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Computer-Based Study of the Static and Dynamic Stability of an Unmanned Aerial Vehicle †

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Abstract

This paper describes a study of the static and dynamic stability of a simulated unmanned aerial vehicle (UAV) platform using the XFLR5 virtual aerodynamic environment. The OpenVSP 3.51.2 Released software product was used to validate the study results, and a comparative analysis of aerodynamic characteristics obtained from the two tools is presented. Using the data, an open-loop model for longitudinal and lateral motion was developed in MATLAB-Simulink Release R2025b and analyzed.

Keywords: UAV; open loop system; longitudinal motion; lateral motion; static stability; dynamic stability

1. Introduction

With their development over the past few decades, unmanned aerial vehicles (UAVs) have found increasingly widespread application in various areas of everyday life. This has led to their use in a diverse range of tasks, such as surveillance [1], mapping, logistics, and others. This places high demands on their reliability and flight safety, which necessitates research into the aerodynamic characteristics of UAVs.

UAVs are gaining popularity in transportation services, such as package delivery. The main challenge is stabilizing the payload during delivery. As described in [2], the analysis of the flight path and the application of feedback for stabilizing, optimizing, and correcting the UAV's intended trajectory can be achieved using artificial intelligence.

The study of the static and dynamic stability of UAVs in horizontal and vertical motion is crucial for selecting an appropriate configuration and is also the subject of research in [3]. The process of designing and optimizing the structure and parameters of individual UAV components has been the subject of numerous studies [4–6].

There are various methods and tools for software modeling and analysis of the structural and aerodynamic characteristics of UAVs. The use of open-source software enables the design, analysis, and optimization of unmanned aerial vehicles to achieve the objectives of the assigned mission. Evaluation of the aircraft's characteristics aids in selecting the appropriate type of UAV depending on the specifics of the tasks.

Selecting the appropriate UAV configuration is also of paramount importance when determining the power supply batteries, on which the ability to sustain a long flight depends. A review of aviation rechargeable batteries [7] and their energy storage technology [8] highlights the need for more energy on board unmanned aerial vehicles during flight.

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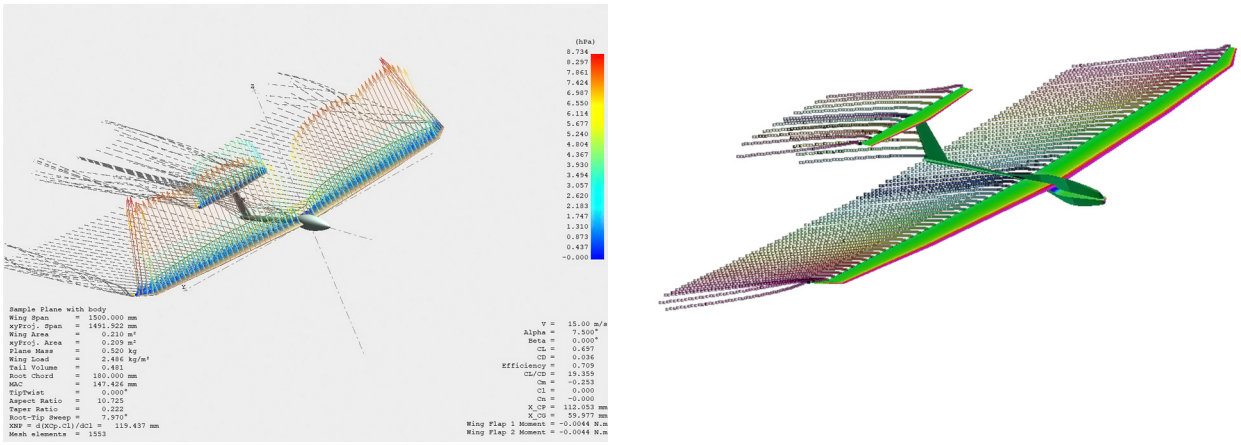
In [9], a study was conducted aimed at determining the optimal configuration of the airfoil and tail for the design of an unmanned aerial vehicle. Another study [10] presents a preliminary methodology for designing a UAV wing. The dimensions of the wing and engine were determined, and the drag and lift coefficients were predicted. An optimization process using a genetic algorithm was applied to maximize durability.

Based on the analysis of static and dynamic stability, a mathematical state-space model of the UAV is developed and used for the design of algorithms and control systems that ensure successful mission execution. This report examines the software-based modeling of an unmanned aerial vehicle for the purpose of analyzing its stability characteristics under small and large deviations from the equilibrium state using mathematical models and simulation environments. The results show that the proposed integrated simulation workflow allows for reliable evaluation and validation of UAV performance in multiple software environments. The comparative analysis shows good agreement between XFLR5, OpenVSP/VSPAERO 3.51.2 and MATLAB-Simulink, characterizing the aerodynamic stability.

