AERODYNAMIC CHARACTERIZATION AND FLIGHT DYNAMICS ASSESSMENT OF A MODIFIED GENERAL AVIATION AIRCRAFT FOR ELECTRIC PROPULSION INTEGRATION

OCTAVIAN-MIRCEA CRISAN[1], ALEXANDRU PASULA[1], IONUT BUNESCU[2,3], MIHAI-VLADUT HOTHAZIE[2,3], MIHAI-VICTOR PRICOP[2,3], BOGDAN RUSU[2], DUMITRU PEPELEA[2], MIHAITA-GILBERT STOICAN[2,3]

Abstract. The ongoing transition toward sustainable aviation has accelerated research efforts focused on hybrid-electric and fully electric aircraft concepts. While significant advances have been achieved in electric propulsion technologies, the integration of energy storage systems within conventional aircraft platforms remains a major engineering challenge due to their impact on aerodynamic performance, mass distribution, stability characteristics, and structural loading conditions. The present work investigates the aerodynamic and flight dynamic characteristics of a modified general aviation aircraft intended as a demonstrator platform for future electric propulsion integration. A representative low-wing general aviation aircraft was selected as the baseline configuration and subsequently modified through the incorporation of a ventral energy-storage container designed to accommodate battery systems. Aerodynamic analyses were conducted using the USAF Digital DATCOM methodology under representative cruise conditions. Lift, drag, and pitching moment coefficients were evaluated over a broad angle-of-attack range, while static and dynamic stability derivatives were determined to assess longitudinal and lateral-directional stability characteristics. A nonlinear six-degree-of-freedom flight dynamics model was subsequently developed to investigate aircraft responses to control surface and propulsion commands. Numerical simulations involving aileron, elevator, rudder, and differential propulsion inputs were performed in order to evaluate controllability, stability margins, and dynamic coupling effects. The obtained results demonstrate that the modified configuration preserves satisfactory aerodynamic efficiency and dynamic stability while exhibiting only a moderate increase in drag associated with the external energy-storage system. The investigated configuration therefore represents a viable candidate for future studies involving hybrid-electric and fully electric propulsion architectures. The present work establishes a preliminary framework for multidisciplinary investigations combining aerodynamics, structures, flight mechanics, and propulsion system integration.

Key words: general aviation aircraft, electric aviation, aerodynamic analysis, flight dynamics, stability derivatives, aircraft control.

[1]ATNOM SRL, Bicazului Street No. 6-8 Oradea
[2]INCAS - National Institute for Aerospace Research “Elie Carafoli”, B-dul Iuliu Maniu 220, Bucharest 061126, Romania
[3]National University of Science and Technology POLITEHNICA, Splaiul Independenței nr. 313, Sector 6, Cod Poștal 060042, Bucharest, Romania

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1. INTRODUCTION

The aviation industry is currently experiencing one of the most significant technological transitions since the introduction of jet propulsion. Increasing environmental concerns, ambitious carbon-emission reduction targets, and the anticipated growth of global air traffic have motivated extensive research into alternative propulsion technologies capable of reducing the environmental footprint of future aircraft [1–3]. Among the various solutions under investigation, electric propulsion has emerged as one of the most promising approaches due to its potential to significantly reduce emissions, improve energy efficiency, and decrease operational noise levels [1].

Recent advancements in electric motor technology, power electronics, and battery systems have enabled the development of numerous experimental electric aircraft and urban air mobility concepts [2, 4, 6]. Nevertheless, despite these technological improvements, the practical implementation of electric propulsion remains constrained by the relatively low energy density of contemporary battery systems when compared with conventional aviation fuels [4–6]. Consequently, electric propulsion integration requires careful consideration of aircraft configuration, energy-storage placement, structural design, thermal management, and aerodynamic performance.

General aviation aircraft provide an ideal platform for investigating such technologies [4, 5]. Their relatively low operational complexity, moderate performance requirements, and flexible design characteristics enable researchers to evaluate novel propulsion architectures before implementation in larger commercial aircraft. However, even for general aviation applications, the integration of battery systems may significantly alter aircraft characteristics. Additional mass and volume requirements frequently necessitate modifications to the airframe, potentially affecting aerodynamic efficiency, stability margins, flight dynamic behavior, and structural loading conditions.

The aerodynamic implications of integrating external energy-storage systems have become an increasingly important research topic. While the addition of external containers may provide practical solutions for battery placement and maintenance accessibility, such modifications generally increase parasite drag and may alter pressure distributions around critical aircraft components. Moreover, changes in mass distribution may influence the location of the center of gravity and therefore affect both static and dynamic stability characteristics.

Several researchers have investigated the aerodynamic performance of modified aircraft configurations intended for electric propulsion applications [4, 5, 15]. Preliminary design studies have demonstrated that aerodynamic penalties associated with battery integration can be minimized through careful geometric optimization and flow-control strategies. Similarly, flight dynamics investigations have highlighted the importance of evaluating control authority, stability derivatives, and dynamic coupling effects following propulsion system modifications.

The successful integration of electric propulsion systems therefore requires a multidisciplinary design approach combining aerodynamics, structures, propulsion, and flight mechanics. During the conceptual and preliminary design stages, rapid aerodynamic assessment tools remain essential for evaluating large numbers of design configurations before more computationally intensive numerical simulations are performed. Semi-empirical methods such as the USAF Digital DATCOM continue to represent valuable engineering tools due to their ability to provide reliable estimates of aerodynamic coefficients and stability derivatives with relatively low computational cost. The present study contributes to these ongoing research efforts by investigating the aerodynamic and flight dynamic characteristics of a modified general aviation aircraft equipped with an external energy-storage container. The work combines aerodynamic analysis and flight mechanics simulations in order to provide a comprehensive assessment of the modified configuration.

For this study, the specific objectives are to determine the lift, drag, and pitching moment characteristics across a representative flight envelope for a general electrified aviation aircraft. The study also aims to evaluate the aircraft's static and dynamic stability derivatives, assess the aerodynamic penalties associated with the integration of external battery packs, and develop a nonlinear flight dynamics model. Furthermore, it seeks to investigate the aircraft's response to control surface deflections and propulsion commands, as well as to identify potential stability and controllability issues arising from the integration of electric propulsion systems. The results presented herein provide useful insights into the preliminary design of electrically modified aircraft and establish a foundation for future investigations involving high-fidelity computational fluid dynamics simulations, aeroelastic analyses, structural optimization procedures, and multidisciplinary aircraft design methodologies [13].

2. AIRCRAFT CONFIGURATION AND GEOMETRIC MODELLING

The baseline configuration considered in the present investigation corresponds to a conventional single-engine, low-wing general aviation aircraft representative of modern personal and training aviation applications. Such aircraft constitute an important category within the general aviation sector due to their versatility, favorable aerodynamic efficiency, and relatively low operational costs. Furthermore, their moderate payload requirements and mission profiles make them suitable candidates for future electrification efforts.

