UDC 62-503.5
DOI https://doi.org/10.15589/znp2023.4(493).18

SIMULATION OF THE UNMANNED AERIAL VEHICLES LATERAL MOVEMENT

МОДЕЛЮВАННЯ БОКОВОГО РУХУ БЕЗПІЛОТНОГО ЛІТАЛЬНОГО АПАРАТУ

Stanislav F. Kolesnychenko[1]
ORCID: 0000-0003-2350-3957
Serhii V. Rahulin[2]
ragulin_s@ukr.net
ORCID: 0000-0001-8955-0380

С. Ф. Колісніченко[1],
канд. техн. наук, доцент
С. В. Рагулін[2],
канд. техн. наук, доцент

[1]Flight Academy of the National Aviation University, Kropyvnytskyi
[2]Kherson State agrarian and economic University, Kherson
[1]Льотна академія Національного авіаційного університету, м. Кропивницький
[2]Херсонський державний аграрно-економічний університет, м. Херсон

Abstract. In the given research, we managed to achieve the desired result. The main task of the research was to solve the problem of increasing the maneuverability of the unmanned aerial vehicle lateral movement by means of a direct control of the lateral force.
In the given research, the model of the unmanned aerial vehicle lateral movement was considered. Based on the fact that the unmanned aerial vehicle is moving in a three-dimensional space, a complete description of the movement is characterized by the Euler equations.
There were provided methods for solving the problem of lateral maneuvering. The provided methods are important for unmanned aerial vehicle which are distributing agricultural chemicals, and also which are maintaining surveillance and terrain photography for which bank angle displacements are unacceptable, and high accuracy in lateral displacement is required.
The second section simulates: lateral movement using coordinated turns; unmanned aerial vehicle lateral movement when sliding with a bank angle unmanned aerial vehicle; lateral movement during a flat turn; unmanned aerial vehicle lateral movement with direct control of the lateral force.
The simulation is based on the formulas derived and implemented in the software complex intended for modeling control systems Mathlab-Simulink.
In the third section, with the help of simulation there were defined aerodynamic characteristics of unmanned aerial vehicle control surfaces. For this, the ANSYS software was used, which allows solving a wide range of problems in the areas of strength, heat, hydrogas dynamics, electromagnetism, as well as interdisciplinary analysis that combines all four areas.
The main purpose of the simulation was to develop a methodology for determining the aerodynamic parameters that characterize the effectiveness of a control when displacing the rudder or by turning the entire surface.
Because of the simulation, there were obtained the values of the parameters that confirm the high efficiency of the all-moving stabilizer.
Key words: modeling; maneuvering control; ANSYS; system; unmanned aerial vehicle; aerodynamic; graphical programming environment.

Анотація. В даній роботі була розглянута модель бічного руху безпілотного літального апарату. Виходячи з того, що безпілотного літальний апарат рухається в тривимірному просторі, повний опис руху характеризується рівняннями Ейлера.
Викладено методи для вирішення задачі бокового маневрування. Запропоновані методи є важливими для безпілотних літальних апаратів, які виконують авіаційні хімічні роботи, а також виконують спостереження або фотозйомку, кутові зміщення по крену, для яких є неприйнятними, та потрібна висока точність по боковому ухиленню.
У другому розділі змодельовано : бічний рух з використанням координованих розворотів; бічний рух літального апарату при ковзанні з креном; бічний рух літального апарату при плоскому розвороті; бічний рух літального апарату при безпосередньому керуванні боковою силою.

Розв’язок та формалізація опису кінематичних параметрів базується на диференціальних рівняннях бокового руху безпілотного літального апарату та математичного моделювання, що були виведені в першому розділі роботи.
Моделювання побудоване на основі формул і реалізоване в програмному комплексі, що призначенений для моделювання систем керування Mathlab-Simulink.
У третьому розділі за допомогою моделювання визначено аеродинамічні характеристики керуючих поверхонь безпілотного літального апарату. За для цього використано програмне забезпечення ANSYS, яке дозволяє вирішувати широке коло задач в областях міцності, тепла, гідрогазодинаміки, електромагнетизму, а також міждисциплінарного аналізу, що об'єднує всі чотири області.
Основною метою моделювання було відпрацювання методики для визначення аеродинамічних параметрів, які характеризують ефективність управління при відхиленні керма напряму або шляхом повороту всієї поверхні.
В результаті моделювання були отримані відповідні значення параметрів які, підтверджують високу ефективність цільноповоротного стабілізатора.
Ключові слова: моделювання; маневрування управління; система ANSYS; безпілотний літальний апарат; аеродинаміка; графічне середовище програмування.

INTRODUCTION

The research paper set sights on how to increase the lateral mode maneuver capability of unmanned aerial vehicles (UAV) by directly controlling the side force.

The principal aim of the given research is to determine the parameters and aerodynamic characteristics of the control surfaces during the UAV lateral movement.

The control surface of UAV is the subject of investigation.

The focus of this research are characteristics of the control surfaces during the UAV lateral movement.