2. Software Modeling of UAVs

2.1. Selection of UAV Structural Configuration

For the purposes of this study, a virtual wind tunnel was used within the XFLR5 environment, which enables the modeling and analysis of wing airfoils and the UAV platform configuration. Figure 1a shows the experimental setup for the selected UAV model used for the simulation in the XFLR5 v.6.62 software environment. The software enables the calculation of aerodynamic coefficients, allowing us to predict the aircraft's behavior under various flight conditions.



(**a**) (**b**)

Figure 1. An experimental setup used for UAV research: (**a**) in XFLR5; (**b**) in OpenVSP.

Figure 1b shows the experimental setup within the OpenVSP environment, which is suitable for the visual design and geometric modeling of unmanned aerial vehicles (UAVs), providing the ability to visualize 3D configurations using CAD geometry. A key advantage of modeling with OpenVSP is the detailed interface for refining the architecture of the entire UAV, which is crucial for calculating the center of gravity, volumes, and areas of individual components.

For the purposes of this study, a lightweight, aircraft-type UAV with a large wingspan was selected, which ensures sustained flight at low speeds. The main geometric and mass parameters of the modeled UAV in the XFLR5 environment include:

- Wingspan—1.50 m;
- Wing area—0.210 m^2;

- Chord—180 mm;
- UAV weight—0.520 kg;
- Lift-to-drag ratio $\approx 8^{\circ}$.

The aerodynamic characteristics from XFLR5 were additionally verified using OpenVSP/VSPAERO. While OpenVSP provides detailed geometric modeling capabilities, XFLR5 offers more extensive tools for dynamic stability analysis.

2.2. Development of a Mathematical Model of a UAV in the MATLAB-Simulink Environment

Using state-space matrices (1), a mathematical model of the UAV was developed in the environment of MATLAB-Simulink:

$$\dot{x} = A \cdot x + B \cdot u, \quad y = C \cdot x + D \cdot u \tag{1}$$

where the state vector for the UAV's longitudinal motion is described by Equation (2), and the state vector for the UAV's lateral motion is given by Equation (3):

$$x = \begin{bmatrix} U \\ W \\ Q \\ \theta \end{bmatrix} \tag{2}$$

$$x = \begin{bmatrix} V \\ P \\ R \\ \phi \end{bmatrix} \tag{3}$$

The main components of the vector describing the longitudinal motion are:

- u—longitudinal velocity;
- w—lateral velocity/side-slip velocity;
- q—pitch rate;
- θ—pitch angle.

The main components of the vector describing lateral movement are:

- v—side velocity;
- p—roll rate;
- r—yaw rate;
- ϕ—roll angle.

The control vector for the system's longitudinal motion is described by Equation (4), and for the lateral motion by Equation (5):

$$u = \begin{bmatrix} \delta_{elevator} \\ \delta_{throttel} \end{bmatrix} \tag{4}$$

$$u = \begin{bmatrix} \delta_{aileron} \\ \delta_{ruder} \end{bmatrix} \tag{5}$$

A graphical representation of the open-loop system for each of the state-space motions in the MATLAB-Simulink environment is shown in Figure 2.

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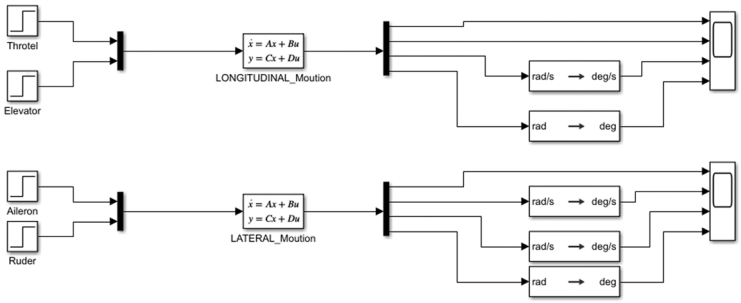


Figure 2. Model of the open-loop system for the longitudinal and lateral motion of an UAV.

2.3. Selecting a Wing Profile

When selecting a UAV model for research, it is necessary to choose a suitable wing airfoil with the required:

- Lift coefficient (CL);
- Drag coefficient (CD);
- The profile's longitudinal strength;
- Wing strength;
- The ability to install appropriate equipment on the control surfaces, etc.

The analysis of the aerodynamic characteristics of a wing profile contributes to flight safety, reduces energy consumption, increases payload and flight duration, and facilitates control and design. The correct choice of profile is a key factor in achieving optimal flight performance for UAVs.

For the purposes of this study, an asymmetric airfoil was selected that generates lift even at low angles of attack. The National Advisory Committee for Aeronautics (NACA) provides airfoils described by numerical codes that are easy to manufacture and are widely used in the design of various types of UAVs. The NACA 1410 airfoil used is shown in Figure 3. It is suitable for large wingspans and ensures stable flight through sufficient lift at low speeds and easy control.