The aircraft configuration consists of a cantilever low-wing arrangement combined with a conventional empennage configuration composed of a horizontal stabilizer and a vertical stabilizer mounted at the rear section of the fuselage. The fuselage presents a streamlined geometry designed to minimize pressure drag during cruise flight while simultaneously providing sufficient internal volume for occupants, fuel storage, avionics equipment, and auxiliary systems.

From an aerodynamic perspective, the selected configuration exhibits characteristics commonly associated with efficient subsonic aircraft, including moderate wing loading, favorable aspect ratio, and adequate tail volume coefficients. These features contribute to stable flight behavior and acceptable handling qualities throughout the operational envelope.

The aircraft was selected as a representative platform for evaluating the aerodynamic consequences of integrating electric propulsion technologies and associated energy-storage systems. Since the primary objective of the investigation is the assessment of general design trends rather than the analysis of a particular commercial product, all results are presented in terms of a generic general aviation aircraft configuration.

One of the principal challenges associated with electric aircraft development concerns the accommodation of battery systems. Due to the relatively low gravimetric energy density of current battery technologies, substantial storage volumes are typically required in order to achieve mission ranges comparable to those of conventionally powered aircraft.

Several integration strategies have been proposed in the literature, including wing-integrated battery systems, fuselage-mounted battery compartments, distributed battery modules, external battery containers [4–6, 13].

The present investigation considers an external ventral container positioned beneath the fuselage. This solution offers several practical advantages, including simplified installation procedures, improved accessibility for maintenance operations, and minimal intrusion into the occupied cabin volume. The ventral location was selected to preserve aircraft symmetry and minimize adverse effects on lateral-directional stability. Furthermore, positioning the container near the longitudinal center of gravity reduces trim changes associated with battery mass variations during operation. Fig. 1 illustrates the investigated battery-integrated configuration and its relationship with the baseline aircraft geometry.

Fig. 1 – Geometric representation of the modified configuration with externally integrated batteries used for the aerodynamic and flight dynamics analyses.

The introduction of an external energy-storage container inevitably modifies the local flow field surrounding the fuselage. Consequently, careful attention must be devoted to the geometric design of the container in order to minimize aerodynamic penalties. The principal aerodynamic objectives considered during the design process were the minimization of drag, the reduction of flow separation regions, the preservation of longitudinal stability characteristics, the minimization of interference effects between the fuselage and the battery container, and the limitation of additional pitching moments induced by the external installation. These objectives were established to ensure that the integration of the battery system would have the least possible adverse impact on the aircraft's aerodynamic performance and stability characteristics.

To achieve these objectives, the container geometry incorporates streamlined fore and aft sections characterized by gradual area variations. Such shaping reduces adverse pressure gradients and delays flow separation, thereby decreasing pressure drag generation. The integration region between the fuselage and the container was designed to ensure smooth geometric transitions and avoid abrupt discontinuities capable of generating local vortical structures and flow disturbances. The addition of energy-storage systems influences not only the aerodynamic characteristics of the aircraft but also its mass distribution [4, 5]. Consequently, the position of the center of gravity must be carefully considered throughout the design process. The placement of the battery container was selected such that the resulting center-of-gravity shift remained within conventional operational limits. Maintaining an appropriate static margin is essential for preserving satisfactory longitudinal stability and controllability characteristics.

Excessive forward movement of the center of gravity may increase trim drag and elevator control requirements, whereas excessive aft movement may significantly reduce static stability margins and potentially compromise flight safety. Consequently, the selected integration strategy seeks to balance aerodynamic efficiency, structural feasibility, and flight mechanics requirements. The aerodynamic analyses presented in this work were conducted under representative cruise conditions corresponding to a low-subsonic flight regime. The selected operating point is characterized by an altitude of approximately 5300 m and a flight Mach number of 0.35. This flight condition was chosen because it represents a typical cruise environment for modern general aviation aircraft and provides an appropriate basis for evaluating the aerodynamic effects associated with electric propulsion integration. The investigated angle-of-attack range extends from −6° to 14°, encompassing both low-incidence cruise conditions and moderate-incidence maneuvering flight regimes. Throughout the analysis, the sideslip angle was maintained at zero in order to isolate the effects of longitudinal aerodynamic behavior.

The resulting geometric and operational framework establishes the basis for the aerodynamic analyses presented in the following sections. Particular emphasis is placed on the determination of aerodynamic coefficients, stability derivatives, and the aerodynamic consequences of integrating external energy-storage systems into conventional aircraft configurations.

3. AERODYNAMIC METHODOLOGY

The aerodynamic assessment of the investigated aircraft configuration was performed using the United States Air Force Digital DATCOM methodology [7]. Digital DATCOM represents a semi-empirical aerodynamic prediction tool that combines analytical formulations, wind-tunnel correlations, and experimental databases to estimate aerodynamic coefficients and stability derivatives of complete aircraft configurations.

During preliminary aircraft design phases, the use of high-fidelity Computational Fluid Dynamics (CFD) methods is often impractical due to the large number of design iterations required. Consequently, engineering methods such as DATCOM provide an effective compromise between computational efficiency and prediction accuracy [7, 8, 9]. The methodology has been extensively validated for conventional subsonic aircraft configurations and remains widely employed during conceptual and preliminary design activities. The present investigation focuses on determining the aircraft's lift, drag, and pitching moment characteristics, as well as its static and dynamic stability derivatives. In addition, the aerodynamic center location and control effectiveness coefficients are evaluated to provide a comprehensive characterization of the aircraft's aerodynamic behavior. The resulting aerodynamic database serves as the foundation for the flight dynamics simulations and stability analyses presented in the subsequent sections.

The aerodynamic analyses were conducted under representative cruise flight conditions corresponding to a low-subsonic operating regime. The selected flight condition was defined by an altitude of 5300 m, a Mach number of 0.35, a sideslip angle of 0°, and an angle-of-attack range extending from −6° to 14°. This Mach number was chosen to ensure that compressibility effects remained moderate while still representing realistic cruise conditions for modern general aviation aircraft. Throughout the analysis, the flow was assumed to be steady, subsonic, fully turbulent, and symmetric with respect to the aircraft longitudinal plane. These assumptions are consistent with the intended application of the methodology and provide a suitable framework for determining aerodynamic characteristics required for preliminary design assessments and subsequent flight dynamics investigations. The aerodynamic behavior of the aircraft is described through the conventional nondimensional force and moment coefficients [9, 14].

