



INTERNATIONAL UNIVERSITY LIAISON INDONESIA (IULI)

BACHELOR'S THESIS

**DESIGN AND ANALYSIS OF FLAPERONS FOR A MEDIUM ALTITUDE
LONG ENDURANCE UNMANNED AERIAL VEHICLE**

By

Regita Nandini

11202201009

Presented to the Faculty of Engineering and Life Sciences
In Partial Fulfilment Of the Requirements for the Degree of

SARJANA TEKNIK

In

AVIATION ENGINEERING

FACULTY OF ENGINEERING AND LIFE SCIENCES

Gading Serpong, Tangerang 15332
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APPROVAL PAGE

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I hereby declare that this submission is my own work and to the best of my knowledge, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma at any educational institution, except where due acknowledgement is made in the thesis.

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ABSTRACT

Design and Analysis of Flaperons for a Medium Altitude Long Endurance
Unmanned Aerial Vehicle

by

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Dr. Eng. Ressa Octavianity, Co-Advisor

An existing Medium-Altitude Long-Endurance (MALE) Unmanned Aerial Vehicle (UAV) incorporated flaperons, but their geometry and roll-control performance had not been systematically sized and verified. This thesis aimed to determine an appropriate flaperon geometry, evaluate its roll-control and high-lift effectiveness, assess roll-related stability, and perform preliminary standards-based verification. A heuristic sizing method was combined with XFLR5 aerodynamic and stability analyses. Six Path B candidates were evaluated using roll rate, bank-response time, lift increment, adverse yaw, flaperon area, and estimated hinge moment, followed by Pareto-based selection and additional verification. Configuration C-02 was selected with $\eta_{in} = 0.10$, $\eta_{out} = 0.90$, and $c_f/c = 0.25$, corresponding to a flaperon span of 6.392 m per side and 20.018% of the wing area. At the approach condition, C-02 achieved a steady-state roll rate of 34.754 deg/s, a 30° bank time of 0.956 s, a lift increment of $\Delta C_L = 0.833$, and an adverse-yaw ratio of 0.086. Roll rates of 36.754 deg/s and 30.108 deg/s were obtained at cruise and loiter, respectively. Roll subsidence remained stable, while the approach spiral mode showed a slow divergence with a 23.81 s doubling time. The Method 2 roll-rate result differed from XFLR5 by 1.07%, while the single-flaperon failure cases produced 17.596 deg/s and 19.740 deg/s and were classified as marginal. Overall, C-02 was established as a suitable preliminary flaperon configuration for the investigated MALE UAV.

Keywords: *MALE UAV, flaperon, roll control, XFLR5, Pareto analysis*

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List of Abbreviations

MALE	Medium Altitude Long Endurance
UAV	Unmanned Aerial Vehicle
STANAG	Standardization Agreement
CFR	Code of Federal Regulations
FAA	Federal Aviation Administration
NATO	North Atlantic Treaty Organization
USAF	United States Air Force
CAD	Computer Aided Design
MAC	Mean Aerodynamic Chord
COG	Center Of Gravity
VLM	Vortex Lattice Method
NLF	Natural Laminar Flow
NACA	National Aeronautics and Space Administration

Dedicated to the curiosity and the pursuit of discovery.

CHAPTER 1

INTRODUCTION

1.1 Background

Unmanned Aerial Vehicles (UAVs) have become increasingly important in both civil and military operations. They are widely used for surveillance, reconnaissance, environmental monitoring, disaster management, mapping, and agricultural observation [1]. Compared with manned aircraft, UAVs can reduce human exposure to hazardous environments and perform repeated missions over remote or extensive geographical areas [2]. These capabilities make UAVs particularly suitable for operations that require continuous monitoring, long operating durations, and access to locations that are difficult to reach using conventional aircraft.

The growing importance of UAV technology is particularly relevant to Indonesia. As an archipelagic country consisting of thousands of islands, Indonesia faces challenges in conducting maritime patrol, border surveillance, disaster response, environmental monitoring, and infrastructure observation across widely separated areas. Research on UAV applications in the ASEAN region has shown that Indonesia has contributed actively to studies related to disaster management, forestry, and environmental monitoring [1]. This development reflects the increasing need for unmanned aircraft that can operate effectively over large geographical areas.

Among the different categories of UAVs, MALE UAVs are designed to conduct extended missions over broad operational areas. UAVs are commonly classified according to parameters such as operating altitude, aircraft weight, and mission capability, as illustrated in Figure 1.1 [3]. MALE UAVs generally operate at altitudes of approximately 10,000–30,000 ft and are typically designed for endurance exceeding 24 hours [2], [3]. These characteristics make them suitable for persistent surveillance, reconnaissance, maritime patrol, and border monitoring.

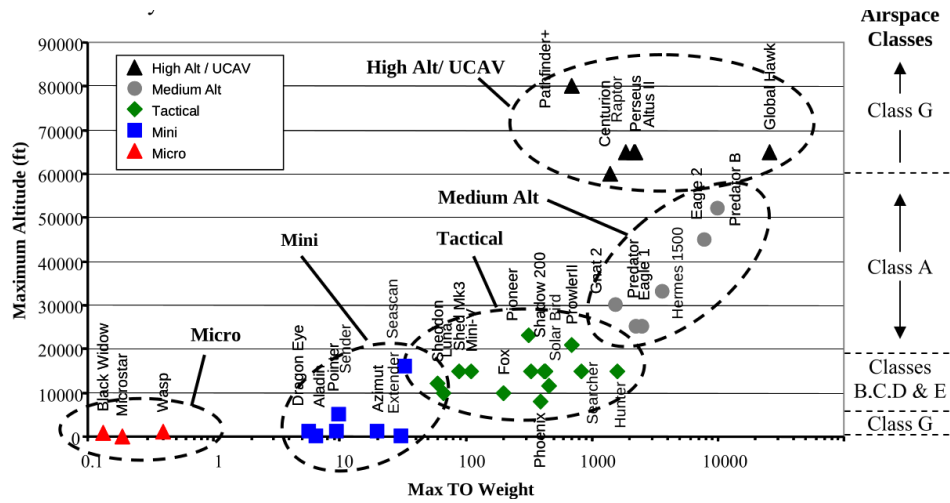


FIGURE 1.1: Classifications of UAVs reprinted from [3].

Indonesia's interest in developing domestic MALE UAV capability can be seen through the Elang Hitam programme. The aircraft was developed to support long-duration surveillance and national security operations, with an intended operating altitude of approximately 20,000 ft and an endurance of up to 24 hours [4]. Although the Elang Hitam programme is not the main subject of this study, it demonstrates the strategic relevance of MALE UAV development in Indonesia. It also highlights the need for reliable aerodynamic, stability, and control characteristics during the aircraft design process.

Long endurance alone does not guarantee effective mission performance. A MALE UAV must also maintain stable and controllable flight throughout its intended operating conditions. Inadequate roll-control authority may limit the aircraft's ability to perform bank manoeuvres or respond to lateral disturbances, while poor stability characteristics may result in undesirable flight behaviour and increased operational risk. Roll stability and control must therefore be considered systematically during the preliminary design of a long-endurance aircraft.

A standards-based approach provides a structured framework for evaluating these characteristics. One relevant reference is Title 14 of the Code of Federal Regulations Part 23, commonly known as 14 CFR Part 23. This regulation was developed by the Federal Aviation Administration for the certification of normal-category aircraft and includes requirements related to aircraft stability, controllability, and flight characteristics [5]. Although 14 CFR Part 23 was primarily developed for manned aircraft,

its fundamental stability and control principles can provide useful references for preliminary UAV design.

In addition to regulations developed for manned aircraft, STANAG 4671 provides an airworthiness framework specifically intended for UAV systems. The standard was issued by NATO to support the safe development and operation of unmanned aircraft and addresses UAV-specific considerations including flight characteristics, stability, and controllability [6]. In this thesis, selected provisions from 14 CFR Part 23 and STANAG 4671 are used as reference frameworks for the preliminary assessment of roll controllability and lateral stability. Their use does not constitute complete aircraft certification.

The aircraft examined in this thesis is based on an existing conceptual MALE UAV developed through two previous undergraduate studies at International University Liaison Indonesia. Akbar Lazuardy Ihsan focused on the avionics selection and structural design of the aircraft, including the development of the high-aspect-ratio wing and X-tail configuration using Onshape [7]. Alibananda Tito Ash Shidiqi focused on the aerodynamic and stability design, developing the aircraft geometry in OpenVSP and analysing the configuration using XFLR5 [8]. The previous studies established the baseline aircraft geometry, mass distribution, aerodynamic characteristics, and an initial assessment of its stability characteristics.

The present study therefore continues the development of an existing aircraft rather than beginning with a completely new configuration. The baseline XFLR5 model used as the foundation of this thesis is shown in Figure 1.2.

The baseline aircraft uses a high-aspect-ratio wing equipped with flaperons. A flaperon combines the functions of an aileron and a flap, allowing the same trailing-edge surface to provide differential roll control and symmetric high-lift capability. Its geometry therefore influences both the available rolling moment and the aerodynamic characteristics of the aircraft during symmetric deployment.

Although flaperons were already incorporated in the previous aircraft model, their chord ratio, spanwise coverage, and resulting control effectiveness were not determined through a systematic sizing process. The previous aerodynamic and stability study also recommended further investigation of the control-surface design because this aspect was not covered in its original scope [8].

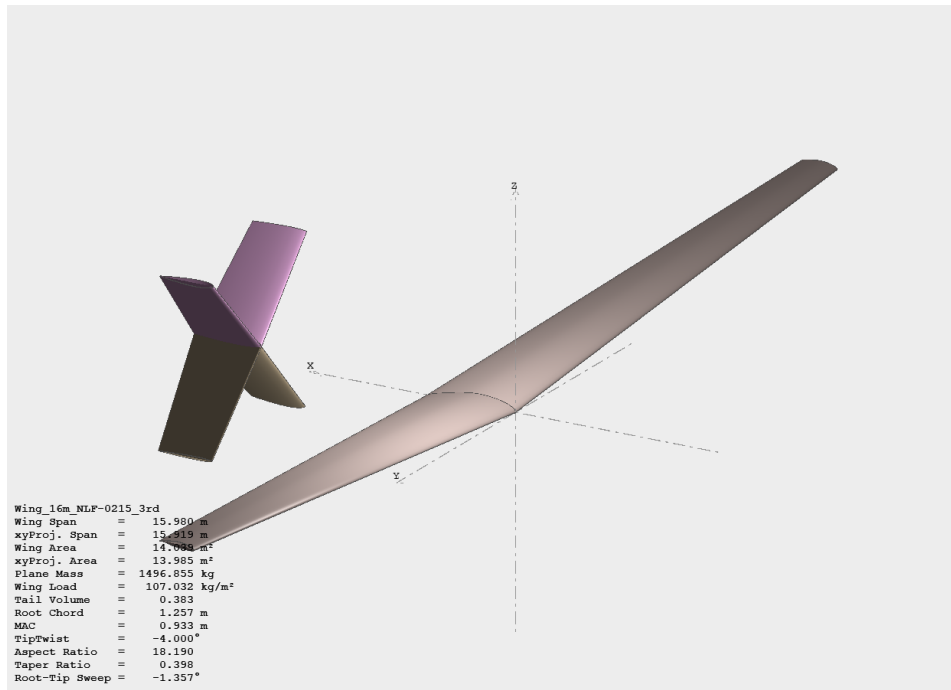


FIGURE 1.2: Initial XFLR5 model of the MALE UAV.

Proper flaperon sizing is important because an undersized surface may not generate sufficient rolling moment, whereas an unnecessarily large surface may increase aerodynamic drag, hinge moment, structural loading, and adverse-yaw coupling. The flaperon geometry must therefore provide sufficient roll authority without introducing unnecessary geometric and actuation penalties.

The present study applies a heuristic preliminary-design approach to determine a suitable flaperon geometry for the existing MALE UAV. Candidate configurations are analysed using XFLR5 to evaluate roll-control effectiveness, steady-state roll-rate capability, symmetric high-lift performance, and roll-related stability characteristics. The results are also assessed with reference to selected relevant provisions of 14 CFR Part 23 and STANAG 4671.

This study remains within the preliminary-design phase and is intended to establish a baseline flaperon configuration for future detailed development. Accordingly, systematic flaperon sizing and roll-performance verification are required before this aspect of the existing MALE UAV preliminary design can be considered sufficiently defined.

1.2 Problem Statement

An existing conceptual Medium-Altitude Long-Endurance UAV with a high-aspect-ratio wing and X-tail configuration was developed through previous undergraduate studies at International University Liaison Indonesia. The baseline aircraft geometry, mass distribution, aerodynamic characteristics, and initial stability characteristics have been established using Onshape, OpenVSP, and XFLR5 [7], [8]. However, the preliminary design of its flaperon has not yet been systematically established.

The existing aircraft model includes wing-mounted flaperons for roll control and symmetric high-lift operation. Although these surfaces are present in the model, their chord ratio and spanwise coverage have not been systematically sized using defined roll-control and aerodynamic requirements. Consequently, the effect of flaperon geometry on the available rolling moment and roll response remains insufficiently established.

The current design also lacks complete verification of flaperon control effectiveness. In particular, the achievable steady-state roll rate, roll-response time, symmetric lift increment, adverse-yaw tendency, and roll-related stability characteristics require quantitative evaluation. The influence of flaperon geometry on these characteristics must therefore be established before a final preliminary configuration can be selected.

In addition, the flaperon configuration has not been quantitatively assessed against the selected roll-related stability and controllability provisions referenced from 14 CFR Part 23 and STANAG 4671. Consequently, the extent to which the preliminary configuration is consistent with these reference frameworks remains to be evaluated.

Without an appropriately sized and verified flaperon, the aircraft may not provide sufficient roll-control capability for the intended operating conditions, while an unnecessarily large surface may introduce avoidable aerodynamic and actuation penalties. Therefore, the main problem addressed in this thesis is the incomplete sizing and verification of the flaperon of the existing MALE UAV.

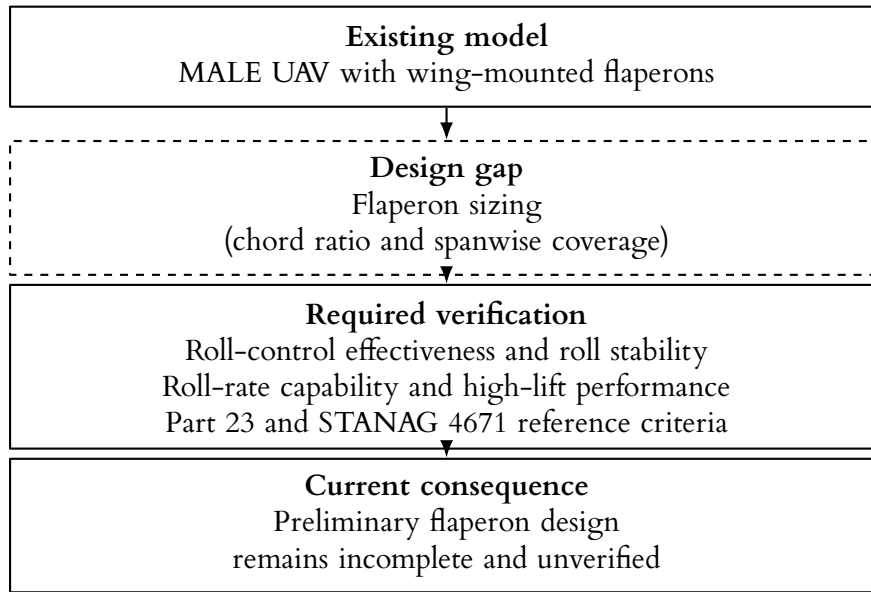


FIGURE 1.3: Problem statement visualization for the MALE UAV flaperon design.

1.3 Research Objectives

The primary objective of this research is to design and analyse the flaperon of an existing MALE UAV to provide adequate roll-control capability while maintaining acceptable aerodynamic and roll-stability characteristics.

To achieve this primary objective, the specific objectives of this research are as follows:

1. To determine an appropriate flaperon geometry in terms of chord ratio and spanwise coverage using a heuristic preliminary-design approach.
2. To analyse the roll-control effectiveness of the flaperon and verify the achievable steady-state roll rate and roll-response capability.
3. To evaluate the aerodynamic effects of symmetric flaperon deployment, including the resulting lift increment and associated aerodynamic changes.
4. To evaluate the roll-related stability characteristics of the selected flaperon configuration using XFLR5 stability derivatives and eigenvalue analysis.
5. To assess the final flaperon configuration under selected off-design and degraded-control conditions and compare the results with relevant provisions of 14 CFR Part 23 and STANAG 4671.

The expected outcome of this research is a preliminary flaperon design for the existing MALE UAV that provides adequate roll-control capability and can serve as a baseline for subsequent detailed design, actuator development, higher-fidelity analysis, and experimental validation.

1.4 Research Scope and Limitation

1.4.1 Analysis Scope

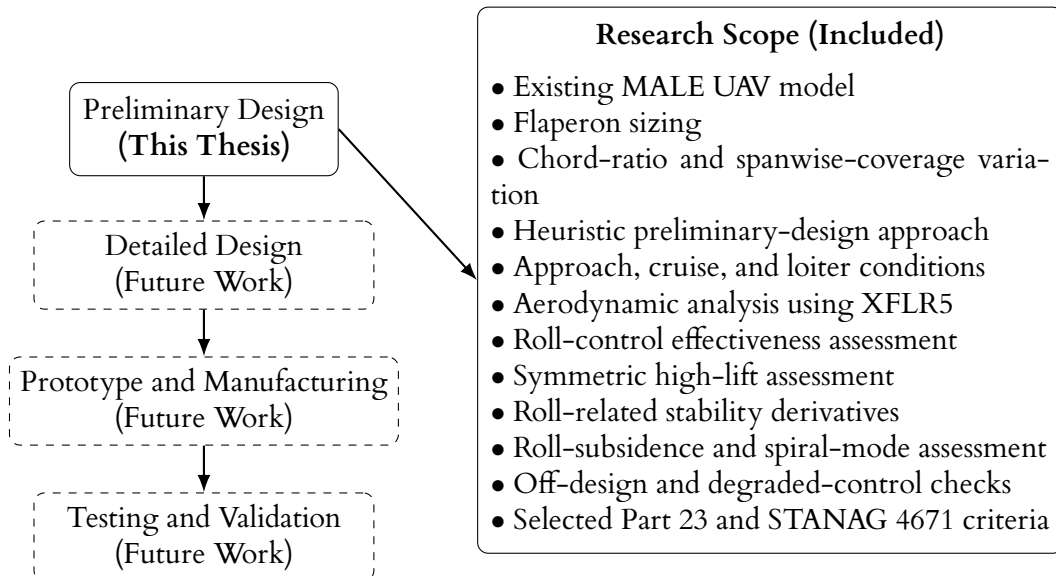


FIGURE 1.4: Research scope within the overall UAV design cycle.

Figure 1.4 illustrates the position of this research within the overall UAV design cycle. The study is conducted within the preliminary-design stage. Detailed design, prototype manufacturing, and experimental validation are outside this stage and are considered subsequent development activities.

This research focuses on the preliminary design and analysis of the flaperon of an existing Medium-Altitude Long-Endurance UAV. The study uses the conceptual aircraft developed in previous undergraduate research at International University Li-aion Indonesia as its baseline [7], [8]. The existing aircraft geometry and aerodynamic model are retained as the basis of the analysis, while the flaperon geometry is varied.

The geometric parameters considered are flaperon chord ratio and spanwise coverage. A heuristic preliminary-design approach is applied using selected roll-control, aerodynamic, stability, and controllability criteria. Candidate configurations are evaluated to identify geometries that provide adequate roll authority while avoiding unnecessary increases in surface area, adverse yaw, and estimated hinge moment.

The analysis is conducted using XFLR5 at selected approach, cruise, and loiter operating conditions. The aerodynamic assessment includes differential flaperon effectiveness for roll control and symmetric flaperon deployment for the high-lift function. The resulting rolling moment derivatives are used to evaluate steady-state roll-rate capability.

The scope also includes roll-related stability assessment using C_{l_β} , C_{l_p} , and the lateral eigenvalue modes most directly associated with roll behaviour, namely roll subsidence and spiral motion. Additional verification includes selected mass and density variations, an analytical Method 2 cross-check, and single-flaperon failure cases.

Finally, the final flaperon configuration is compared with relevant roll-related provisions of 14 CFR Part 23 and STANAG 4671 [5], [6]. These standards are used as reference frameworks for preliminary assessment and not as evidence of complete aircraft certification.

1.4.2 Limitations

Methodological Limitations

The aerodynamic and stability analyses in this study are conducted using XFLR5, which applies linear, potential-flow-based methods for three-dimensional aircraft analysis. Viscous airfoil polar data are used where available; however, the method does not fully represent nonlinear aerodynamic behaviour, extensive flow separation, stall, or post-stall conditions. The flaperon sizing process also follows a heuristic approach based on selected roll-control, stability, and aerodynamic requirements. Therefore, the study does not apply a formal mathematical optimisation method and does not claim that the selected configuration is a global optimum.

The analyses are limited to the selected approach, cruise, and loiter conditions together with the specific off-design cases considered in the final verification. Variations across the complete aircraft flight envelope are not examined. Consequently,

the conclusions apply only to the flaperon configurations and operating conditions included in the analysis.

Analysis Limitations

The numerical results are not validated through wind-tunnel testing, prototype testing, or flight testing. High-fidelity computational fluid dynamics simulations are not performed, and finite-element or structural stress analyses are not included. Detailed structural loads, aeroelastic deformation, flutter, fatigue, and control-surface manufacturing considerations are outside the present analysis.

Hinge moments are used only as preliminary comparative estimates for candidate ranking and actuator-demand assessment. They are not treated as actuator-grade loads. Final actuator selection and sizing, mechanical linkage design, actuator dynamics, control-system hardware, stability-augmentation systems, autopilot functions, and flight-control software development are outside the scope of this research.

The fuselage is not included in the XFLR5 aerodynamic model. Therefore, fuselage aerodynamic effects and detailed wing-fuselage interference are not represented.

Scope Boundaries

The baseline wing, fuselage, and X-tail arrangement are retained from the previous conceptual aircraft design. No aircraft-configuration trade study is performed. The geometric design variation considered in this thesis is limited to the flaperon chord ratio and spanwise coverage.

The completed study is limited to flaperon aerodynamic performance and roll control. Pitch-control and yaw-control effectiveness, ruddervator sizing, X-tail control mixing, and integrated three-axis flight-control analysis are not included and are reserved for future work.

Detailed manufacturing design, material selection, production planning, cost estimation, maintainability assessment, prototype manufacturing, and flight testing are also excluded. The resulting flaperon configuration therefore represents a preliminary design and is not considered ready for manufacturing without further engineering analysis and validation.

Finally, 14 CFR Part 23 and STANAG 4671 are used only as reference frameworks for selected roll-related stability and controllability provisions. The study does not constitute a complete airworthiness or aircraft-certification assessment.

1.5 Significance of the Study

This study is expected to provide academic and practical significance related to the preliminary design and analysis of flaperons for Medium-Altitude Long-Endurance UAVs. The potential significance of this research is discussed from academic and practical perspectives.

1.5.1 Academic Significance

From an academic standpoint, this study provides educational value by demonstrating a systematic approach to the preliminary sizing and analysis of a flaperon for a MALE UAV. The research applies aircraft stability and control theory to a practical engineering problem, allowing theoretical concepts related to roll-control effectiveness and roll stability to be connected with an existing aircraft design case.

The study also demonstrates the application of selected regulatory and airworthiness provisions during preliminary UAV development. Relevant roll-related provisions from 14 CFR Part 23 and STANAG 4671 are used as references in the evaluation process. This approach illustrates how established aviation standards can be incorporated within the limited scope of a preliminary UAV design study. In addition, the use of XFLR5 provides practical experience in aerodynamic analysis, control-derivative extraction, roll-performance assessment, and stability evaluation.

In terms of contribution to knowledge, this research documents a structured preliminary methodology for sizing and evaluating the flaperon of an existing MALE UAV. The heuristic sizing, candidate screening, Pareto comparison, XFLR5 analysis, and final verification procedure may serve as reference material for future students conducting similar flaperon or UAV roll-control studies. Although the research does not introduce a new aerodynamic or stability theory, it contributes to the institutional knowledge base by documenting the application of these methods to an existing aircraft configuration.