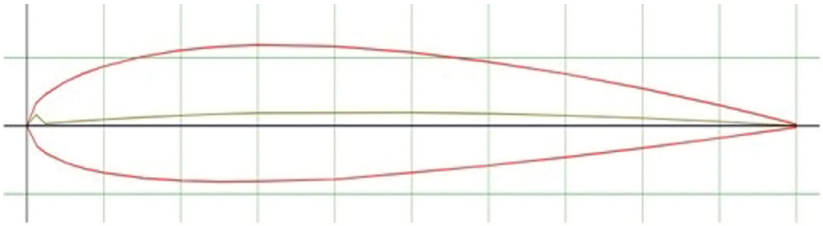


Figure 3. Graphical representation of an aerodynamic profile, NACA 1410.

The aerodynamic characteristics of the selected airfoil and the developed UAV virtual models were investigated. The objective is to determine whether the selected model is statically and dynamically stable in each of the motions that determine flight safety.

3. Study of the Aerodynamic Characteristics of the UAV Model and Validation of the Results

3.1. Analysis of the Aerodynamic Characteristics of the Wing Airfoil

An analysis of the wing airfoil characteristics was performed, and the results of the study under various conditions are shown in Figure 4. The profile generates lift even at a small angle of attack, which ensures sustained flight with lower energy consumption and allows the wing to carry a heavier load.

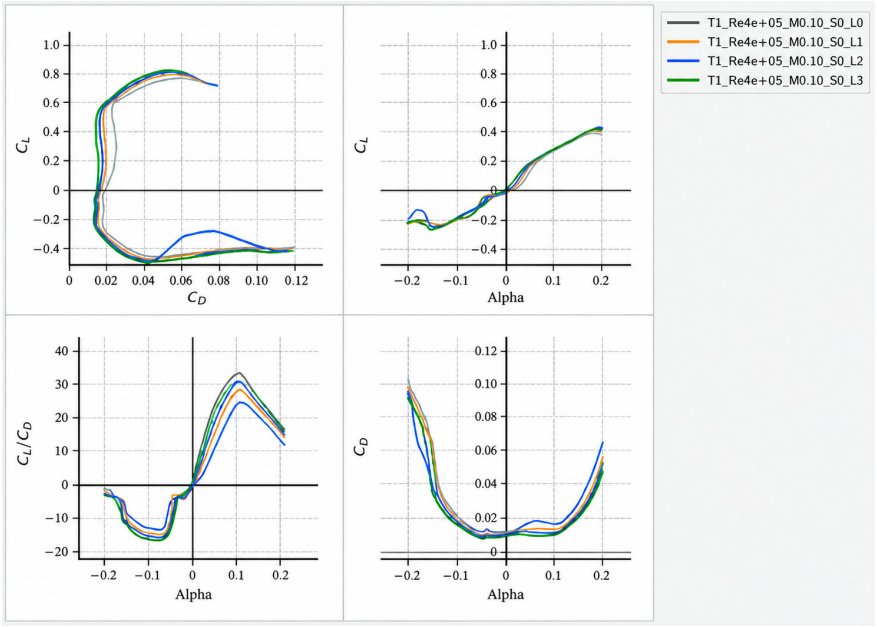
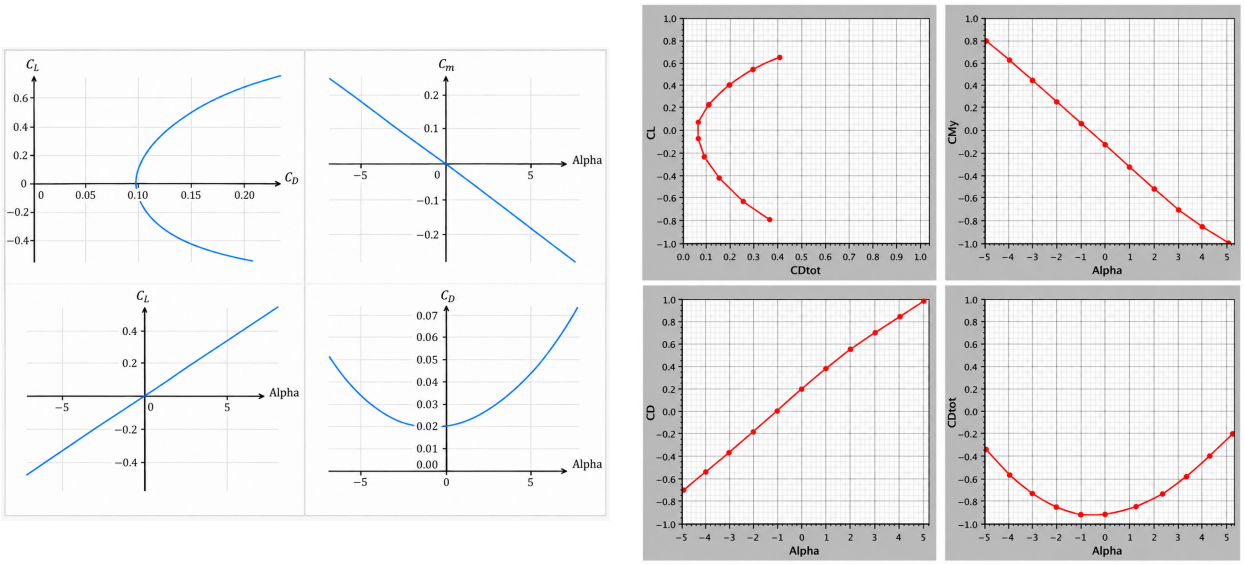


Figure 4. Study of the NACA 1410 airfoil in the XFLR5 wind tunnel.

