Design and Integration Study of a Single-Panel Krueger Flap with “Butterfly” Kinematics for HLFC Applications

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Abstract: *This study focuses on the mechanical design, kinematics and integration assessment of Krueger flap configurations developed for application on a Hybrid Laminar Flow Control (HLFC) Ground Based Demonstrator (GBD). Two high-lift flap geometries were initially explored: articulated “bull-nose” Krueger and a simplified single-panel configuration. Following a series of CAD analyses, the single-panel Krueger with a sharp leading edge was optimized, demonstrating favorable behavior while providing superior integration within the GBD framework. This configuration, coupled with a novel “butterfly” kinematic system, fulfills stringent geometric constraints without requiring modifications to the wing’s leading edge. Moreover, the design enables reliable sealing between the Krueger panel and the wing lower surface, ensuring operational robustness. The work encompasses design studies conducted using CATIA v5 environment. Additional attention was given to geometrical and operational constraints, including insect-shielding requirements, minimum chord dimensions, and stowage limitations, all while maintaining compatibility with suction-based laminar flow technologies. Both configurations—the bull-nose and the sharp leading edge Krueger—are presented, together with the kinematic design philosophy and results based on the space allocation into the wing leading edge . These results establish a practical framework for implementing advanced Krueger flap and kinematic concepts for hybrid laminar flow control technology.*

Key Words: *Hybrid Laminar Flow Control, High-lift device, Krueger flap, Kinematic actuation system*

1. INTRODUCTION

The aeronautical community has consistently pursued fuel-efficient and environmentally sustainable aircraft, a goal that has become increasingly urgent with the rapid growth of global air traffic and heightened environmental concerns. Key drivers for this trend include rising fuel costs, stricter emission regulations, and the need to mitigate aviation’s contribution to climate change [1]. To meet these challenges, research has focused not only on propulsion efficiency but also on aerodynamic optimization and noise reduction—two complementary directions in sustainable aviation development.

Recent studies emphasize that achieving low-emission, low-noise flight requires a multidisciplinary approach combining aerodynamics, structures, and advanced modeling tools. Deaconu et al. [2] analyzed in-cabin acoustic environments of the Puma 330 helicopter, demonstrating that aerodynamic and mechanical interactions play a crucial role in overall environmental comfort and highlighting the need for quieter aerodynamic surfaces. In parallel, Sterpu et al. [3] developed a hybrid deep learning framework for predicting aerodynamic coefficients from airfoil geometry, reinforcing the growing role of data-driven tools in optimizing aerodynamic design and enhancing laminar flow performance.

Within this context, **Hybrid Laminar Flow Control (HLFC)** technology remains one of the most promising aerodynamic strategies to improve efficiency and reduce emissions. HLFC has evolved over several decades, achieving higher levels of maturity in integration, safety, and maintainability [4]. The concept builds upon earlier **Laminar Flow Control (LFC)** research dating back to the 1930s, also referred to as *Artificial Laminar Flow (ALF)* to distinguish it from *Natural Laminar Flow (NLF)* [5]. LFC aims to extend laminar boundary-layer regions over large wing areas by extracting low-momentum air through micro-perforations in the surface, whereas HLFC combines NLF with localized suction near the leading edge, reducing the energy required to delay transition [6].However, these active systems also introduce design and operational challenges, including the need for power to maintain suction and the potential contamination of perforated surfaces by insects and particulates [7]. To counteract such effects, leading-edge Krueger flaps have been explored as protective devices for HLFC wings, acting as both *insect shields* and *high-lift devices*. In HLFC configurations, suction is generally applied at the leading edge of a swept wing to suppress contamination and crossflow instabilities, while optimized pressure distributions stabilize mid-chord Tollmien–Schlichting waves [8]. The feasibility of these concepts has been demonstrated in several major flight test programs, such as the Boeing 757 HLFC experiment (1990) and the Airbus A320 vertical tailplane test (1998) [9].

In this paper, the kinematic Krueger panel has been designed and analyzed to address the primary challenges while adhering to stringent geometric constraints [10]. The proposed butterfly mechanism ensures that the leading-edge skin remains uninterrupted when fully deployed, and although sealing solutions are still under investigation, several viable approaches have been identified.