The following methods were used: comparative analysis, consolidation, taxonomy and synthesis, data science by means of application program package Mathlab and cross-functional finite element analysis (FEA) software ANSYS.

The obtained results have a certain practical significance.

1. Differential equations of UAV lateral movement

1.1. Total linear model of UAV lateral movement

For as much as, UAV is moving in three-dimensional space, and it itself has six degrees of freedom (6DoF), then, according to this, a complete description of the movement is characterized by six differential equations (Euler equations). Solving equations of this type poses some problems, which include non-linearity and their multiplicity of connections. These problems can be avoided by means of the following simplifications:

– separation of movement into longitudinal and lateral;

– linearization of these equations, which transfers them into an algebraic category with all the simplifications for motion analysis and its modeling.

The lateral motion equation assumes independent control in the roll and yaw axes, the determination of translational motion along Y-axis and rotational motion relatively to X and Z axes.

The equation of lateral motion(1.1.)connects the moments acting around axis Z andaxis^{Y},as well as angular and linear parameters. These are rotation rates and linear motions. Usually, deflection angles of rudder δ_r and ailerons δ_a act in the capacity of control signals. If as undisturbed motion, we take 1-g flight with a small angle of attack and pitch angle $V_y = 0,\ V_x = 0,\ V_z = V\beta,\ \Delta V_z = V\Delta\beta$ then $\cos\gamma = 1,\ \cos\vartheta = 1\ \sin\vartheta = 0$ and $\Delta\omega_x = \Delta\dot{\gamma},\ \Delta\omega_y = \Delta\dot{\psi}$ andlateral-directional equation acquire the form:

$$\begin{aligned} &\Delta\dot{\beta} + \Delta\dot{\psi} + a_z^{\beta}\Delta\beta + a_z^{\gamma}\Delta\gamma = 0; \\ &\Delta\ddot{\psi} + a_{m_y}^{\omega_y}\Delta\dot{\psi} + a_{m_y}^{\omega_x}\Delta\dot{\gamma} + a_{m_y}^{\beta}\Delta\beta = a_{m_y}^{\delta_r}\Delta\delta_r; \\ &\Delta\ddot{\gamma} + a_{m_x}^{\omega_y}\Delta\dot{\psi} + a_{m_x}^{\omega_x}\Delta\dot{\gamma} + a_{m_x}^{\beta}\Delta\beta = a_{m_x}^{a}\Delta\delta_a; \end{aligned} \tag{1.1}$$

where

$$a_z^{\beta} = -\frac{1}{mV}\left(\frac{\partial Z}{\partial\beta}\right),\quad a_z^{\gamma} = -\frac{g}{V},\quad a_{m_y}^{\omega_y} = -\frac{1}{I_y}\left(\frac{\partial M_y}{\partial\omega_y}\right);$$

$$a_{m_y}^{\omega_x} = -\frac{1}{I_y}\left(\frac{\partial M_y}{\partial\omega_x}\right);\quad a_{m_y}^{\beta} = -\frac{1}{I_x}\left(\frac{\partial M_y}{\partial\beta}\right);\quad a_{m_y}^{\delta_r} = -\frac{1}{I_y}\left(\frac{\partial M_y}{\partial\delta_r}\right);$$

$$a_{m_x}^{\omega_x} = -\frac{1}{I_x}\left(\frac{\partial M_x}{\partial\omega_x}\right);\quad a_{m_x}^{\omega_y} = -\frac{1}{I_x}\left(\frac{\partial M_x}{\partial\omega_y}\right);$$

$$a_{m_y}^{\beta} = -\frac{1}{I_y}\left(\frac{\partial M_x}{\partial\beta}\right);\quad a_{m_x}^{\delta_a} = -\frac{1}{I_x}\left(\frac{\partial M_y}{\partial\delta_a}\right)\square$$

The task of lateral maneuvering can be solved in several ways:

• Well-done lateral control (in this case, effective lateral movement of the aerial vehicles is observed), however, this occurs with a loss of altitude (curve 1);

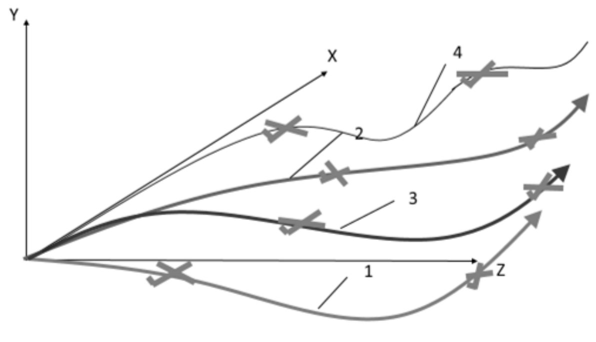

Fig. 1. General patternof the UAV lateral movement

• control via elevator (curve 2),in this case, movement in the direction of the axis Z occurs due to deviation in the heading. In this situations, we are not going to observe the loss of altitude, but the control is complicated by the availability of lateral stability connected with a restoring moment relatively to the Y axis;

- linear movement maneuver in the direction of the Z axis is implemented in the usual way for air pilotage in 360 deg. steady turn (curve 4); in such a case, lateral movement can occur without loss, but in this case, complex control, both lateral in roll and longitudinal, should be applied in order to increase the angle of attack, which prevents the loss of height;
- the most effective and simplest method is the method of direct lateral force control; in this case, we observe highly-efficient linear movement maneuvering in the Z-axisdirection and no loss of height (curve 3).