1.5.2 Practical Significance

From a practical standpoint, this research supports the continued development of the existing MALE UAV project by providing a defined preliminary flaperon geometry

and an assessment of its aerodynamic and roll-control performance. The resulting geometry and performance data provide a baseline for subsequent activities including actuator-grade load determination, structural analysis, higher-fidelity aerodynamic analysis, prototype development, and experimental validation.

The study may also contribute to domestic UAV design capability in Indonesia by demonstrating a structured approach to preliminary flaperon sizing and roll-control analysis. Selected provisions from 14 CFR Part 23 and STANAG 4671 are incorporated as reference criteria within a local aerospace design project, providing an example of how established aircraft-design practices may be applied during preliminary UAV development.

From an industry perspective, the heuristic sizing and XFLR5-based assessment provide a relatively accessible method for screening candidate flaperon geometries before more resource-intensive analysis or testing is conducted. The methodology may therefore support early-stage UAV feasibility and preliminary-design activities.

This research also provides practical value to International University Liaison Indonesia and its Aviation Engineering programme by extending an existing UAV development project with a documented flaperon-design workflow. The results provide a foundation for future work involving ruddervator design, integrated flight-control development, actuator and structural design, computational fluid dynamics, wind-tunnel testing, prototype manufacturing, and flight validation.

CHAPTER 2

LITERATURE REVIEW

2.1 Aircraft Stability and Control Theory

2.1.1 Introduction to Stability

In aircraft flight mechanics, stability refers to the tendency of an aircraft to maintain or recover its equilibrium flight condition after experiencing a disturbance. Disturbances may result from external factors, such as atmospheric gusts and turbulence, or from internal factors, such as aerodynamic changes caused by control inputs. In simple terms, aircraft stability describes whether the aircraft tends to return towards its original flight condition, remain at the disturbed condition, or move progressively farther from its equilibrium state [9].

Stability is important because it directly affects aircraft controllability, predictability, and flight safety. An aircraft with adequate stability requires less continuous corrective control input to maintain the intended flight condition. In contrast, insufficient stability may cause oscillatory or divergent motion and may increase the control effort required to maintain flight.

Stability is particularly important for Unmanned Aerial Vehicles because no pilot is physically present onboard to directly sense and respond to unexpected aircraft behaviour. The UAV therefore depends on its inherent aerodynamic characteristics and flight-control system to maintain the required flight condition. For a Medium-Altitude Long-Endurance UAV, adequate stability is essential because the aircraft is expected to operate continuously for long periods while maintaining predictable and controllable flight behaviour.

2.1.2 Aircraft Body Axes and Motions

Aircraft motion and stability are commonly described using a body-fixed coordinate system. This coordinate system is attached to the aircraft and moves with it during flight. Its origin is generally located at the aircraft centre of gravity because both translational and rotational motions are analysed about this reference point [9].

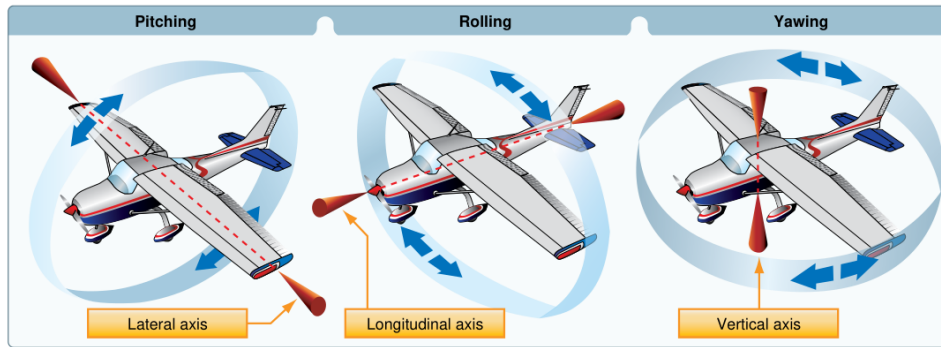


FIGURE 2.1: Aircraft motions reprinted from [10].

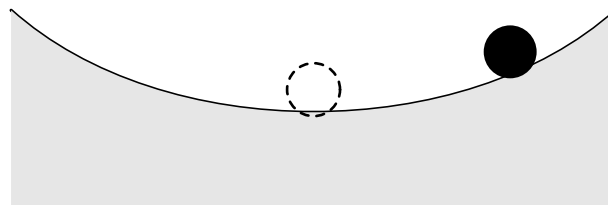
As illustrated in Figure 2.1, the body-fixed coordinate system consists of three mutually perpendicular axes. The longitudinal axis, denoted by x , is aligned approximately with the fuselage and points forward. The lateral axis, denoted by y , points towards the right wing, while the vertical axis, denoted by z , points downwards. Together, these axes form the right-handed coordinate system commonly used in aircraft flight-dynamics analysis.

Rotation about the longitudinal x -axis is called roll, rotation about the lateral y -axis is called pitch, and rotation about the vertical z -axis is called yaw. These rotational motions provide the basic reference for aircraft stability and control analysis. In the present study, the wing-mounted flaperons are investigated specifically for their roll-control function about the longitudinal axis.

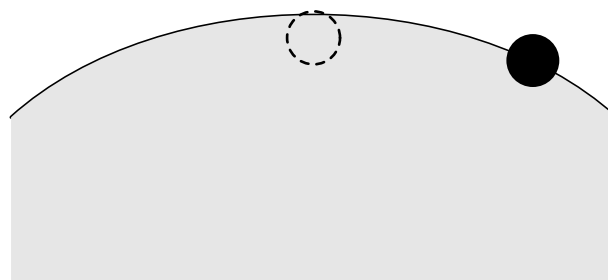
2.1.3 Types of Stability

2.1.3.1 Static Stability

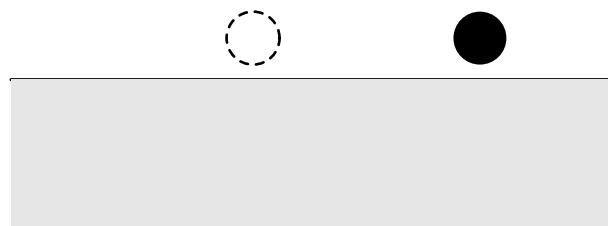
Static stability describes the *initial tendency* of an aircraft immediately after it is disturbed from its equilibrium or trim condition. It only considers the first reaction of the aircraft and does not describe how the motion continues over time [9].



(a) Statically stable



(b) Statically unstable



(c) Neutral stability

FIGURE 2.2: Sketches illustrating various conditions of static stability
reprinted from [9].

To help visualize this concept, Figure 2.2 uses a simple analogy of a ball placed on different surface shapes. The position of the ball represents the equilibrium condition of the aircraft.

In Figure 2.2(a), the ball is placed inside a bowl. If the ball is slightly pushed, it will roll back toward the center. This represents *positive static stability*, where the aircraft naturally tends to return to its original flight condition after being disturbed.

In Figure 2.2(b), the ball is placed on top of a hill. If it is slightly pushed, it will move farther away from its original position. This represents negative static stability, where the aircraft continues to diverge from the equilibrium condition.

In Figure 2.2(c), the ball is placed on a flat surface. If it is moved slightly, it will remain in the new position without returning or moving farther away. This represents *neutral static stability*, where the aircraft neither restores itself nor becomes more unstable after the disturbance.

In aircraft analysis, this restoring or diverging tendency is related to the aerodynamic moments that arise due to small changes in the aircraft state. If these aerodynamic moments act in a direction that reduces the disturbance, the aircraft is considered statically stable [9].

2.1.3.2 Dynamic Stability

Dynamic stability describes the time history of aircraft motion after the aircraft has been disturbed from its equilibrium or trim condition. Whereas static stability describes only the initial tendency immediately after the disturbance, dynamic stability describes how the resulting motion develops with time, including whether it converges, remains constant, or diverges [9].

The relationship between static and dynamic stability is important in flight mechanics. An aircraft may possess positive static stability, meaning that it initially tends to return towards its equilibrium condition, but its overall response still depends on the subsequent time history of the motion. Therefore, static stability alone is not sufficient to describe the complete behaviour of an aircraft, and dynamic stability must also be considered.

Figure 2.3 presents several typical dynamic responses after a disturbance. Figure 2.3(a) shows non-oscillatory motions. A *subsidence* response represents dynamic stability because the displacement gradually decreases with time and returns towards

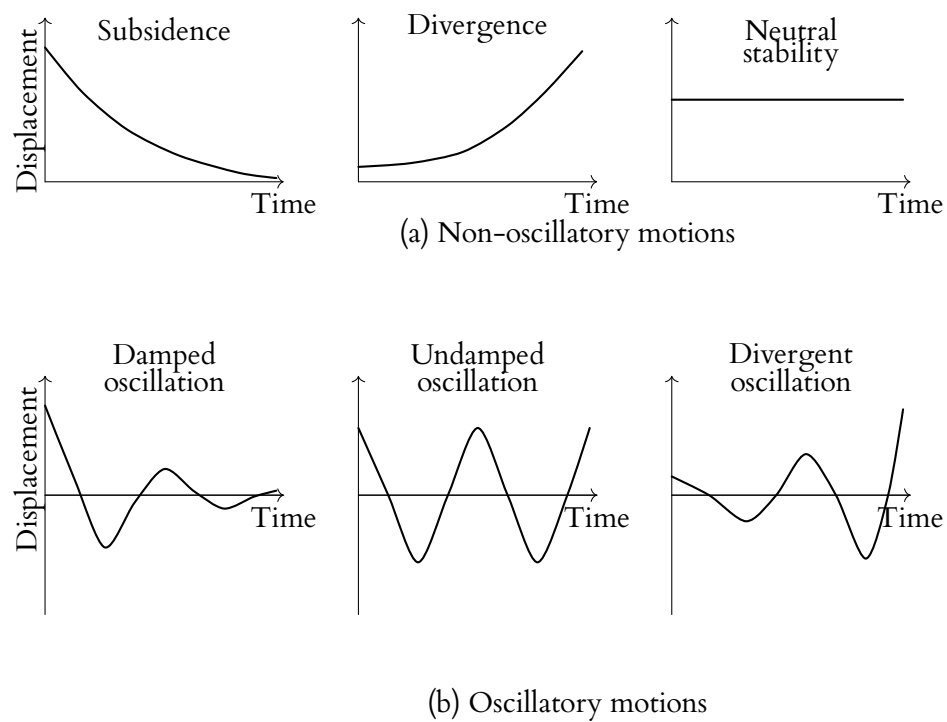


FIGURE 2.3: Illustration of typical dynamic responses of aircraft motion, adapted from [9].

equilibrium. A *divergence* response represents dynamic instability because the displacement continues to increase with time. Neutral dynamic stability occurs when the displacement remains constant without increasing or decreasing.

Figure 2.3(b) shows oscillatory motions. A *damped oscillation* represents dynamic stability because the oscillation amplitude decreases with time. An *undamped oscillation* represents neutral dynamic stability because the oscillation continues with constant amplitude. A *divergent oscillation* represents dynamic instability because the oscillation amplitude grows with time.

A key factor influencing dynamic stability is aerodynamic damping. Damping refers to the tendency of aerodynamic forces and moments to reduce the amplitude of motion as time progresses. Even when an aircraft has positive static stability, insufficient damping may cause the motion to persist for a long time or to diverge. Therefore, dynamic stability depends not only on the restoring tendency of the aircraft but also on the magnitude of the damping present in the response [9].

2.1.4 Roll-Related Lateral Stability

Roll-related lateral stability concerns the aircraft response to disturbances that produce rolling motion or alter the lateral aerodynamic state. Roll is the rotation of the aircraft about its longitudinal body axis [9].

In a conventional aircraft, roll control is primarily provided by ailerons. Differential aileron deflection produces an asymmetric lift distribution between the left and right wings and consequently generates a rolling moment. In the aircraft considered in this study, the same roll-control function is provided by the wing-mounted flaperons.

Although the present study focuses on roll control, lateral aircraft motion is not completely independent of sideslip and yaw. A sideslip disturbance can produce a rolling moment, while differential flaperon deflection can generate an accompanying yawing moment. The latter is important because excessive yaw relative to the commanded rolling moment may reduce the quality of the roll-control response.

Two derivatives are particularly relevant to the roll-related assessment. The derivative C_{l_β} describes the change in rolling-moment coefficient with sideslip angle, while C_{l_p} describes the change in rolling-moment coefficient with roll rate. Under the

sign convention adopted in this study, negative values of these derivatives represent a restoring lateral tendency and aerodynamic roll damping, respectively.

The corresponding dynamic behaviour is evaluated primarily through the roll-subsidence and spiral modes. These modes describe the rapid damping of roll rate and the slower long-term lateral tendency of the aircraft.

2.1.5 Dynamic Modes of Motion

After an aircraft experiences a small disturbance, its motion can be described through several characteristic modes. Each mode represents a typical pattern of aircraft response and is associated with the eigenvalues of the linearised equations of motion. The eigenvalues indicate whether the motion is stable or unstable and provide information about its characteristic response time [9].

For the roll-related assessment conducted in this thesis, the principal dynamic modes of interest are the *roll-subsidence* and *spiral* modes.

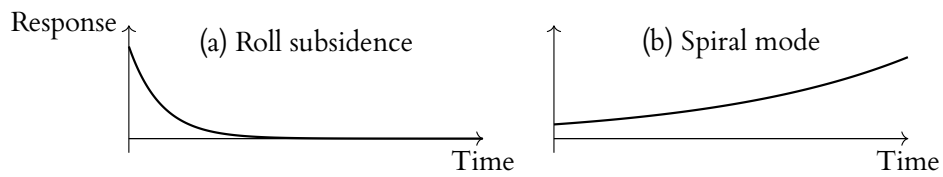


FIGURE 2.4: Schematic representation of the roll-subsidence and spiral modes, adapted from [9].

The roll-subsidence mode is a non-oscillatory motion dominated by roll rate. Following a disturbance, aerodynamic roll damping normally causes the roll rate to decay rapidly. A negative real eigenvalue therefore indicates a stable roll-subsidence response, while its magnitude determines how rapidly the disturbance decays.

The spiral mode is a much slower non-oscillatory lateral motion. Its eigenvalue may be negative, indicating slow convergence, or positive, indicating slow divergence. Because spiral motion develops over a comparatively long time scale, both the sign of the eigenvalue and the corresponding time to half or double the disturbance amplitude are useful when interpreting this mode.

These two modes are used in the present study to assess whether the selected flaperon configuration retains acceptable roll-related dynamic behaviour.

2.1.6 Roll Control versus Stability Trade-off

Aircraft roll-control authority and aerodynamic roll damping must be considered together. Increasing flaperon size generally increases the rolling moment available from a differential control input. However, the resulting configuration should also retain an appropriate aerodynamic response to roll disturbances.

For a Medium-Altitude Long-Endurance UAV, sufficient roll damping is desirable because the aircraft is expected to maintain predictable lateral behaviour during long-duration autonomous operation [2]. At the same time, the flaperon must provide sufficient rolling moment to perform the required bank manoeuvres and respond to disturbances.

The present study therefore evaluates both the roll-control effectiveness and roll-damping characteristics of each configuration. Candidate flaperon geometries are not selected solely by maximizing roll rate; control authority is considered together with roll damping, surface area, adverse-yaw tendency, lift increment, and estimated hinge moment.

2.2 Flaperon Fundamentals

2.2.1 Purpose of a Flaperon

A flaperon is a combined wing control surface that performs both flap and aileron functions. When the left and right flaperons are deflected symmetrically, they act as high-lift devices and modify the lift generated by the wing. When they are deflected differentially, they produce an asymmetric lift distribution and consequently generate a rolling moment about the aircraft longitudinal axis.

This combination is particularly relevant to the MALE UAV considered in this study because a single trailing-edge surface is used for both the approach high-lift function and roll control. The two functions therefore share the same geometric surface and mechanical deflection envelope.

During differential operation, the difference in aerodynamic loading between the two wings generates the desired rolling moment. An additional yawing moment may also occur because the aerodynamic loading and drag on the two sides of the

wing are no longer identical. This accompanying response is considered through the adverse-yaw metric used during candidate evaluation.

2.2.2 Flaperon Effectiveness

Flaperon effectiveness refers to the ability of the surface to generate a change in aerodynamic force or rolling moment when it is deflected. For roll control, the principal aerodynamic derivative considered in this study is

$$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a}, \quad (2.1)$$

where C_l is the rolling-moment coefficient and δ_a represents the differential flaperon control input.

The magnitude of $C_{l_{\delta_a}}$ indicates the amount of rolling moment generated per unit differential input. A larger magnitude generally represents greater roll-control effectiveness.

Differential flaperon deflection may also generate a yawing moment. The corresponding derivative is $C_{n_{\delta_a}}$. In this study, the relative amount of yaw generated by the roll command is evaluated using

$$\left| \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} \right|. \quad (2.2)$$

A smaller value indicates that the flaperon generates relatively little yawing moment compared with the available rolling moment.

For the symmetric flap function, effectiveness is evaluated primarily through the incremental lift coefficient,

$$\Delta C_L = C_{L,\text{deflected}} - C_{L,\text{reference}}. \quad (2.3)$$

The flaperon must therefore provide sufficient effectiveness in both its differential roll-control mode and symmetric high-lift mode.

2.2.3 Flaperon Geometric Parameters

The principal geometric parameters investigated in the flaperon design are chord ratio and spanwise coverage. An aileron-type trailing-edge geometry is used as an illustrative example in Figure 2.5.

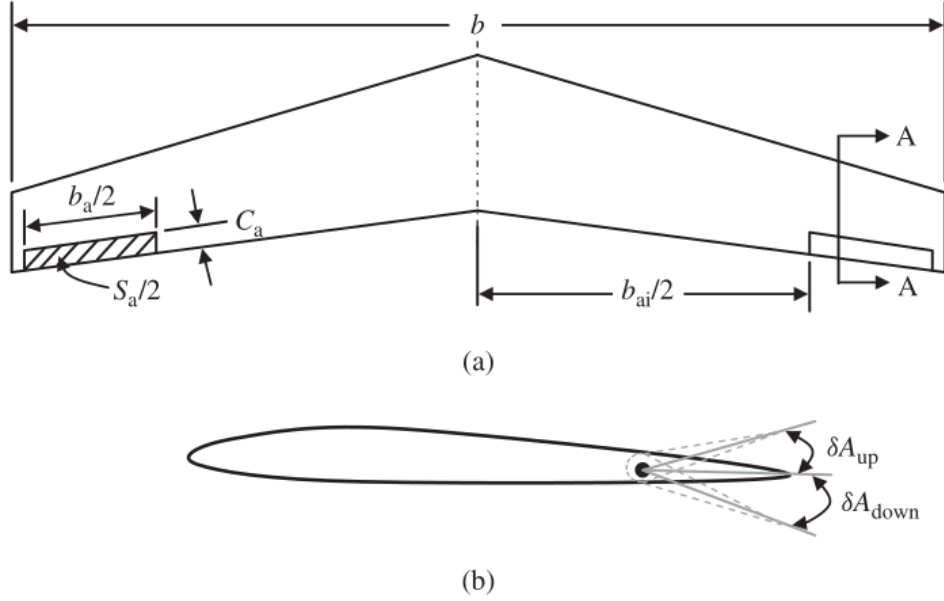


FIGURE 2.5: Trailing-edge control-surface geometry: (a) top view and (b) sectional view of a deflected surface, reprinted from [14].

The local flaperon chord, c_f , is measured from the hinge line to the wing trailing edge. Because the wing is tapered, the dimensional flaperon chord changes along the span. The geometry is therefore defined using the nondimensional chord ratio

$$\frac{c_f}{c}, \quad (2.4)$$

where c is the corresponding local wing chord.

The spanwise position is represented using the nondimensional coordinate

$$\eta = \frac{y}{b/2}, \quad (2.5)$$

where y is the distance from the aircraft centreline and b is the wing span. The inboard and outboard boundaries of the flaperon are therefore represented by η_{in} and η_{out} , respectively.

The physical flaperon span on one side of the aircraft is

$$b_f = y_{\text{out}} - y_{\text{in}}. \quad (2.6)$$

For a tapered wing, the flaperon planform area is more appropriately determined from the local chord distribution,

$$S_f = \int_{y_{\text{in}}}^{y_{\text{out}}} c_f(y) dy. \quad (2.7)$$

Increasing either chord ratio or spanwise coverage generally increases the aerodynamic influence of the flaperon. However, it also increases surface area and may increase hinge moment, aerodynamic drag, and structural loading. These penalties are therefore considered during the candidate-selection process.

2.2.4 Flaperon Deflection

A flaperon shares its available deflection range between the symmetric flap function and differential roll-control function. The left and right surface deflections can be represented as

$$\delta_L = \delta_{\text{sym}} - \delta_{\text{diff}}, \quad \delta_R = \delta_{\text{sym}} + \delta_{\text{diff}}. \quad (2.8)$$

Here, δ_{sym} represents the common symmetric component, while δ_{diff} represents the differential component.

At approach, symmetric flaperon deployment is required for the high-lift function. Consequently, part of the available mechanical deflection range is already occupied, reducing the remaining differential motion available for roll control. This interaction is an important characteristic of the Path B flaperon-only configuration examined in this thesis.

2.2.5 Hinge Moment and Actuation Considerations

The aerodynamic hinge moment is the moment acting about the flaperon hinge line. It provides an indication of the aerodynamic torque that must ultimately be overcome by the actuation system. A general representation may be written as

$$H = q_{\infty} S_f c_f C_h, \quad (2.9)$$

where q_{∞} is the dynamic pressure, S_f is the flaperon area, c_f is a representative flaperon chord, and C_h is the hinge-moment coefficient.

Increasing flaperon area, chord, dynamic pressure, or deflection can increase the corresponding hinge moment. Therefore, a configuration that provides greater aerodynamic roll authority may also impose a greater actuation requirement.

In the present preliminary design, hinge-moment estimates are used as a relative candidate-ranking parameter. They are not treated as actuator-grade loads. Final actuator selection requires a more detailed hinge-moment assessment together with actuator dynamics, structural loads, linkage efficiency, and appropriate design margins.

2.2.6 Design Considerations for a MALE UAV

For MALE UAV applications, flaperon design must be consistent with the long-endurance mission profile. Because the aircraft is required to remain airborne for extended periods, aerodynamic efficiency is an important design consideration. An oversized flaperon may provide substantial roll authority but may also increase surface area, drag, hinge moment, structural demand, and actuation requirements [15].

The flaperon must also remain effective over the relevant operating conditions. The dimensional aerodynamic forces generated by the surface depend on dynamic pressure,

$$q_{\infty} = \frac{1}{2} \rho V^2, \quad (2.10)$$

and therefore vary with air density and flight speed. Reynolds number, angle of attack, and aircraft configuration may also influence the resulting nondimensional aerodynamic coefficients.

The approach condition is particularly important because the surface is required to provide symmetric high-lift deployment while retaining sufficient differential roll-control capability. Cruise and loiter conditions are additionally evaluated to examine whether roll authority is retained away from the primary sizing condition.

The final geometry is therefore selected using several competing considerations: steady-state roll rate, roll-response time, symmetric lift increment, adverse-yaw tendency, flaperon area, and estimated hinge moment. This multi-criterion approach avoids selecting a configuration solely because it produces the largest possible rolling moment.

2.3 Stability Analysis Methods

2.3.1 Overview of Stability Analysis

Stability analysis is conducted to determine how an aircraft responds after experiencing a small disturbance. Depending on whether the disturbance response decreases, remains constant, or increases, the corresponding motion may be classified as stable, neutrally stable, or unstable at the evaluated condition [9], [12].

Aircraft stability may be investigated using analytical and numerical approaches. Analytical methods use simplified aerodynamic relationships and the linearised equations of motion to provide theoretical insight into stability derivatives, characteristic modes, and aircraft response.

Numerical methods apply these aerodynamic and flight-dynamic relationships to a computational representation of the aircraft. In the present study, XFLR5 is used as the principal numerical tool to obtain the roll-related stability derivatives and eigenvalues required to assess the final flaperon configuration.

The numerical results are subsequently interpreted using the fundamental stability concepts introduced in the preceding sections.

2.3.2 Linearized Equations of Motion

Aircraft motion is inherently nonlinear because aerodynamic forces and moments depend on variables such as velocity, angle of attack, attitude, and angular rates. However, when stability is analysed about an equilibrium flight condition, the equations of motion can be linearised by assuming that the perturbations from the reference condition are small [9].

Under this assumption, higher-order terms involving the perturbation variables can be neglected. The resulting linear differential equations describe how small

changes in the aircraft states develop with time. This representation enables the use of linear-system methods, particularly eigenvalue analysis.