The longitudinal aerodynamic characteristics of the aircraft are described through the lift, drag, and pitching moment coefficients, defined as

$$C_L = \frac{L}{q_\infty S},\ C_D = \frac{D}{q_\infty S},\ C_m = \frac{M_y}{q_\infty S \bar{c}}, \tag{1}$$

where L is the lift force, D is the drag force, M_y is the pitching moment about the aircraft center of gravity, S is the reference wing area, $\bar{c}$ is the mean aerodynamic chord, and q_∞ denotes freestream dynamic pressure. The lateral-directional aerodynamic behavior is characterized by the side-force, rolling moment, and yawing moment coefficients:

$$C_Y = \frac{Y}{q_\infty S},\ C_l = \frac{M_x}{q_\infty S b},\ C_n = \frac{M_z}{q_\infty S b}, \tag{2}$$

where Y is the side force, M_x is the rolling moment, N is the yawing moment, and b is the wing span. These coefficients provide a quantitative measure of the aircraft's lateral-directional stability and controllability characteristics. For moderate flight perturbations, the longitudinal aerodynamic coefficients may be represented as linear functions of angle of attack, angular rate, and control surface deflection [10, 11]. The lift coefficient can be approximated by:

$$C_L = C_{L_0} + C_{L_\alpha}\alpha + C_{L_q}\frac{q\bar{c}}{2V} + C_{L_{\delta_e}}\delta_e, \tag{3}$$

where C_{L_0} represents the lift coefficient at zero incidence, C_{L_α} denotes the lift-curve slope, C_{L_q} represents the pitch-rate derivative, $C_{L_{\delta_e}}$ denotes elevator effectiveness. Similarly, the pitching moment coefficient may be expressed as:

$$C_m = C_{m_0} + C_{m_\alpha}\alpha + C_{m_q}\frac{q\bar{c}}{2V} + C_{m_{\delta_e}}\delta_e. \tag{4}$$

The sign and magnitude of C_{m_α} play a central role in determining longitudinal static stability. A negative value indicates that an increase in angle of attack produces a restoring pitching moment tending to return the aircraft toward equilibrium. The lateral-directional dynamics are governed primarily by the sideslip angle, roll rate, yaw rate, and control surface deflections. The corresponding side-force, rolling moment, and yawing moment coefficients may be expressed as:

$$C_Y = C_{Y_\beta}\beta + C_{Y_p}\frac{pb}{2V} + C_{Y_r}\frac{rb}{2V} + C_{Y_{\delta_r}}\delta_r, \tag{5}$$

$$C_l = C_{l_\beta}\beta + C_{l_p}\frac{pb}{2V} + C_{l_r}\frac{rb}{2V} + C_{l_{\delta_a}}\delta_a, \quad (6)$$

$$C_n = C_{n_\beta}\beta + C_{n_p}\frac{pb}{2V} + C_{n_r}\frac{rb}{2V} + C_{n_{\delta_r}}\delta_r. \quad (7)$$

These relationships provide the foundation for assessing aircraft directional stability and control effectiveness.

For conventional subsonic aircraft, the aerodynamic center of the wing is generally located near the quarter-chord position [9, 12]. However, for a complete aircraft configuration, contributions from the fuselage, horizontal tail, and vertical tail modify the overall aerodynamic center location. The longitudinal position of the aerodynamic center may be estimated through moment equilibrium considerations according to

$$x_{AC} = x_{ref} - \frac{\partial C_m / \partial\alpha}{\partial C_L / \partial\alpha}\bar{c}, \quad (8)$$

where x_{ref} denotes the selected reference position. The relative position between the aerodynamic center and the center of gravity directly determines the aircraft static margin.

One of the primary objectives of aerodynamic analysis is the determination of the stability derivatives that govern an aircraft's response to small perturbations from its equilibrium flight condition [10–12]. These derivatives provide a quantitative measure of how aerodynamic forces and moments vary with changes in flight attitude and motion variables, thereby allowing the assessment of both static and dynamic stability characteristics. The principal static stability derivatives include the lift-curve slope, C_{L_α}, the longitudinal stability derivative, C_{m_α}, the side-force derivative, C_{Y_β}, the dihedral effect derivative, C_{l_β}, and the directional stability derivative, C_{n_β}. Among these parameters, C_{m_α} and C_{n_β} are of particular importance because they determine longitudinal and directional static stability, respectively. A negative value of C_{m_α} indicates a restoring pitching moment following a change in angle of attack, while a positive value of C_{n_β} signifies a restoring yawing moment in response to a sideslip disturbance.

Dynamic stability characteristics are described by damping derivatives, which quantify the aerodynamic forces and moments generated by rotational motions [10, 11]. These include C_{m_q}, C_{l_q}, C_{l_p}, C_{n_r}, and C_{Y_r}, representing the effects of pitch rate, roll rate, and yaw rate on the aircraft dynamics. In general, negative values of these derivatives indicate favorable damping behavior, as they oppose the perturbing motion and contribute to the attenuation of oscillations, thereby enhancing overall flight stability.

4. RESULTS

The aerodynamic and flight dynamic characteristics of the modified general aviation aircraft were investigated under representative cruise conditions corresponding to an altitude of 5300 m and a Mach number of 0.35. The objective of the analysis was to evaluate the influence of the external energy-storage container on aircraft performance, stability, and controllability. The obtained results include aerodynamic force and moment coefficients, stability derivatives, pressure coefficient distributions, and nonlinear flight dynamics simulations corresponding to a series of control-surface and propulsion commands.

The aerodynamic performance of the modified configuration is first assessed through the variation of lift coefficient with angle of attack, presented in Fig. 2. The lift curve exhibits a nearly linear behavior throughout the investigated incidence range, with the lift coefficient increasing from values close to zero at low incidence to approximately 1.45 at an angle of attack of 14°. The calculated lift-curve slope is representative of conventional low-subsonic general aviation aircraft and demonstrates that the addition of the external battery container does not significantly affect the lift-generating capability of the wing. This observation is expected since the energy-storage system is positioned beneath the fuselage and therefore does not directly interfere with the pressure distribution over the primary lifting surfaces.

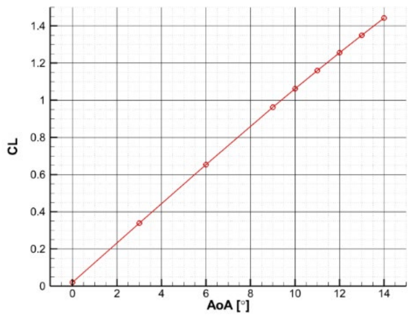


Fig. 2 – Variation of lift coefficient C_L with angle of attack for the modified aircraft configuration.

The drag characteristics of the modified aircraft are illustrated in Fig. 3. As expected, the drag coefficient exhibits a nonlinear increase with angle of attack. At low incidences corresponding to cruise flight conditions, the drag coefficient remains relatively small, indicating favorable aerodynamic efficiency. As the angle of attack increases, the drag coefficient grows progressively due to the increasing contribution of induced drag associated with higher lift production.