The proposed method of lateral control (without loss of height and without angular displacement) is important for such types of UAVs. These UAV's are aerials distributing agricultural chemicals, where the flight takes place at a height of 2–5 m and any roll control will be connected with the loss of height proportional to the flight heights values, as well as UAV'smaintainingsurveillance and terrain photography for which angular displacements in roll are unacceptable, and high accuracy in lateral deviation is required.

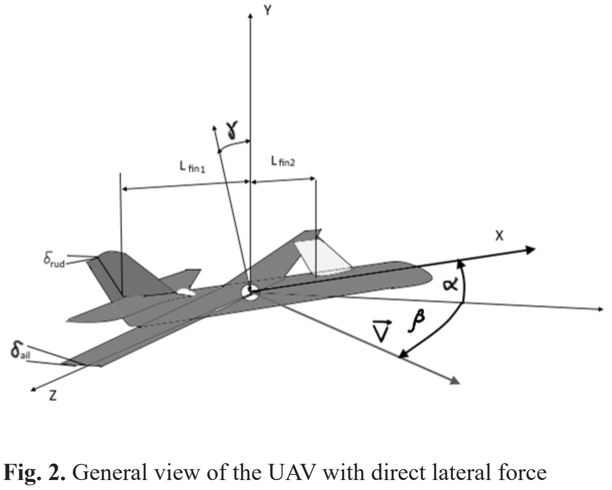

Fig. 2. General view of the UAV with direct lateral force control

A general view of the UAV with direct lateral force control is shown in Fig. 2, which shows the general view and linkage parameters of a movement.

A characteristic feature of the design is the availability of two vertical stabilizers that allow you to create a lateral force Z. Concurrently, it should not create a moment towards the Y axis, that is, without yawing.

Please note that this design has certain peculiarities:

- in order to ensure longitudinal stability during the normal flight, the rear stabilizer must be of a larger size I comparison to the normal scheme. This is connected with the deterioration of longitudinal stability due to the presence of the front vertical stabilizer;
- in order to avoid a destabilizing moment ΔM_y, side force control must be carried out by the all-moving front stabilizer and the rudder of the rear stabilizer;
- such assumptions are permissible: during lateral movement, a transverse restoring moment appears ΔM_x from the Z force, acting on vertical stabilizers (to estimate its value, it is necessary to carry out calculations and evaluate the degree of its influence on ω_x and γ;
- longitudinal stability of the proposed design (without front stabilizer)will be reduced by the value of front stabilizer imbalance. In this case, the rear stabilizer should be enlarged or the front stabilizer should be operated in feathering mode in the absence of side force control.

1.2. Simplified models of lateral movement

In many modes, with minor deviations, the roll and direction controls can be considered separately. In such cases, the equations of lateral motion in the absence of sliding $\Delta\beta = 0$ can be represented as

$$\Delta\ddot{\gamma} + a_{m_x}^{\omega_x}\Delta\dot{\gamma} = a_{m_x}^{a}\Delta\delta_a; \qquad (1.2)$$

in the second case, in the absence of a roll $\Delta\gamma = 0$ (in flat turn mode) the equations of lateral motion can be represented as

$$\begin{cases} \Delta\dot{\beta} + \Delta\dot{\psi} + a_z^{\beta}\Delta\beta = 0; \\ \Delta\ddot{\psi} + a_{m_y}^{\omega_y}\Delta\dot{\psi} + a_{m_y}^{\beta}\Delta\beta = a_{m_y}^{\delta_r}\Delta\delta_r; \end{cases} \qquad (1.3)$$

Let's consider a simplified model of a coordinated turn targeted at elimination of a lateral deviation. In this case, a coordinated turn is characterized by a change in direction without loss of a height. Please note that in this case, in a manned flight, the loss of height is compensated by the control of the elevation rudder in the longitudinal channel.