The resulting graphs are compared with the official data for the selected profile [11]. It can be seen that the coefficients shown are close in absolute value in this comparison. A comprehensive analysis of the UAV wing is required.

3.2. Analysis of Static Stability in Longitudinal Motion of UAV

The static resilience of the UAV in the vertical plane was investigated and the results are described in [12]. The aerodynamic characteristic curves are shown in Figure 5a. The figure shows graphs of the lift-to-drag ratio (CL/CD), an investigation of the pitch moment Cm as a function of the angle of attack (Cm = f(α)), and CL and CD as functions of the angle of attack α in the longitudinal channel.



(**a**) (**b**)

Figure 5. Study of the static stability of the synthesized UAV during longitudinal motion: (**a**) in XFLR5; (**b**) in VSPAERO.

The UAV model was also analyzed using the OpenVSP software and the findings of the aerodynamic analysis of static stability in the vertical channel are shown in Figure 5b.

The study of the static longitudinal resilience of the UAV in XFLR5 and OpenVSP has been compared and validated, which determines the selected model as suitable for the implementation of the tasks set and the successful completion of the mission.

3.3. Analysis of Static Stability in Lateral Motion of UAV

The study of the lateral static equilibrium of the UAV is shown in Figure 6a. The graphs show the ratio of the roll moment coefficient (C_l) to the yaw moment coefficient (C_n), the aircraft's lateral equilibrium along the course, and the lateral force coefficient (C_Y) relative to the slip angle (β) as the flight speed changes. The results show that the aircraft is statically stable in lateral motion, along the heading, and exhibits correct roll behavior with respect to β.

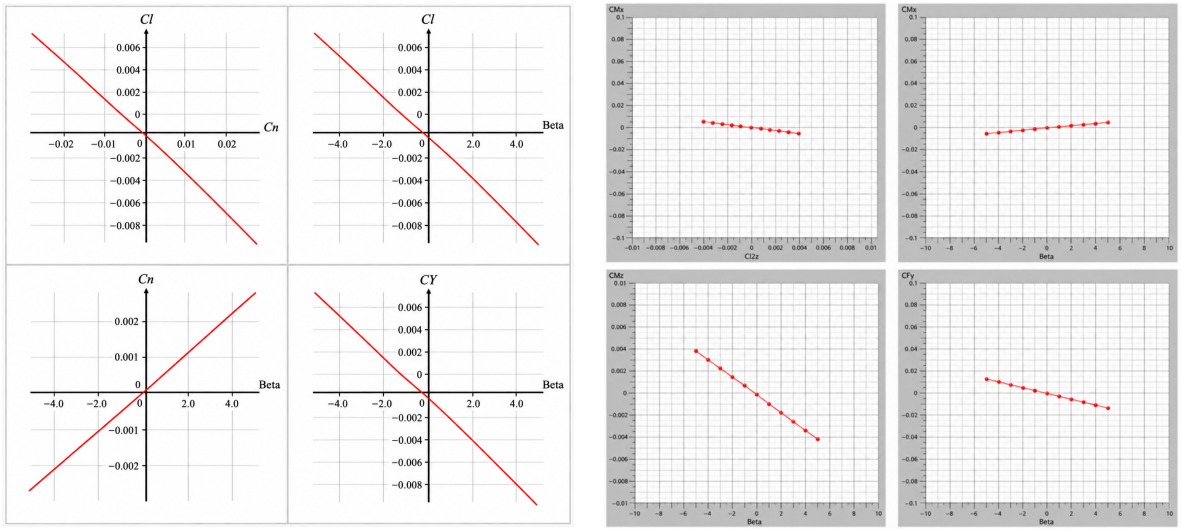


Figure 6. Study of the static stability of the synthesized UAV during lateral motion: (**a**) in XFLR5; (**b**) in VSPAERO.

To validate the static lateral stability, the model of the selected UAV was also analyzed using the OpenVSP software. The findings of this analysis are shown in Figure 6b. It is important to note that the direction of the *Y*-axis and the direction of the moments about the *X*-axis (roll) in the OpenVSP coordinate system are reversed compared to those in XFLR5. Due to this discrepancy in the orientation of the coordinate systems of the two software products, the result of the pitch direction is reversed, but the physical meaning and the form of the functional relationship are equivalent. Therefore, it can be concluded that the selected UAV model is statically laterally stable.