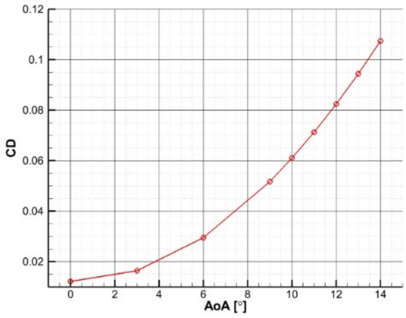


Fig. 3 – Variation of drag coefficient C_D with angle of attack for the modified aircraft configuration.

The smooth variation of the drag curve indicates the absence of abrupt flow separation phenomena and confirms that the aerodynamic integration of the external energy-storage container was achieved successfully. Although the additional external structure inevitably increases the parasite drag of the aircraft, the resulting penalty remains moderate and acceptable for the intended application.

Further insight into the aerodynamic efficiency of the modified configuration is obtained through the drag polar presented in Fig. 4. The relationship between lift coefficient and drag coefficient exhibits the classical parabolic behavior associated with conventional subsonic aircraft. The drag polar confirms that the modified aircraft preserves favorable aerodynamic characteristics despite the presence of the external battery installation. The moderate increase in drag observed throughout the operating range suggests that the chosen integration strategy successfully balances energy-storage requirements and aerodynamic performance. This finding is particularly important for electric aircraft applications, where energy efficiency directly influences achievable range and endurance.

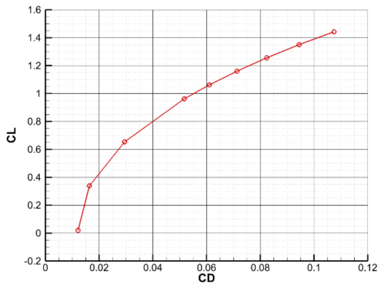
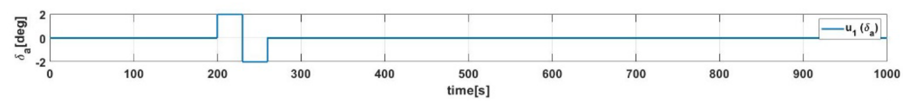


Fig. 4 – C_L vs C_D for the modified aircraft configuration.

The longitudinal stability characteristics of the modified aircraft may be evaluated through the computed pitching moment derivatives. The obtained value of the longitudinal static stability derivative remains negative throughout the investigated flight envelope, confirming that the aircraft satisfies the fundamental requirement for static longitudinal stability. Consequently, any increase in angle of attack generates a restoring pitching moment tending to return the aircraft toward its equilibrium condition. Similarly, the dynamic stability derivatives associated with pitch damping remain negative, indicating that oscillatory longitudinal motions are naturally attenuated by aerodynamic forces and moments. These characteristics contribute to predictable handling qualities and enhance flight safety.

The lateral-directional stability derivatives further demonstrate the favorable dynamic behavior of the investigated configuration. The directional stability derivative remains positive, indicating the presence of restoring yawing moments in response to sideslip disturbances, while the roll and yaw damping derivatives remain negative, providing effective attenuation of oscillatory motion. Collectively, these results indicate that the aircraft preserves the stability characteristics expected from a conventional general aviation platform despite the addition of the external energy-storage system.

At higher angles of attack, the pressure gradients become more pronounced as lift production increases. The suction peaks on the upper wing surfaces intensify, while the pressure recovery near the trailing edge remains gradual. Although stronger pressure gradients develop throughout the flow field, no evidence of large-scale flow separation is observed within the investigated operating range. This observation is consistent with the lift and drag characteristics discussed previously and confirms that the modified configuration remains aerodynamically efficient throughout the analyzed flight envelope.



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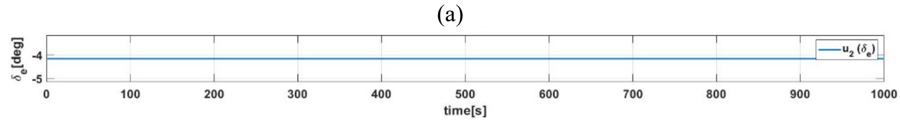

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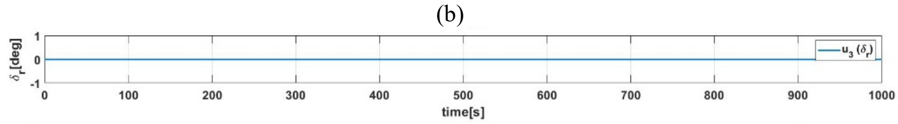

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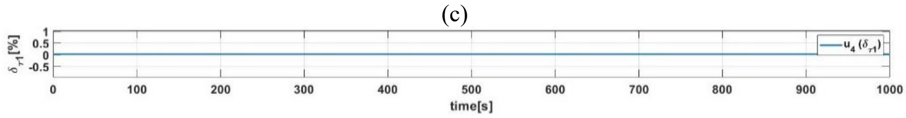

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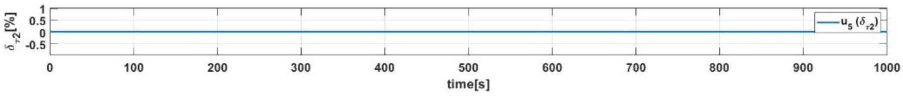


(e)

Fig. 5 – Aileron step input command $\delta_a = \pm 2^{\circ}$ applied during the roll-response simulation.

Following the aerodynamic assessment, a series of nonlinear flight dynamics simulations were performed in order to evaluate the stability and controllability characteristics of the modified aircraft. The simulations were conducted using a six-degree-of-freedom flight dynamics model incorporating the aerodynamic database generated through the DATCOM analysis. Step commands were applied to the primary control surfaces and propulsion system, and the resulting aircraft responses were analysed. The roll response was investigated through the application of an antisymmetric aileron step input with an amplitude of ±2°, as illustrated in Fig. 5. The command was maintained for 20 s before being reversed for an additional 20 s, thereby producing a symmetric excitation of the lateral dynamics.

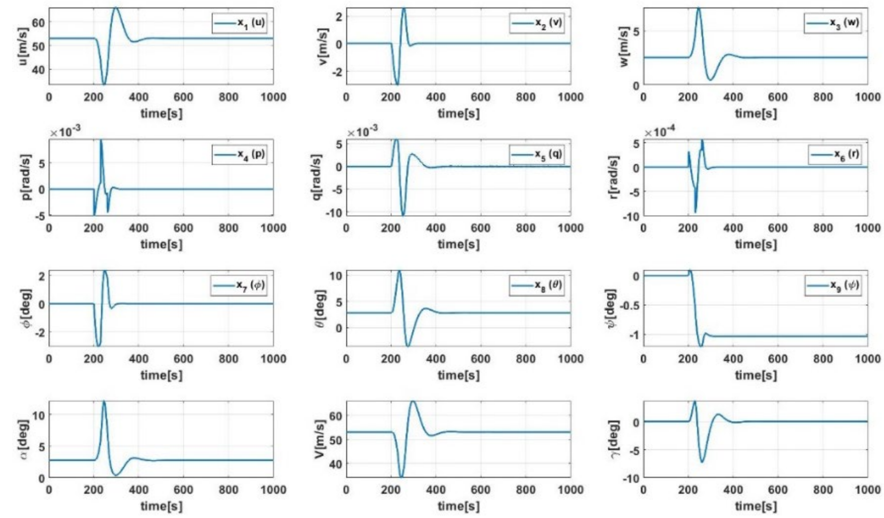


Fig. 6 – Aircraft response to the aileron step input showing roll, pitch, yaw, and associated state-variable evolution.