While the configuration does not achieve the aerodynamic optimum, it represents a carefully considered compromise between aerodynamic performance and seamless integration within the demonstrator.

Structural integrity has been confirmed through detailed stress analyses on the main rods and lugs, and a comprehensive design sequence has been established to implement an effective sealing solution. Overall, this design approach demonstrates a balanced integration of mechanical functionality, structural reliability, and aerodynamic considerations. The aerodynamic performances and stress results will be subject to another paper.

2. INPUTS AND REQUIREMENTS

Starting from the geometrical constraints for the Krueger panel (minimum dimensions as percent of reference chord, insects shielding criteria) space allocation and integration of the Krueger flap into the Ground Base Demonstrator, two different versions for this flap were developed: “single” and “bull-nose” configuration. The work started with a "bull-nose" flap configuration knowing that the aerodynamic coefficients will be better than the single flap (because of the length of the chord) but after a series of computations and integration studies we develop single flap geometry, and as a consequence between this 2 variants, it was optimized the single Krueger Panel-Sharp Leading Edge Krueger– where the aerodynamic characterization is lower than the articulated bull-nose but is the best compromise from integration into the demonstrator point of view.

2.1 Concept Requirements and Functionalities

The Ground Based Demonstrator (GBD) was conceived to reproduce, as accurately as possible, the geometric and functional characteristics of a full-scale aircraft leading-edge configuration, while allowing experimental flexibility for research purposes. Its design had to reconcile two main objectives: on the one hand, to ensure a high level of representativeness relative to a serial production aircraft, and on the other, to integrate specific features required for testing and validation activities.

Given that the demonstrator was developed under a Research and Technology (R&T) framework, several adaptations were introduced to facilitate modularity, instrumentation, and access for measurement systems during ground and wind tunnel testing. The GBD integrates a hybrid configuration that replicates the structural, aerodynamic, and mechanical behaviors of a real leading-edge, while maintaining the capability to host various high-lift and hybrid laminar flow control (HLFC) systems.

The concept also needed to accommodate compatibility for integrating a fully functional high lift device –a Krueger panel in this case, also the wing ice protection systems (WIPS) and suction networks without compromising the aerodynamic contour or the mechanical structural behavior of the assembly.

2.2 GBD General Requirements

The general design requirements of the Ground Based Demonstrator aimed to ensure that the integrated systems reflected realistic operational conditions while maintaining experimental flexibility. The leading edge configuration was required to include a continuous suction surface, internal chambers, and structural ribs, ensuring uninterrupted suction flow along the span. Representative WIPS and suction subsystems were implemented with geometrically accurate dimensions and interface components, including simulated bleed air or electrical de-icing lines.

Geometric constraints were established to preserve the aerodynamic fidelity of the Krueger flap system. The Krueger device was required to have a minimum deployed chord length of approximately 11% of the local reference chord, while its stowed position could not extend forward more than 1% of the same reference. Moreover, mechanical segregation between movable and fixed components was enforced to prevent interference during deployment or retraction.

All actuation mechanisms and structural components were designed in compliance with the Engineering Configuration Models (ECMs), while their mechanical behavior had to align with the GBD justification documentation. These constraints ensured that the system could deliver representative aerodynamic and mechanical performance under realistic loading conditions.

2.3 Krueger Panel and Kinematics Requirements

The design of the Krueger flap system was primarily governed by the shielding and aerodynamic efficiency criteria established within the AFLoNext project [11]. The deployed Krueger panel not only contributes to lift augmentation but also acts as an insect shield, protecting the HLFC leading edge from contamination during takeoff and climb phases.

Kinematic optimization was performed to achieve smooth motion, adequate deployment angles, and minimal aerodynamic disturbance during actuation. The linkage geometry was defined to ensure a compact stowed position, sufficient rotation clearance, and stable aerodynamic loads in both stowed and deployed configurations.

Structural stiffness, load transfer paths, and hinge locations were optimized to ensure durability and mechanical reliability during repeated actuation cycles.