Lateral movement during a coordinated turn (Fig. 3) will be determined by the formula

$$\Delta Z = \int_0^t V\, tg\psi\, dt \qquad (1.4)$$

where

ψ – yawing angle

V – flight speed

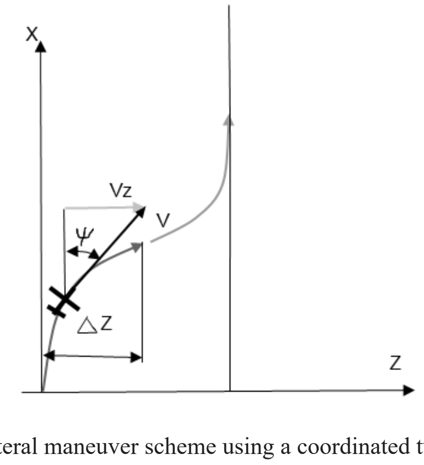

Fig. 3. Lateral maneuver scheme using a coordinated turn

When applying roll and sideslip for lateral movement, the equation of motion in the vertical and horizontal planes will be as follows.

$$\Delta H = \Delta Y = \int_0^t V_y dt \quad (1.5)$$

$$V_y = \int_0^t -g(1-\cos\gamma)dt \quad (1.6)$$

$$\Delta Z = \iint_t g \sin\gamma dt \quad (1.7)$$

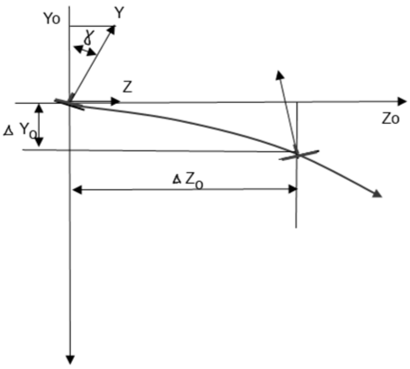

Fig. 4. Scheme of loss of a height during lateral movement using a sideslip

In the flat turn mode (Fig. 5), the lateral movement can be determined by the formula

$$\Delta Z = \int_0^t V\, tg\psi dt \quad (1.8)$$

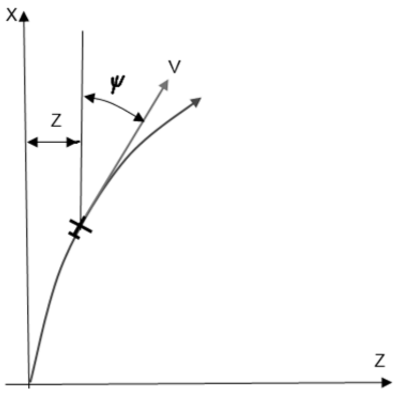

Fig. 5. A diagram of lateral movement using the rudder in flat turn mode

2. Analysis of aerial vehicle control systems of lateral movement

2.1. Development of the UAV model and parameters determination

With the purpose of carrying out a comparative analysis of the effectiveness of lateral control systems, as an example, let's consider an UAV with a mass of *m=100 kg* and a flight speed of *V=25 m/s*. Geometric characteristics and general view of the UAV are shown in Fig. 6

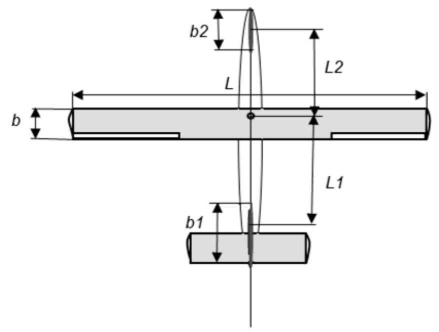

Fig. 6. Geometric characteristics and general view of the UAV

$$L = 9m;\ b = 0.75m;\ L_1 = 2,8m;\ L_2 = 2,2m;\ b_1 = 1,5m;\ b_2 = 1m$$

The wing area, wing airfoil were chosen from the conditions of flight with maximum quality at a speed of V=25 m/s. The Mynk-12 airfoil was chosen as the wing profile. The aerodynamic characteristics of which are presented in Fig. 7. In cruise mode $\alpha = 5^0; Cy = 0,4; K = 20$.

A symmetrical airfoil NASA-0015 was chosen for the vertical stabilizers with aerodynamic characteristics (Fig. 8).

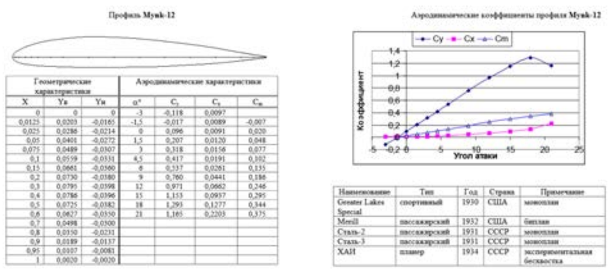

Fig. 7. Wing airfoil and its characteristics

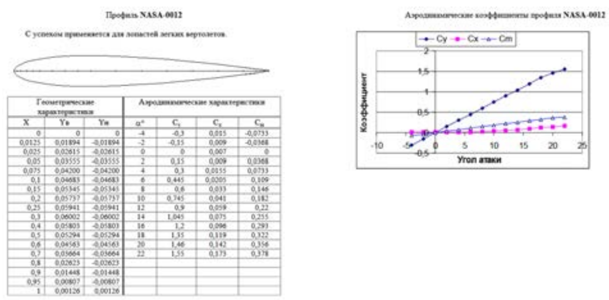

Fig. 8. Airfoil sections of vertical stabilizers and its characteristics

2.2. Analysis of lateral maneuvering under different types of input controls

In this section, we will simulate lateral control using various methods, such as:

- lateral control in a coordinated turn mode;
- sideslip using a bank angle;
- flat turn mode;
- mode of direct control of a lateral force.