The resulting aircraft response is presented in Fig. 6. Following the application of the control input, the aircraft develops the expected rolling motion and reaches a new equilibrium condition before returning toward its initial attitude when the command is reversed. The response remains stable throughout the maneuver and exhibits nearly symmetric behavior with respect to the positive and negative control actions.

At the conclusion of the simulation, the roll attitude returns to a value close to its initial condition, indicating satisfactory roll stability. A residual variation of the yaw angle remains visible due to the inherent coupling between roll and yaw dynamics; however, this effect does not compromise overall stability and is characteristic of conventional aircraft configurations. The longitudinal dynamic response was evaluated by imposing a symmetric elevator step command of ±2°, as shown in Fig. 7.

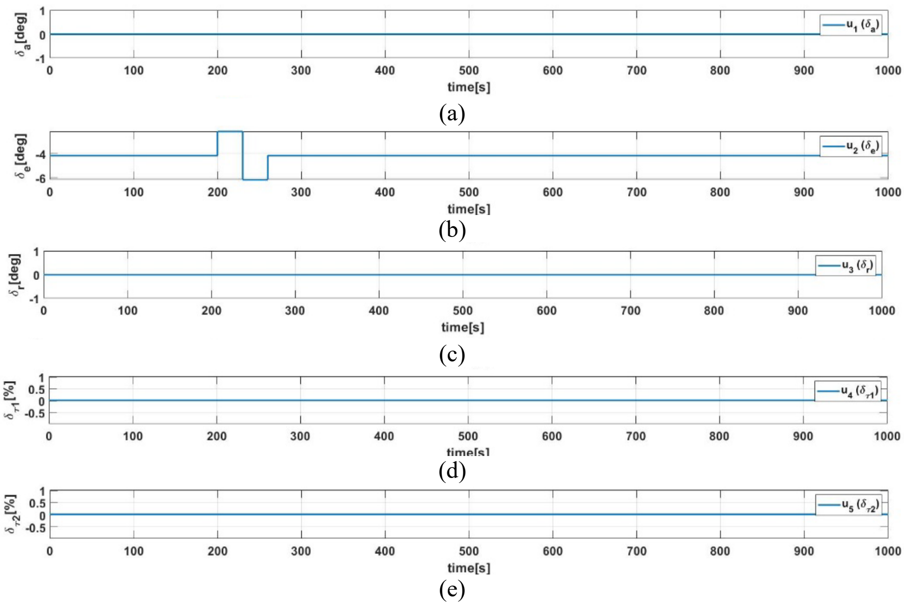


Fig. 7 – Elevator step input command $\delta_e = \pm 2^{\circ}$ applied during the pitch-response simulation.

The corresponding aircraft response is presented in Fig. 8. The elevator deflection produces the expected variation of pitch attitude and associated longitudinal state variables. Following the transient phase, the aircraft gradually returns toward equilibrium conditions due to the action of the aerodynamic damping mechanisms. The response remains highly symmetric, and the aircraft recovers its initial pitch attitude after completion of the maneuver. A notable feature of the simulation is the very weak coupling between longitudinal and lateral-directional dynamics.

The roll and yaw attitudes remain essentially unchanged throughout the maneuver, demonstrating that the aircraft possesses well-separated longitudinal and lateral modes. Such behavior is desirable because it contributes to predictable handling qualities and simplifies control-system design.

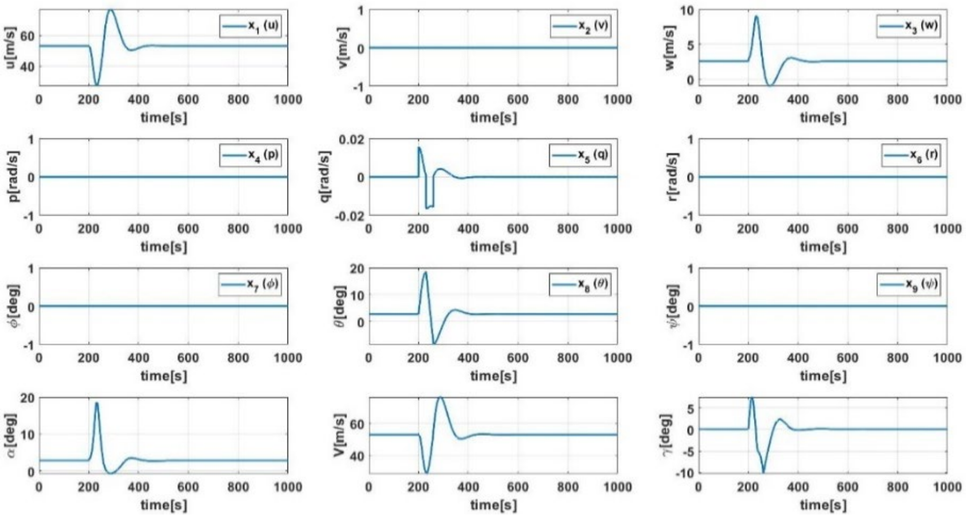


Fig. 8 – Aircraft response to the elevator step input demonstrating longitudinal stability and damping characteristics.

Directional stability was assessed through the application of a rudder step command of ±2°, illustrated in Fig. 9.

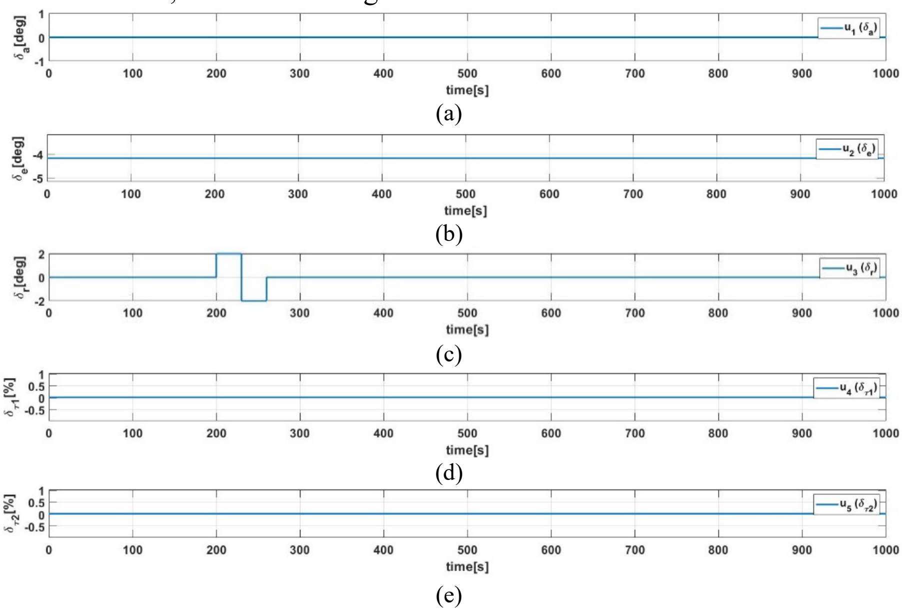


Fig. 9 – Rudder step input command $\delta_r = \pm 2^{\circ}$ applied during the yaw-response simulation.

