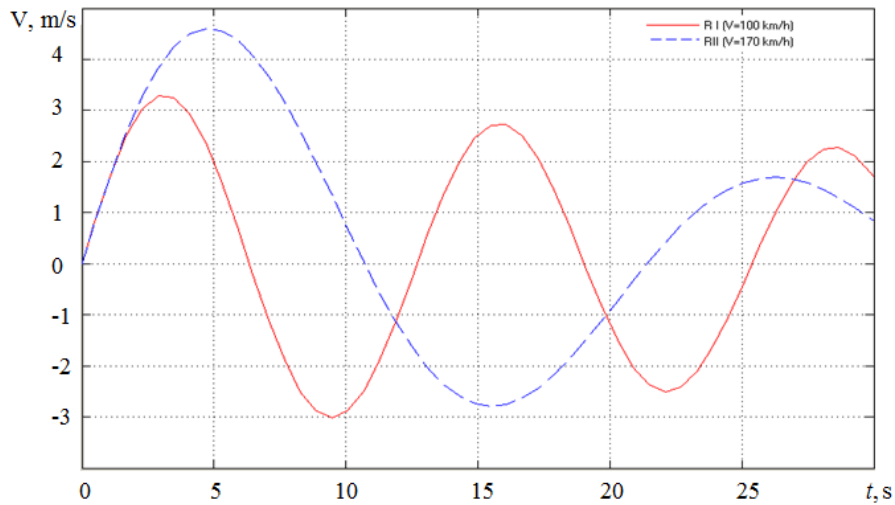


Fig. 6. Speed change over time in RI and RII modes

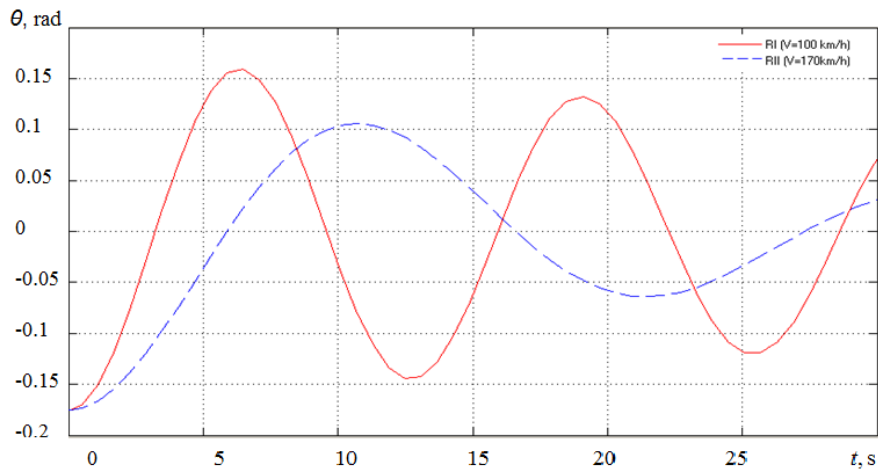


Fig. 7. Changing the angle of inclination of the trajectory in time in RI and RII modes

Table 3

Variants of initial data for simulation of UAV free long-period motion

Parameter	Flight mode RI	Flight mode RII
$V_0, \text{ km/h}$	100	170
$H_0, \text{ m}$	2400	2400
$\bar{P}^V, \text{ N/m/sek}$	-0,0353	-0,0558
$\bar{X}_a^V, \text{ N/m/sek}$	-0,006	0,038
$\theta_0, ^\circ$	-10	-10

The simulation results are presented in the form of time changes in speed, trajectory inclination and flight altitude. The angle of inclination of the trajectory was chosen as the initial disturbance -10° . Due to this, the UAV begins to descend, its speed increases, there is an increase in lifting force, which tends to curve the trajectory further up.

The angle of inclination of the trajectory and pitch gradually increase, the UAV exits the descent, and then goes into the climb. As the altitude increases, the speed begins to decrease, and with it the lift. At some altitude, the UAV reaches its original speed and the lift gain becomes zero. However, the angle of inclination of the trajectory in

this case will be maximum positive, and the UAV continues to climb, reducing the speed.

A decrease in speed will cause a negative increase in lift, directed downward. It will begin to bend the trajectory downward, the angle of inclination of the trajectory decreases with a subsequent increase in speed, etc.

Thus, a change in speed at an unchanged position of the elevator and engine control knob is accompanied by an oscillatory motion, which is associated with a cyclic change in lifting force. The damping role is played by the drag and thrust of the propeller.

Increases in lift cause the center of mass to move in the direction of its action and change the angle of attack. In this case, the moment of longitudinal stability comes into effect, which by means of rotation of the UAV around the transverse axis seeks to prevent the angle of attack from deflection from the specified initial value.