In compact form, the linearised aircraft dynamics can be expressed as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t), \quad (2.11)$$

where $\mathbf{x}(t)$ is the state vector containing the small perturbation variables describing the aircraft motion, and $\mathbf{u}(t)$ is the control-input vector. The system matrix $\mathbf{A}$ describes the natural aircraft dynamics and interactions between the states, while the control matrix $\mathbf{B}$ describes how the applied control input affects the aircraft response [9], [12].

The relationship between the control input, linearised aircraft dynamics, and resulting aircraft states is illustrated conceptually in Figure 2.6.



FIGURE 2.6: Conceptual state-space representation of the linearised aircraft dynamics, adapted from [12].

For the natural response of the aircraft, the control input is set to zero. The resulting motion is therefore governed by the system matrix $\mathbf{A}$. The eigenvalues of this matrix determine whether the aircraft response decreases, remains constant, or increases with time.

2.3.3 Eigenvalue Analysis

Eigenvalue analysis is used to evaluate the dynamic stability of an aircraft after its equations of motion have been linearised about an equilibrium flight condition. Each eigenvalue is associated with a natural mode of aircraft motion and describes how that mode develops with time following a small disturbance [12].

An eigenvalue may be written as

$$\lambda = \sigma \pm j\omega, \quad (2.12)$$

where $\sigma = \text{Re}(\lambda)$ is the real part and $\omega = \text{Im}(\lambda)$ is the imaginary part.

The real part determines whether the response decreases or increases with time. When $\sigma < 0$, the response decays and the corresponding mode is stable. When $\sigma > 0$, the response grows and the corresponding mode is unstable. When $\sigma = 0$, the response neither grows nor decays in the linear analysis.

The imaginary part indicates whether the response is oscillatory. When $\omega \neq 0$, the eigenvalues occur as a complex-conjugate pair and represent an oscillatory mode. When $\omega = 0$, the eigenvalue is purely real and represents a non-oscillatory response.

The locations of representative eigenvalues in the complex plane are shown in Figure 2.7.

Eigenvalues located in the left half-plane have negative real parts and represent stable modes, whereas eigenvalues in the right half-plane have positive real parts and represent unstable modes. Their distance from the imaginary axis indicates the time scale over which the response decays or grows.

Purely real eigenvalues are particularly relevant to the present roll-related assessment because the roll-subsidence and spiral modes are represented by real eigenvalues. Their signs and magnitudes therefore indicate whether the corresponding response converges or diverges and the time scale over which that behaviour develops.

2.3.4 Stability Derivatives

Stability derivatives are aerodynamic coefficients that describe how the forces and moments acting on an aircraft change in response to small variations in its motion variables [9], [12].

For the roll-related assessment conducted in this thesis, two derivatives are of particular interest. The derivative

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta} \quad (2.13)$$

describes the change in rolling-moment coefficient with sideslip angle. Under the sign convention adopted in this study, $C_{l_\beta} < 0$ represents a restoring rolling-moment tendency following a sideslip disturbance.

The roll-damping derivative is

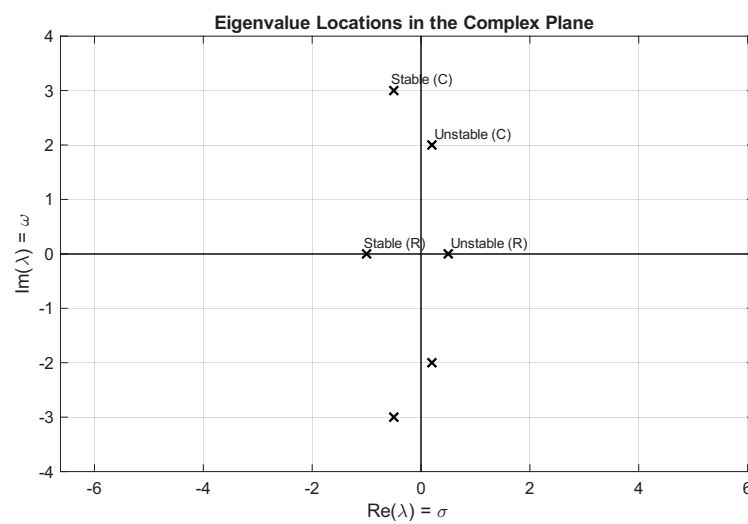


FIGURE 2.7: Representative eigenvalue locations in the complex plane showing stable and unstable oscillatory and non-oscillatory modes.

$$C_{l_p} = \frac{\partial C_l}{\partial (pb/2V)}, \quad (2.14)$$

where p is the aircraft roll rate, b is the wing span, and V is the flight speed. A negative value of C_{l_p} indicates that the aerodynamic rolling moment opposes the existing roll motion and therefore provides roll damping.

In the present study, these derivatives are obtained from XFLR5 for the selected flaperon configuration and operating cases. Together with the aircraft mass and inertia properties, they support the interpretation of the roll-related dynamic behaviour.

2.3.5 Analysis Process

The roll-related stability analysis follows a numerical procedure based on the linear flight-dynamics formulation introduced previously. The analysis is conducted using the final flaperon geometry for the approach, cruise, and loiter Type 7 model definitions.

The aircraft geometry, mass properties, and aerodynamic model are first defined in XFLR5. Type 7 stability analysis is then used to obtain the relevant aerodynamic derivatives and lateral eigenvalues for each evaluated case.

The sign of C_{l_β} is used to assess the restoring rolling-moment tendency associated with sideslip, while C_{l_p} is used to evaluate aerodynamic roll damping. The eigenvalues are subsequently examined to identify the roll-subsidence and spiral modes.

For a stable real eigenvalue,

$$\lambda < 0, \quad (2.15)$$

the corresponding disturbance decays with time. Its characteristic time constant may be expressed as

$$\tau = -\frac{1}{\lambda}, \quad \lambda < 0. \quad (2.16)$$

For a positive real eigenvalue, the disturbance grows. The time scale of a slowly unstable mode may be represented by its time to double amplitude,

$$t_2 = \frac{\ln 2}{\lambda}, \quad \lambda > 0. \quad (2.17)$$

These results are used to determine whether the selected flaperon configuration retains acceptable roll-related stability characteristics. The detailed XFLR5 setup and numerical procedure are presented in Chapter 3.

2.4 Design Standards and Criteria

2.4.1 Importance of Design Standards

Aircraft design standards provide established criteria that support the development of safe, controllable, and predictable aircraft behaviour. They are based on accumulated engineering knowledge, operational experience, and accepted design practice.

Although the present study is academic and does not constitute a complete certification assessment, selected provisions from recognised standards are used as reference frameworks for evaluating the MALE UAV. This approach provides a structured basis for assessing the final flaperon configuration while acknowledging that complete certification would require additional analyses, documentation, verification, and testing.

2.4.2 Overview of 14 CFR Part 23

Title 14 of the Code of Federal Regulations Part 23 establishes airworthiness requirements for normal-category airplanes. Although it is not applied in this thesis as a complete UAV certification basis, selected flight-characteristic provisions provide useful references for the preliminary assessment of flaperon roll-control performance [5].

The provisions most relevant to the completed scope are Section 23.143, concerning controllability and manoeuvrability; Section 23.157, concerning rate of roll; and Section 23.177, concerning lateral static stability.

The numerical roll-rate criterion adopted for flaperon sizing is not presented as a direct numerical requirement of 14 CFR Part 23. Furthermore, the XFLR5 analysis does not reproduce every prescribed certification manoeuvre. The regulation is therefore used as a standards-based reference rather than as evidence of complete regulatory compliance.

TABLE 2.1: 14 CFR Part 23 provisions relevant to the flaperon study.

Section	Requirement Area	Relevance to This Study
§23.143	Controllability and manoeuvrability	Provides a general reference for assessing whether adequate roll-control capability is retained.
§23.157	Rate of roll	Provides a prescribed roll-reversal manoeuvre for the applicable aircraft weight category.
§23.177	Lateral static stability	Provides a reference for the restoring lateral response of the aircraft.

2.4.3 Overview of STANAG 4671

STANAG 4671 provides the UAV System Airworthiness Requirements for fixed-wing military unmanned aircraft systems [6]. The standard provides an airworthiness framework that includes flight characteristics, controllability, stability, systems, and verification requirements.

For the completed flaperon scope, the most relevant provisions are USAR.143, which addresses controllability and manoeuvrability, and USAR.171, which addresses aircraft stability and the effects of the flight-control system. USAR.157 is titled “Rate of roll” but is identified as not applicable in the edition used in this study. Consequently, STANAG 4671 does not provide the numerical 20 deg/s roll-rate requirement adopted in the flaperon sizing procedure.

The standard is therefore used to provide a structured airworthiness reference for interpreting the roll-control and roll-stability results. Complete STANAG 4671 compliance is outside the scope of the present numerical preliminary-design study.

2.4.4 Flaperon Performance Criteria

The flaperon candidates are evaluated using four preliminary performance criteria established for the sizing procedure. These criteria address both the differential roll-control function and the symmetric high-lift function.

These values are preliminary design criteria used to screen candidate flaperon geometries. They should not be interpreted as direct numerical certification requirements from 14 CFR Part 23 or STANAG 4671.

TABLE 2.2: Preliminary flaperon performance criteria adopted in this study.

Parameter	Criterion	Purpose
Steady-state roll rate, p_{ss}	$p_{ss} \geq 20$ deg/s	Minimum approach roll authority
Time to 30° bank, t_{30}	$t_{30} \leq 2.5$ s	Roll-response capability
Lift increment, ΔC_L	$\Delta C_L \geq 0.60$	Symmetric high-lift effectiveness
Adverse-yaw ratio	$ C_{n_{\delta_a}}/C_{l_{\delta_a}} \leq 0.20$	Limit yaw coupling during roll control

2.4.5 Roll-Stability Criteria

The roll-related stability assessment considers the restoring tendency associated with sideslip, aerodynamic roll damping, and the behaviour of the roll-subsidence and spiral modes.

Under the sign convention adopted in this study,

$$C_{l_\beta} < 0 \quad (2.18)$$

indicates a restoring rolling-moment tendency following a sideslip disturbance, while

$$C_{l_p} < 0 \quad (2.19)$$

indicates aerodynamic roll damping.

For the roll-subsidence mode, a negative real eigenvalue represents a stable decaying roll-rate response. The magnitude of the eigenvalue determines the corresponding response time.

The spiral mode may be stable or weakly unstable. When the spiral eigenvalue is positive, the rate of divergence is assessed using the time required for the disturbance amplitude to double,

$$t_2 = \frac{\ln 2}{\lambda}. \quad (2.20)$$

A slowly divergent spiral response is therefore distinguished from a rapid instability by considering both the eigenvalue sign and its associated time scale.

These criteria are used to interpret roll-related stability behaviour and do not constitute a complete assessment of the aircraft's three-axis dynamic stability.

2.4.6 Application to This Thesis

The standards and preliminary design criteria introduced in this chapter are used to support the sizing and evaluation of the flaperon candidates.

The primary screening quantities are steady-state roll rate, t_{30} , symmetric lift increment, and adverse-yaw ratio. Feasible candidates are subsequently compared using additional design considerations including flaperon area and estimated hinge moment.

The final configuration is also evaluated using roll-related stability derivatives, Type 7 eigenvalue results, selected off-design cases, and single-flaperon failure cases. Relevant provisions of 14 CFR Part 23 and STANAG 4671 are then used to provide a standards-based interpretation of the final results.

The criteria therefore support the preliminary design and comparison process and are not used to claim complete regulatory compliance.

2.5 Previous Related Works

This section reviews previous research relevant to MALE UAV aerodynamic design, wing roll-control surfaces, flaperon sizing, stability analysis, and numerical methods used during preliminary aircraft design. The review focuses on the methods and findings that support the flaperon sizing and roll-control assessment conducted in this thesis.

2.5.1 Previous MALE UAV Design Studies

Panagiotou et al. [16] presented an integrated aerodynamic-design procedure for a Medium-Altitude Long-Endurance UAV covering the conceptual and preliminary design stages. During the conceptual stage, several candidate configurations were developed from common mission requirements. The selected configuration was subsequently refined through detailed aerodynamic analysis of the wing, fuselage, and empennage.

The study combined preliminary analytical calculations with numerical aerodynamic methods to evaluate aircraft performance, stability, and endurance. Its main contribution was the demonstration of a systematic design process in which the aerodynamic components were assessed as part of an integrated aircraft configuration.

However, the study primarily addressed the overall aerodynamic design of the MALE UAV and did not investigate detailed parametric flaperon sizing or roll-control performance. Therefore, although the work provides an important reference for the overall MALE UAV design process, it does not directly resolve the flaperon-sizing problem investigated in the present thesis.

Adeleke et al. developed the wing of a lightweight MALE UAV intended for intelligence and surveillance missions. The investigated aircraft had a maximum take-off mass of 650 kg, a wing area of 10.36 m², a cruise altitude of 15,000 ft, and a target endurance of 24 h [17]. The initial aircraft and wing parameters were estimated using empirical design methods and data from comparable UAV configurations.

The study established manoeuvre and gust envelopes with reference to STANAG 4671 and calculated the aerodynamic, inertia, shear, and bending loads acting on the wing. Athena Vortex Lattice was used to obtain aerodynamic quantities, while analytical calculations were used to determine the load distribution. The maximum aileron deflection at manoeuvring speed and maximum take-off mass was identified as the critical wing-body loading case.

The work is relevant because it demonstrates that wing-control deflection can become an important structural load case for a MALE UAV. Nevertheless, its primary objective was wing structural design rather than aerodynamic flaperon sizing. The aileron geometry was not systematically varied, and the study did not evaluate the combined high-lift and roll-control functions of a flaperon.

The MALE UAV examined in the present thesis was established through earlier conceptual-design studies by Ihsan and Shidiqi. Ihsan addressed the aircraft configuration, avionics selection, and structural design, while Shidiqi evaluated the aerodynamic and stability characteristics of the baseline aircraft [7], [8]. These studies established the high-aspect-ratio wing, pusher-propeller arrangement, and baseline aircraft geometry inherited by the present work.

Although the preceding studies established the overall aircraft geometry and baseline aerodynamic and stability characteristics, they did not complete a systematic

parametric investigation of the wing-mounted flaperon. The present thesis therefore extends the existing aircraft design by investigating flaperon geometry, aerodynamic effectiveness, roll-control capability, and roll-related stability.

TABLE 2.3: Summary of previous MALE UAV design studies

Study	Main Objective	Method	Relevance and Limita- tion
Panagiotou et al. (2016)	Integrated aero- dynamic design of a MALE UAV	Conceptual sizing, analytical calcula- tions, and numerical aerodynamic analy- sis	Provides a systematic MALE aerodynamic- design process but does not investigate detailed parametric flaperon sizing.
Adeleke et al. (2022)	Structural design of a lightweight MALE UAV wing	Empirical sizing, vortex-lattice anal- ysis, analytical load calculations, CAD, and finite-element analysis	Demonstrates the impor- tance of aileron-induced wing loading but does not evaluate combined flap- eron high-lift and roll- control performance.
Ihsan (2024)	Structural and system devel- opment of the baseline MALE UAV	Conceptual design, component selec- tion, and structural design	Establishes the aircraft configuration inherited by the present thesis but does not complete aerodynamic flaperon sizing.
Shidiqi (2024)	Aerodynamic and stability develop- ment of the base- line MALE UAV	Numerical aerody- namic and stability analysis	Establishes the aero- dynamic and stability baseline but does not per- form systematic flaperon sizing and roll-control verification.

2.5.2 Wing Roll-Control and Stability Studies

Rauf et al. [18] developed a methodology for analysing the stability and control characteristics of a small fixed-wing loitering UAV. The study used aerodynamic and stability analysis tools to obtain stability derivatives and subsequently evaluate the aircraft dynamic response.

The study included aileron sizing for roll control and demonstrated the importance of verifying a preliminary geometric design using aerodynamic derivatives and aircraft-response calculations. This approach is relevant to the present work because

the differential function of the flaperon is aerodynamically similar to an aileron during roll control.

However, the aircraft considered by Rauf et al. was a small loitering UAV rather than a high-aspect-ratio MALE UAV, and the wing control surface was a conventional aileron rather than a combined flaperon. The study therefore did not address the interaction between symmetric high-lift deployment and the remaining differential roll-control authority that is central to the present Path B design.

2.5.3 Flaperon Design Considerations

A flaperon combines the flap and aileron functions within the same trailing-edge surface. This arrangement avoids separate wing-mounted flap and aileron surfaces but creates a direct interaction between high-lift deployment and roll-control authority.

During symmetric deployment, both flaperons deflect in the same direction to increase wing lift. During differential operation, the left and right surfaces deflect by different amounts to produce the asymmetric lift distribution required for roll control. Because both functions use the same mechanical deflection envelope, increasing the symmetric approach setting reduces the remaining differential motion available for roll control.

Flaperon sizing must therefore consider more than the rolling moment generated by the surface. Spanwise coverage and chord ratio also influence the high-lift increment, adverse-yaw tendency, surface area, and hinge moment. These competing effects provide the basis for the parametric and Pareto-based design procedure adopted in the present thesis.

2.5.4 Preliminary Flaperon Sizing Methods

Preliminary flaperon sizing may be performed using empirical geometric ranges, analytical control-effectiveness approximations, and comparisons with existing aircraft. Raymer presents statistical and analytical procedures for conceptual aircraft design, while Gudmundsson provides practical methods for estimating control-surface dimensions and evaluating their effects on stability and control [11], [15].

Empirical methods are useful for establishing initial ranges for parameters such as surface area, span, chord ratio, and maximum deflection. Their main advantages are

low computational cost and ease of application during the conceptual-design stage. However, their results depend strongly on the aircraft classes and databases from which the empirical relationships were derived.

Analytical approaches use relations based on control derivatives, aerodynamic force and moment relationships, and simplified spanwise load distributions. These methods provide physical insight and allow the influence of individual parameters to be examined. However, they generally rely on simplified aerodynamic assumptions and may not represent detailed planform geometry or interaction effects.

Numerical parametric analysis allows candidate flaperon geometries to be evaluated using a representation of the actual aircraft geometry. Parameters such as spanwise coverage, chord ratio, and deflection can be varied systematically, after which the aerodynamic coefficients and control derivatives can be compared. The accuracy of this approach nevertheless depends on the assumptions and limitations of the numerical method.

The present study combines analytical and numerical approaches. Analytical estimates are used to establish preliminary reference values and provide an independent cross-check. XFLR5 is then used to compare the candidate flaperon configurations for the actual MALE UAV geometry.

2.5.5 Application of XFLR5 in UAV Design

XFLR5 is widely used during preliminary aircraft design to evaluate airfoil, wing, and complete-aircraft aerodynamic characteristics. The software combines two-dimensional airfoil analysis with lifting-line, vortex-lattice, and panel-based methods for three-dimensional aerodynamic analysis. It can calculate aerodynamic coefficients, stability derivatives, control derivatives, and eigenvalue-based stability results.

The principal advantage of XFLR5 is its ability to evaluate multiple aircraft geometries with relatively low computational cost. This makes it suitable for a parametric study in which flaperon spanwise coverage, chord ratio, and deflection are varied over a set of candidate configurations.

However, XFLR5 is based mainly on linear potential-flow methods for three-dimensional analysis. It therefore has limitations in predicting strongly separated flow, nonlinear aerodynamic behaviour, large control-surface deflections, and absolute hinge moments. Its results are more suitable for comparing aerodynamic trends

TABLE 2.4: Comparison of preliminary flaperon sizing methods

Method	Main Basis	Strength	Limitation
Empirical sizing	Statistical ranges and data from previous aircraft	Fast and suitable for establishing initial dimensions	May not accurately represent the geometry or mission of the investigated aircraft.
Analytical sizing	Control derivatives and simplified aerodynamic relationships	Transparent and provides physical insight into design-variable effects	Requires simplified aerodynamic and geometric assumptions.
Parametric numerical analysis	Repeated aerodynamic analysis of candidate geometries	Represents the actual aircraft plan-form and allows direct candidate comparison	Accuracy depends on the aerodynamic model and input data.
High-fidelity CFD or experimental testing	Detailed flow-field simulation or physical measurement	Can represent nonlinear, viscous, and separated-flow effects	Requires substantially greater computational resources, cost, and development time.

between candidates than for replacing high-fidelity computational or experimental verification.

In the present study, two-dimensional viscous airfoil polars are applied where valid coverage is available to represent Reynolds-number-dependent airfoil behaviour. The three-dimensional aircraft analysis is then used to compare aerodynamic coefficients, roll-control derivatives, and roll-related stability characteristics of the candidate flaperon configurations. XFLR5 is also used for Type 7 stability analysis of the selected configuration. The resulting numerical values are interpreted within the assumptions and limitations of the method.

2.5.6 Application of Design Standards in Previous UAV Studies

Previous UAV design studies have used established airworthiness standards to define flight envelopes, structural load cases, stability requirements, and control-performance references. Adeleke et al., for example, used STANAG 4671 to establish the manoeuvre and gust conditions for the structural design of a MALE UAV wing [17].

The application of standards developed for manned or military aircraft does not automatically demonstrate that a UAV design is certifiable. Instead, selected provisions may be used as preliminary reference criteria when appropriate. The chosen criteria must therefore be interpreted according to the aircraft configuration, mission, operating conditions, and level of design maturity.

In the present thesis, selected provisions from 14 CFR Part 23 and STANAG 4671 are used together with preliminary flaperon performance criteria to guide the assessment of roll authority and roll-related stability. These references support the interpretation of the candidate and final-design results but are not presented as evidence of complete regulatory compliance.

2.5.7 Research Gap

The reviewed studies provide established methods for MALE UAV aerodynamic design, wing structural analysis, preliminary control-surface sizing, and aircraft stability analysis. Panagiotou et al. demonstrated an integrated MALE UAV aerodynamic-design process, while Adeleke et al. [17] showed the importance of aileron deflection in MALE UAV wing loading. Rauf et al. demonstrated the connection between wing-control-surface sizing, aerodynamic derivatives, and aircraft dynamic response.

However, the previous studies do not resolve the specific flaperon-sizing problem of the high-aspect-ratio MALE UAV investigated in this thesis. The baseline aircraft already contains wing-mounted flaperons, but their chord ratio and spanwise coverage were not systematically varied and compared using defined roll-control and high-lift criteria [7], [8].

In particular, the effects of flaperon geometry on steady-state roll rate, roll-response time, symmetric lift increment, adverse-yaw tendency, surface area, and estimated hinge moment had not been evaluated together. The roll-related stability behaviour of the selected flaperon configuration also required verification.

The present thesis addresses this gap through a structured parametric assessment of six Path B flaperon configurations. Analytical estimates are used to establish preliminary reference values, while XFLR5 is used to evaluate the candidate geometries at the selected operating conditions. Candidates are first screened using the adopted

hard constraints and are then compared using aerodynamic and geometric trade-offs to identify a balanced preliminary flaperon configuration.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview of Methodology

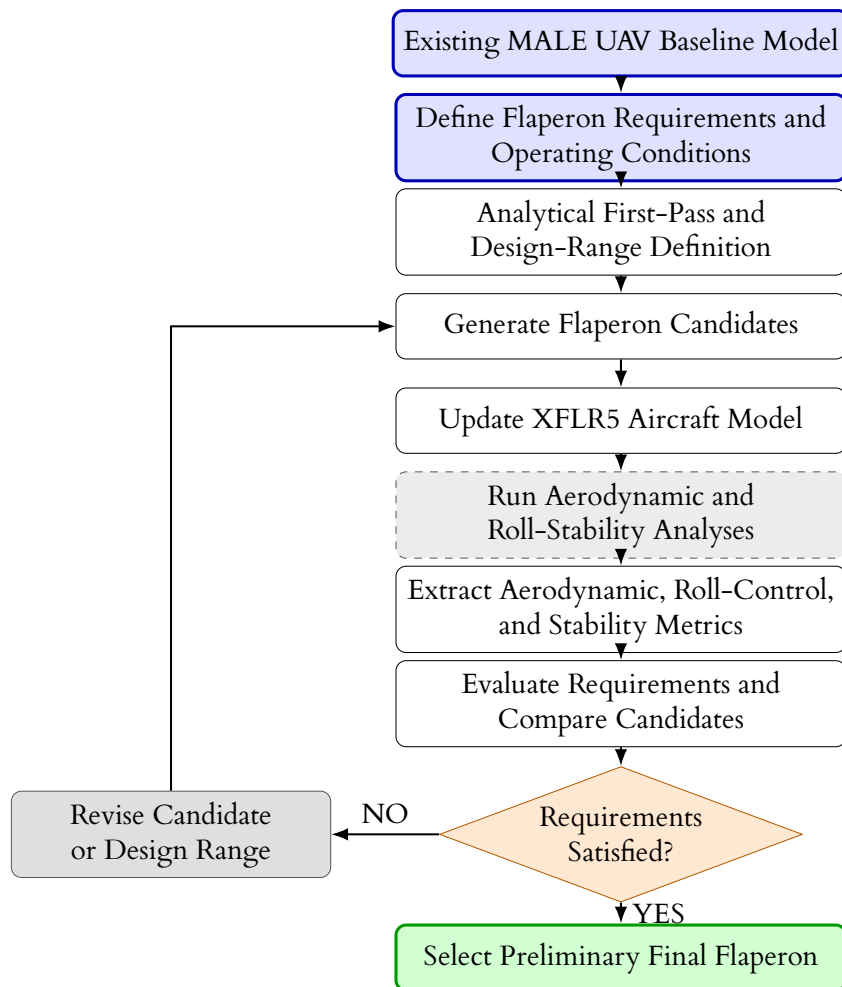


FIGURE 3.1: Overall methodology for the preliminary sizing and evaluation of the MALE UAV flaperon.