The corresponding aircraft response is shown in Fig. 10. The rudder input generates the expected yawing motion and produces a stable directional response throughout the maneuver. Unlike the elevator case, however, the yaw excitation introduces measurable coupling between lateral-directional and longitudinal dynamics. Variations in yaw attitude induce secondary changes in pitch angle and vertical motion, reflecting the interconnected nature of aircraft dynamics.

Despite these interactions, all state variables remain bounded and converge smoothly toward equilibrium conditions following removal of the control input. The response confirms that the modified configuration retains adequate directional stability and damping characteristics.

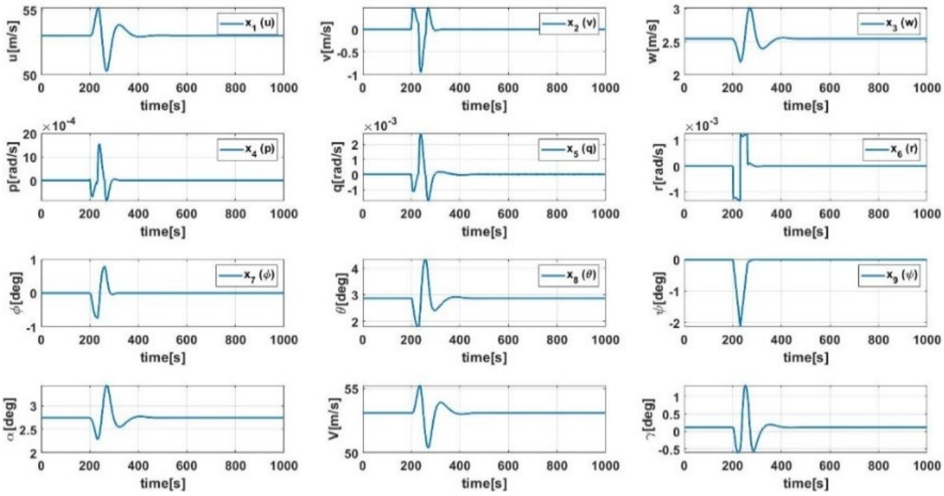
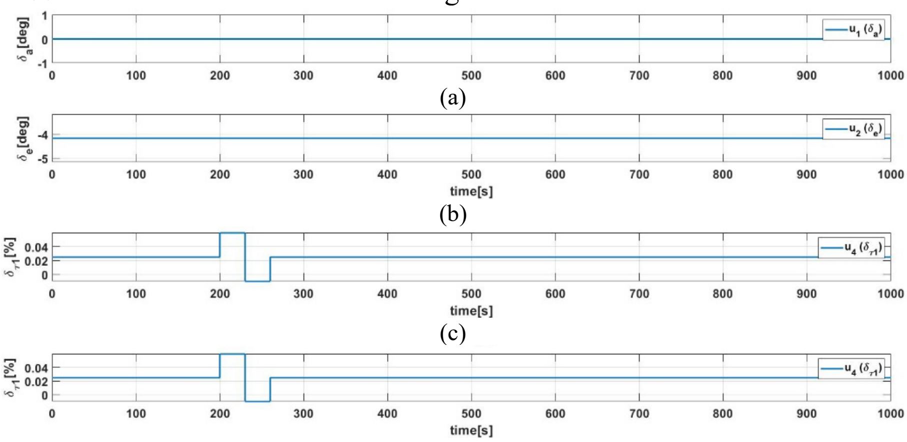


Fig. 10 – Aircraft response to the rudder step input showing directional stability and coupling effects between motion modes.

The influence of asymmetric propulsion was subsequently investigated through independent variations of the propulsion systems. Fig. 11 presents the command applied to the right propulsion unit, consisting of a step variation of ±3.5% relative to the cruise thrust setting.



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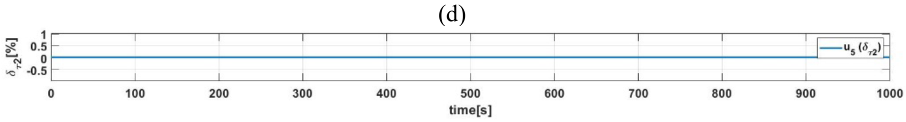


(e)

Fig. 11 – Right-engine thrust variation command ($\Delta T_R = \pm 3.5\%$ of cruise thrust) used for asymmetric propulsion analysis.

The resulting aircraft response is illustrated in Fig. 12. The simulations reveal that asymmetric thrust influences all state variables, including both longitudinal and lateral-directional motion. Variations in propulsion generate changes in velocity, angular rates, and attitude angles due to the additional forces and moments introduced into the system. The roll and pitch responses remain largely symmetric; however, the yaw response exhibits a noticeable asymmetry, resulting in a final heading angle that differs from the initial value. This behavior is consistent with the expected effect of asymmetric thrust and confirms the sensitivity of directional dynamics to propulsion-system variations.