The aerodynamic contour continuity between the Krueger element and the main leading-edge surface was also considered critical, as any misalignment could negatively affect suction flow uniformity and laminarity on the HLFC surface. The final kinematic configuration provided an effective balance between mechanical simplicity, aerodynamic efficiency, and structural integrity.

2.4 Integration Requirements

The integration of all subsystems within the GBD followed a representative but pragmatic approach. Each component expected in a serial HLFC wing leading edge was included or simulated within the demonstrator, maintaining realistic geometric fidelity and interface positioning. Elements not directly under investigation, such as electrical motors, gear rotary actuators, and wiring harnesses, were represented through equivalent dummy components to ensure appropriate mass distribution and volume constraints (space allocation).

Particular attention was paid to the interfaces between the suction system, WIPS components, and the Krueger actuation assembly to avoid mutual interference and ensure adequate access for instrumentation. The integration process also required coordination of load paths and mechanical fixations to maintain the structural stiffness of the leading edge, especially in regions of high aerodynamic pressure.

Overall, the integration strategy aimed to reproduce the operational environment of a serial aircraft while preserving flexibility for future test configurations, instrumentation upgrades, and aerodynamic optimization campaigns.

3. CONCEPTS DISCUSSION: PRO VS CONS

The conceptual development of the Krueger flap within the Ground Based Demonstrator (GBD) aimed to identify a configuration that ensures a robust balance between aerodynamic efficiency, sealing effectiveness, and structural feasibility.

Two alternative configurations were analyzed: the *Bull Nose* concept (v1) and the *Sharp Leading Edge* concept (v2). Figure 1 presents the aerodynamic requirements that needs to be fulfilled with respect to shielding criteria and also geometric integration of the Krueger flap in the leading edge of the wing.

Figure 2 later illustrates a direct comparison between *Sharp Leading Edge* configuration, which was developed as an alternative to the *Bull Nose* solution to overcome sealing and kinematic limitations configurations in their retracted and deployed states.