This study applies a preliminary design methodology for the sizing and evaluation of the flaperon of the existing MALE UAV. The methodology combines analytical first-pass calculations with parametric aerodynamic and roll-related stability analyses using XFLR5.

The work is entirely analytical and computational. No wind-tunnel, prototype, or flight testing is conducted. The methodology is intended to identify an engineering-feasible preliminary flaperon configuration rather than a mathematically optimal solution.

3.1.1 Overall Process Flow

The methodology begins with the existing MALE UAV baseline model in XFLR5. The baseline geometry, mass properties, aerodynamic reference dimensions, and flight-condition data are retained as the reference for all subsequent flaperon modifications.

The flaperon requirements and operating conditions are then defined. The assessment considers approach, cruise, and loiter, with approach treated as the principal sizing condition because the flaperon must simultaneously provide symmetric high-lift deployment and retain differential roll-control authority.

Analytical first-pass calculations are used to establish suitable ranges for the flaperon design variables and to provide reference values for comparison with the XFLR5 results. Based on these ranges, six candidate flaperon geometries are generated.

Each candidate geometry is implemented in the XFLR5 aircraft model. The required operating lift coefficient is determined for the selected flight condition, and the corresponding operating angle of attack is identified from the aerodynamic polar. Aerodynamic and control analyses are then conducted using Type 1 fixed-speed analysis, while Type 7 analysis is used to obtain the roll-related stability derivatives and eigenvalues required for the final stability assessment.

The principal extracted quantities for the flaperon candidates are $C_{l_{\delta_a}}$, C_{l_p} , ΔC_L , ΔC_D , ΔC_m , and $C_{n_{\delta_a}}$. These quantities are used to evaluate roll authority, roll damping, symmetric high-lift effectiveness, aerodynamic penalties, and adverse-yaw coupling.

The calculated results are compared with the adopted preliminary flaperon criteria. Candidates satisfying the hard constraints are retained for trade-off assessment.

The feasible candidates are then compared using steady-state roll rate, flaperon area, estimated hinge moment, and adverse-yaw tendency.

A Pareto comparison is used to identify non-dominated candidates based primarily on roll performance and flaperon area. The remaining engineering metrics are then considered to select the final preliminary configuration.

The selected configuration is subsequently subjected to additional verification, including mass variation, density variation, an independent Method 2 cross-check, and single-flaperon failure cases.

3.1.2 Methodology Summary

In summary, the methodology combines analytical estimation, parametric candidate generation, XFLR5 aerodynamic analysis, roll-related stability analysis, requirement screening, Pareto comparison, and final-design verification.

Analytical methods are used to establish preliminary reference values and provide an independent comparison, while XFLR5 is used to evaluate the effects of the actual aircraft and flaperon geometry.

The procedure is intended for preliminary design. It does not seek a global mathematical optimum, but instead identifies a balanced flaperon configuration that satisfies the adopted roll-control and high-lift criteria within the investigated design space.

3.2 UAV Configuration and Parameters

3.2.1 Baseline UAV Description

The aircraft considered in this study is a fixed-wing MALE UAV intended for long-endurance missions. The aircraft employs a high-aspect-ratio wing, a rear-mounted single-engine pusher arrangement, and an existing four-panel X-tail.

The X-tail is retained from the preceding aircraft design and is not geometrically modified in the present flaperon study. Roll control is provided primarily by the wing-mounted flaperons.

For the present analysis, the aircraft uses the Path B flaperon-only wing configuration. One continuous flaperon is installed on each side of the wing and performs

both the symmetric high-lift function and the differential roll-control function. No separate inboard flap is used.

The main aircraft geometry and mass properties are retained while the flaperon chord ratio and spanwise coverage are varied during the candidate analysis.

Figure 3.2 presents the general layout and principal dimensions of the baseline aircraft.

The principal geometric and aerodynamic parameters of the aircraft are summarised in Table 3.1.

TABLE 3.1: Geometric and aerodynamic parameters of the MALE UAV

Parameter	Symbol	Value	Unit
Wingspan	b	15.98	m
Overall aircraft length	L	8.34	m
Wing reference area	S	13.92	m ²
X-tail surface area	S_X	2.81	m ²
Wing airfoil	–	NASA/Langley NLF(1)-0215F	–
Tail airfoil	–	NACA 0012	–
Wing aspect ratio	AR	18.34	–
Wing taper ratio	λ	0.40	–

The XFLR5 wing model has a mean aerodynamic chord of 0.93 m, a projected span of 15.92 m, and a projected area of 13.87 m². The NASA/Langley NLF(1)-0215F airfoil is used for the wing and its modified flaperon sections.

The mass properties used in the stability analysis are taken directly from the XFLR5 aircraft model. The same mass, centre-of-gravity position, and moments of inertia are maintained for all flaperon candidates to ensure a consistent comparison.

The centre-of-gravity coordinates are measured relative to the coordinate origin of the XFLR5 model and should not be interpreted as distances from the aircraft nose. The inertia values correspond to the body-axis reference system used by XFLR5.

3.2.2 Design Flight Conditions

The flaperon analysis is performed at approach, cruise, and loiter conditions. The approach condition is treated as the principal sizing condition because the aircraft

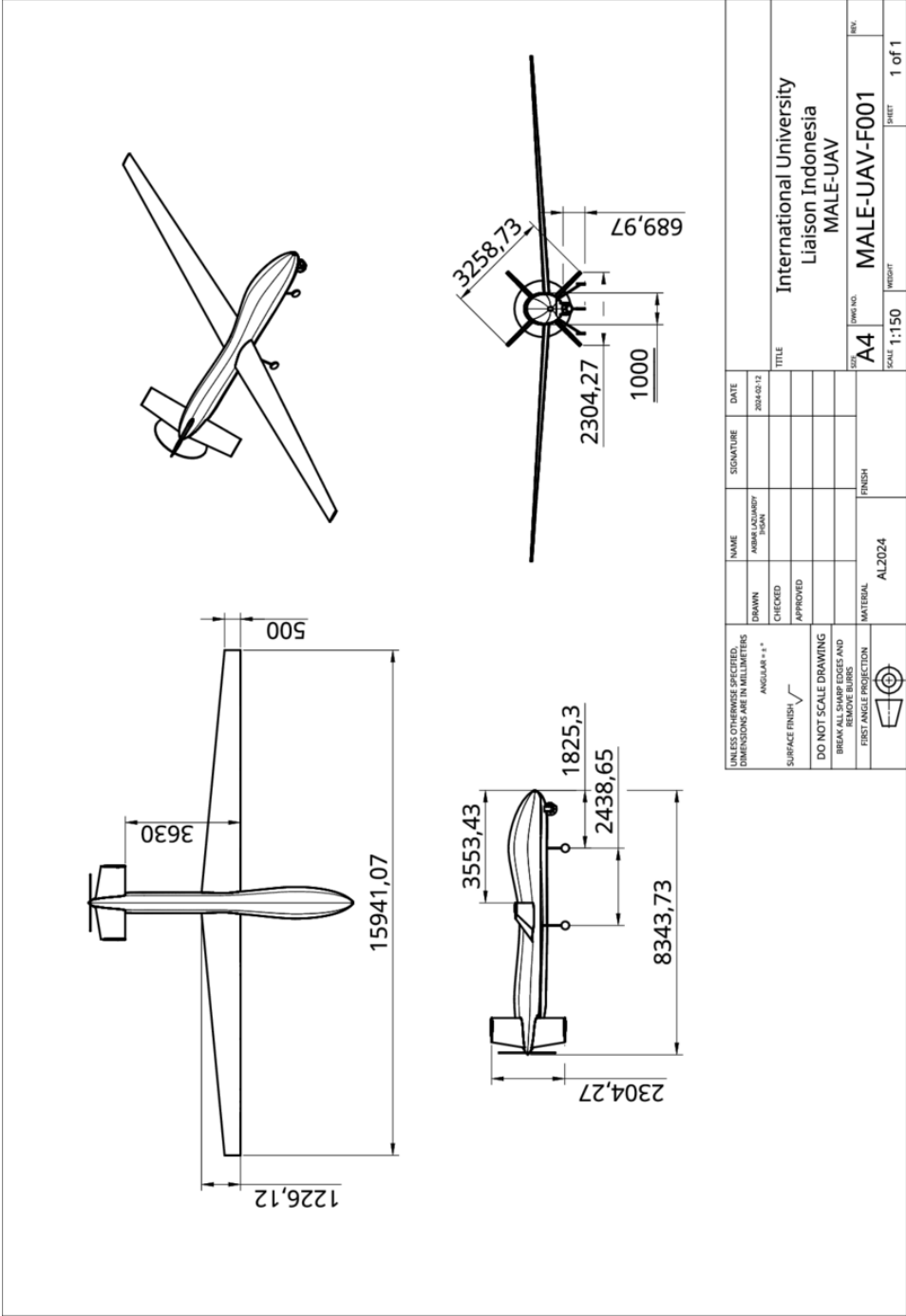


FIGURE 3.2: Three-view drawing of the baseline MALE UAV; dimensions are in millimetres.

TABLE 3.2: Mass properties used in the XFLR5 model

Parameter	Symbol	Value	Unit
Total aircraft mass	m	1450.00	kg
Longitudinal CG coordinate	x_{CG}	0.14	m
Lateral CG coordinate	y_{CG}	0.00	m
Vertical CG coordinate	z_{CG}	0.03	m
Roll moment of inertia	I_{xx}	2293.11	kg m ²
Pitch moment of inertia	I_{yy}	4293.67	kg m ²
Yaw moment of inertia	I_{zz}	6525.78	kg m ²
Product of inertia	I_{xz}	3.90	kg m ²

operates with symmetric flaperon deployment while sufficient differential deflection must remain available for roll control.

Cruise and loiter are evaluated as additional operating cases to determine whether the selected configuration retains roll-control effectiveness away from the primary approach sizing condition.

The design flight conditions used in the analysis are summarised in Table 3.3.

TABLE 3.3: Design flight conditions used in the flaperon analysis

Condition	V m/s	ρ kg/m ³	q Pa	δ_f (°)
Approach	36.00	1.225	793.80	20.00
Cruise	36.00	1.225	793.80	0.00
Loiter	30.00	1.225	551.25	0.00

The atmospheric properties used in the completed XFLR5 analyses were $\rho = 1.225 \text{ kg/m}^3$ and $\nu = 1.4608 \times 10^{-5} \text{ m}^2/\text{s}$ for all three operating conditions. Consequently, the cruise and loiter cases represent the specified analysis cases using sea-level atmospheric properties rather than altitude-corrected mission conditions.

3.2.3 XFLR5 Model Status

The baseline XFLR5 aircraft model was developed before the present flaperon study. The existing model includes the main wing, X-tail, mass distribution, CG location, and inertia properties. These elements are retained as the reference aircraft configuration.

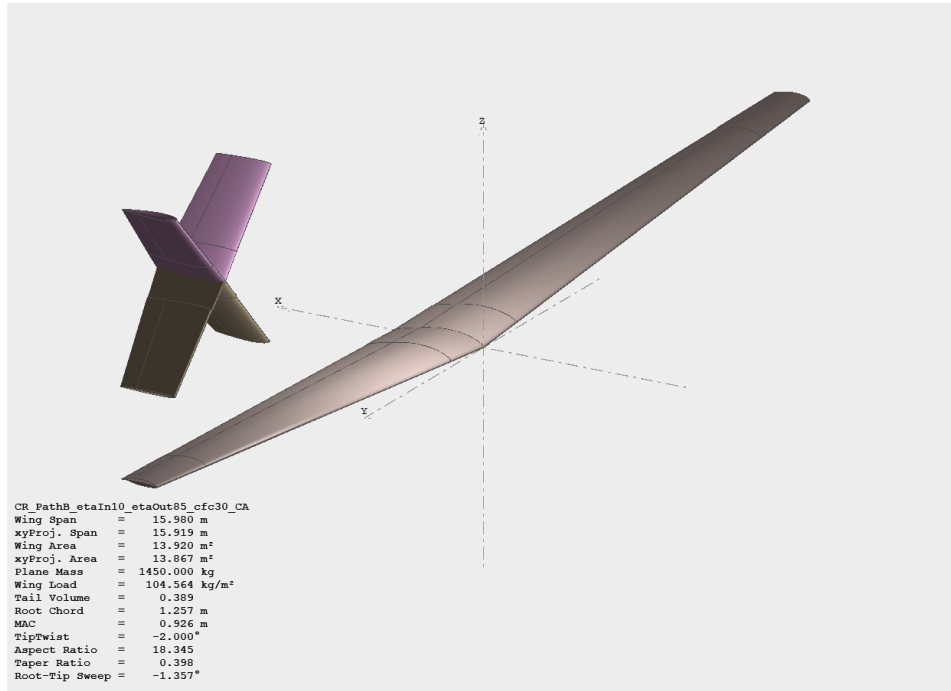


FIGURE 3.3: Baseline MALE UAV model in XFLR5.

The flaperon geometry is modified according to the candidate definitions investigated in this thesis. The wing and existing tail surfaces are represented as discretised lifting surfaces, while the flaperon is implemented through the corresponding trailing-edge geometry and prescribed deflection.

The final baseline model contains 550 VLM panels on the wing and 1122 three-dimensional panels for the complete aircraft lifting-surface model.

Several modelling simplifications are recognised. The method assumes predominantly attached flow and is therefore less reliable near stall or under strongly non-linear aerodynamic conditions. The physical hinge gap and detailed local flaperon geometry are not represented explicitly.

The fuselage is not included in the XFLR5 aerodynamic model. Consequently, fuselage aerodynamic contributions and detailed wing–fuselage interference are not represented.

Hinge-moment estimates used later in the methodology are treated only as preliminary comparative quantities and not as actuator-grade loads.

3.3 Flaperon Sizing

3.3.1 Design Requirements

The flaperon design requirements were defined using the preliminary sizing procedure adopted for the present MALE UAV. These values are used as preliminary design criteria rather than as direct certification requirements under 14 CFR Part 23 or STANAG 4671.

For roll control, the flaperon is required to provide a steady-state roll rate of at least

$$p_{ss} \geq 20^\circ/\text{s} \quad (3.1)$$

at the approach condition.

The aircraft must also reach a 30° bank angle within

$$t_{30^\circ} \leq 2.50 \text{ s}. \quad (3.2)$$

The symmetric high-lift function must provide

$$\Delta C_L \geq 0.60, \quad (3.3)$$

while the yawing-moment response associated with differential flaperon operation is limited through

$$\left| \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} \right| \leq 0.20. \quad (3.4)$$

The complete preliminary flaperon requirements are summarised in Table 3.4.

TABLE 3.4: Flaperon sizing requirements

Requirement	Symbol	Criterion	Unit
Steady-state roll rate at approach	p_{ss}	≥ 20.00	deg/s
Time to reach 30° bank	t_{30°	≤ 2.50	s
Approach lift increment	ΔC_L	≥ 0.60	–
Adverse-yaw ratio	$ C_{n_{\delta_a}}/C_{l_{\delta_a}} $	≤ 0.20	–

3.3.2 Heuristic Sizing Method

The flaperon sizing procedure is conducted in three principal steps.

Step 1: Initial sizing.

The initial geometric range is defined from the preliminary sizing procedure. The flaperon chord ratio is varied as

$$\frac{c_f}{c} \in \{0.25, 0.30\} . \quad (3.5)$$

The inboard spanwise station is fixed at

$$\eta_{in} = 0.10, \quad (3.6)$$

while the outboard station is varied as

$$\eta_{out} \in \{0.85, 0.90, 0.95\} . \quad (3.7)$$

Step 2: Control-power estimation.

Increasing the flaperon chord ratio or spanwise coverage increases the movable aerodynamic area and generally increases roll-control effectiveness. However, the resulting roll performance also depends on the flight speed, roll-damping derivative, wing span, and roll moment of inertia.

Analytical relationships and XFLR5-derived aerodynamic derivatives are therefore used together to quantify candidate roll performance.

Step 3: Candidate generation and screening.

The two chord ratios and three outboard stations form a six-candidate design matrix. Each candidate is analysed using the same baseline aircraft, operating conditions, mass properties, and numerical method.

Candidates are subsequently evaluated against the adopted hard constraints before Pareto-based trade-off analysis.

3.3.3 Initial Sizing and Design Variables

Path B was selected for the wing arrangement. This configuration uses one continuous flaperon on each wing and does not include a separate inboard flap. The same surface therefore provides symmetric lift augmentation and differential roll control.

The inboard station was fixed at

$$\eta_{\text{in}} = 0.10, \quad (3.8)$$

where η is measured as a fraction of the wing half-span. Using the actual wing span,

$$b = 15.98 \text{ m}, \quad (3.9)$$

the half-span is

$$\frac{b}{2} = 7.99 \text{ m}. \quad (3.10)$$

The physical inboard position is therefore

$$y_{\text{in}} = \eta_{\text{in}} \frac{b}{2} = 0.10(7.99) = 0.799 \text{ m}. \quad (3.11)$$

The outboard station was varied as

$$\eta_{\text{out}} \in \{0.85, 0.90, 0.95\}. \quad (3.12)$$

The corresponding outboard positions are

$$y_{\text{out},0.85} = 0.85(7.99) = 6.792 \text{ m}, \quad (3.13)$$

$$y_{\text{out},0.90} = 0.90(7.99) = 7.191 \text{ m}, \quad (3.14)$$

$$y_{\text{out},0.95} = 0.95(7.99) = 7.591 \text{ m}. \quad (3.15)$$

The resulting one-side flaperon spans are

$$b_{f,0.85} = 6.792 - 0.799 = 5.993 \text{ m}, \quad (3.16)$$

$$b_{f,0.90} = 7.191 - 0.799 = 6.392 \text{ m}, \quad (3.17)$$

$$b_{f,0.95} = 7.591 - 0.799 = 6.792 \text{ m}. \quad (3.18)$$

The flaperon chord ratio was varied as

$$\frac{c_f}{c} \in \{0.25, 0.30\}. \quad (3.19)$$

The corresponding hinge-line position is

$$\frac{x_h}{c} = 1 - \frac{c_f}{c}. \quad (3.20)$$

Therefore,

$$\frac{c_f}{c} = 0.25 \Rightarrow \frac{x_h}{c} = 0.75, \quad (3.21)$$

$$\frac{c_f}{c} = 0.30 \Rightarrow \frac{x_h}{c} = 0.70. \quad (3.22)$$

At the approach condition, both flaperons are deflected symmetrically by

$$\delta_{\text{sym}} = 20^\circ. \quad (3.23)$$

The corresponding baseline physical configuration is

$$\delta_L = \delta_R = 20^\circ. \quad (3.24)$$

The physical deflection limit of each flaperon is

$$|\delta_f| \leq 30^\circ. \quad (3.25)$$

The remaining differential-command margin about the 20° approach setting is therefore

$$|\delta_{\text{diff,max}}| = 30^\circ - 20^\circ = 10^\circ. \quad (3.26)$$

At the limiting approach roll command, the physical flaperon positions are

$$\delta_L = 10^\circ, \quad \delta_R = 30^\circ, \quad (3.27)$$

or the opposite combination for the reverse roll direction.

The complete candidate grid is presented in Table 3.5.

TABLE 3.5: Path B flaperon candidate grid

Candidate	η_{in}	η_{out}	c_f/c	x_h/c
C-01	0.10	0.85	0.25	0.75
C-02	0.10	0.90	0.25	0.75
C-03	0.10	0.95	0.25	0.75
C-04	0.10	0.85	0.30	0.70
C-05	0.10	0.90	0.30	0.70
C-06	0.10	0.95	0.30	0.70

3.3.4 Flaperon Control-Power Evaluation

For each operating condition, the required aircraft lift coefficient is

$$C_{L,\text{required}} = \frac{W}{qS}, \quad (3.28)$$

where

$$q = \frac{1}{2}\rho V^2. \quad (3.29)$$

The operating angle of attack is identified from the XFLR5 aerodynamic polar by selecting the point corresponding as closely as possible to $C_{L,\text{required}}$. This angle of attack is used as the reference operating point for the coefficient and derivative extraction. It is not treated as a complete control-trim solution.

The roll-control derivative is obtained using the baseline and differentially perturbed configurations. At approach, the baseline configuration is

$$\delta_L = \delta_R = 20^\circ. \quad (3.30)$$

A differential perturbation of

$$\Delta\delta = 2^\circ \quad (3.31)$$

per side produces

$$\delta_L = 18^\circ, \quad \delta_R = 22^\circ. \quad (3.32)$$

The roll-control derivative is calculated as

$$C_{l_{\delta_a}} = \frac{C_{l,B} - C_{l,A}}{2\Delta\delta}, \quad (3.33)$$

where the total differential separation, $2\Delta\delta$, is expressed in radians.

The associated yaw-control derivative is calculated from

$$C_{n_{\delta_a}} = \frac{C_{n,B} - C_{n,A}}{2\Delta\delta}. \quad (3.34)$$

The adverse-yaw ratio is then

$$R_{\text{yaw}} = \left| \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} \right|. \quad (3.35)$$

The yawing moment is considered only as an aerodynamic coupling generated by the roll command; yaw-control authority is not assessed in this study.

The roll-damping derivative, C_{l_p} , is obtained from the XFLR5 stability analysis.

The steady-state roll rate is calculated using

$$p_{ss} = -\frac{C_{l_{\delta_a}} \delta_{a,\max}}{C_{l_p}} \frac{2V}{b}, \quad (3.36)$$

where $\delta_{a,\max}$ represents the adopted differential roll-command input.

The roll time constant is calculated as

$$\tau_R = \frac{2I_{xx}V}{|C_{l_p}|qSb^2}. \quad (3.37)$$

The time required to reach a 30° bank angle is approximated by

$$t_{30^\circ} = \frac{30^\circ}{|p_{ss}|} + \tau_R. \quad (3.38)$$

When p_{ss} is used in Equation 3.38, it is expressed in deg/s.

The symmetric high-lift effect is evaluated by comparing the 20° and 0° flaperon configurations:

$$\Delta C_L = C_{L,20^\circ} - C_{L,0^\circ}, \quad (3.39)$$

$$\Delta C_D = C_{D,20^\circ} - C_{D,0^\circ}, \quad (3.40)$$

$$\Delta C_m = C_{m,20^\circ} - C_{m,0^\circ}. \quad (3.41)$$

The change in pitching-moment coefficient is retained as an aerodynamic effect of symmetric flaperon deployment but is not used to evaluate pitch-control authority.

The flaperon hinge moment is estimated using

$$H = q S_f c_f |C_h|, \quad (3.42)$$

where

$$C_h = C_{h_\alpha} \alpha + C_{h_\delta} \delta. \quad (3.43)$$

The hinge-moment estimate is used only for preliminary candidate ranking and actuator-demand assessment. It is not treated as an actuator-grade load.

The resulting values of p_{ss} , t_{30° , ΔC_L , R_{yaw} , flaperon area, and estimated hinge moment are used to screen and compare the six candidates.

3.3.5 Flaperon Geometry Definition

The principal geometric parameters used in the flaperon sweep are the inboard station, η_{in} , outboard station, η_{out} , chord ratio, c_f/c , hinge-line position, x_h/c , and allowable deflection range.