It is noteworthy that any maneuvering is optimized in terms of minimum time, and in this particular case the principle of maximum control will be applied. Maneuver time is limited to 10 seconds. Under these conditions, the performance function is the maximum value of the lateral displacement. ΔZ_{max}. Maximum bank angle 15^0. Maximum deflection of governing surfaces -20^0.

To simulate control, we will use generally accepted blocks from the matlab Simulink library (Fig. 9).

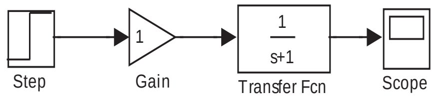

Fig. 9. A typical scheme for simulating the control over dynamic objects in matlab Simulink system

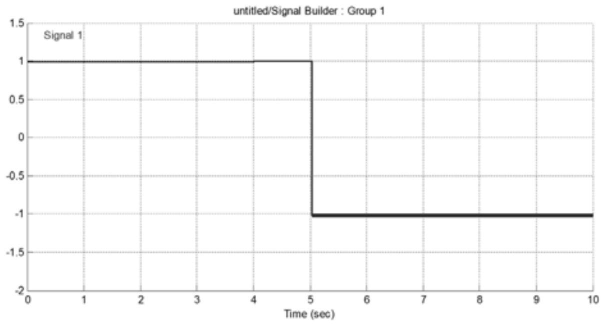

Fig. 10. Design of input command which secures maximum performance

Applied relay-type input signals (fig. 10), as control signals, provide maximum performance.

2.2.1. Modeling of lateral movements via coordinated turns

For modeling, we use the equation of motion in accordance with formula (1.4), the lateral displacement will depend on the yawing angle and at a constant speed it will be determined by the formula

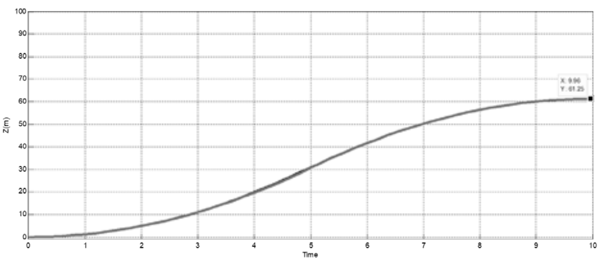

Fig. 11. Lateral deviation plot when while performing a coordinated turn

As is shown on the plot, with a coordinated turn and aileron deflection in order to create 15^0 bank angle, after 10 sec, UAV is displaced at Δ Z = 62 m without loss of a height.

2.2.2. Simulation of the UAV lateral movement of an aircraft when sliding with a bank angel $\gamma = 15^0$

In such cases, there is created a bank angle $\gamma = 15^0$, yaw angle remains unchanged $\Delta\psi = 0$, after 5 seconds the bank angle changes to reverse.

In order to evaluate, the development of the bank angle over a time, the bank angle control was simulated, the plot of which is shown in Fig. 12. It can be seen from the plot, that the bank angel development $\gamma = 15^0$ is achieved during t = 6 sec. which is insignificant if to compare to the entire process of lateral movement which equals 10 sec.

The result of such lateral maneuvering shows that UAV deviated in lateral direction at a value Δ Z = 62 mandlosses a height ΔH = 20 m (Fig. 13, 14).

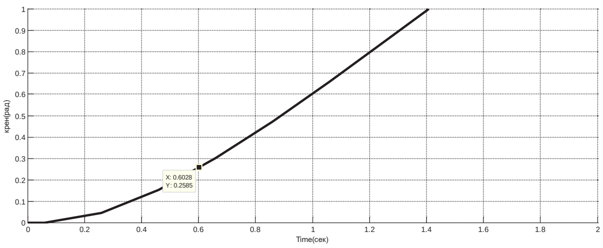

Fig. 12. Plot of bank angle development aimed at creation of lateral sideslip

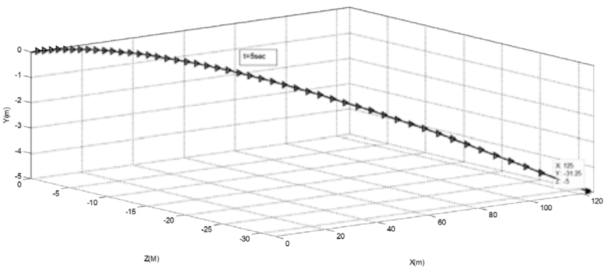

Fig. 13. Plot of lateral movement and loss of height while sliding during t = 5 sec.