The relationship between C_n and C_l shows the interaction between the angle of attack and the flight path. The graph is nearly a perfect straight line with a negative slope and symmetry around zero, indicating a balanced relationship between the dihedral effect and the vertical stabilizer. This is a stabilizing "cross-reaction" characteristic of the behavior of a stable aircraft. The study shows that the test lines under different conditions overlap almost completely, proving that the aerodynamic coefficients are correctly normalized and do not depend on airspeed.

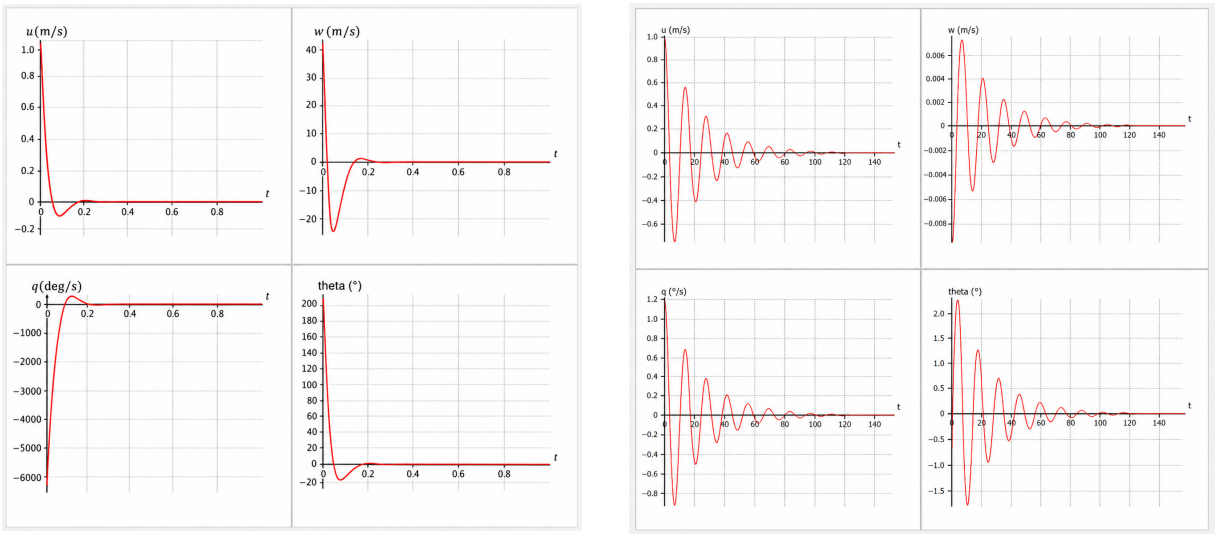
An analysis of the graphs shows that the rolling moment coefficient Cl = f(β) has a negative sign, while the yawing moment coefficient (Yawing Moment) C_n = f(β) has a positive sign, and the change in the lateral force coefficient CY = f(β) has a negative sign.

This determines the ability of the selected UAV model to return to its initial state even in the event of random noise disturbances. These characteristics are key to the aircraft's balance and static equilibrium. The results of the study of the designed aircraft show that the selected aircraft is balanced in the lateral plane and is statically stable.

4. Analysis of the Dynamic Stability of the UAV Model and Validation of the Results

4.1. Analysis of Dynamic Stability in Longitudinal Motion of UAV

The dynamic stability of the synthesized UAV was evaluated by determining the roots of the characteristic equation in the complex plane, defining two symmetric phugoid modes and two symmetric short-period modes. The perturbation analysis capabilities of the XFLR5 software environment were applied to examine these dynamic responses. The corresponding simulation responses are presented in Figure 7a,b. The obtained data provide the basis for the subsequent development of UAV control systems.



(**a**) (**b**)

Figure 7. Dynamic stability study in longitudinal motion: (**a**) of short-period motion; (**b**) of long-period motion.

An analysis of the static and dynamic lateral stability of the synthesized UAV in XFLR5 environment yielded the following state-space matrices (6), which were used to study the mathematical model of the open-loop system within the MATLAB-Simulink environment:

Longitudinal state matrix (A)

$$A = \begin{bmatrix} -0.0856146 & 0.328178 & 0 & -9.81 \\ -0.889862 & -26.2502 & 18.472 & 0 \\ -0.0235932 & -22.8169 & -14.0612 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (6)$$

The matrix describes the internal dynamics of the system and enables an analysis of the system behavior and transient processes, including the identification of characteristic modes of motion such as short-period and fugoid oscillations.

The obtained responses were compared with those generated in the XFLR5 environment. Figure 8 presents the corresponding Simulink simulations. The comparative analysis demonstrates close agreement between the XFLR5 and MATLAB-Simulink models.