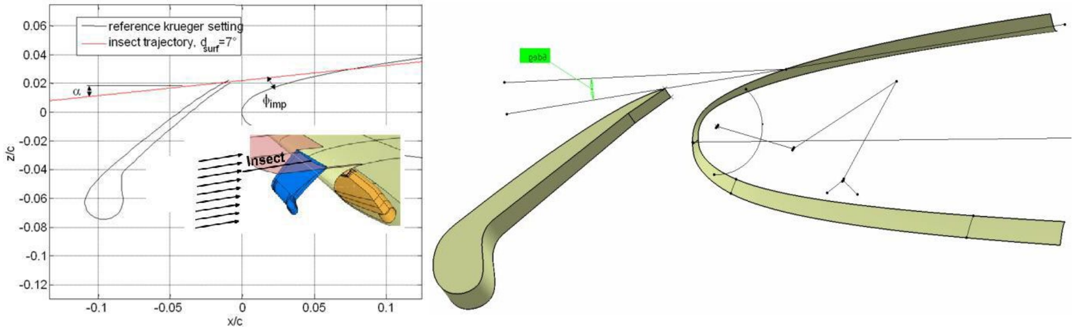

Figure 1. Kruger panel shielding and integration requirements

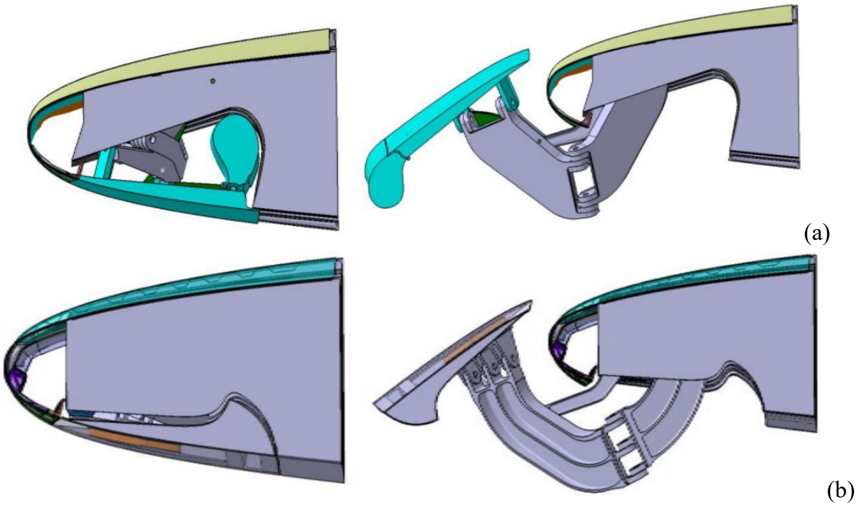

Figure 2. Bull-Nose- Concept (a) vs. Sharp Leading Edge Concept (b)
(retracted and extended positions)

3.1 Bull Nose Configuration

The *Bull Nose* Krueger flap represented the initial design approach, chosen primarily for its favorable aerodynamic performance and smooth leading-edge contour. Its rounded geometry enables gradual flow attachment and contributes to increased lift during high-incidence flight conditions. This configuration also benefits from an extended chord length, which allows for improved aerodynamic efficiency at moderate angles of attack.

However, as illustrated by the GBD integration studies, this concept also poses several practical challenges. The primary issue concerns **the sealing problem** between the Krueger panel and the fixed leading edge when stowed. Due to its larger geometric volume, the *Bull Nose* design requires additional space within the leading-edge structure, which complicates the arrangement of suction ducts and the HLFC chambers. Moreover, the associated kinematic system becomes more complex, requiring multiple linkages and a larger deployment envelope, which limits its mechanical robustness and integration feasibility. Although it demonstrates good aerodynamic potential, the *Bull Nose* configuration proved less suitable for the compact space available in the leading edge wing demonstrator and less effective in achieving reliable sealing during stowage.

3.2 Motivation for an Alternative Configuration

To mitigate the integration and sealing issues associated with the *Bull Nose* configuration, an alternative concept was investigated - the *Sharp Leading Edge* Krueger flap. The main motivation for this design evolution, shown in Figure 2, was to achieve a tighter aerodynamic seal in the stowed position while simplifying the mechanical layout and maintaining adequate aerodynamic behavior.

The refinement of the geometry was driven by three key requirements:

(1) The Krueger flap must have a **sharp leading edge** to ensure an effective seal against the fixed structure;

(2) No component should extend forward of this sharp contour, allowing unobstructed deployment; and

(3) The rear section must maintain a **minimum structural thickness of 3 mm** to ensure sufficient rigidity.

These constraints were derived from the kinematic and integration analyses performed within the AFLoNext project, aiming to provide a mechanically feasible and aerodynamically robust solution that could be implemented within the GBD envelope.

3.3 Sharp Leading Edge Configuration

The *Sharp Leading Edge* Krueger flap (v2) incorporates a simplified geometry with reduced curvature, allowing easier installation in the leading-edge region while preserving compatibility with suction and ice-protection systems. Compared to the *Bull Nose* design, this configuration enables improved sealing performance and a more compact mechanical layout. The reduced geometric volume minimizes interference with other internal components, leading to greater structural efficiency and lower actuation loads.

As seen in Figure 2, the retraction mechanism of the *Sharp Leading Edge* Krueger is smoother, with fewer moving elements, resulting in increased reliability and simplified maintenance. Despite its slightly lower aerodynamic efficiency due to the sharper contour, the design provides a realistic balance between aerodynamic function and mechanical feasibility, which is critical for the GBD's experimental objectives.

Numerical and experimental studies confirmed that the *Sharp Leading Edge* configuration maintains adequate flow uniformity in the HLFC region and stable aerodynamic performance, validating its selection as the baseline configuration for subsequent testing.

As a conclusion, while the *Bull Nose* Krueger concept demonstrates aerodynamic advantages, its complex integration and sealing challenges limit its applicability within the Ground Based Demonstrator framework. Conversely, the *Sharp Leading Edge* concept provides a practical and balanced solution, combining simplified mechanics with reliable sealing and structural efficiency.This comparative assessment highlights the trade-off between aerodynamic refinement and system integration—a fundamental consideration in the design of high-lift devices for hybrid laminar flow control application

4. KRUEGER KINEMATICS - DESIGN AND INTEGRATION STUDY

The kinematic design of the Krueger flap system within the Ground Based Demonstrator (GBD) was aimed at achieving reliable deployment and retraction sequences while ensuring mechanical simplicity, compactness, and integration compatibility with the HLFC (Hybrid Laminar Flow Control) leading-edge structure. The kinematic system was conceived to reproduce, as accurately as possible, the behavior of a full-scale aircraft mechanism under realistic geometric and structural constraints.