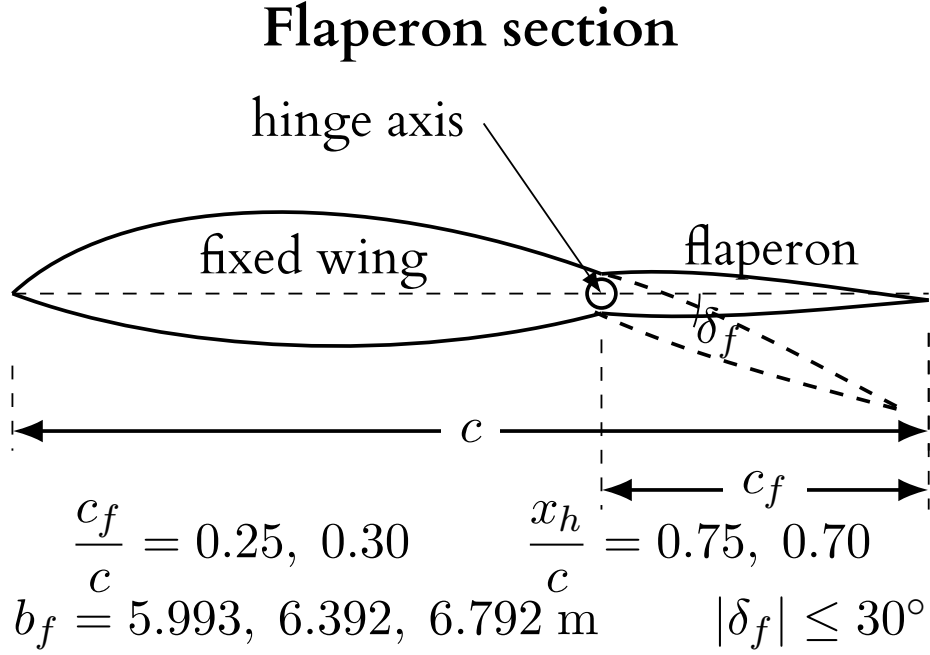


FIGURE 3.4: Principal geometric parameters of the flaperon.

3.4 XFLR5 Analysis

3.4.1 XFLR5 Software Overview

The aerodynamic and roll-related stability analyses in this study are performed using XFLR5 version 6.61. The software provides two-dimensional airfoil-polar generation, three-dimensional lifting-surface analysis, flaperon modelling, and aircraft stability analysis within a preliminary-design environment.

The capabilities relevant to the present study include calculation of aerodynamic force and moment coefficients, stability derivatives, rotational damping derivatives, and eigenvalues. XFLR5 is also used to determine the aerodynamic response to prescribed symmetric and differential flaperon deflections.

The required control derivatives are calculated from the differences between baseline and perturbed cases using the finite-difference relationships presented in Section 3.3.

The three-dimensional analyses use VLM2 with thin lifting-surface representations. Viscous analysis is prioritised by preparing the required two-dimensional

viscous airfoil polars before the aircraft-level analysis is conducted.

The validity of a viscous three-dimensional solution depends on the availability of corresponding airfoil-polar data over the local Reynolds number, angle-of-attack, and lift-coefficient ranges encountered by the aircraft model.

XFLR5 remains subject to the assumptions of linear aerodynamic analysis and small perturbations about the evaluated condition. It does not fully represent separated flow, deep-stall behaviour, large aerodynamic nonlinearities, structural flexibility, or unsteady aerodynamic effects. The results are therefore used for comparative flaperon sizing and preliminary stability assessment rather than final aerodynamic validation or certification.

3.4.2 Model Setup

The UAV geometry described in Section 3.2 is implemented in XFLR5 using the prescribed wing and existing tail planforms, airfoil sections, reference locations, and panel distributions. The numerical values already presented in Section 3.2 are not repeated here.

The main wing is defined using its spanwise stations, local chord lengths, twist angles, dihedral angles, airfoil assignments, and panel distributions. The NASA/Langley NLF(1)-0215F airfoil is assigned to the wing sections. Modified airfoil definitions are prepared where required to represent the selected flaperon chord ratio and symmetric deflection.

The existing X-tail is retained as part of the baseline aircraft model but is not varied as a design parameter in the present study.

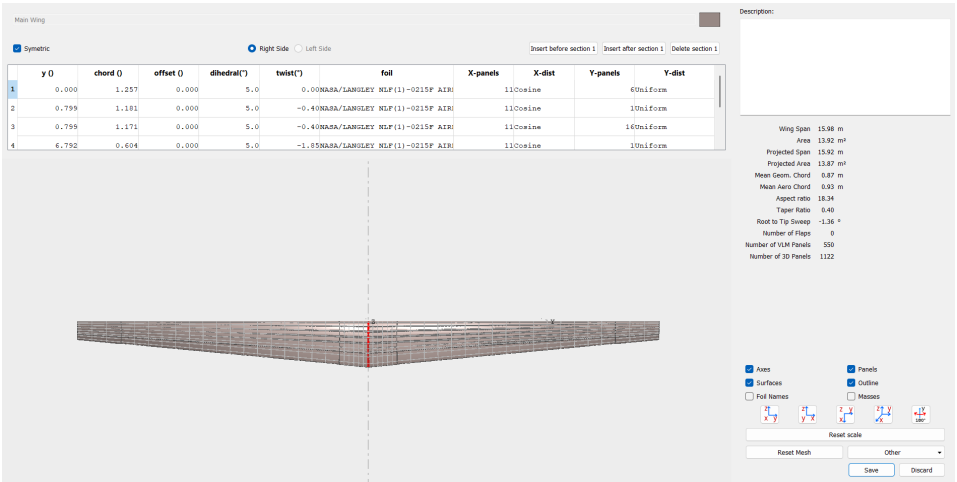
The wing geometry input and complete lifting-surface arrangement are shown in Figure 3.5.

The flaperons are implemented as hinged trailing-edge regions of the main wing. Their movable chord ratios, hinge-line positions, spanwise extents, and deflections follow the candidate definitions established in Section 3.3.

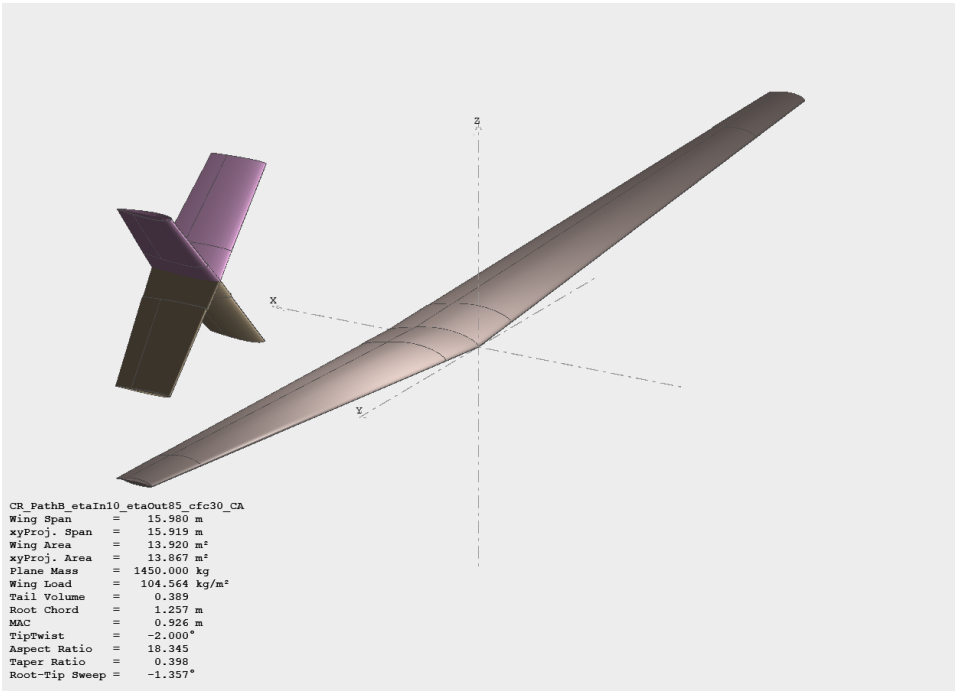
At the airfoil level, the trailing-edge flap function is used to define the hinge position and prescribed deflection. At the aircraft level, the left and right flaperons are assigned independently so that both symmetric and differential configurations can be evaluated.

The XFLR5 control-parameter interface is shown in Figure 3.6.

DESIGN AND ANALYSIS OF FLAPERONS FOR A MEDIUM ALTITUDE LONG ENDURANCE UNMANNED AERIAL VEHICLE



(A) Wing-section, airfoil, and panel definition.



(B) Complete baseline lifting-surface model.

FIGURE 3.5: Geometry implementation in XFLR5.

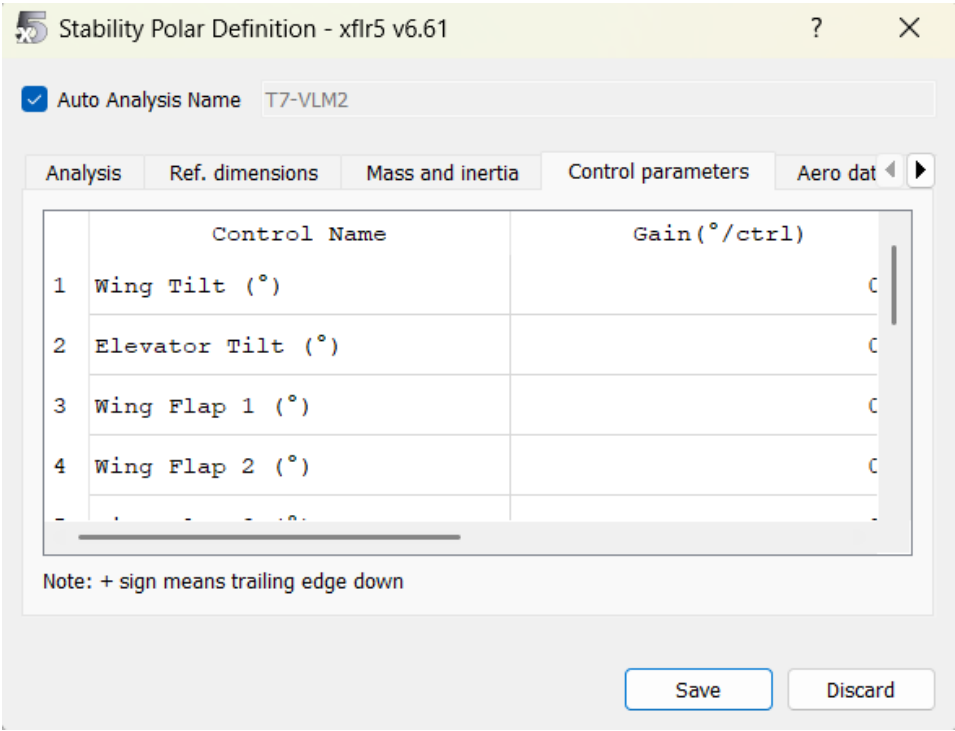


FIGURE 3.6: XFLR5 flaperon control-parameter interface.

The fuselage is not included in the XFLR5 aerodynamic model. Consequently, aerodynamic interference between the fuselage and lifting surfaces is not captured and is treated as a limitation of the present model.

3.4.3 Analysis Setup

The approach, cruise, and loiter conditions defined in Section 3.2 are used for the flaperon analysis. Their corresponding airspeeds, atmospheric properties, and base-line flaperon settings are entered according to the selected operating case.

The aircraft mass, CG location, moments of inertia, and product of inertia established in Section 3.2 are assigned to the XFLR5 model and retained consistently throughout the candidate analyses.

Two principal analysis types are used. Type 1 fixed-speed analyses are employed to obtain the aerodynamic force and moment coefficients required for flaperon-effectiveness evaluation. Type 7 stability analyses are used to obtain the roll-related stability derivatives and eigenvalues.

A representative Type 1 analysis definition is shown in Figure 3.7.

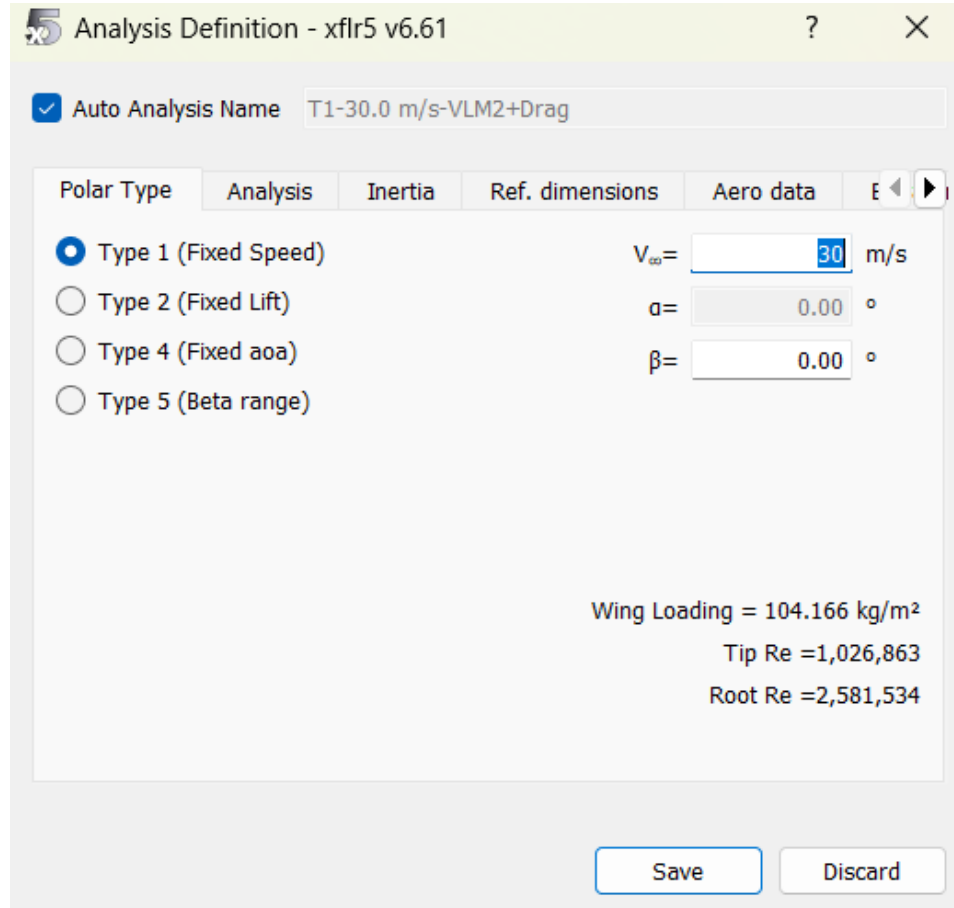


FIGURE 3.7: Representative XFLR5 Type 1 fixed-speed analysis definition.

The three-dimensional analyses use VLM2 with ring vortices, Neumann boundary conditions, and thin lifting-surface representations. The same numerical method, panel distribution, reference dimensions, and general analysis settings are retained across the candidate cases.

The primary workflow uses viscous two-dimensional airfoil polars and viscous three-dimensional analysis. Before an aircraft-level analysis is accepted, the corresponding airfoil polars are checked for sufficient coverage of the required Reynolds numbers, angles of attack, and lift-coefficient ranges.

A separate residual-based convergence tolerance is not prescribed in the adopted

workflow. Analysis validity is instead checked by confirming that the required airfoil-polar data are available, the intended analysis range is completed, and the selected operating point remains within the usable polar envelope.

3.4.4 Analysis Procedure

The XFLR5 analysis follows four principal steps.

Step 1: Flight-case definition.

The aircraft geometry, airfoil polars, flight condition, mass properties, CG location, and inertia properties are first assigned to the XFLR5 model. The flaperons are then set to the baseline configuration corresponding to the selected operating case.

The required operating lift coefficient is determined using the aircraft weight, dynamic pressure, and reference area. The corresponding angle of attack is identified from the aerodynamic polar and used as the operating point for coefficient and derivative extraction.

Step 2: Roll-related stability analysis.

A Type 7 stability analysis is generated for the final configuration. The relevant lateral stability derivatives and eigenvalues are extracted.

The primary derivatives retained are C_{l_β} and C_{l_p} . The lateral eigenvalues are examined to identify the roll-subsidence and spiral modes.

The Type 7 solution determines its own equilibrium condition. Therefore, the resulting modal solution is interpreted at the equilibrium speed reported by XFLR5 rather than assumed to remain at the nominal Type 1 mission speed.

Step 3: Flaperon-effectiveness analysis.

A baseline case and a prescribed differentially perturbed case are analysed for roll-control evaluation. The changes in rolling- and yawing-moment coefficients are recorded and used to calculate $C_{l_{\delta_a}}$ and $C_{n_{\delta_a}}$.

For symmetric high-lift evaluation, the aerodynamic coefficients of the undeployed and deployed flaperon configurations are compared. The resulting ΔC_L , ΔC_D , and ΔC_m are retained for post-processing.

Step 4: Data extraction and post-processing.

The relevant aerodynamic coefficients, roll-related stability derivatives, eigenvalues, and flaperon-case results are exported from XFLR5.

The exported values are compiled in the analysis spreadsheet using a consistent naming system that identifies the flight condition, candidate, baseline or perturbed configuration, and analysis type.

The spreadsheet is then used to calculate the control derivatives, aerodynamic increments, roll-performance quantities, requirement margins, flaperon areas, hinge-moment estimates, and candidate-comparison metrics.

3.4.5 Output Data

The Type 1 analyses provide the aerodynamic force and moment coefficients for the baseline and perturbed configurations. The principal outputs retained are

$$C_L, \quad C_D, \quad C_Y, \quad C_m, \quad C_l, \quad C_n. \quad (3.44)$$

The lift, drag, and pitching-moment coefficients are used to evaluate the symmetric flaperon function, while C_l and C_n are used to evaluate differential roll effectiveness and associated yaw coupling.

The Type 7 analysis provides the derivatives and eigenvalues required for the roll-related stability assessment. The primary quantities retained are C_{l_β} , C_{l_p} , the roll-subsidence eigenvalue, and the spiral eigenvalue.

The selected operating angle of attack, baseline flaperon configuration, and corresponding aerodynamic coefficients are retained for each analysed case. The selected angle of attack represents the operating point used for coefficient and derivative extraction and is not described as a complete automatic control-trim solution.

The collected XFLR5 outputs form the basis of the flaperon sizing, roll-performance, stability, final-design verification, and standards assessment presented in Chapter 4.

3.5 Data Analysis and Evaluation

This section defines the procedure used to evaluate the aerodynamic, roll-control, and roll-related stability results obtained from XFLR5.

The assessment is conducted in four stages. First, each flaperon candidate is screened against the adopted hard constraints. Second, the feasible candidates are

compared using Pareto and engineering trade-off criteria. Third, the selected configuration is evaluated for roll-related stability. Finally, the selected configuration is subjected to additional off-design, analytical cross-check, and degraded-control verification.

The numerical limits adopted in this section are preliminary-design criteria from the flaperon sizing procedure. References to 14 CFR Part 23 and STANAG 4671 provide broader airworthiness context, but the analysis does not constitute complete certification compliance.

3.5.1 Roll-Stability Evaluation

The roll-related stability evaluation uses the derivatives and eigenvalues obtained from the XFLR5 Type 7 analysis.

A restoring rolling-moment tendency with sideslip is represented by

$$C_{l_\beta} < 0. \quad (3.45)$$

Aerodynamic roll damping requires

$$C_{l_p} < 0. \quad (3.46)$$

The roll-subsidence and spiral modes are identified from the corresponding real eigenvalues.

For a real eigenvalue,

$$\lambda = \sigma, \quad (3.47)$$

a negative value indicates a decaying response and a positive value indicates a divergent response.

For a stable real mode, its characteristic time constant is calculated as

$$\tau = -\frac{1}{\lambda}, \quad \lambda < 0. \quad (3.48)$$

For a positive spiral eigenvalue, the disturbance-amplitude doubling time is calculated using

$$t_2 = \frac{\ln 2}{\lambda}, \quad \lambda > 0. \quad (3.49)$$

A weak positive spiral eigenvalue is reported together with its characteristic divergence time rather than automatically being treated as equivalent to a rapidly unstable mode.

The roll-related evaluation criteria are summarised in Table 3.6.

TABLE 3.6: Roll-related stability evaluation criteria

Evaluation Item	Parameter	Desired Tendency
Restoring rolling moment with sideslip	C_{l_β}	< 0
Roll damping	C_{l_p}	< 0
Roll-subsidence mode	λ_{roll}	< 0
Spiral mode	λ_{spiral}	Negative preferred; positive value assessed by divergence time

This assessment is limited to roll-related stability and is not intended to represent complete three-axis aircraft stability verification.

3.5.2 Flaperon-Effectiveness Evaluation

The primary flaperon-performance parameters are the steady-state roll rate, time to a 30° bank angle, symmetric lift increment, and adverse-yaw ratio.

A candidate is considered feasible only when it satisfies all of the following conditions:

$$p_{ss} \geq 20.00 \text{ deg/s}, \quad (3.50)$$

$$t_{30^\circ} \leq 2.50 \text{ s}, \quad (3.51)$$

$$\Delta C_L \geq 0.60, \quad (3.52)$$

$$\left| \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} \right| \leq 0.20. \quad (3.53)$$

The first two criteria assess roll-control performance, the third assesses the symmetric high-lift function, and the fourth limits yaw coupling during differential roll control.

A candidate that fails any hard constraint is classified as infeasible before the Pareto comparison.

The requirements are summarised in Table 3.7.

TABLE 3.7: Flaperon-effectiveness requirements

Requirement	Parameter	Criterion
Steady-state roll rate at approach	p_{ss}	$\geq 20.00 \text{ deg/s}$
Time to reach 30° bank	t_{30°	$\leq 2.50 \text{ s}$
Approach lift increment	ΔC_L	≥ 0.60
Adverse-yaw ratio	$ C_{n\delta_a}/C_{l\delta_a} $	≤ 0.20

3.5.3 Candidate Screening and Pareto Selection

Candidate evaluation is conducted in two stages.

First, each candidate is subjected to the four hard constraints defined in Section 3.5.2. A candidate that fails any one of these criteria is classified as infeasible.

Second, the feasible configurations are subjected to Pareto comparison. The two primary Pareto objectives are:

- maximising steady-state roll rate, p_{ss} ; and
- minimising total flaperon area.

A candidate is Pareto optimal when no other feasible candidate provides at least as much roll performance with equal or smaller flaperon area.

The Pareto procedure identifies the non-dominated set rather than automatically selecting the candidate with the highest roll rate. Additional engineering quantities, particularly estimated hinge moment and adverse-yaw tendency, are then considered to distinguish between the remaining candidates.

The final configuration is therefore selected by balancing roll performance against geometric and actuation penalties rather than by maximising a single aerodynamic metric.

The selected standards from 14 CFR Part 23 and STANAG 4671 are used only to provide broader standards-based context. The numerical hard constraints used for candidate screening are preliminary design criteria and are not presented as direct certification limits from those documents.

3.5.4 Final Design Verification

After selection of the final candidate, additional analyses are performed to determine whether its nominal result remains consistent under selected off-design and degraded-control cases.

Off-design mass verification.

The final geometry is evaluated at

$$m \in \{1305, 1450, 1595\} \text{ kg}, \quad (3.54)$$

corresponding to the baseline mass and approximately $\pm 10\%$ variation.

For each case,

$$C_{L,\text{required}} = \frac{W}{qS}, \quad (3.55)$$

and the nearest operating angle of attack is selected from the XFLR5 polar.

The lift-coefficient matching error is defined as

$$C_{L,\text{error}} = C_{L,\text{XFLR5}} - C_{L,\text{required}}. \quad (3.56)$$

The adopted matching tolerance is

$$|C_{L,\text{error}}| \leq 0.03. \quad (3.57)$$

Off-design density verification.

The same procedure is repeated for the selected low- and high-density cases while retaining the final flaperon geometry. These cases are used to determine whether the selected configuration remains consistent under the investigated variation in dynamic pressure.

Method 2 cross-check.

An analytical Method 2 calculation is used as an independent sanity check of the XFLR5-based roll-performance calculation.

The principal quantities compared are $C_{l_{\delta_a}}$, C_{l_p} , and p_{ss} . Differences in the control-derivative convention are accounted for before the analytical and numerical values are compared.

An agreement range of approximately $\pm 20\%$ is used as the preliminary consistency criterion for the principal roll derivatives. The corresponding steady-state roll-rate predictions are also compared.

The analytical ΔC_L estimate is retained as a comparative high-lift reference rather than as a hard validation criterion.

Single-flaperon failure verification.

Two degraded-control cases are investigated:

1. left flaperon fixed while the right flaperon remains active;
2. right flaperon fixed while the left flaperon remains active.

The residual rolling-moment coefficient, roll-damping derivative, steady-state roll rate, and t_{30° are evaluated for each failure condition.