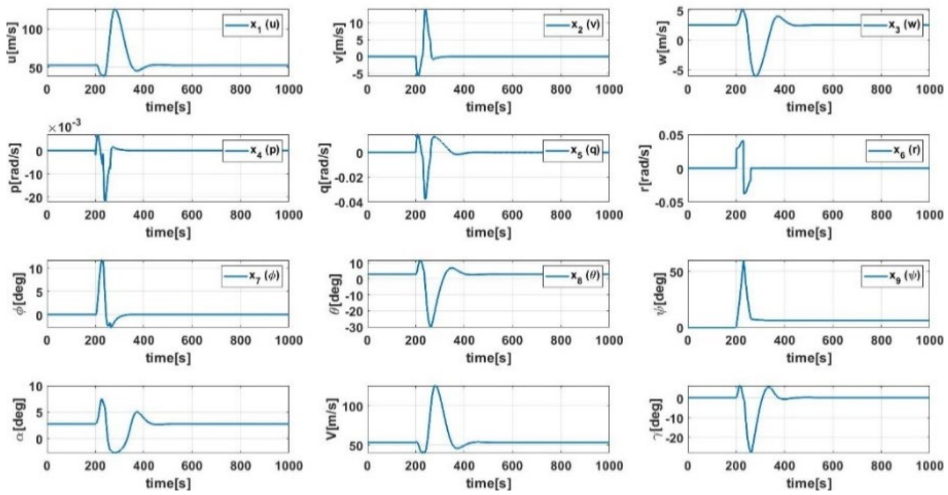
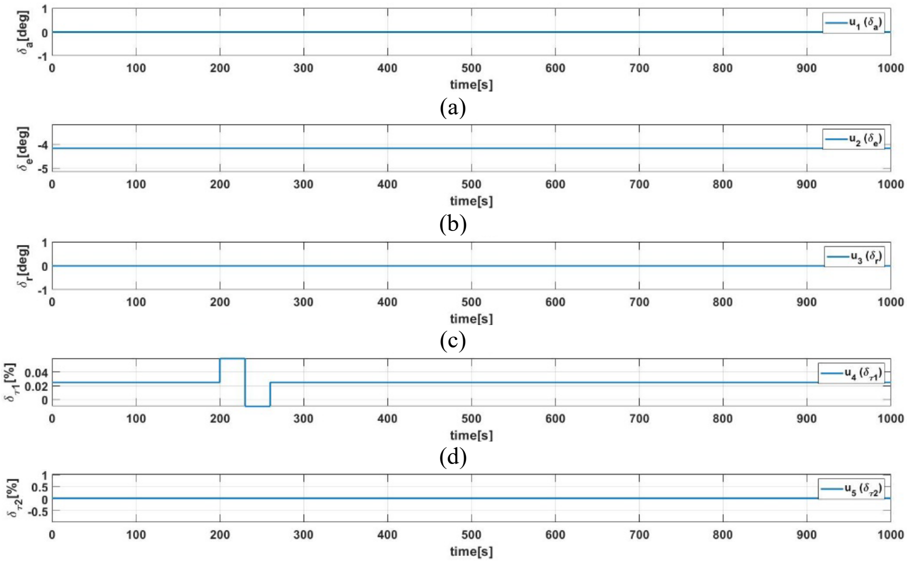


Fig. 12 – Aircraft response to right-engine asymmetric thrust input showing coupled longitudinal and lateral-directional dynamics.

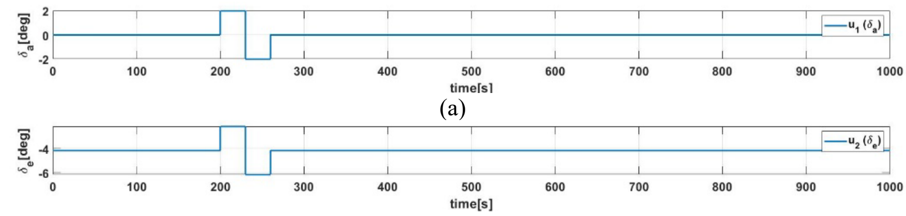
A similar analysis was performed for the left propulsion unit. The imposed command is presented in Fig. 13, while the corresponding aircraft response is shown in Fig. 14. The overall dynamic behavior closely resembles that observed for the right propulsion system. All state variables remain bounded and exhibit stable behavior throughout the maneuver. The similarity between the two responses demonstrates the balanced nature of the aircraft model and confirms that the propulsion installation does not introduce undesirable asymmetries into the flight dynamics. As in the previous case, the final yaw attitude differs slightly from the initial condition due to the cumulative effect of the asymmetric propulsion input. The influence of the left propulsion unit was investigated through the application of an asymmetric thrust command consisting of a ±3.5% variation relative to the cruise thrust setting. The imposed command profile provides a controlled excitation of the aircraft dynamics and enables the assessment of the response to propulsion-induced disturbances.



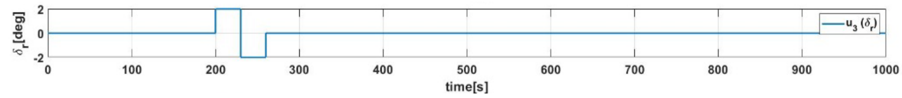
(a) (b) (c) (d) (e)

Fig. 13 – Left-engine thrust variation command ($\Delta T_R = \pm 3.5\%$ of cruise thrust) used for asymmetric propulsion analysis.

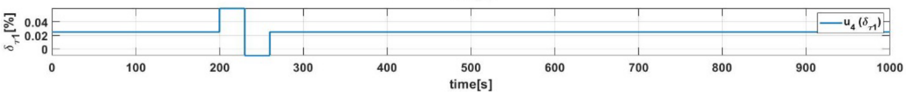
The aircraft response resulting from the left-engine thrust variation is shown in Fig. 14. The overall dynamic behavior closely resembles that observed for the right propulsion system, with all state variables remaining bounded and exhibiting stable characteristics throughout the maneuver. The similarity between the responses confirms the balanced nature of the aircraft model and indicates that the propulsion installation does not introduce significant asymmetries into the flight dynamics.



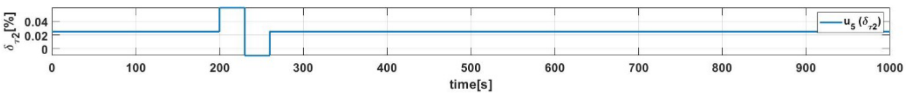
(a) (b)



(c)



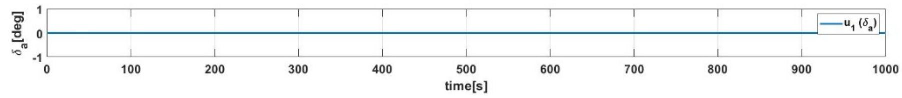
(d)



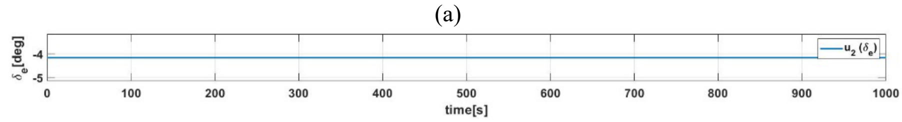
(e)

Fig. 14 – Aircraft response to right-engine asymmetric thrust input showing coupled longitudinal and lateral-directional dynamics.

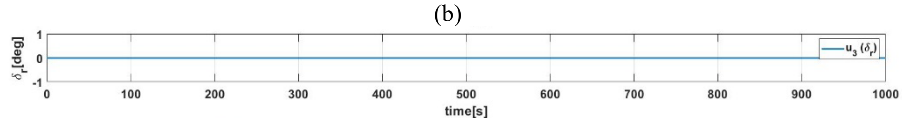
A final simulation was conducted to evaluate the aircraft behavior under simultaneous excitation of all control channels. The combined command profile is presented in Fig. 15 and consists of simultaneous step inputs applied to the aileron, elevator, rudder, and propulsion systems.