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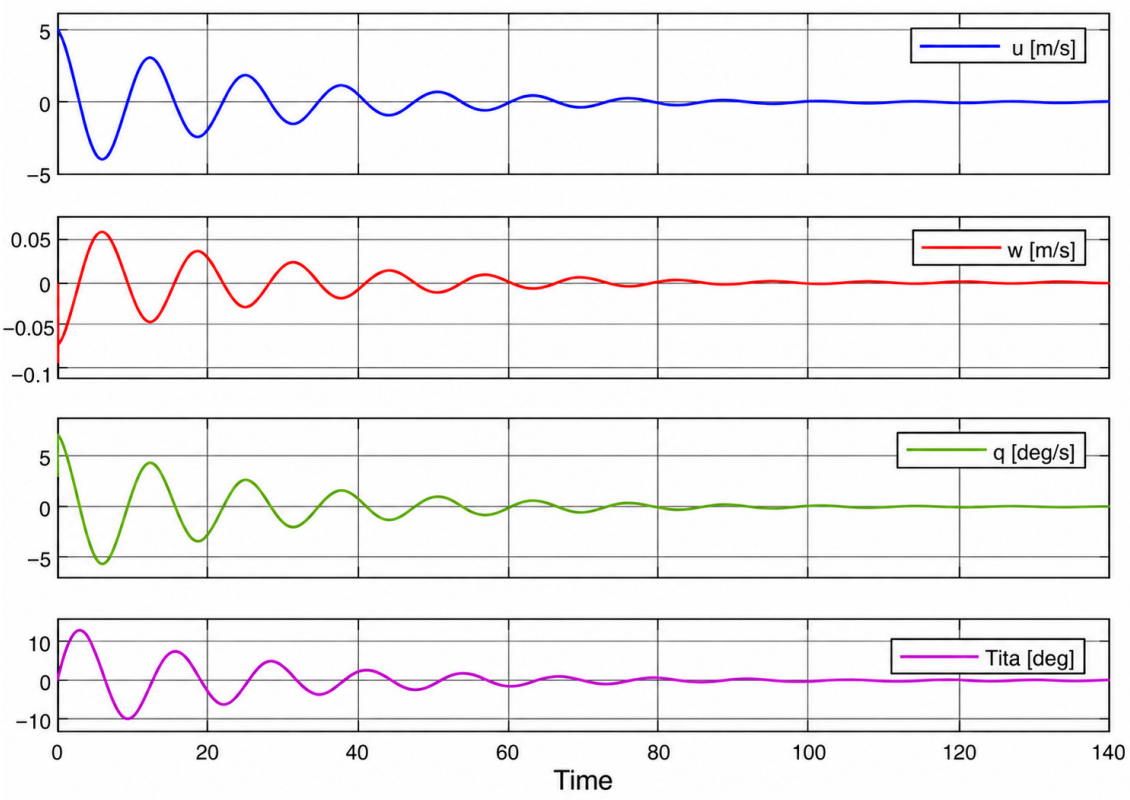


Figure 8. Analysis of long-period motion in MATLAB-Simulink using data from the XFLR5 software product.

The phugoid mode is characterized by low damping and a long period. It describes slow longitudinal oscillations of the UAV around steady-state flight with variations in altitude and speed, and allows for the assessment of flight behavior under small disturbances. It is investigated through the response to a step input, while the short-period mode is analyzed through impulse response.

The analysis shows that short-period motion quickly restores equilibrium, which indicates good longitudinal stability and controllability. Rapid damping is key to control, as the mode is related to the angle of attack and overload, which confirms the model's suitability for stable flight.

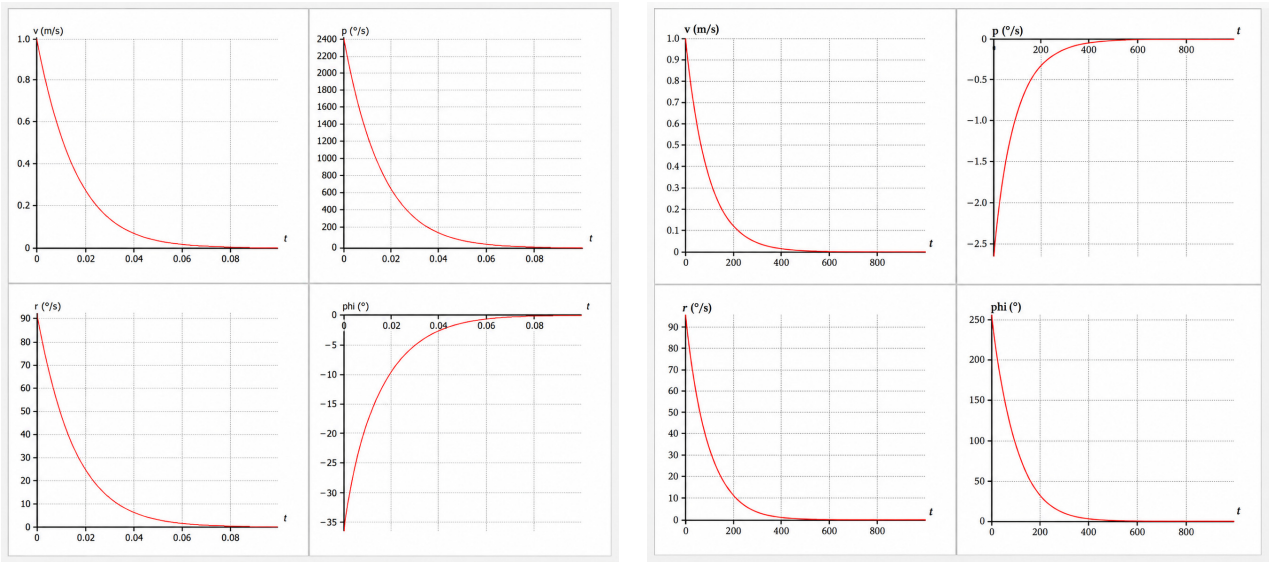
4.2. Analysis of Dynamic Stability in Lateral Motion of UAV