The nominal 20 deg/s roll-rate floor is retained as a reference for interpreting the degraded result. Cases falling slightly below this value are classified as marginal rather than being treated as nominally satisfactory.

3.5.5 Iteration Strategy

If a candidate fails the roll-rate, bank-time, lift-increment, or adverse-yaw requirement, the flaperon spanwise extent or chord ratio is reviewed within the prescribed candidate design space. The corresponding XFLR5 analysis, derivative extraction, and post-processing are then repeated.

If all candidates satisfy the hard constraints, the design is not automatically enlarged further. The feasible configurations are instead compared using Pareto analysis and the associated area, hinge-moment, and adverse-yaw trade-offs.

The candidate-selection stage is considered complete when:

1. the hard flaperon requirements have been evaluated;
2. the feasible candidate set has been identified;
3. the Pareto-optimal candidates have been determined; and

4. a final configuration has been selected using the relevant aerodynamic and geometric trade-offs.

The final design is then subjected to the off-design, Method 2, and single-flaperon failure verification described previously.

3.5.6 Documentation of Results

The results are documented using separate tables and plots for candidate screening, final configuration selection, roll stability, control performance, and final-design verification.

The candidate comparison reports:

- $C_{l_{\delta a}}$ and C_{l_p} ;
- p_{ss} , τ_R , and t_{30° ;
- ΔC_L , ΔC_D , and ΔC_m ;
- adverse-yaw ratio;
- flaperon area;
- estimated hinge moment;
- hard-constraint feasibility; and
- Pareto status.

The roll-stability results report:

- C_{l_β} ;
- C_{l_p} ;
- roll-subsidence eigenvalue and characteristic time; and
- spiral eigenvalue and its corresponding convergence or divergence time scale.

The final-design verification reports:

- mass-variation results;
- density-variation results;
- Method 2 comparison;
- single-flaperon failure results; and
- the corresponding nominal, pass, or marginal assessment.

The selected configuration is justified using both the hard-constraint results and the engineering trade-offs among roll authority, flaperon area, adverse yaw, and estimated hinge moment.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Design Exploration and Final Sizing

4.1.1 Overview of the Design Process

The flaperon was developed through an exploratory sizing process based on the preliminary heuristic method described in Chapter 3. The geometry was then varied systematically in XFLR5 to evaluate the influence of spanwise extent and chord ratio on roll-control performance.

A total of six configurations, designated C-01 to C-06, were investigated. The inboard position was fixed at $\eta_{\text{in}} = 0.10$, where $\eta = y/(b/2)$ is the nondimensional spanwise position. The outboard position was varied between $\eta_{\text{out}} = 0.85, 0.90$, and 0.95 , while two chord ratios, $c_f/c = 0.25$ and 0.30 , were considered. This produced a 2×3 design matrix for assessing the effects of spanwise coverage and control-surface chord.

The six configurations were screened using the preliminary criteria established in Chapter 3: $p_{ss} \geq 20$ deg/s, $t_{30} \leq 2.5$ s, $\Delta C_L \geq 0.60$, and $|C_{n_{\delta_a}}/C_{l_{\delta_a}}| \leq 0.20$. The roll-damping derivative, C_{l_p} , was also monitored, with a negative value indicating the expected stabilizing roll-damping tendency.

Configurations satisfying these criteria were subsequently compared using roll authority, control-surface area, adverse-yaw tendency, and estimated hinge moment. The objective was therefore to identify an adequate roll-control configuration without unnecessarily increasing surface size or estimated actuator loading.

4.1.2 Initial Sizing

Configuration C-01 represented the lower-bound geometry of the investigated design space. Based on the preliminary sizing approach described in Chapter 3, it combined the smaller chord ratio, $c_f/c = 0.25$, with the shortest investigated spanwise extent.

The flaperon extended from $\eta_{in} = 0.10$ to $\eta_{out} = 0.85$. For the wing span of 15.98 m, these locations correspond to $y_{in} = 0.799$ m and $y_{out} = 6.792$ m, giving a flaperon span of 5.993 m per side. The chord ratio of $c_f/c = 0.25$ placed the hinge line at $x_h/c = 0.75$.

The physical deflection envelope was $\pm 30^\circ$. At the approach condition, the flaperons were deployed symmetrically by 20° for the high-lift function, while differential motion was applied about this nominal setting for roll control. A small $\pm 2^\circ$ perturbation was used for extraction of the differential control derivatives.

C-01 produced $p_{ss} = 31.357$ deg/s, $t_{30} = 1.049$ s, $\Delta C_L = 0.788$, and an adverse-yaw ratio of 0.052, satisfying all four preliminary screening criteria. The roll-damping derivative was $C_{l_p} = -0.63434$, indicating that the expected stabilizing roll-damping tendency was retained.

Although C-01 was feasible, it represented the smallest investigated control surface and produced the lowest steady-state roll rate among the six candidates. The geometry was therefore extended farther outboard to evaluate whether additional roll authority could be obtained without introducing excessive design penalties.

4.1.3 Design Iterations and Explorations

The first geometric variation retained $c_f/c = 0.25$ while progressively increasing the outboard spanwise location. C-02 extended to $\eta_{out} = 0.90$, increasing the flaperon span from 5.993 m to 6.392 m per side. This increased p_{ss} from 31.357 deg/s to 34.754 deg/s and reduced t_{30} from 1.049 s to 0.956 s, while the surface area increased from 19.169% to 20.018% of the wing area.

The span was extended further for C-03 to $\eta_{out} = 0.95$, corresponding to 6.792 m per side. The resulting steady-state roll rate increased to 37.734 deg/s and t_{30} decreased to 0.889 s. However, the flaperon area increased to 20.813% of the wing

area, while the adverse-yaw ratio and estimated balanced hinge moment increased to 0.097 and 38.322 N m, respectively.

The geometric progression of the investigated configurations is illustrated in Figure 4.1.

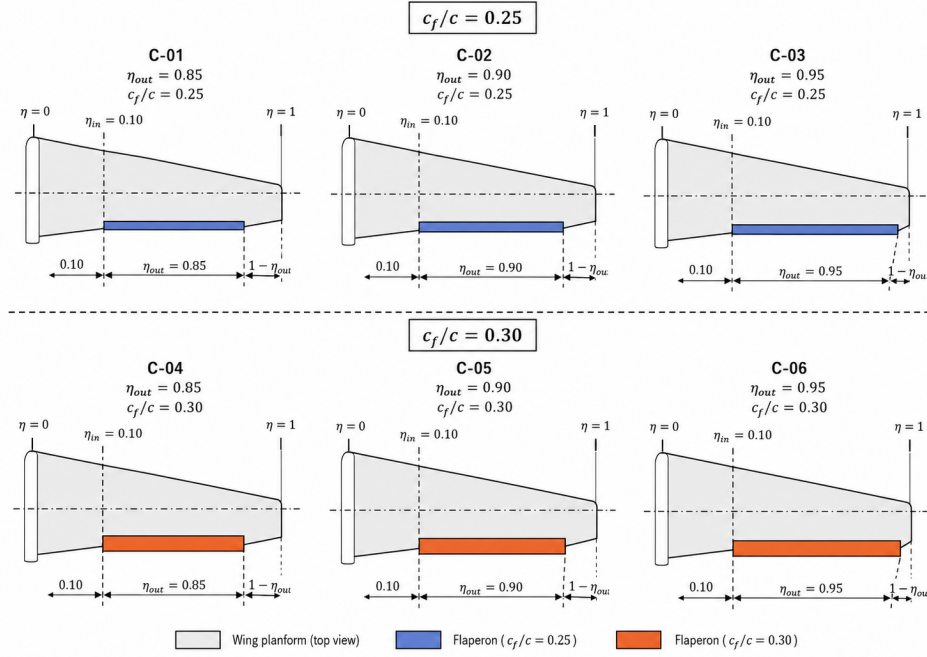


FIGURE 4.1: Evolution of the investigated flaperon sizing configurations. C-01 to C-03 use $c_f/c = 0.25$, while C-04 to C-06 use $c_f/c = 0.30$.

A second design branch, consisting of C-04 to C-06, used the same three spanwise locations with the larger chord ratio $c_f/c = 0.30$. Increasing the chord raised the steady-state roll rate to 35.169 deg/s, 38.981 deg/s, and 42.348 deg/s for C-04, C-05, and C-06, respectively. However, the corresponding flaperon area increased to between 23.002% and 24.976% of the wing area, while the estimated balanced hinge moments increased to between 53.047 and 55.185 N m.

The complete comparison of the six configurations is presented in Table 4.1.

All six configurations satisfied the adopted preliminary screening criteria, and C_{l_p} remained negative throughout the design matrix. Increasing either spanwise extent or chord ratio increased roll authority, but also increased the geometric and actuator-related penalties.

TABLE 4.1: Comparison of the investigated flaperon configurations at the approach condition.

ID	η_{out}	c_f/c	$ C_{l_{\delta a}} $ (rad^{-1})	C_{l_p}	p_{ss} (deg/s)	t_{30} (s)	ΔC_L	Adv. yaw	Area (%)	H_{bal50} (N m)	Screening
C-01	0.85	0.25	0.221	-0.63434	31.357	1.049	0.788	0.052	19.169	36.841	Pass
C-02	0.90	0.25	0.243	-0.62878	34.754	0.956	0.833	0.086	20.018	37.666	Pass
C-03	0.95	0.25	0.261	-0.62428	37.734	0.889	0.871	0.097	20.813	38.322	Pass
C-04	0.85	0.30	0.246	-0.63126	35.169	0.946	0.894	0.160	23.002	53.047	Pass
C-05	0.90	0.30	0.271	-0.62548	38.981	0.863	0.945	0.150	24.021	54.236	Pass
C-06	0.95	0.30	0.292	-0.62056	42.348	0.803	0.988	0.142	24.976	55.185	Pass

4.1.4 Pareto-Based Candidate Selection

All six Path B candidates satisfied the adopted hard constraints and were therefore retained for the final trade-off assessment. A Pareto analysis was conducted using flaperon area as the parameter to be minimized and steady-state roll rate, p_{ss} , as the parameter to be maximized. The estimated balanced hinge moment was included as an additional engineering indicator.

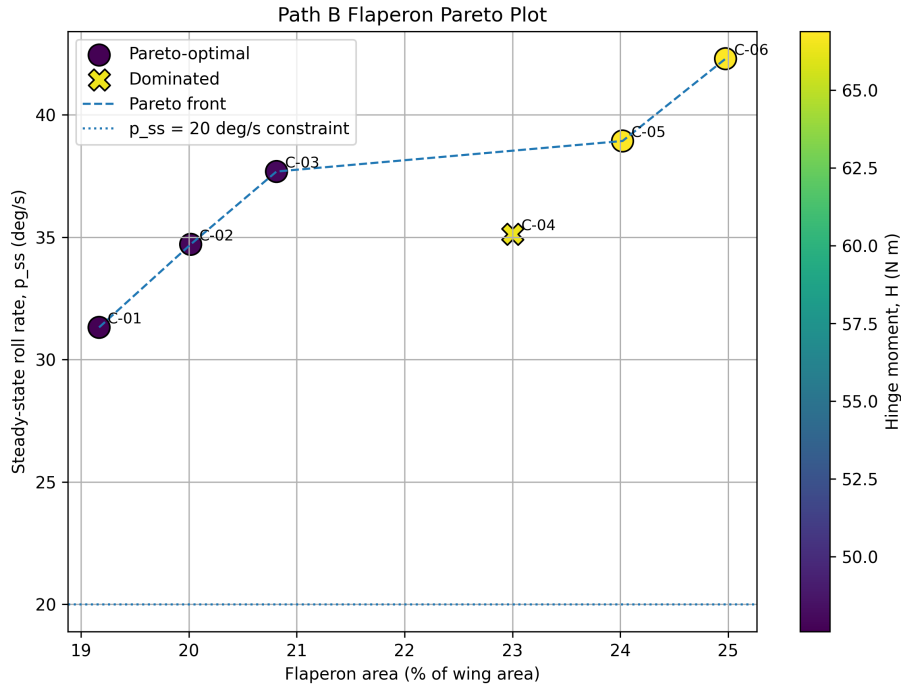


FIGURE 4.2: Pareto comparison of the Path B flaperon candidates based on flaperon area and steady-state roll rate, with the estimated balanced hinge moment indicated by the colour scale.

As shown in Figure 4.2, C-01, C-02, C-03, C-05, and C-06 form the Pareto-optimal set, while C-04 is dominated. C-04 provides a lower roll rate than C-03 despite having a larger flaperon area and higher estimated hinge moment.

Configuration C-02 was selected as the final design because it provides a balanced compromise between roll performance and design penalties. It achieves a steady-state roll rate of 34.754 deg/s, exceeding the adopted 20 deg/s minimum requirement, while occupying 20.018% of the wing area. Its estimated balanced hinge moment is 37.666 N m, and its adverse-yaw ratio is 0.086.

Although C-03 provides a higher roll rate of 37.734 deg/s, it also requires a larger flaperon area, higher estimated hinge moment, and slightly greater adverse-yaw ratio. The additional roll-rate capability was therefore not considered sufficient to justify these penalties. The detailed numerical data supporting the Pareto assessment are provided in Appendix E.1.

4.1.5 Final Design

Based on the screening and Pareto evaluation, C-02 was selected as the final flaperon configuration. Its final geometric parameters are summarized in Table 4.2.

TABLE 4.2: Final geometric parameters of the selected C-02 flaperon configuration.

Parameter	Final C-02 Design
Inboard spanwise location, η_{in}	0.10
Outboard spanwise location, η_{out}	0.90
Inboard physical location, y_{in}	0.799 m
Outboard physical location, y_{out}	7.191 m
Flaperon span per side, b_f	6.392 m
Chord ratio, c_f/c	0.25
Hinge-line position, x_h/c	0.75
Physical deflection limit	$\pm 30^\circ$
Symmetric approach setting	20°
Available differential motion at approach	$\pm 10^\circ$
Flaperon area per side	1.393 m ²
Total flaperon area	2.787 m ²
Flaperon area / wing area	20.018%

The selected flaperon extends from 10% to 90% of the wing semi-span and occupies the aft 25% of the local wing chord. Since the wing is tapered, $c_f/c = 0.25$ provides a more representative definition than a single dimensional chord value. The corresponding hinge line is located at $x_h/c = 0.75$.

At the approach condition, the 20° symmetric setting provides the high-lift function while retaining up to $\pm 10^\circ$ of differential motion per side within the physical $\pm 30^\circ$ deflection envelope.

The final C-02 geometry implemented in XFLR5 is shown in Figure 4.3.

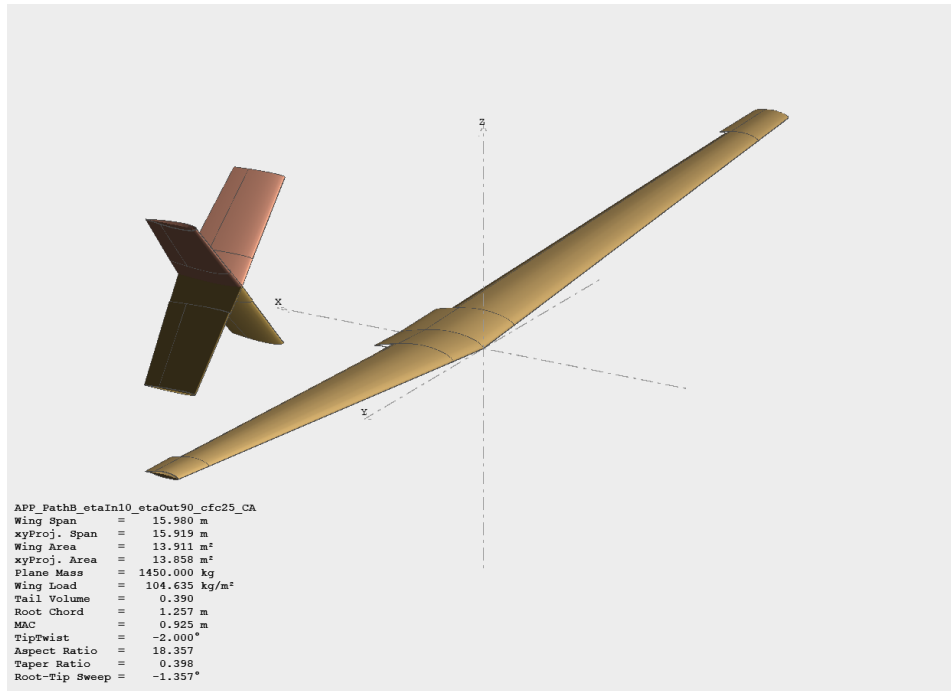


FIGURE 4.3: XFLR5 model incorporating the selected C-02 flaperon configuration.

C-02 was selected as a compromise between roll-control capability and the associated design penalties. It produced $p_{ss} = 34.754$ deg/s and $t_{30} = 0.956$ s, while $\Delta C_L = 0.833$ and the adverse-yaw ratio was 0.086. These values satisfied the preliminary flaperon criteria adopted in this study. Furthermore, $C_{l_p} = -0.62878$ indicated that the expected stabilizing roll-damping tendency was retained.

Although greater spanwise coverage or chord ratio produced higher roll rates, these configurations also required greater surface area and estimated hinge moment.

C-02 was therefore adopted as the final geometry and carried forward to the subsequent stability, control-performance, and verification analyses.

4.2 Stability Results

The stability assessment in this study is limited to the roll-related characteristics relevant to the selected C-02 flaperon configuration. Although XFLR5 Type 7 automatically provides complete longitudinal and lateral-directional stability outputs, only the derivatives and dynamic modes directly related to roll behaviour are reported here.

Three Type 7 cases corresponding to the three operating points such as approach (APP), cruise (CR), and loiter (LO) model definitions were evaluated. XFLR5 internally determined the zero-moment equilibrium condition and corresponding balancing speed for each Type 7 solution. The resulting equilibrium speed was 56.820 m/s for APP and 116.116 m/s for both CR and LO. The CR and LO Type 7 cases produced identical roll-related stability results.

4.2.1 Stability Derivatives

The principal stability derivatives retained for the flaperon assessment were the rolling-moment derivative with sideslip angle, C_{l_β} , and the roll-damping derivative, C_{l_p} . Their values for the final C-02 configuration are summarized in Table 4.3.

TABLE 4.3: Stability derivatives of the final C-02 configuration.

Parameter	APP	CR	LO
Rolling-moment derivative with sideslip angle, C_{l_β}	-0.07986	-0.09244	-0.09244
Roll-damping derivative, C_{l_p}	-0.62878	-0.64269	-0.64269

The derivative C_{l_β} remained negative in all three cases. According to the sign convention used in the analysis, this indicates that a sideslip disturbance generates a rolling-moment tendency opposing the associated lateral displacement.

The roll-damping derivative, C_{l_p} , was also negative for all cases. The APP condition produced $C_{l_p} = -0.62878$, while CR and LO produced $C_{l_p} = -0.64269$. The negative sign indicates that an existing roll rate generates an aerodynamic rolling

moment opposing the motion. Therefore, the selected C-02 configuration retained the expected stabilizing roll-damping tendency throughout the evaluated Type 7 cases.

4.2.2 Dynamic Stability

The lateral eigenvalue solutions from XFLR5 were used to evaluate the dynamic modes most directly relevant to roll behaviour. For the present flaperon study, the retained modes were roll subsidence and spiral motion. The corresponding eigenvalues are summarized in Table 4.4.

TABLE 4.4: Dynamic modes of the final C-02 configuration.

Case	Mode	Eigenvalue	Time Constant (s)	Status
APP	Roll subsidence	−16.590	0.060	Stable
APP	Spiral	+0.02911	34.35	Unstable
CR	Roll subsidence	−35.470	0.028	Stable
CR	Spiral	−0.0008524	1173.16	Stable
LO	Roll subsidence	−35.470	0.028	Stable
LO	Spiral	−0.0008524	1173.16	Stable

Roll-subsidence mode.

The roll-subsidence mode was represented by a negative real eigenvalue in all three cases. The APP case produced an eigenvalue of −16.590, corresponding to a time constant of approximately 0.060 s. The CR and LO cases produced an eigenvalue of −35.470, corresponding to a shorter time constant of approximately 0.028 s.

The negative eigenvalues indicate that a roll-rate disturbance decays without oscillation. Therefore, roll subsidence was stable for all three evaluated Type 7 cases.

Spiral mode.

The spiral mode showed different behaviour between APP and the CR/LO cases. For APP, the spiral eigenvalue was

$$\lambda_{\text{spiral}} = +0.02911,$$

which indicates a slowly divergent spiral response. The corresponding characteristic growth time is approximately 34.35 s, while the time required for the disturbance amplitude to double is approximately

$$t_2 = \frac{\ln 2}{0.02911} = 23.81 \text{ s.}$$

In contrast, the CR and LO cases produced

$$\lambda_{\text{spiral}} = -0.0008524,$$

indicating a very slowly convergent spiral response.

The roll-related dynamic assessment therefore showed stable roll subsidence in all three Type 7 cases, while the APP case exhibited a weak spiral instability. The significance of this spiral behaviour and its implication for the final flaperon design are discussed further in Section 4.5.

4.2.3 Dynamic Modes Characteristics

For the present flaperon study, the dynamic-mode assessment was limited to the modes directly associated with roll behaviour. Therefore, the roll-subsidence and spiral modes obtained from the XFLR5 Type 7 lateral eigenvalue solution are considered. The longitudinal modes and Dutch-roll mode are not discussed further because they are outside the roll-control scope of the present analysis.

Roll-subsidence mode.

The roll-subsidence mode was represented by a single negative real eigenvalue for all three analyzed cases. At APP, the eigenvalue was

$$\lambda_{\text{roll}} = -16.590,$$

corresponding to a roll-mode time constant of approximately

$$\tau_{\text{roll}} = \frac{1}{|\lambda_{\text{roll}}|} = 0.060 \text{ s.}$$

For CR and LO, the eigenvalue was

$$\lambda_{\text{roll}} = -35.470,$$

with a corresponding time constant of approximately 0.028 s.

The negative eigenvalues indicate that roll-rate disturbances decay without oscillation. Thus, the roll-subsidence mode was stable in all three Type 7 solutions. The shorter time constant obtained for CR and LO indicates a faster decay of the roll-rate disturbance than in the APP solution.

Spiral mode.

The spiral mode exhibited different behaviour between the APP and CR/LO solutions. At APP, the spiral eigenvalue was

$$\lambda_{\text{spiral}} = +0.02911.$$

Because the eigenvalue is positive, the spiral response is divergent. However, the small magnitude indicates that the divergence develops slowly. The corresponding time required for the disturbance amplitude to double is

$$t_{\text{double}} = \frac{\ln 2}{\lambda_{\text{spiral}}} = 23.81 \text{ s.}$$

For both CR and LO, the spiral eigenvalue was

$$\lambda_{\text{spiral}} = -0.0008524,$$

indicating a slowly convergent spiral response. The corresponding characteristic decay time was approximately 1173.16 s.

The roll-related modal results therefore show stable roll subsidence for all three operating point cases. The APP solution exhibited a weak spiral divergence, whereas the CR and LO solutions exhibited very slow spiral convergence. The acceptability and design implications of the APP spiral divergence are considered separately in the verification and discussion sections.

4.2.4 XFLR5 Roll-Stability Plot and Summary

The roll-related stability characteristics of the final C-02 configuration were evaluated from the lateral Type 7 stability solution. The corresponding roll-subsidence

and spiral-mode eigenvalues were presented previously in Table 4.4. Because the spiral mode was the only roll-related mode showing a positive eigenvalue, its location in the complex plane is shown in Figure 4.4.