4.1 Concept philosophy

The proposed kinematic configuration, known as the **"butterfly mechanism"**, was designed to provide controlled motion with minimal linkage complexity and consistent force transmission throughout the deployment cycle.

The concept is based on two symmetrical pairs of lugs serving as hinge points for each axis, a central **drive shaft**, two **geared rotary actuators (GRA)**, and an **electric motor** responsible for synchronized motion. The actuators are coupled via the drive shaft to ensure simultaneous deployment across the span wise sections of the Krueger panel.

This architecture enables a compact, modular layout suitable for integration within the limited space available in the GBD's leading edge. The design philosophy emphasizes mechanical efficiency, ease of maintenance, and consistent load transmission between the actuators, lever arms, and the Krueger structure.

Figure 3 illustrates the overall configuration of the Krueger mechanism, showing both the retracted and deflected positions in an axonometric view, highlighting the compactness and symmetry of the system.

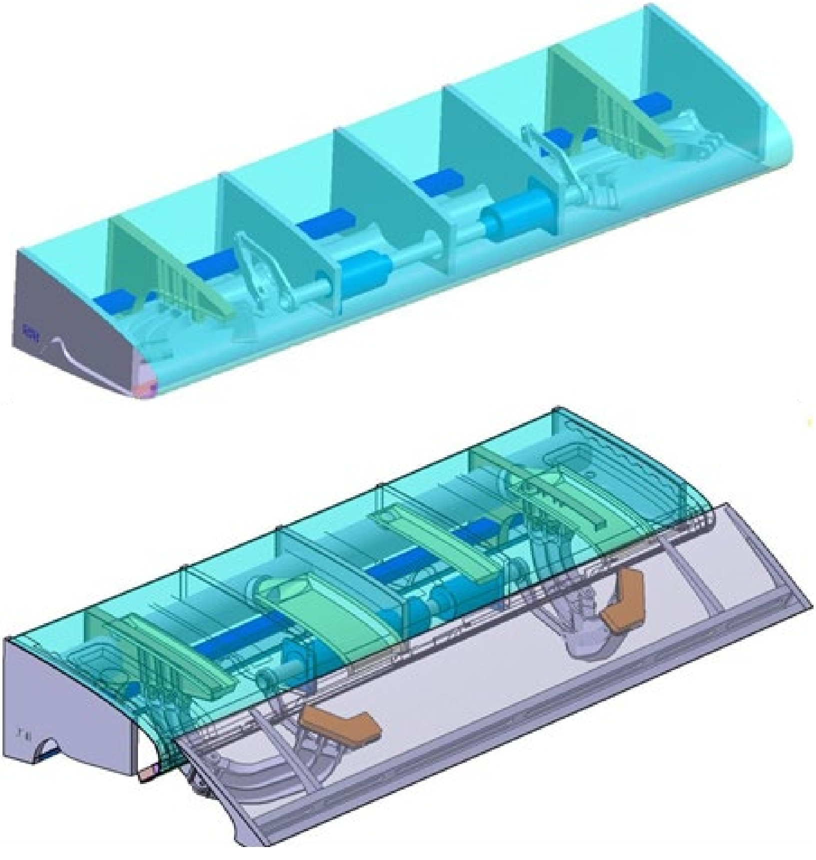

Figure 3. Krueger Flap and "Butterfly" Mechanism –
Retracted-Deflected Position Axonometric view

4.2 Description and Philosophy of the kinematic chain

The kinematic chain transmits actuation forces from the motorized system to the Krueger flap through a coordinated motion of linked components. As shown in **Figure 4**, the rotary actuators are connected to a main drive shaft that supports two **articulated lever arms**, which in turn drive the Krueger panel rotation.