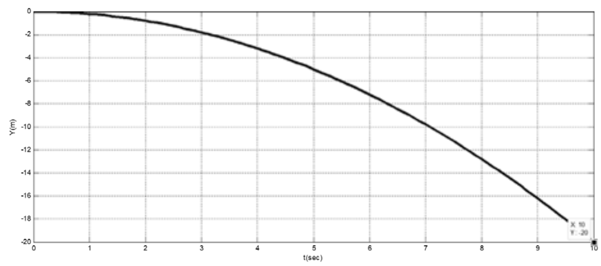

Fig. 14. Plot of height loss ΔH when sliding with a bank angle of 15 degrees for 10 seconds

2.2.3. Simulation of the UAV lateral movement during a flat turn

In this case, lateral movement is implemented via a change of a course direction by means of deflecting the rudder. Bank angle equals zero $\Delta\gamma = 0$.

This movement is performed under the influence of a control signal $\Delta\delta_r$ andcounteracting recoverable moment providing directional stability. In this case, the trajectory is of indefinite character (Fig. 15), when averaging the parameters $\Delta Z \approx 50m$.

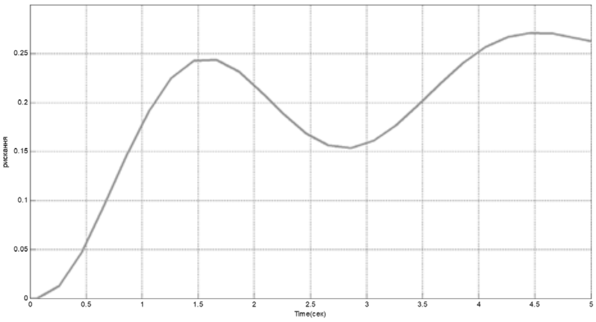

Fig. 15. Change of yawing angle ψ during flat turn

2.2.4. Simulation of the UAV lateral movement with direct control of the lateral force

In this case, we are simulating lateral linear movement in the Z-axis direction using front and rear stabilizers by deflecting the rudder and an all-moving front stabilizer. For simulation, we calculate a force $Fz = 250N$ which equals to the lateral force of the aircraft with a bank angle of 15 degrees.

In such a case, we achieve the lateral displacement Δ Z = 60 m after t = 10 sec, which is appropriate to an aircraft with a maneuver in the coordinated turn mode. Concurrently, control is greatly simplified. It is carried out only through one linear channel and there are no losses in height and rotation of the aircraft around any of the axes (Fig. 16).

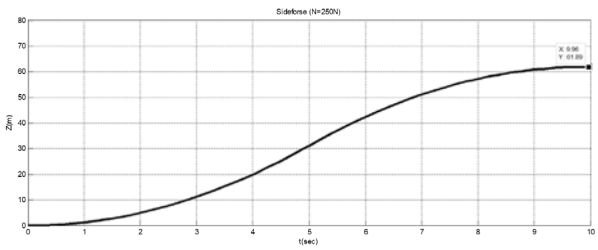

Fig. 16. Plot of UAV lateral maneuver using direct lateral force control Fz

3. Determining the parameters and aerodynamic characteristics of control surfaces using simulation in the ANSYS system

3.1. Determination Control Surface Parameters

Stabilizing and control surfaces by the means of vertical stabilizers provide us with lateral control and way stabilization due to their dynamic characteristics of step responses. Namely, damping coefficient ζ and oscillation frequency ω. As a first step, we simulate dynamic processes with different values of the indicated parameters (Fig. 17).

The plot shows step responses that differ in damping coefficient and oscillation frequency. From the point of view of acceptable piloting, we choose a model with parameters $\omega = 2$ and $\zeta = 0.7$.

$$1 - \omega = 2; \zeta = 0.7; \quad 2 - \omega = 1; \zeta = 0.7;$$

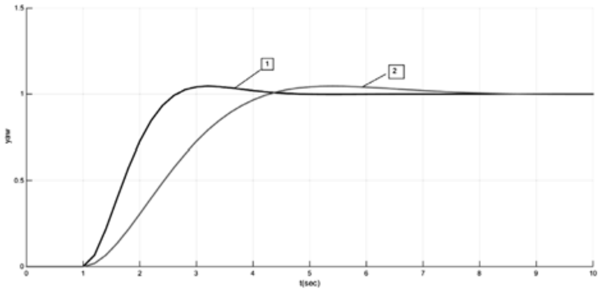

Fig. 17. Step responses of directional stability with different parameters of stabilizing surfaces

The necessary parameters of step responses can be achieved by determining them from the following dependencies

$$\omega^2 = a_{m_y}^{\beta} + \frac{1}{T_\beta T_\psi}; \quad (3.1)$$

Most basically, the frequency of self-oscillation is determined by the first component because the second one has a small value in terms that the time constants T_β, T_ψ are of a great importance. For a given $\omega = 2$ geometric parameter of the stabilizers, we define the correlation:

$$a_{m_y}^{\beta} = -\frac{1}{I_y}\left(\frac{\partial M_y}{\partial \beta}\right); \quad \Delta M_y = C_{yst}^{\beta} \frac{\rho V^2}{2} S_{st} \Delta\beta \quad (3.2)$$

With a normal UAV layout (without a front stabilizer), the needed area of the rear stabilizer, which can provide necessary direction stability equals S = 0.25 m^2.