In the study of the selected UAV in lateral motion, three main modes are examined that determine the UAV's ability to return to its initial equilibrium state without additional intervention by the control system.

The plot of the fastest decaying flight mode during horizontal roll is shown in Figure 9a and illustrates how aerodynamics generate a moment that opposes the roll rotation and stops it. The study shows that the lateral velocity, roll angular velocity, and slip angular velocity decrease exponentially to zero, while the roll angle stabilizes as a constant and determines how the UAV recovers its position without oscillations.

The second mode in the study of the dynamic lateral stability is Spiral mode, which develops gradually over time and determines the UAV's smooth entry into a spiral. The graphs of the results shown in Figure 9b indicate that the selected UAV is dynamically stable in this mode.

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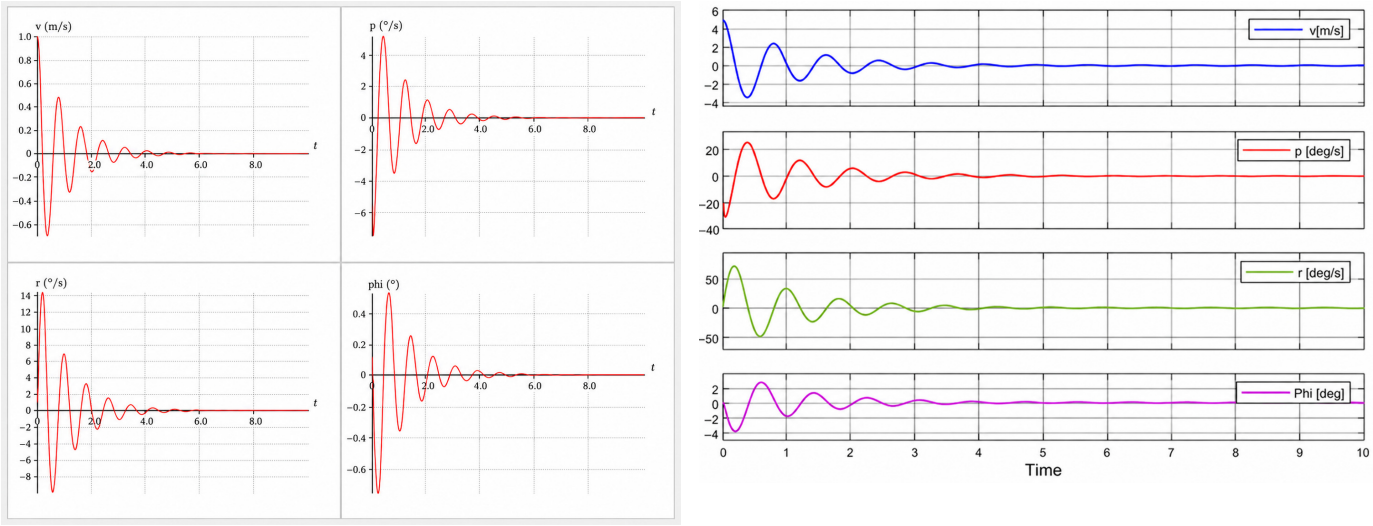
(**a**) (**b**)

Figure 9. A study in lateral motion (**a**) of Roll mode; (**b**) of Spiral mode.

Analysis of the presented results shows:

- v (m/s) decays to zero over time, which means that the slip disappears;
- p (°/s) starts at a negative value and goes toward zero, which means there is no yaw;
- r (°/s) approaches zero;
- The roll angle ϕ (°) graph is the most important in this mode and returns to zero exponentially.