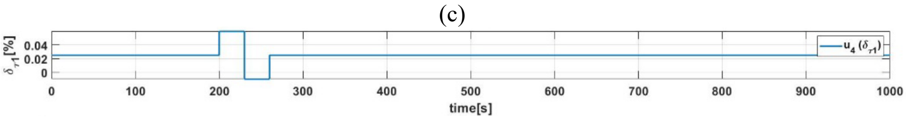
(a)



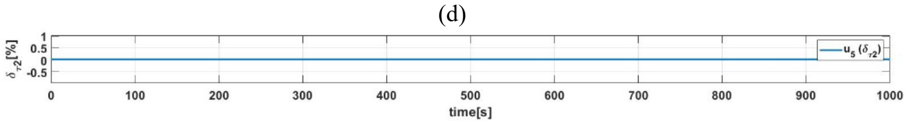
(b)



(c)



(d)



(e)

Fig. 15 – Combined control and propulsion command profile including simultaneous aileron, elevator, rudder, and thrust inputs.

The resulting aircraft response is shown in Fig. 15. Despite the complexity of the imposed maneuver, the aircraft remains stable throughout the simulation. All state variables exhibit bounded behavior and gradually return toward equilibrium conditions following the transient phase. The roll and pitch responses remain largely symmetric, while the yaw response exhibits the same residual asymmetry observed during the asymmetric propulsion investigations. Nevertheless, no divergent oscillations or loss-of-control tendencies are observed.

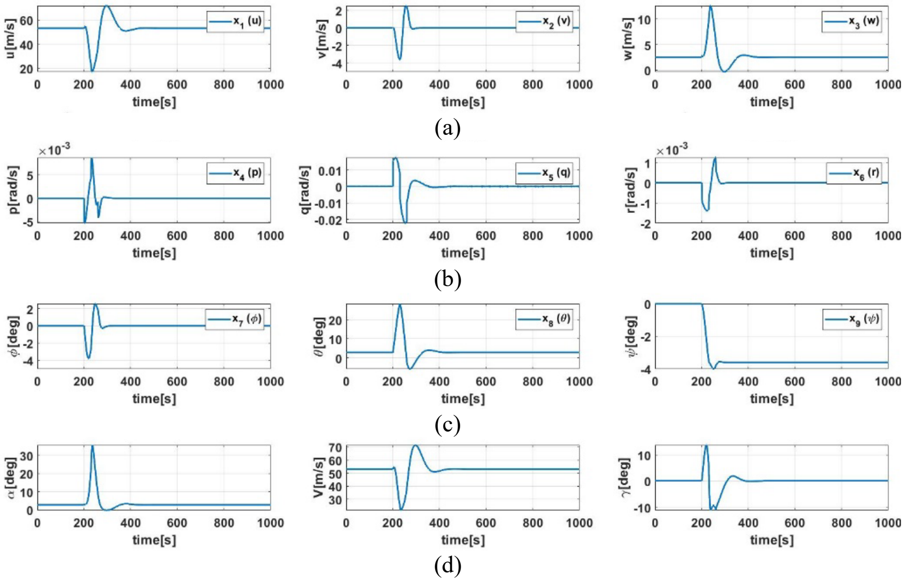


Fig. 16 – Aircraft response to simultaneous control-surface and propulsion excitations demonstrating overall dynamic stability and controllability.

The combined aerodynamic and flight dynamics results demonstrate that the modified aircraft configuration successfully preserves the essential characteristics of the baseline platform while accommodating the additional requirements associated with electric propulsion integration. The lift-generating capability remains largely unaffected, the drag increase associated with the external energy-storage system remains moderate, and the aircraft satisfies both longitudinal and lateral-directional stability criteria. Furthermore, the nonlinear flight dynamics simulations confirm that the modified configuration retains satisfactory controllability and handling qualities under a wide range of control and propulsion inputs. These findings indicate that the investigated integration strategy constitutes a feasible solution for future electric aircraft developments and provides a solid foundation for subsequent investigations involving high-fidelity computational fluid dynamics simulations, aeroelastic analyses, structural optimization, and multidisciplinary design studies.

5. CONCLUSIONS

The present study investigated the aerodynamic and flight dynamic characteristics of a modified general aviation aircraft incorporating an external energy-storage container intended for future electric propulsion applications. A comprehensive analysis was performed using the USAF Digital DATCOM methodology combined with nonlinear flight dynamics simulations in order to evaluate the effects of the configuration modification on aerodynamic performance, stability, and controllability.

The aerodynamic assessment demonstrated that the modified configuration preserves the principal characteristics of the baseline aircraft. The lift coefficient exhibited a nearly linear variation throughout the investigated angle-of-attack range, indicating stable lift generation and the absence of significant flow separation phenomena under the considered operating conditions. The drag characteristics revealed the expected increase associated with the integration of the external energy-storage system; however, the aerodynamic penalty remained moderate due to the streamlined design and favorable placement of the container. The resulting drag polar confirmed that the aircraft retains acceptable aerodynamic efficiency and remains suitable for cruise operations representative of general aviation missions.

The stability analysis showed that both longitudinal and lateral-directional stability requirements are satisfied. The computed static stability derivatives indicate the presence of restoring aerodynamic moments following perturbations in angle of attack and sideslip angle, while the dynamic derivatives demonstrate adequate damping characteristics.

The nonlinear flight dynamics simulations provided additional insight into the controllability and handling qualities of the aircraft. The responses to aileron, elevator, and rudder step commands demonstrated stable and predictable behavior throughout the investigated flight envelope. The aircraft exhibited satisfactory recovery characteristics following all control inputs, and no divergent oscillatory modes were observed. Roll, pitch, and yaw responses remained consistent with those expected from a conventional general aviation aircraft, indicating that the integration of the external energy-storage container does not adversely affect the fundamental flight dynamic behavior.

The asymmetric propulsion investigations demonstrated that differential thrust influences both longitudinal and lateral-directional motion; however, all responses remained bounded and stable. Although residual heading changes were observed following asymmetric propulsion commands, the aircraft preserved adequate controllability and directional stability. The combined-control simulations further confirmed the robustness of the modified configuration, showing that simultaneous excitation of multiple control channels does not compromise flight stability or handling qualities. Overall, the results indicate that the investigated integration strategy represents a viable approach for incorporating electric propulsion technologies into existing general aviation aircraft platforms. The aerodynamic penalties associated with the external energy-storage system remain limited, while the aircraft continues to satisfy the principal stability and controllability requirements necessary for safe operation. Future research should focus on high-fidelity Reynolds-Averaged Navier–Stokes simulations, aeroelastic analyses, structural optimization studies, battery thermal-management investigations, and multidisciplinary design optimization. Experimental validation through wind-tunnel testing and flight-test campaigns will also be necessary to further quantify the aerodynamic and flight dynamic effects associated with electric propulsion integration and to support the development of next-generation sustainable aviation platforms.

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