Then we define the distribution of forces between the front and rear stabilizers (Fig. 18), and also the areas of stabilizers required for this. The front and rear stabilizers differ in design. In particular, the front stabilizer is all-moving, and the rear stabilizer, which provides stability and controllability, is designed with a rudder deflection.

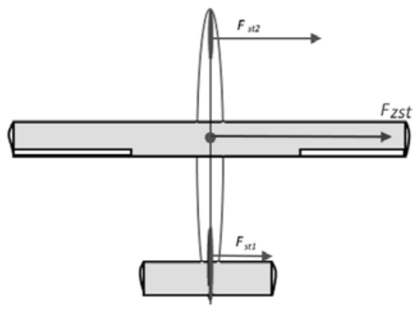

Fig. 18. The distribution of lateral forces between the front and rear vertical stabilizers

Required value of lateral forces:

Fst1=110N; Fst2=140N;

The required area for the front and rear stabilizers is determined by means of the following formulas:

$$\text{Fst1} = C_{yst}^{\delta 1} \delta_1 \frac{\rho V^2}{2} S_{st1};$$

$$Fst2 = C_{yst}^{\delta 1}\delta_2 \frac{\rho V^2}{2} S_{st2};\ C_{yst}^{\delta 1} = 7;\quad C_{yst}^{\delta 2} = 4;\quad (3.3)$$

Concordantly, the areas of the front and rear stabilizers are equal

$$1\,S_{st1}=0.57\text{m}^2,\ S_{st2}=0.36\text{m}^2$$

3.2. Determining the aerodynamic characteristics of control surfaces using ANSYS system

The main purpose of the simulation is to develop a methodology for determining the following aerodynamic parameters: $C_{yst}^{\delta 1}$, $C_{yst}^{\delta 2}$.

These parameters characterize the effectiveness of control when deflecting only the rudder or by displacing the entire surface.

The simulation consists of the following stages:

- simulation of geometric forms;
- simulation of the air masses flow with a speed 25 m/sec (fig. 19, 20);
- defining of parameters: distribution of pressure and speeds (fig. 21, 22);
- defining of the total lateral force acting on the control surface via different methods of generating the control signal (fig. 21, 22).

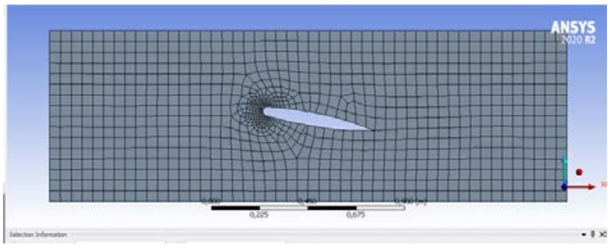

Fig. 19. Simulation of a flow around front stabilizer

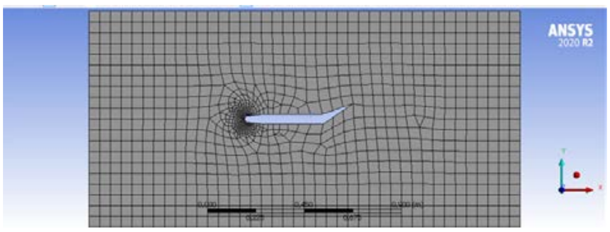

Fig. 20. Simulation of a flow around rear stabilizer

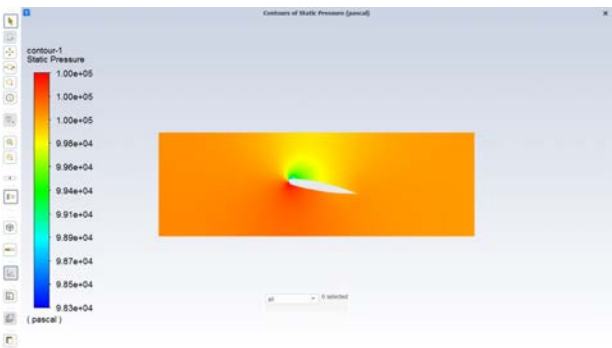

Fig. 21. Pressure distribution on the airfoil of the front stabilizer

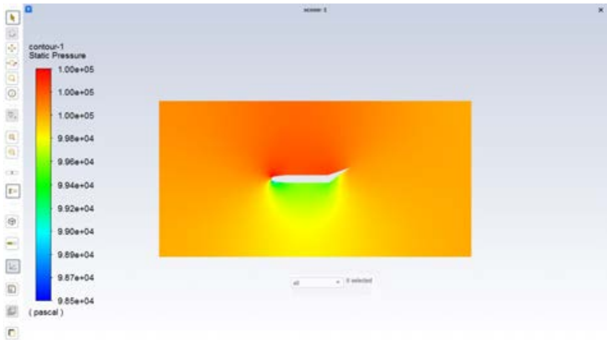

Fig. 22. Pressure distribution on the airfoil of the rear stabilizer

As a consequence of implementing a simulation, there were defined the following values of the parameters:

$$C_{yst}^{\delta 1} = 7;\quad C_{yst}^{\delta 2} = 4;\ n = \frac{C_{yst}^{\delta 2}}{C_{yst}^{\delta 1}} = 0,57$$

which show that the efficiency of the all-movable stabilizer is higher than operation only with the rudder.