Each lever is mounted on a pair of **lugs** that define the axis of rotation and ensure the correct deployment trajectory.

The *butterfly* configuration enables a smooth and simultaneous movement of the entire Krueger flap, ensuring a consistent deployment angle and avoiding asymmetrical stresses during operation. The design also minimizes backlash and mechanical hysteresis—critical aspects for precise aerodynamic testing.

Figure 4 presents the internal architecture of the mechanism, where the actuators, levers, and ribs are integrated in a compact and modular arrangement suitable for instrumentation and structural monitoring.

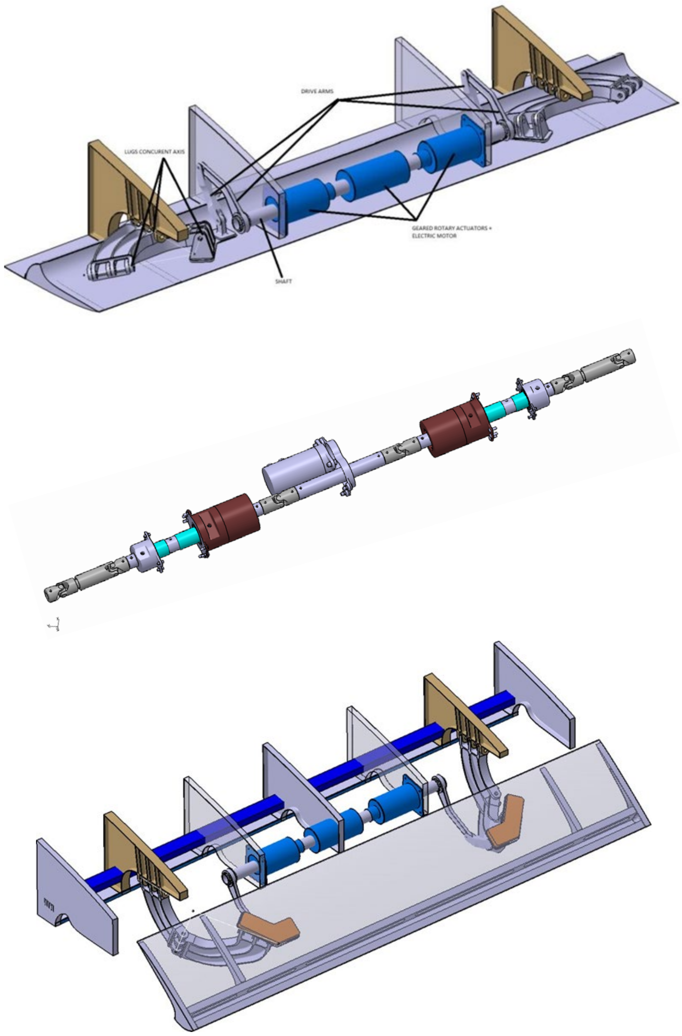

Figure 4. “Butterfly” mechanism, actuation chain (detailed) and Krueger flap
Internal structure. Axonometric view

4.3 Mechanism Integration and Structural Layout

Integration of the kinematic chain into the Krueger panel required detailed coordination between structural stiffness, aerodynamic contouring, and space management. **Figure 5** shows a side view of the Krueger panel, highlighting the spatial distribution of the actuators and the linkage system relative to the aerodynamic surface.

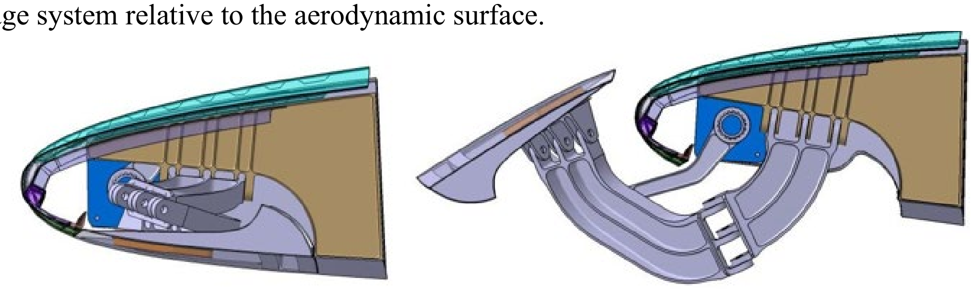

Figure 5. Krueger Panel –Retracted and Deployed positions

In the **axonometric representation** of **Figure 6**, the arrangement of the mechanical components demonstrates the precise alignment between the structural ribs and the hinge axes, essential for maintaining geometric accuracy during repeated deployment cycles.