The investigation of the relationship between roll and yaw is conducted in a horizontal Dutch roll flight mode and is shown in Figure 10a. This mode describes the behavior of the UAV as it rolls and simultaneously yaws with its nose. The graphs show a sinusoidal oscillation with decreasing amplitude that decays over approximately 4–6 s. A stable, well-damped Dutch roll is observed, in which yaw dominates, roll is secondary, and all oscillations decay within a few seconds—an aerodynamically stable UAV.



(**a**) (**b**)

Figure 10. Study of Dutch roll mode during lateral motion: (**a**) in XFLR5 software product; (**b**) in MATLAB-Simulink.

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An analysis of the synthesized UAV in the XFLR5 environment yielded the following state-space matrix (7), which is used to analyze the synthesized open-loop system in the MATLAB-Simulink environment:

Lateral state matrix (A)

$$A = \begin{bmatrix} -0.67059 & -0.433256 & -25.2998 & -9.81 \\ -8.34515 & -66.2067 & 3.12323 & 0 \\ 1.95098 & -2.56564 & -1.24328 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (7)$$

Simulation studies were conducted by applying a single step signal to the system input. Figure 10b shows the results of the Simulink simulations.

The simulated Dutch roll responses were compared with those obtained in the XFLR5 environment. The results in XFLR5 are in phase with those from MATLAB-Simulink, confirming the lateral dynamic stability of the synthesized UAV.

5. Conclusions

The comparative evaluation performed using XFLR5, OpenVSP/VSPAERO, and MATLAB-Simulink demonstrates satisfactory results regarding the static and dynamic stability of the synthesized UAV model. The developed simulation approach enables efficient validation of aerodynamic characteristics and dynamic behavior during the preliminary design stage and can support future development of UAV control systems.

The synthesized UAV configuration demonstrated satisfactory longitudinal and lateral stability and can serve as a basis for future control system development.

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References

1. Bikov, T.; Mihaylov, G.; Iliev, T.; Stoyanov, I. Drone Surveillance in the Modern Agriculture. In Proceedings of the 8th International Conference on Energy Efficiency and Agricultural Engineering, EE and AE, Ruse, Bulgaria, 30 June–2 July 2022; pp. 1–4. [CrossRef]
2. Georgieva, T.; Ivanov, A.; Anchev, A. Payload Stabilization in Multidirectional Robot Motion by Applying Trajectory Analysis Algorithm and Feedback Encoders. In Proceedings of the International Conference Automatics and Informatics (ICAI), Varna, Bulgaria, 5–7 October 2023; pp. 179–185. [CrossRef]

3. Biliderov, S.; Stanchev, J. Study the lateral stability of unmanned aerial vehicle using virtual wind tunnel. In Proceedings of the XXVIII International Scientific and Technical Conference "Automation of Discrete Manufacturing", Sozopol, Bulgaria, 29 June–2 July 2019.
4. Kanchev, N. Fixed wing topology optimization: A numerical procedure for computational design model generation. *J. Aeronaut. Res. Dev.* **2023**, *2*, 68–76.
5. Shubov, M.A. Asymptotic analysis of aircraft wing model in subsonic air flow. *IMA J. Appl. Math.* **2001**, *66*, 319–356. [CrossRef]
6. Jang, J.-H.; Ahn, S.-H. Optimum Design of UAV Wing Skin Structure with a High Aspect Ratio Using Variable Laminate Stiffness. *Appl. Sci.* **2022**, *12*, 9436. [CrossRef]
7. Georgiev, Y. Aviation batteries—Trends and perspectives. In Proceedings of the Annual International Scientific Conference of "Georgi Benkovski" Bulgarian Air Force Academy, Dolna Mitropolia, Bulgaria, 8 October 2021; pp. 226–231. (In Bulgarian)
8. Suárez, M.Z.; Valdés, R.M.A.; Arnaldo, C.G.; Delgado-Aguilera Jurado, R.; Pérez Moreno, F.; Comendador, V.F.G. Battery-Powered Aircraft: Technologies and Designs. *Eng. Proc.* **2026**, *133*, 54. [CrossRef]
9. Victor Antonio, C.R.; Yan, S. Preliminary Design and Performance-Stability Analysis of a Fixed-Wing UAV Using XFLR5. *J. Aircr. Spacecr. Technol.* **2023**, *7*, 8–16. [CrossRef]
10. Sahraoui, M.; Boutemedjet, A.; Mahmoud, M.; Scholz, D. Automated Design Process of a Fixed Wing UAV Maximizing Endurance. *J. Appl. Fluid Mech.* **2024**, *17*, 11. [CrossRef]
11. NACA 1410 (Naca1410-il). Available online: http://airfoiltools.com/airfoil/details?airfoil=naca1410-il (accessed on 5 January 2026).
12. Calovska, R.; Genchev, A.; Biliderov, S. Synthesizing and study a fuzzy control system for the longitudinal motion of an unmanned aerial vehicle. *AIP Conf. Proc.* **2024**, *3063*, 040003. [CrossRef]

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