UAVs fly at low altitudes in a dense atmosphere, so the deviation of the flight parameters from the initial values is small. Thus, at initial speed of 170 km/h in the first period the speed deviates from the initial by 4.6 m/s (17 km/h), the angle of inclination of the trajectory - by 0.15 rad (8.6 deg), height – by -30 m. After the oscillations stop, the UAV will descend along a curvilinear trajectory.

The described movement is typical for UAV in case of failure of the control and stabilization system. In this case, the UAV goes into a phugoid flight, loses altitude and makes an emergency landing even with the engine running and with a supply of fuel.

Conclusions

1. The article shows the features of stability and controllability of an unmanned aerial vehicle in a route flight mode. Attention is paid to the complexity of piloting and safety of flight in the second modes. It shows the method of determining the boundary between the first and second modes of flight.

2. Criteria for stability of motion in rectilinear horizontal flight and methods of their formation have been determined.

3. The mathematical model of longitudinal long-period (fugoid) motion has been substantiated. An

example of its use on a concrete example of a hypothetical sample is given.

4. Simulation of free long-period motion was performed in order to analyze the factors affecting the flight parameters under various UAV application conditions.

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Зірка А., Зірка М., Кадет Н.

ЗАБЕЗПЕЧЕННЯ СТІЙКОСТІ БЕЗПІЛОТНОГО ЛІТАЛЬНОГО АПАРАТУ ЗА ШВИДКІСТЮ НА РІЗНИХ РЕЖИМАХ ПОЛЬОТУ

У публікації розглядається питання забезпечення стійкості польоту безпілотного літального апарата за швидкістю. Проведено аналіз фізичної сутності процесу забезпечення стійкості безпілотного літального апарата за швидкістю. Приділено увагу режимам польоту за яких оператор (зовнішній пілот) може зіткнутися з труднощами практичного пілотування безпілотного літального апарата.

Проаналізовано можливі причини виникнення позаштатних ситуацій під час польоту безпілотного літального апарата на швидкостях близьких до гранично малих. Розглянуто можливі дії оператора (зовнішнього пілота) щодо повернення безпілотного літального апарата в експлуатаційний діапазон швидкостей з області нестійкості.

У статті продемонстровано особливості стійкості та керованості безпілотного літального апарату в режимі маршрутного польоту. Приділено увагу складності пілотування та безпеки польоту на других режимах. У статті продемонстровано методику визначення межі між першим і другим режимами польоту. Показано особливості керування безпілотним літальним апаратом та забезпечення стійкості в першому та другому режимах.

Досліджено питання динамічної стійкості безпілотного літального апарата. Проведено чисельне моделювання позовжнього руху безпілотного літального апарата у вільному, некерованому польоті, отримано траєкторії руху для безпілотного літального апарата обраної конфігурації зі зміною швидкості та кута нахилу траєкторії в часі. Побудовано графіки траєкторій руху зі зміною швидкості та висоти за часом, побудовано графіки перехідних процесів для випадків стійкого та нестійкого режимів польоту. Проведено аналіз зовнішніх факторів, що найбільше впливають на параметри польоту в різних умовах застосування безпілотного літального апарата.

Ключові слова: безпілотний літальний апарат, стабільність швидкості, стійкість до перевантажень, довгоперіодичний рух, частота вібрації, ступінь затухання, зрив.

Zirka A., Zirka M., Kadet N.

ENSURING SPEED STABILITY OF THE UNMANNED AERIAL VEHICLE IN DIFFERENT FLIGHT MODES

The publication deals with the issue of ensuring the stability of an unmanned aerial vehicle flight by speed. An analysis of the physical essence of the process of ensuring the unmanned aerial vehicle stability by speed is presented. Attention is paid to the flight modes in which the operator (external pilot) may encounter difficulties in the practical piloting of the unmanned aerial vehicle.

The possible causes of abnormal situations when flying the unmanned aerial vehicle at speeds close to the borderline low are analyzed. Possible actions of the operator (external pilot) to return the unmanned aerial vehicle to the operating speed range from the area of instability are considered.

The article shows the features of stability and controllability of an unmanned aerial vehicle in a route flight mode. Attention is paid to the complexity of piloting and safety of flight in the second modes. The article demonstrates the method of determining the boundary between the first and second flight modes. The features of unmanned aerial vehicle management and ensuring stability in the first and second modes are shown.

The issue of dynamic stability of the unmanned aerial vehicle is investigated. Numerical modeling of the longitudinal movement of the unmanned aerial vehicle in free, uncontrolled flight was carried out, trajectories for the unmanned aerial vehicle of the selected configuration with a change in speed and angle of inclination of the trajectory in time were obtained. Graphs of movement trajectories with changes in speed and height over time were constructed, graphs of transient processes were constructed for cases of stable and unstable flight modes. An analysis of the external factors that most affect the flight parameters in various conditions of unmanned aerial vehicle use was carried out.

Keywords: unmanned aerial vehicle, speed stability, overload stability, long-period motion, vibration frequency, attenuation degree, stall.

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