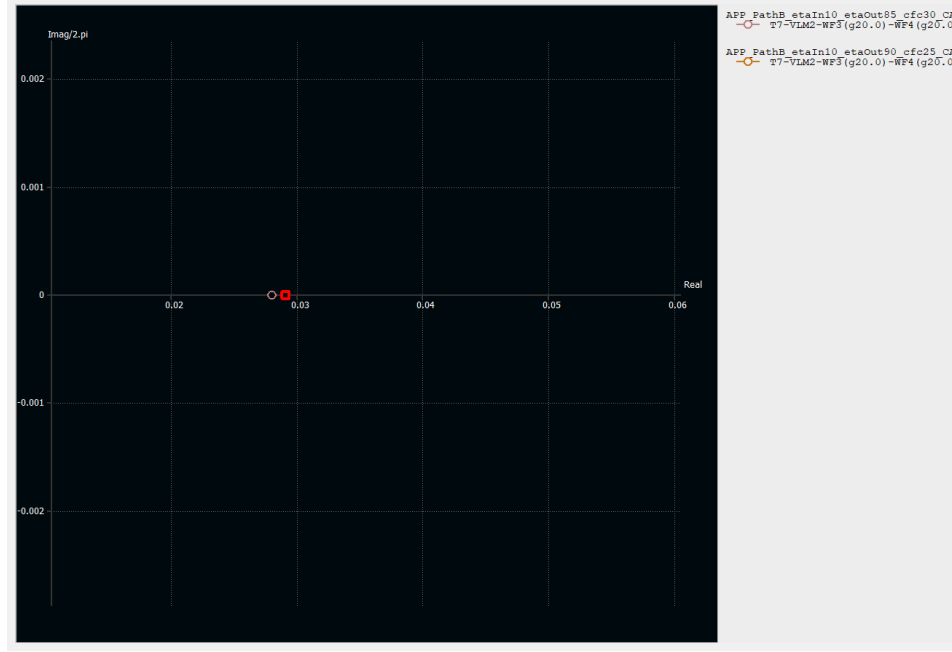


FIGURE 4.4: XFLR5 complex-plane representation of the spiral mode at the approach Type 7 condition, highlighting the final C-02 configuration.

As shown in Figure 4.4, the spiral eigenvalue of the final C-02 configuration lies slightly on the positive side of the real axis. This is consistent with the APP eigenvalue of $\lambda_{\text{spiral}} = +0.02911$ obtained from the Type 7 analysis. The positive sign indicates a divergent spiral mode; however, the small magnitude of the eigenvalue means that the divergence develops slowly. The corresponding time to double the disturbance amplitude is approximately 23.81 s.

In contrast, the roll-subsidence mode remained stable in all evaluated cases. Its eigenvalue was negative for APP, CR, and LO, indicating that roll-rate disturbances decay with time. The roll-damping derivative, C_{l_p} , also remained negative in all three cases, supporting the same stabilizing roll-damping tendency.

For CR and LO, the spiral eigenvalue was slightly negative, $\lambda_{\text{spiral}} = -0.0008524$, corresponding to a very slowly convergent spiral response. Therefore, the only roll-related instability identified in the Type 7 results occurred at APP and consisted of a

weak, slowly divergent spiral mode.

According to the preliminary stability guidance adopted in this study, a slightly unstable spiral mode may remain acceptable when the divergence is sufficiently slow. The APP result is therefore not treated as an automatic rejection of the C-02 configuration. Instead, it is retained as an identified stability characteristic of the final design and is considered together with the roll-control performance and verification results presented in the following sections. Its broader implications are discussed further in Section 4.5.

4.3 Control Performance Results

The control-performance assessment of the final C-02 configuration was limited to the roll-control function of the flaperon. Accordingly, the primary control derivative considered in this section is the rolling-moment coefficient derivative with respect to differential flaperon deflection, $C_{l_{\delta_a}}$.

4.3.1 Control Derivative

The roll-control effectiveness of the selected C-02 configuration was quantified using $C_{l_{\delta_a}}$, which represents the change in rolling-moment coefficient produced by differential flaperon deflection. The values obtained for the evaluated operating cases are summarized in Table 4.5.

TABLE 4.5: Roll-control derivative of the final C-02 flaperon configuration.

Operating Case	$C_{l_{\delta_a}}$	Units
APP	-0.24250	rad ⁻¹
CR	-0.26213	rad ⁻¹
LO	-0.25768	rad ⁻¹

The negative sign of $C_{l_{\delta_a}}$ follows the adopted XFLR5 control-deflection and rolling-moment sign convention. For comparison of roll-control effectiveness, the magnitude of the derivative is therefore used.

For the APP case, the derivative was extracted using a small differential perturbation about the nominal 20° symmetric flaperon setting. This provided the local

rolling-moment response used for the subsequent roll-control performance assessment.

4.3.2 Roll-Control Effectiveness Analysis

The effectiveness of the final C-02 flaperon was evaluated from the rolling-moment response to differential flaperon deflection. The relevant quantity is the rolling-moment coefficient, C_l , whose variation with differential flaperon deflection provides a direct indication of the control authority generated by the surface.

For the approach condition, the derivative obtained previously was

$$C_{l_{\delta_a}} = -0.24250 \text{ rad}^{-1}.$$

The negative sign results from the adopted XFLR5 control-deflection and rolling-moment sign convention. Therefore, the magnitude of the derivative is used when assessing control effectiveness. This control effectiveness is used together with the aerodynamic roll-damping derivative to determine the achievable steady-state roll rate.

4.3.3 Roll-Rate Results

The achievable steady-state roll rate, p_{ss} , was evaluated for the final C-02 configuration at the approach, cruise, and loiter conditions. The results are summarized in Table 4.6.

TABLE 4.6: Steady-state roll-rate performance of the final C-02 configuration.

Operating Case	Required Rate (deg/s)	Achieved Rate (deg/s)	Margin (%)	Status
Approach	20	34.754	+73.8	Pass
Cruise	–	36.754	–	Additional check
Loiter	–	30.108	–	Additional check

At the primary approach sizing condition, C-02 achieved $p_{ss} = 34.754 \text{ deg/s}$, corresponding to a 73.8% margin above the adopted minimum requirement of 20 deg/s.

The cruise and loiter cases produced 36.754 deg/s and 30.108 deg/s, respectively. These cases were included as additional operating-condition checks because no separate minimum roll-rate criterion was specified for them in the adopted sizing requirements.

The approach result confirms that the selected C-02 flaperon provides sufficient roll authority relative to the adopted requirement. Roll authority was also retained in the additional cruise and loiter cases, with both conditions producing steady-state roll rates above 30 deg/s.

The relatively large approach margin should not be interpreted by itself as excessive control authority. The final configuration was selected through the preceding multi-objective comparison, in which increased roll performance was considered together with flaperon area, adverse-yaw tendency, and estimated hinge moment.

Control-effectiveness plot.

4.4 Verification Against Standards

The final C-02 configuration was compared with the roll-related requirements of 14 CFR Part 23 and STANAG 4671. The comparison uses the XFLR5 results and the final verification cases presented in the preceding sections. Since the present work is limited to preliminary numerical analysis, the assessment is reported as a standards-based verification rather than a certification demonstration.

4.4.1 14 CFR Part 23 Verification

The comparison with the applicable roll-related provisions of 14 CFR Part 23 is summarized in Table 4.7.

The nominal roll-control results support the controllability requirement for the operating cases considered. The lateral derivative also retained the required restoring tendency. However, the exact bank-reversal manoeuvre prescribed by Section 23.157 was not reproduced; therefore, direct compliance with that requirement is not claimed.

TABLE 4.7: 14 CFR Part 23 verification summary for the final C-02 configuration.

Reference	Requirement	C-02 Result	Assessment
§23.141 / §23.143	Controllable and manoeuvrable over the applicable flight conditions	$p_{ss} = 34.754$ deg/s (APP), 36.754 deg/s (CR), and 30.108 deg/s (LO). Corresponding t_{30} values were 0.956 , 0.907 , and 1.106 s.	Supported for analysed cases
§23.157(c)	At approach, reverse from a steady 30° bank through 60° within 4 s	APP result: $p_{ss} = 34.754$ deg/s and $t_{30} = 0.956$ s. The complete 60° reversal manoeuvre was not simulated.	Not directly verified
§23.177(b)	Positive lateral static-stability tendency	$C_{l_\beta} = -0.07986$ at APP and -0.09244 at CR/LO, indicating a restoring rolling-moment tendency under the adopted sign convention.	Consistent

4.4.2 STANAG 4671 Verification

The 1450 kg aircraft lies within the primary 150–20 000 kg applicability range stated by STANAG 4671. The roll-related comparison is summarized in Table 4.8.

The nominal C-02 configuration retained roll authority at all three operating conditions and maintained negative roll-damping derivatives. The additional off-design weight checks also remained within the adopted C_L -matching tolerance.

The principal limitations were identified in the degraded and dynamic cases. The APP Type 7 solution contained a weak spiral divergence, while the two single-flaperon failure cases produced roll rates slightly below the adopted 20 deg/s preliminary design floor. These failure cases were therefore classified as marginal in the final verification sheet.

Overall, the C-02 configuration satisfies the preliminary roll-control criteria adopted in this thesis and provides results consistent with the relevant controllability and lateral-stability provisions within the analysed conditions. Direct certification compliance is not claimed where the prescribed regulatory manoeuvre, complete flight envelope, FCS augmentation, or flight-test demonstration was not performed.

TABLE 4.8: STANAG 4671 verification summary for the final C-02 configuration.

Reference	Requirement	C-02 Result	Assessment
USAR.141	Flight characteristics evaluated over relevant loading and operating conditions	APP, CR, and LO were evaluated. Additional weight cases of 1305, 1450, and 1595 kg gave C_L errors of -0.02079 , -0.00121 , and $+0.01706$, respectively.	Partial coverage
USAR.143	Safe controllability and manoeuvrability through relevant flight phases	$p_{ss} = 34.754$, 36.754 , and 30.108 deg/s for APP, CR, and LO, respectively.	Supported for analysed cases
USAR.171	Stability including degraded modes of the flight-control system	$C_{l_p} = -0.62878$ at APP and -0.64269 at CR/LO; roll subsidence was stable in all cases. APP spiral: $\lambda = +0.02911$ with $t_{\text{double}} = 23.81$ s. Single-flaperon failure cases produced $p_{ss} = 17.596$ and 19.740 deg/s.	Partial / marginal

4.5 Discussion

The preceding sections presented the sizing, stability, control-performance, off-design verification, and standards-based assessment of the final C-02 flaperon configuration. This section interprets those results in relation to the roll-control objectives of the present study. The discussion is limited to the flaperon and therefore does not extend the conclusions to pitch control, yaw control, or X-tail ruddervator performance.

4.5.1 Interpretation of Roll-Stability Results

The final C-02 configuration retained the expected restoring and damping tendencies associated with roll motion. The rolling-moment derivative with sideslip, C_{l_β} , remained negative for all evaluated Type 7 solutions, while the roll-damping derivative, C_{l_p} , ranged from -0.62878 at APP to -0.64269 at CR and LO. The signs of these derivatives indicate that the aerodynamic response acts against the corresponding lateral disturbance and roll rate.

The magnitude of the roll damping did not result in an excessively sluggish roll response. At the approach sizing condition, C-02 still achieved a steady-state roll rate of 34.754 deg/s with $t_{30} = 0.956$ s. This indicates that the selected geometry retains substantial commanded roll authority while maintaining aerodynamic roll damping.

The roll-subsidence mode was stable in all three Type 7 solutions, with time constants of approximately 0.060 s at APP and 0.028 s at CR and LO. Consequently, roll-rate disturbances decay rapidly once the disturbing input is removed. This characteristic is favourable for a long-endurance UAV because persistent uncommanded roll motion would otherwise require continuous corrective control input.

The main roll-related stability concern was the APP spiral mode. Its positive eigenvalue,

$$\lambda_{\text{spiral}} = +0.02911,$$

corresponded to a disturbance-amplitude doubling time of approximately 23.81 s.

The instability therefore develops slowly rather than as a rapid divergence. According to the preliminary stability guidance adopted in this study, a weak spiral instability may remain acceptable when the divergence develops sufficiently slowly. The result was therefore not treated as a rejection criterion for C-02.

The spiral behaviour is nevertheless relevant to future automatic-flight control. The rapid decay of roll subsidence and much slower growth of the spiral mode indicate that the two phenomena occur on substantially different time scales. A future autopilot would therefore be expected to provide longer-term bank-angle correction against the spiral tendency. However, no stability-augmentation or closed-loop autopilot model was included in the present work, and its ability to suppress the spiral mode cannot be concluded from the present analysis.

It should also be noted that the Type 7 stability solutions did not retain the nominal mission speeds used in the Type 1 analysis. XFLR5 internally determined equilibrium speeds of 56.820 m/s for APP and 116.116 m/s for CR and LO. The modal results therefore represent the corresponding XFLR5 equilibrium solutions and should not be interpreted as direct dynamic-stability verification at the nominal 36 m/s APP/CR and 30 m/s LO conditions.

4.5.2 Interpretation of Roll-Control Results

The final configuration provided more than the minimum roll authority required by the adopted sizing criterion. At APP, $p_{ss} = 34.754$ deg/s exceeded the minimum 20 deg/s requirement by 73.8%, while the corresponding $t_{30} = 0.956$ s was well below the adopted 2.5 s limit. Roll authority was also retained in the additional CR and LO cases, where p_{ss} was 36.754 deg/s and 30.108 deg/s, respectively.

The preliminary design guidance used in Chapter 3 places the typical roll-rate target in the range of approximately 20–30 deg/s. The APP result therefore lies above the upper end of this nominal design range. This was not treated as a failure, because the 30 deg/s value was not imposed as a hard maximum criterion. Nevertheless, it confirms that the final geometry contains a substantial roll-control reserve rather than merely satisfying the minimum requirement.

The available control margin should not be considered independently from the geometry-selection process. C-02 was not the candidate with the largest roll authority. C-03, C-05, and C-06 all generated higher steady-state roll rates, with

C-06 reaching 42.348 deg/s. These configurations were not selected because the additional performance was accompanied by increases in flaperon area, hinge-moment estimate, or adverse-yaw tendency. The final roll authority was therefore intentionally obtained through a compromise rather than by maximizing p_{ss} .

The differential-control results also indicate that roll commands produce only a limited adverse-yaw contribution within the investigated model. For C-02 at APP,

$$\left| \frac{C_{n_{\delta a}}}{C_{l_{\delta a}}} \right| = 0.086,$$

which is below the adopted upper limit of 0.20. This result indicates that the yawing-moment response generated by differential flaperon deflection is small relative to the available rolling moment. It should not, however, be interpreted as verification of yaw-control capability, because the ruddervator and X-tail yaw-control system were not analysed in the completed scope.

The dual function of the flaperon was also demonstrated at approach. A symmetric 20° deployment generated

$$\Delta C_L = 0.833,$$

which exceeded the adopted minimum of 0.60. The same condition produced $\Delta C_D = 0.06024$ and $\Delta C_m = -0.24280$. Therefore, the increase in approach lift is accompanied by additional drag and a change in pitching moment. The pitching-moment effect is reported here only as an aerodynamic consequence of flaperon deployment; the corresponding ruddervator trim requirement was not evaluated in the final scope.

The independent Method 2 check further supports the nominal roll-rate prediction. For C-02, Method 2 predicted $p_{ss} = 34.385$ deg/s compared with the XFLR5-based value of 34.754 deg/s, a difference of approximately 1.07%. The corresponding Method 2 and XFLR5 values of t_{30} were 0.952 s and 0.956 s, respectively. Although the Method 2 and XFLR5 control derivatives use different differential-deflection conventions, the close agreement in the resulting roll-rate prediction provides a useful independent consistency check.

The final verification cases indicate that the nominal result is also reasonably robust within the limited off-design range considered. The 1305, 1450, and 1595 kg

cases, together with the $\rho = 0.98$ and 1.47 kg/m^3 density cases, all remained within the adopted ± 0.03 lift-coefficient matching tolerance. However, the single-flaperon failure checks gave a less favourable result. Residual roll rates decreased to 17.596 deg/s and 19.740 deg/s , both slightly below the 20 deg/s preliminary floor. The degraded cases were therefore classified as marginal. This indicates that the nominal configuration has adequate control margin, but failure tolerance remains an area requiring further development.

4.5.3 Design Trade-offs and Actuator Implications

Following the nominal performance assessment, the final C-02 configuration was subjected to additional verification cases to examine its sensitivity to changes in operating condition and to a degraded single-flaperon condition. The verification included off-design mass, off-design density, an independent Method 2 cross-check, and single-flaperon failure cases.

Off-design mass and density checks.

The off-design aerodynamic checks are summarized in Table 4.9. The required lift coefficient for each case was compared with the corresponding XFLR5 result using the adopted tolerance of $|\Delta C_L| \leq 0.03$.

TABLE 4.9: Off-design verification of the final C-02 configuration.

Verification Case	Mass (kg)	ρ (kg/m^3)	α ($^\circ$)	$C_{L,\text{req}}$	$C_{L,\text{XFLR5}}$	C_L Error
Light mass	1305	1.225	-1.0	1.158	1.13721	-0.02079
Baseline mass	1450	1.225	0.5	1.287	1.28579	-0.00121
Heavy mass	1595	1.225	2.0	1.416	1.43306	+0.01706
Low density	1450	0.980	4.0	1.609	1.62705	+0.01805
High density	1450	1.470	-1.5	1.073	1.08742	+0.01442

All five cases remained within the adopted ± 0.03 lift-coefficient matching tolerance. The largest absolute error was 0.02079 in the light mass case. Within the investigated range, the selected C-02 geometry therefore retained a consistent aerodynamic solution under the imposed mass and density variations.

Independent roll-performance cross-check.

The final nominal roll result was also compared with the simplified Method 2 calculation. The comparison is presented in Table 4.10.

TABLE 4.10: Method 2 cross-check of the final C-02 roll-performance result.

Parameter	Method 2	XFLR5-based Result	Difference
$ C_{l_{\delta q}} $ (rad ⁻¹)	0.562	0.485	13.75%
p_{ss} (deg/s)	34.385	34.754	1.07%
t_{30} (s)	0.952	0.956	0.42%

The steady-state roll-rate predictions differed by only 1.07%, while the t_{30} predictions were also nearly identical. Although a larger difference was obtained for the control derivative, the roll-rate result remained well within the adopted 20% method-agreement criterion. This provides an independent check on the nominal roll-performance prediction.

Single-flaperon failure verification.

The most demanding verification involved loss of one flaperon while the opposite surface remained active. The resulting roll performance is summarized in Table 4.11.

TABLE 4.11: Single-flaperon failure verification of the final C-02 configuration.

Failure Case	WF3 (°)	WF4 (°)	C_{l_p}	p_{ss} (deg/s)	t_{30} (s)	Assessment
Left stuck / right active	0	+10	- 0.63997	17.596	1.796	Marginal
Right stuck / left active	-10	0	- 0.64119	19.740	1.611	Marginal

Both degraded cases retained negative C_{l_p} and therefore preserved the expected roll-damping tendency. However, the available steady-state roll rates decreased to 17.596 deg/s and 19.740 deg/s, respectively. These values are slightly below the preliminary 20 deg/s roll-rate floor, whereas both t_{30} values remained below the 2.5 s criterion. Consequently, both single-flaperon cases are classified as *marginal* rather than fully satisfactory.

For the right-stuck/left-active case, a trimmed solution at the commanded deflection could not be obtained in the corresponding Type 7 analysis; therefore, the

failure-case C_{l_p} was evaluated using the available reference condition. This limitation is retained in the interpretation of the result.

Overall verification outcome.

The final verification results are summarized in Table 4.12.

TABLE 4.12: Overall verification outcome for the final C-02 configuration.

Verification Item	Outcome
Nominal APP roll performance	Pass
Off-design mass variation	Pass
Off-design density variation	Pass
Method 2 cross-check	Pass
Left stuck / right active	Marginal
Right stuck / left active	Marginal
Overall C-02 verification	Marginal

The verification therefore distinguishes between nominal robustness and degraded-control capability. C-02 passed the nominal, off-design, and independent analytical checks, while the two single-flaperon failure cases were marginal. The final design is consequently considered satisfactory for the nominal preliminary roll-control objective, with degraded single-surface operation remaining an important limitation for subsequent flight-control and failure-management development.

4.5.4 Comparison with Design Guidance and Previous Work

The final results were compared with the preliminary analytical guidance used to establish the flaperon-design methodology in Chapter 3. This comparison was used as a consistency check rather than as an additional design requirement.

The six candidate configurations were first evaluated using the four hard constraints adopted in the design procedure: $p_{ss} \geq 20$ deg/s, $t_{30} \leq 2.5$ s, $\Delta C_L \geq 0.60$, and $|C_{n_{\delta_a}}/C_{l_{\delta_a}}| \leq 0.20$. All six candidates satisfied these constraints. Consequently, the hard constraints alone did not reduce the candidate set.

The subsequent Pareto analysis identified five of the six candidates as non-dominated, with only C-04 being dominated. The preliminary design guidance suggested that a six-candidate matrix would normally produce a smaller Pareto subset. The relatively large non-dominated set obtained in the present analysis therefore indicates

that the adopted hard constraints were not highly discriminating for this particular design matrix. Accordingly, Pareto membership alone was insufficient to determine the final configuration, and the selection of C-02 required consideration of surface area, adverse yaw, and estimated hinge moment in addition to roll rate.

A separate Method 2 sanity check was performed before accepting the XFLR5-based roll-performance results. The comparison for the selected C-02 configuration is summarized in Table 4.13.

TABLE 4.13: Comparison of the final C-02 results with the Method 2 preliminary design guidance.

Parameter	Method 2	XFLR5	Difference	Assessment
$ C_{l_{\delta_a}} $ (rad^{-1})	0.562	0.485	13.75%	Pass
C_{l_p}	0.737	0.629	14.66%	Pass
p_{ss} (deg/s)	34.385	34.754	1.07%	Pass
ΔC_L	0.405	0.833	105.52%	Outside expected range

For the roll-control derivative, Method 2 predicted $|C_{l_{\delta_a}}| = 0.562 \text{ rad}^{-1}$, compared with 0.485 rad^{-1} from the corresponding XFLR5 comparison convention. The difference of 13.75% remained within the adopted $\pm 20\%$ agreement limit. Similarly, the Method 2 estimate of $C_{l_p} = -0.737$ differed from the XFLR5 value of -0.62878 by approximately 14.66%, also remaining within the adopted agreement limit.

The resulting steady-state roll rates showed substantially closer agreement. Method 2 predicted $p_{ss} = 34.385 \text{ deg/s}$, while the XFLR5-based calculation produced 34.754 deg/s , corresponding to a difference of only 1.07%. The XFLR5 result also remained within the 25–50 deg/s range anticipated by the preliminary guidance for the investigated Path B configurations. This agreement provides confidence that the nominal roll-rate prediction is consistent with the analytical sizing method.

A different trend was obtained for the high-lift comparison. For C-02, Method 2 predicted $\Delta C_L = 0.405$, whereas XFLR5 produced $\Delta C_L = 0.833$. The XFLR5 increment was therefore approximately 105.5% greater than the candidate-specific Method 2 estimate and was outside the expected analytical-numerical comparison range. This discrepancy does not cause C-02 to fail the adopted hard constraint,

because the XFLR5 value remains above the required $\Delta C_L = 0.60$. However, it indicates that the simplified Method 2 high-lift estimate does not reproduce the magnitude of the XFLR5 result for the final configuration. The ΔC_L result should therefore be interpreted primarily from the XFLR5 analysis rather than as a closely validated analytical prediction.

The Method 2 comparison therefore provides strong agreement for the quantities governing roll performance, particularly $C_{l_{\delta a}}$, C_{l_p} , and p_{ss} , while showing substantially weaker agreement for the symmetric lift increment. This distinction is important because the primary objective of the present design is flaperon roll-control performance.

The present work also extends the previous aerodynamic and stability analysis of the same MALE UAV [8]. The earlier study established the baseline aircraft aerodynamic and stability characteristics, whereas the present work introduces systematic flaperon sizing, candidate screening, Pareto selection, and quantitative roll-performance verification. A direct numerical comparison with unrelated MALE UAVs is not made because equivalent flaperon geometry, deflection conventions, aircraft inertia, and operating conditions were not available in the reviewed references.

4.5.5 Limitations of the Design and Analysis

The conclusions of this study should be interpreted within the limitations of the preliminary design and numerical methodology.

The geometric exploration was limited to six candidates formed from two flaperon chord ratios and three outboard spanwise locations, while the inboard location was fixed at $\eta_{in} = 0.10$. C-02 is therefore the preferred configuration within the investigated design matrix and should not be interpreted as a mathematically optimized global solution.

The aerodynamic model was based on XFLR5 VLM2 with thin lifting surfaces. The method is most appropriate for predominantly attached-flow conditions and does not resolve strongly separated or highly nonlinear flow in the same manner as higher-fidelity CFD or experimental testing. Two-dimensional viscous polar data were used where valid coverage was available, but the three-dimensional model remains subject to the assumptions of the panel method.

The fuselage was not included in the aerodynamic model. Consequently, fuselage aerodynamic forces and moments, wing–fuselage interference, and detailed flow interaction with the aircraft body are not represented. The physical hinge gap and detailed local geometry of the flaperon were also not modelled.

Only a limited set of operating conditions was analysed. APP, CR, and LO were considered together with selected mass and density variations, but the complete aircraft flight envelope was not evaluated. In addition, the CR and LO aerodynamic analyses used the atmospheric properties specified in the completed model rather than a complete altitude-dependent mission atmosphere.