The internal configuration was designed to ensure adequate load transfer between the panel skin and internal frames, limiting deformations that could impact aerodynamic smoothness. The integration also accounted for thermal and vibrational loads that might occur during experimental runs, ensuring long-term mechanical stability.

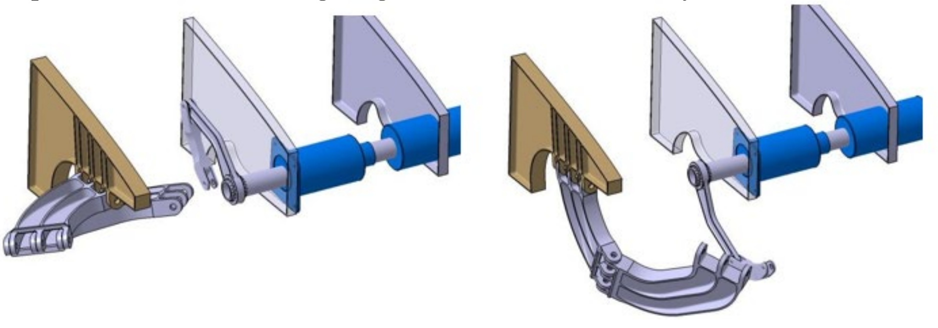

Figure 6. "Butterfly" kinematic mechanism – Retracted and Deployed positions
Axonometric view

4.4 Sealing and Interface with the Leading Edge

One of the critical design aspects for the Krueger flap integration within the GBD was the sealing between the movable panel and the fixed leading-edge surface. Proper sealing is essential to maintain laminarity in the HLFC region and prevent flow leakage that could compromise suction performance.

As shown in **Figure 7**, a detailed view of the sealing interface reveals the tight geometric tolerance between the Krueger's trailing edge and the fixed structure. The design employs a **sharp leading-edge contour** to improve sealing performance, in accordance with the configuration discussed in Section 3.

Additionally, the interface with the GBD's structural frame was carefully evaluated to avoid interference between the sealing lip and the suction duct system. The optimization of this interface represents a key advancement toward the realistic replication of full-scale high-lift systems in research demonstrators.

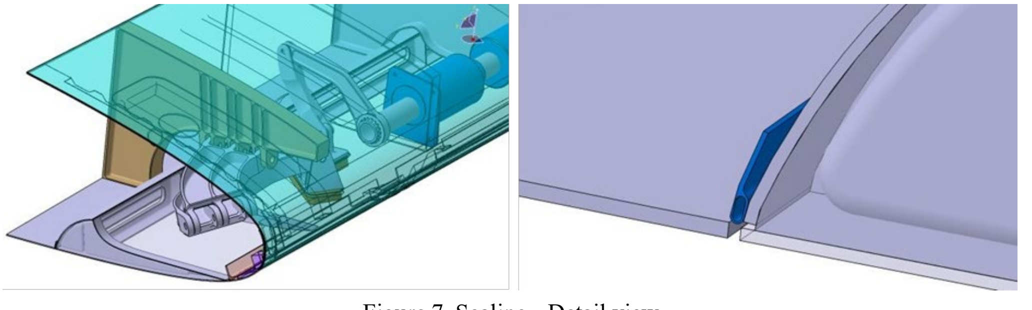

Figure 7. Sealing - Detail view

Beyond the sealing detail, the integration of the Krueger system within the full GBD leading-edge structure is illustrated in the figure 8.

This view highlights the interaction between the flap mechanism, the internal ribs, and the suction system components, offering a realistic representation of the final installation environment.

The configuration demonstrates the spatial constraints and the precision required to accommodate the kinematic assembly within the HLFC-equipped leading edge, ensuring both mechanical functionality and aerodynamic surface continuity.