$$n = \frac{C_{yst}^{\delta 2}}{C_{yst}^{\delta 1}} = 0,57\ .$$

This equates to routine investigations, where the efficiency factor n of the rudder relative to the entire surface is $n = 0,6–0,65$.

CONCLUSIONS

Relevance of problem increase the lateral mode maneuver capability of unmanned aerial vehicles by directly controlling the side force is connected with stepping up the requirements of lateral control, both in terms of speed and accuracy, as well as the elimination of adverse events, such as angular rotations and loss of height. This is important for UAVs which are flying at low altitudes or maintain surveillance and terrain photography. Determination and formalization of linkage parameters description are based on the differential equations of lateral motion of the aerial vehicles and mathematical modeling in the Mathlab-Simulink system.

With the help of simulation, there were defined aerodynamic characteristics of UAV control surfaces via ANSYS software.

The main purpose of the simulation in ANSYS was to develop a methodology for determining the aerodynamic parameters that characterize the effectiveness of a control when displacing the rudder or by turning the entire surface.

Because of the simulation, there were obtained the values of the parameters that confirm the high efficiency of the all-moving stabilizer.

The obtained results have a certain practical significance.

REFERENCES

[1] Certificate of authorship # 1825746 (USSR) dd. 13.10.92. System for controlling the lateral movement of an unmanned small-sized aerial vehicle / KAU; author inventor. L.G. Romanenko, S.V. Filyunin, N.A. Shilova.

[2] EngineeringSimulation& 3D DesignSoftware | ANSYS – [Electronic resource] / Available at: https://www.ansys.com

[3] MatLab – [Electronic resource] / Available at: https://www.mathworks.com/products/matlab.html

[4] Mkhitaryan A.M. Aerodynamics. M., «Mechanical engineering»,1976. 448 p.

[5] Kokunina L.Kh. Fundamentals of aerodynamics. Textbook for schools of civil aviation [Osnovy aerodinamiki. Uchebnik dlya uchilishch grazhdanskoy aviatsii] Moscow: Transport, 1976. 207 p.

[6] Quantik H.R. Agricultural Pilot's Handbook *[Spravochnik pilota sel'skokhozyaystvennoy aviatsii]* Moscow: Transport, 1991. 254 p.

[7] Etkin B. Atmospheric flight dynamics *[Dinamika atmosfernogo poleta],* 1972. 242 p.

[8] Pashkovsky I.M. Aircraft stability and controllability [Ustoychivost' i upravlyayemost' samoleta] Moscow: Mechanical engineering, 1975. 328 p.

[9] Byushgens G.S., Studnev R.V. Aerodynamcis of longitudinal and lateral movement *[Aerodinamika: dinamika prodol'nogo i bokovogo dvizheniya]* Moscow:Mechanical engineering, 1979. 352 p.

[10] Letov A.M. Flight dynamics and control *[Dinamika poleta i upravleniya]* Moscow: Science, 1969. 360 p.

СПИСОК ВИКОРИСТАННОЇ ЛІТЕРАТУРИ

[1] АС № 1825746 (СССР) от 13.10.92. Система управления боковым движением беспилотного малоразмерного летательного аппарата/ КАИ; авт. изобрет. Л.Г.Романенко, С.В.Филюнин, Н.А.Шилова.

[2] Engineering Simulation& 3D Design Software | ANSYS – [Електронний ресурс] / Режим доступу: https://www.ansys.com

[3] MatLab – [Електронний ресурс] / Режим доступу: https://www.mathworks.com/products/matlab.html

[4] Мхитарян А.М. Аэродинамика. М., «Машиностроение», 1976. 448 с.

[5] Кокунина Л.Х. Основы аэродинамики. Учебник для училищ гражданской авиации. М., «Транспорт», 1976. 207 с.

[6] Квонтик Х.Р. Справочник пилота сельскохозяйственной авиации. М.: Транспорт, 1991. 254 с.

[7] Эткин Б. Динамика атмосферного полета., 1972. 242 с.

[8] Пашковский И.М. Устойчивость и управляемость самолета., М., «Машиностроение», 1975. 328 с.

[9] Бюшгенс Г.С., Студнев Р.В. Аэродинамика: динамика продольного и бокового движения. М., «Машиностроение», 1979. 352 с.

[10] Летов А.М. Динамика полета и управления. М.: Наука, 1969. 360 с.

Дата надходження статті до редакції: 02.10.2023
Дата затвердження статті до друку: 16.11.2023