The Type 7 stability results have an additional limitation because XFLR5 internally determined its equilibrium speeds. As a result, the modal solutions did not correspond directly to the nominal fixed speeds used for the Type 1 control-performance analysis. The stability conclusions should therefore be regarded as modal tendencies of the Type 7 equilibrium solutions rather than full flight-envelope dynamic verification.

No structural or aeroelastic analysis of the final flaperon was performed. The study does not evaluate control-surface bending or torsion, hinge and bearing loads, wing structural reinforcement, flutter, control reversal, or structural mass penalties. This limitation is particularly important because the selected flaperon is long and the preliminary hinge-moment estimate is high.

Similarly, actuator dynamics and final actuator selection were not included. The hinge-moment estimates were used only for comparative ranking and are not actuator-grade values. No actuator mass, power consumption, response rate, gearing, linkage efficiency, redundancy, or thermal performance was calculated.

No CFD, wind-tunnel, or flight-test validation was conducted. The Method 2 cross-check provides an independent analytical comparison but does not replace experimental validation of the aerodynamic derivatives, hinge moments, or control response.

Finally, the completed analysis is limited to the flaperon and its roll function. Rudervator sizing, pitch-control authority, yaw-control authority, X-tail control mixing, and complete three-axis flight-control integration were not completed. Consequently, the present results should not be interpreted as verification of total aircraft controllability.

4.5.6 Practical Implications

From the perspective of continued UAV development, C-02 provides a useful preliminary aerodynamic definition for the wing control surface. Its geometry is now defined in terms of chord ratio, spanwise coverage, hinge location, surface area, and deflection limits, and its nominal roll performance has been verified across the investigated operating conditions. This provides a more mature starting point for detailed design than the unsized baseline control surface.

The aerodynamic results indicate that the selected flaperon can support the intended roll-control function at APP, CR, and LO. At approach, the surface simultaneously provides the required high-lift function while retaining differential roll authority. This is advantageous for the Path B concept because one physical surface performs both functions.

However, aerodynamic feasibility does not yet establish manufacturing or mechanical feasibility. The 6.392 m flaperon span per side and the high preliminary hinge-moment estimate make structural stiffness, hinge design, actuator installation, and aeroelastic behaviour important next-stage design considerations. The present study therefore supports continued development of C-02 but does not establish that the surface can be manufactured and actuated without further modification.

For mission performance, the retained roll authority indicates that the aircraft should have sufficient aerodynamic capability to generate bank commands at the analysed conditions. The APP lift increment is also beneficial for the low-speed operating condition. However, the associated $\Delta C_D = 0.06024$ indicates that symmetric flaperon deployment carries a drag penalty. Its effect on total approach performance or mission endurance was not quantified and should not be inferred from the present control-surface analysis alone.

The weak APP spiral divergence has a practical implication for autopilot integration. Because it develops over a much longer time scale than roll subsidence, it is a behaviour that may be manageable by a future closed-loop lateral controller. Similarly, the marginal single-flaperon failure results indicate that future flight-control logic should consider failure detection and control reallocation. These conclusions identify control-system requirements but do not demonstrate their implementation.

The next detailed-design stage should therefore retain the selected C-02 geometry as the aerodynamic baseline while addressing actuator-grade hinge moment, actuator architecture, structural and aeroelastic design, ruddervator sizing, integrated control mixing, and higher-fidelity aerodynamic validation. Wind-tunnel testing, CFD, and ultimately flight testing would then be required to confirm whether the predicted aerodynamic and control characteristics are maintained on the physical aircraft.

Overall, C-02 represents a balanced preliminary flaperon configuration rather than the configuration with maximum achievable roll authority. The final design provides substantial nominal roll-control margin, maintains the expected roll-damping tendency, produces the required high-lift increment, and limits adverse-yaw coupling relative to the adopted criterion. Its principal unresolved issues are the high estimated actuation demand, weak APP spiral divergence, and marginal residual control authority under a single-flaperon failure. These findings define the main priorities for the subsequent detailed-design phase.

CHAPTER 5

SUMMARY, CONCLUSION, RECOMMENDATION

5.1 Summary

This thesis addressed the design and analysis of a flaperon for the existing MALE UAV configuration. Although the baseline aircraft already incorporated a wing trailing-edge control surface, its geometry and resulting roll-control capability had not been systematically sized and verified.

The objectives of the study were to determine an appropriate flaperon geometry, evaluate its roll-control effectiveness and roll-related stability characteristics, assess its performance under selected off-design and degraded conditions, and compare the resulting design with the relevant provisions of 14 CFR Part 23 and STANAG 4671.

A preliminary heuristic sizing method was first used to establish the flaperon design space. Six Path B flaperon-only configurations were then investigated by varying the outboard spanwise location and chord ratio. The candidates were analysed in XFLR5 using VLM2, screened using the adopted roll-rate, roll-response, lift-increment, and adverse-yaw criteria, and subsequently compared using control-surface area, steady-state roll rate, adverse yaw, and estimated hinge moment. A Pareto-based comparison was used to support the final configuration selection. The selected configuration was then evaluated at approach, cruise, and loiter conditions, followed by off-design mass and density checks, an analytical Method 2 cross-check, and single-flaperon failure cases.

Configuration C-02 was selected as the final design. It used $\eta_{in} = 0.10$, $\eta_{out} = 0.90$, and $c_f/c = 0.25$, corresponding to a flaperon span of 6.392 m per side and a total flaperon area of 2.787 m², or 20.018% of the wing area. At the approach condition, C-02 achieved $p_{ss} = 34.754$ deg/s, $t_{30} = 0.956$ s, $\Delta C_L = 0.833$, and an adverse-yaw

ratio of 0.086, satisfying the four preliminary flaperon screening criteria. Cruise and loiter produced steady-state roll rates of 36.754 deg/s and 30.108 deg/s, respectively.

The roll-related stability analysis showed negative C_{l_β} and C_{l_p} values throughout the evaluated Type 7 solutions. Roll subsidence was stable in APP, CR, and LO. The APP case contained a weak spiral divergence with $\lambda_{\text{spiral}} = +0.02911$ and a disturbance-amplitude doubling time of approximately 23.81 s, while CR and LO showed very slow spiral convergence.

The additional verification showed that the investigated mass and density variations remained within the adopted lift-coefficient matching tolerance. Method 2 and the XFLR5-based roll-rate prediction differed by only 1.07% for C-02. In contrast, the two single-flaperon failure cases achieved residual roll rates of 17.596 deg/s and 19.740 deg/s and were classified as marginal. The standards-based assessment showed results consistent with several relevant roll-controllability and lateral-stability provisions of 14 CFR Part 23 and STANAG 4671 within the analysed conditions, although complete certification compliance was not demonstrated.

5.2 Conclusion

The conclusions of this study are stated according to the objectives of the flaperon design and analysis:

1. **Flaperon sizing.** The final flaperon design is configuration C-02, with $\eta_{\text{in}} = 0.10$, $\eta_{\text{out}} = 0.90$, and $c_f/c = 0.25$. The design provides a span of 6.392 m per side and occupies 20.018% of the total wing area. The Pareto assessment supports C-02 as a balanced configuration between roll authority and the associated surface-area, adverse-yaw, and hinge-moment penalties.
2. **Roll stability.** The final C-02 configuration retains the required aerodynamic roll-damping tendency, with $C_{l_p} < 0$ for APP, CR, and LO. The roll-subsidence mode is stable in all evaluated Type 7 cases. The APP condition contains a weak spiral divergence with a 23.81 s disturbance-amplitude doubling time, while the CR and LO spiral modes are slowly convergent.
3. **Roll-control effectiveness.** C-02 provides adequate roll-control authority. At Approach, the design achieves $p_{ss} = 34.754$ deg/s and $t_{30} = 0.956$ s, exceeding the adopted minimum 20 deg/s roll-rate requirement. Roll authority

is also retained at cruise and loiter, where the achieved rates are 36.754 deg/s and 30.108 deg/s, respectively.

4. **Flaperon high-lift and coupling performance.** The 20° symmetric approach deployment produces $\Delta C_L = 0.833$, exceeding the adopted minimum of 0.60. The adverse-yaw ratio of 0.086 remains below the adopted maximum of 0.20, showing that the selected flaperon provides the required roll and high-lift functions within the preliminary design criteria.
5. **Final design verification.** C-02 maintains acceptable aerodynamic performance over the investigated mass and density variations, and the Method 2 roll-rate prediction agrees with the XFLR5-based result within 1.07%. The single-flaperon failure cases are marginal, with residual roll rates of 17.596 deg/s and 19.740 deg/s, identifying degraded roll-control capability as a remaining design consideration.
6. **Standards-based verification.** The C-02 results were consistent with the relevant roll-control and lateral-stability provisions of 14 CFR Part 23 and STANAG 4671 within the analysed conditions. Full regulatory compliance was not demonstrated within the scope of this study.
7. **Overall design outcome.** C-02 provides a suitable preliminary aerodynamic flaperon design for the investigated MALE UAV. The aerodynamic control objective is achieved, while actuator loading remains the principal practical design issue because the preliminary hinge-moment assessment places the configuration in the high-torque category.

5.3 Recommendation

Based on the results and limitations of this study, the following recommendations are proposed for further development of the flaperon design.

Design Refinement

1. Conduct multi-point optimization of the flaperon geometry across a wider flight envelope to improve the balance between roll authority, surface area, adverse yaw, and aerodynamic efficiency.
2. Perform detailed structural and aeroelastic analysis of the flaperon, including stiffness, deformation, mass balancing, and flutter characteristics.

3. Refine the flaperon geometry, including chord ratio, spanwise coverage, and aerodynamic balance, to reduce the estimated hinge moment while maintaining the required roll-control performance.

Analysis Enhancement

4. Perform higher-fidelity CFD analysis to validate the XFLR5 results and investigate nonlinear flow, wing-fuselage interaction, and aerodynamic behaviour at larger flaperon deflections.
5. Extend the flaperon analysis to additional flight conditions, including climb, descent, turns, centre-of-gravity variations, and a wider range of atmospheric conditions.
6. Conduct time-domain flight-dynamics analysis to further evaluate the roll response and the operational significance of the weak spiral divergence identified at the approach condition.

Validation

7. Conduct wind-tunnel testing to experimentally verify the predicted lift increment, roll-control effectiveness, adverse-yaw behaviour, and hinge moment.
8. Perform prototype and flight-test validation after the aerodynamic and structural design has been sufficiently developed.

Manufacturing and Implementation

9. Perform actuator-grade hinge-moment analysis and select the flaperon actuation system based on the required torque, rate, bandwidth, power, and linkage characteristics.
10. Investigate actuator redundancy, failure detection, and control reallocation to improve the marginal roll-control performance observed in the single-flaperon failure cases.

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Appendices

APPENDIX A

FLAPERON CANDIDATE DATA

This appendix provides the supporting geometric and aerodynamic data for the six Path B flaperon candidates evaluated in this study. The inboard spanwise station was fixed at $\eta_{in} = 0.10$ for all candidates, while the outboard station and flaperon chord ratio were varied.

A.1 Candidate Geometry

TABLE A.1: Path B flaperon candidate geometry.

ID	η_{in}	η_{out}	c_f/c	x_h/c	b_f (m)	S_f/S (%)
C-01	0.10	0.85	0.25	0.75	5.993	19.169
C-02	0.10	0.90	0.25	0.75	6.392	20.018
C-03	0.10	0.95	0.25	0.75	6.792	20.813
C-04	0.10	0.85	0.30	0.70	5.993	23.002
C-05	0.10	0.90	0.30	0.70	6.392	24.021
C-06	0.10	0.95	0.30	0.70	6.792	24.976

The span b_f in Table A.1 represents the physical flaperon span on one side of the wing. The corresponding total flaperon areas of C-01 to C-06 were approximately 2.668, 2.787, 2.897, 3.202, 3.344, and 3.477 m², respectively.

A.2 Approach Control-Derivative Data

Table A.2 provides the raw differential control derivatives extracted at the approach condition.

TABLE A.2: Approach flaperon control-derivative data.

ID	$C_{l_{\delta_a}}$	$C_{n_{\delta_a}}$	$ C_{n_{\delta_a}}/C_{l_{\delta_a}} $	C_{l_p}
C-01	-0.22073	0.01146	0.0519	-0.63434
C-02	-0.24250	0.02077	0.0856	-0.62878
C-03	-0.26141	0.02535	0.0970	-0.62428
C-04	-0.24637	0.03939	0.1599	-0.63126
C-05	-0.27058	0.04068	0.1503	-0.62548
C-06	-0.29164	0.04140	0.1419	-0.62056

The derivatives in Table A.2 use the raw XFLR5 extraction convention based on the total left-right differential separation. The Method 2 comparison presented later uses the equivalent lecture-deck differential convention. Therefore, the numerical $C_{l_{\delta_a}}$ values from the two conventions should not be compared directly without applying the corresponding conversion.

A.3 Symmetric Flaperon Aerodynamic Data

The symmetric high-lift effect was obtained by comparing the 20° approach flaperon configuration with the corresponding undeployed configuration.

TABLE A.3: Approach aerodynamic increments due to symmetric flaperon deployment.

ID	ΔC_L	ΔC_D	ΔC_m
C-01	0.78814	0.06341	-0.23865
C-02	0.83270	0.06024	-0.24280
C-03	0.87054	0.05883	-0.24474
C-04	0.89422	0.07621	-0.25255
C-05	0.94478	0.07467	-0.25574
C-06	0.98756	0.07329	-0.25682

APPENDIX B

ROLL-PERFORMANCE AND CANDIDATE SCREENING

B.1 Roll-Performance Calculations

The calculated roll-performance quantities for the six candidates at the approach sizing condition are given in Table B.1.

TABLE B.1: Approach roll-performance results.

ID	C_{l_p}	p_{ss} (deg/s)	τ_R (s)	t_{30} (s)
C-01	-0.63434	31.357	0.0922	1.049
C-02	-0.62878	34.754	0.0931	0.956
C-03	-0.62428	37.734	0.0937	0.889
C-04	-0.63126	35.169	0.0927	0.946
C-05	-0.62548	38.981	0.0935	0.863
C-06	-0.62056	42.348	0.0943	0.803

B.2 Hard-Constraint Screening

The four hard constraints used for the preliminary screening were

$$p_{ss} \geq 20 \text{ deg/s}, \quad (\text{B.1})$$

$$t_{30} \leq 2.5 \text{ s}, \quad (\text{B.2})$$

$$\Delta C_L \geq 0.60, \quad (\text{B.3})$$

and

$$\left| \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} \right| \leq 0.20. \quad (\text{B.4})$$

The resulting screening is presented in Table B.2.

TABLE B.2: Hard-constraint screening of the six flaperon candidates.

ID	p_{ss}	t_{30}	ΔC_L	Adverse Yaw	Feasible
C-01	31.357	1.049	0.788	0.052	Yes
C-02	34.754	0.956	0.833	0.086	Yes
C-03	37.734	0.889	0.871	0.097	Yes
C-04	35.169	0.946	0.894	0.160	Yes
C-05	38.981	0.863	0.945	0.150	Yes
C-06	42.348	0.803	0.988	0.142	Yes

All six configurations satisfied the adopted hard constraints and were therefore retained for the subsequent trade-off assessment.

B.3 Pareto and Hinge-Moment Supporting Data

The supporting area, hinge-moment, and Pareto data are listed in Table B.3.

TABLE B.3: Supporting candidate-ranking and Pareto data.

ID	Area (%S)	$H_{\text{unbalanced}}$ (N m)	H_{bal50} (N m)	Pareto
C-01	19.169	73.682	36.841	Yes
C-02	20.018	75.331	37.666	Yes
C-03	20.813	76.643	38.322	Yes
C-04	23.002	106.094	53.047	No
C-05	24.021	108.471	54.236	Yes
C-06	24.976	110.370	55.185	Yes

The hinge-moment values in Table [B.3](#) are preliminary ranking estimates only and are not actuator-grade loads. C-04 was the only dominated candidate. C-02 was selected from the remaining candidates because it provided sufficient roll authority with lower area, estimated hinge moment, and adverse yaw than C-03, while the additional roll performance of C-03 was not considered sufficient to justify the associated penalties.

APPENDIX C

METHOD 2 CROSS-CHECK

Method 2 was used as an independent analytical sanity check of the XFLR5-based roll-performance calculations.

C.1 Roll-Control Comparison

TABLE C.1: Method 2 and XFLR5 roll-control comparison.

ID	$ C_{l_{\delta_a}} $			p_{ss}		
	M2	XFLR5	Diff. (%)	M2 (deg/s)	XFLR5 (deg/s)	Diff. (%)
C-01	0.516	0.441	14.51	31.576	31.357	0.70
C-02	0.562	0.485	13.75	34.385	34.754	1.07
C-03	0.608	0.523	13.98	37.166	37.734	1.53
C-04	0.570	0.493	13.53	34.848	35.169	0.92
C-05	0.621	0.541	12.80	37.947	38.981	2.72
C-06	0.671	0.583	13.04	41.017	42.348	3.25

All six $C_{l_{\delta_a}}$ comparisons remained within the adopted 20% agreement limit. The roll-rate predictions showed even closer agreement, with differences between approximately 0.70% and 3.25%.

For C-02, the Method 2 roll-damping estimate was

$$C_{l_p, M2} = -0.7368, \quad (C.1)$$

compared with

$$C_{l_p, XFLR5} = -0.62878, \quad (C.2)$$

corresponding to a difference of approximately 14.66%. The Method 2 and XFLR5 values of t_{30} were approximately 0.952 s and 0.956 s, respectively.

C.2 High-Lift Comparison

TABLE C.2: Method 2 and XFLR5 high-lift comparison.

ID	$\Delta C_{L,M2}$	$\Delta C_{L,XFLR5}$	Difference (%)	Assessment
C-01	0.376	0.788	109.88	Outside
C-02	0.405	0.833	105.52	Outside
C-03	0.433	0.871	101.22	Outside
C-04	0.397	0.894	125.35	Outside
C-05	0.430	0.945	119.83	Outside
C-06	0.460	0.988	114.61	Outside

The Method 2 high-lift estimates did not reproduce the magnitude of the XFLR5 ΔC_L results within the expected comparison range. Consequently, Method 2 was treated as a supporting analytical reference rather than a direct validation of the symmetric high-lift result.

APPENDIX D

FINAL C-02 VERIFICATION DATA

The selected C-02 geometry was subjected to additional off-design, analytical, and degraded-control verification.

D.1 Mass Variation

TABLE D.1: C-02 off-design mass verification.

Case	m (kg)	$C_{L,req}$	α (°)	$C_{L,XFLR5}$	$C_{L,error}$
Light	1305	1.158	-1.0	1.13721	-0.02079
Baseline	1450	1.287	0.5	1.28579	-0.00121
Heavy	1595	1.416	2.0	1.43306	0.01706

All three cases remained within the adopted

$$|C_{L,error}| \leq 0.03 \quad (D.1)$$

matching tolerance.

D.2 Density Variation

TABLE D.2: C-02 off-design density verification.

Case	ρ (kg/m ³)	$C_{L,req}$	α (°)	$C_{L,XFLR5}$	$C_{L,error}$
Low density	0.98	1.609	4.0	1.62705	0.01805
High density	1.47	1.073	-1.5	1.08742	0.01442

Both density cases remained within the adopted lift-coefficient matching tolerance.

D.3 Selected Method 2 Verification

TABLE D.3: Final C-02 Method 2 verification.

Parameter	Method 2	XFLR5	Assessment
$ C_{l_{\delta_a}} $	0.562	0.485	Pass
C_{l_p}	-0.7368	-0.62878	Pass
p_{ss} (deg/s)	34.385	34.754	Pass
t_{30} (s)	0.952	0.956	Pass

D.4 Single-Flaperon Failure Cases

TABLE D.4: C-02 single-flaperon failure verification.

Case	δ_L (°)	δ_R (°)	C_l	C_{l_p}	p_{ss} (deg/s)	t_{30} (s)	Result
Left stuck / right active	0	10	-0.04362	-0.63997	17.596	1.796	Marginal
Right stuck / left active	-10	0	-0.04903	-0.64119	19.740	1.611	Marginal

Both degraded-control cases remained slightly below the nominal 20 deg/s roll-rate floor and were therefore classified as marginal. For the right-stuck case, the active -10° condition could not provide the required XFLR5 equilibrium solution; consequently, the corresponding C_{l_p} value was obtained from the available reference stability case.

APPENDIX E

SUPPORTING ROLL-STABILITY DATA

The Type 7 stability analysis was used to obtain the roll-related derivatives and eigenvalues of the selected C-02 configuration.

TABLE E.1: Supporting Type 7 roll-stability results for C-02.

Case	V_{eq} (m/s)	$C_{l\beta}$	C_{lp}	λ_{roll}	λ_{spiral}	Spiral Characteristic
APP	56.820	-0.07986	-0.62878	-16.590	+0.02911	$t_2 = 23.81$ s
CR	116.116	-0.09244	-0.64269	-35.470	-0.0008524	$\tau = 1173.16$ s
LO	116.116	-0.09244	-0.64269	-35.470	-0.0008524	$\tau = 1173.16$ s

The corresponding roll-subsidence time constants were approximately 0.060 s for APP and 0.028 s for CR and LO. The APP spiral root was weakly divergent, whereas the CR and LO spiral roots were very slowly convergent.

The Type 7 equilibrium speeds reported in Table E.1 were determined internally by XFLR5. They therefore differ from the nominal Type 1 mission speeds and should not be interpreted as fixed-speed stability results at 36 m/s or 30 m/s.

E.1 Pareto Supporting Data

Table E.2 provides the numerical data used to construct the Pareto comparison of the six Path B flaperon candidates.

TABLE E.2: Supporting data for the Path B Pareto assessment.

Candidate	Area	p_{ss}	H_{bal50}	Adverse-Yaw Ratio	Pareto Status
	(%S)	(deg/s)	(N m)		
C-01	19.169	31.357	36.841	0.052	Optimal
C-02	20.018	34.754	37.666	0.086	Optimal
C-03	20.813	37.734	38.322	0.097	Optimal
C-04	23.002	35.169	53.047	0.160	Dominated
C-05	24.021	38.981	54.236	0.150	Optimal
C-06	24.976	42.348	55.185	0.142	Optimal

The Pareto assessment considered increasing steady-state roll rate and decreasing flaperon area as the primary objectives. Estimated hinge moment and adverse-yaw ratio were retained as additional engineering considerations during the final selection.

C-04 is dominated because C-03 provides a higher steady-state roll rate with lower flaperon area, lower estimated hinge moment, and lower adverse-yaw ratio. The remaining five candidates are non-dominated within the investigated design matrix.

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Curriculum Vitae



Basic Information	
Name	Regita Nandini
Place of Birth	Palembang, South Sumatra, Indonesia
Date of Birth	May 12, 2002
Address	Mayor Zen St. No.52, Palembang, South Sumatra, Indonesia, 30161
Year	Education
2022 – present	International University Liaison Indonesia (IULI)
2017 – 2020	Pusri Private Senior High School, Palembang, Indonesia
2014 – 2017	Public Junior High School 8, Palembang, Indonesia
2008 – 2014	Public Elementary School 185, Palembang, Indonesia
Year	Seminars & Workshops
2026	MATLAB Onramp
2025	Decoding The Black Box: Investigating with KNKT RI
2024	The Future of Flight with Fly-by-Wire
2024	Thermoelectrics of Low-Dimensional and Topological Materials
2023	F20 Recommendations to the G20
2023	Industrial Revolution and Air Transport Sector
Year	Organization Experiences
2024 – 2025	Director of HIMA AVE
2023 – 2024	Co-Director of HIMA AVE IULI
2023	External Affair Staff of Student Executive Board IULI
2023	External Affair Staff of HIMA AVE IULI
Year	Work Experiences

DESIGN AND ANALYSIS OF FLAPERONS FOR A MEDIUM ALTITUDE LONG
ENDURANCE UNMANNED AERIAL VEHICLE

2026 - Present	Math Teacher at Seriously Addictive Math BSD
2024 - Present	Self-employed Private Science Tutor
2024 - 2025	Private Tutor at Hope Private Course
2024	Liaison Officer at Jakarta Model United Nation
2023 - 2024	Private Tutor at Guma Private Course
2023	Registration Staff of Tradepass at IndoSec
2023	Event Staff of Girls on Track at 2023 Jakarta E-prix
2023	Liaison Officer at Youth Leader Camp
2019	Student Intern at Pupuk Sriwidjaja Company