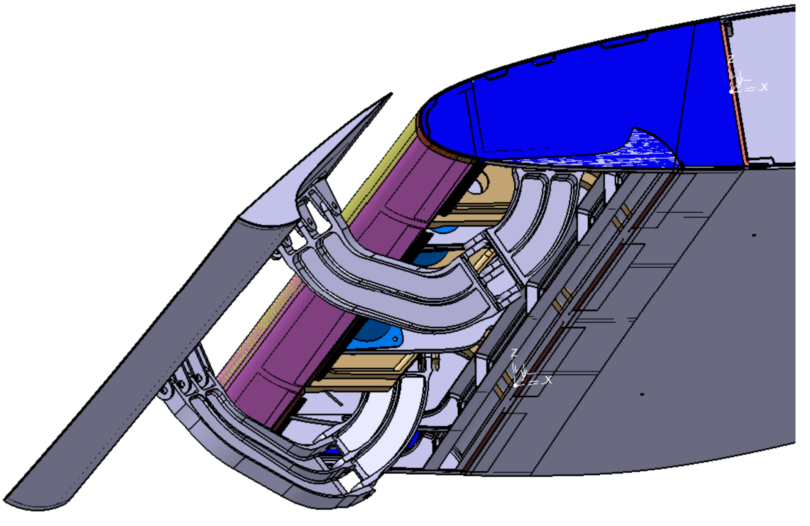

Figure 8. Integration of the Krueger Mechanism within the GBD Leading Edge – Overall View

The resulting kinematic design achieves a robust compromise between functional simplicity and representativeness of real aircraft systems. The modularity of the mechanism allows for rapid replacement or adjustment of components during experimental testing, while the use of rotary actuators provides precise motion control.

This architecture also facilitates the integration of instrumentation for measuring displacement, actuation loads, and sealing efficiency, supporting both aerodynamic and structural investigations.

The design principles and kinematic logic adopted for the GBD Krueger mechanism can serve as a reference for future HLFC demonstrators and for hybrid morphing concepts aiming at improved high-lift performance.

5. CONCLUSIONS

This study addresses the design, kinematics and integration, and also an assessment of Krueger flap configurations developed for a Hybrid Laminar Flow Control (HLFC) Demonstrator Based on geometric constraints - including minimum chord dimensions, insect-shielding requirements, and space allocation for integration - two Krueger flap concepts were developed: a “bull-nose” and a “single-panel” configuration. The design process began with the bull-nose configuration, and subsequent integration studies led to the development and optimization of the single-panel, sharp leading-edge Krueger panel. This optimized configuration demonstrates superior integration within the GBD while maintaining satisfactory aerodynamic performance.

The analysis of the kinematic Krueger panel has addressed the primary challenges while satisfying the geometric constraints. The proposed butterfly kinematics offers several advantages: it avoids interference with the leading-edge skin (cutouts) when fully extended, and although sealing solutions are still under investigation, viable option have been identified. While the configuration does not represent the best aerodynamic characteristics, it achieves a balanced compromise between aerodynamic performance and panel integration

Key advantages include compliance with geometric constraints without cutting the leading-edge skin and the feasibility of achieving effective sealing between the panel and the wing lower surface. The design further incorporates a novel butterfly kinematic mechanism, ensuring smooth deployment and structural integrity. Structural analyses were conducted on main rods and lugs, and a comprehensive design sequence was developed to implement reliable sealing. Both concepts are presented, including the design methodology, kinematic chain philosophy, and integration. Overall, the study provides a robust and balanced solution that integrates mechanical functionality, structural reliability, and aerodynamic performance, contributing to the advancement of HLFC demonstrators.

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This article is dedicated to the memory of Vasile TURCAN, who led the design activities of the AFLoNext project with respect to Krueger and kinematics geometry and passed away during its course. His leadership and vision were essential to the successful development and integration of innovative Krueger "butterfly" kinematics. He will be remembered for his technical expertise, mentorship, and lasting impact on colleagues and the next generation of engineers. His legacy endures through this project and the many professionals he inspired.

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