International Forum on Aeroelasticity and Structural Dynamics
IFASD 2026
17-21 June 2026, Goettingen, Germany

ACTIVE WING FOR FUTURE REGIONAL AIRCRAFT: MORPHING STRUCTURES AND AEROELASTIC CONTROL

Francesco Toffol[1], Vittorio Cavalieri[1], Alessandro De Gaspari[1], Sergio Ricci[1]

[1]Politecnico di Milano Aerospace Science and Technology Department
Via la Masa 34, 20156, Milano, Italy

francesco.toffol@polimi.it
vittorio.cavalieri@polimi.it
alessandro.degaspari@polimi.it
sergio.ricci@polimi.it

Keywords: Active wing, aeroelastic control, morphing control surfaces

Abstract:

The development of future regional aircraft with significantly increased aspect ratio requires overcoming the aeroelastic limitations associated with highly flexible wing structures. Within the framework of the HERWINGT project, this work presents an integrated aeroelastic approach combining three complementary technological pillars: strut-braced wing architectures, morphing control surfaces, and active load alleviation systems. The objective is to demonstrate how the combined application of these technologies enables a new generation of active and intelligent wings capable of simultaneously improving aerodynamic efficiency, reducing structural mass, and mitigating aeroelastic constraints.

A physics-based aeroelastic design framework is adopted to assess both cantilevered and strut-braced configurations under increasing aspect ratio conditions. The results show that the strut-braced architecture effectively mitigates the structural mass growth associated with conventional high-aspect-ratio wings, enabling a significant reduction in wing root bending moments. In parallel, morphing ailerons are developed to provide continuous aerodynamic load tailoring with reduced drag and actuation effort. Compared to a conventional hinged reference configuration, the developed morphing device achieves a drag reduction of approximately 42%, exceeding the project target of 25%, while also reducing structural weight and actuation loads.

Active manoeuvre and gust load alleviation strategies are developed using aeroelastic state-space models generated with NeoCASS and validated in a high-fidelity aero-servo-elastic simulation environment. The proposed control methodologies achieve reductions of 20% and 19.4% in wing root bending moment for critical manoeuvre and gust conditions, respectively, exceeding the project target of 15%.

The paper also presents the experimental validation strategy developed to achieve TRL5 maturity, including a full-scale morphing aileron demonstrator and a dynamically scaled aero-servo-elastic wind tunnel model. The overall results demonstrate the effectiveness of integrating advanced structural concepts, adaptive aerodynamics, and active control within a unified aeroelastic design framework for future sustainable regional aircraft.

1 INTRODUCTION

The transition towards more sustainable aviation, strongly driven by European initiatives such as the Clean Aviation programme, requires disruptive technological advancements to significantly reduce fuel consumption, emissions, and environmental impact. In this context, the development of innovative wing architectures plays a pivotal role, as the wing directly governs aerodynamic efficiency, structural weight, and aeroelastic performance, ultimately determining the overall aircraft efficiency.

The HERWINGT (Hybrid Electric Regional Wing Integration Novel Green Technologies) project [1] addresses these challenges by targeting the design and demonstration of a novel wing for a future hybrid-electric regional aircraft. The project aims at enabling a step change in performance through the development and integration of advanced wing technologies, targeting a fuel burn reduction at aircraft level of up to 50%, with a contribution of approximately 15% from wing improvements alone, and a structural weight reduction of about 20% at component level compared to a state-of-the-art reference configuration . A key aspect of the project is the maturation of these technologies up to Technology Readiness Level 5 (TRL5) through a comprehensive experimental validation campaign.

Among the various design directions explored within HERWINGT, increasing the wing aspect ratio represents a well-established strategy to enhance aerodynamic efficiency by reducing induced drag. However, this approach introduces significant aeroelastic challenges, including increased bending loads, higher sensitivity to atmospheric disturbances, and reduced stability margins. These effects typically lead to structural weight penalties and conservative design choices, ultimately limiting the achievable performance improvements.

Within this framework, aeroelasticity emerges not only as a constraint but as a primary design driver. Traditional passive wing designs are inherently limited in their ability to simultaneously achieve high aerodynamic efficiency, low structural weight, and adequate aeroelastic robustness. As a consequence, a paradigm shift towards actively controlled and adaptive wing systems is required.

This paper presents an overview of the activities carried out by Politecnico di Milano within the HERWINGT project, focusing on three main technological pillars: a strut-braced wing configuration enabling higher aspect ratio with reduced structural mass, morphing control surfaces designed to improve aerodynamic efficiency and enable load tailoring, and active control systems for manoeuvre and gust load alleviation. Rather than addressing these technologies individually, the paper emphasises their combined effect and highlights how their integration enables a new generation of active and intelligent wings.

In particular, the contribution of this work is to provide a system-level perspective on how the interaction between structural concepts, adaptive aerodynamics, and active control can reshape the aeroelastic design space of future regional aircraft wings. The focus is placed on the aeroelastic benefits enabled by this integrated approach, as supported by a coherent experimental validation strategy targeting TRL5 demonstrators.

2 INTEGRATED AEROELASTIC DESIGN FRAMEWORK FOR HIGH-ASPECT-RATIO WINGS

The increase of wing aspect ratio represents one of the most effective strategies to improve aerodynamic efficiency, primarily through induced drag reduction. In the HERWINGT framework,

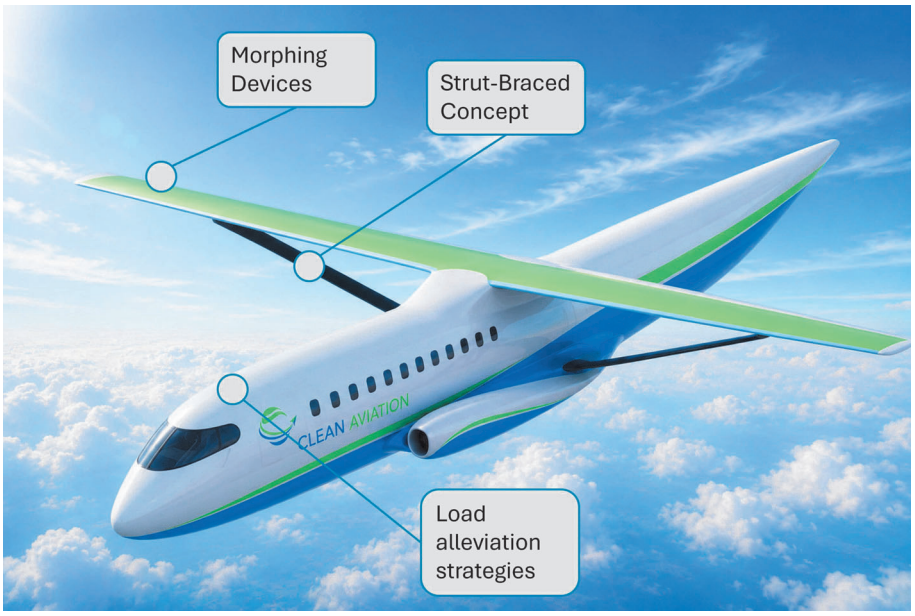

Figure 1: Technological pillars investigated by Polimi within the HERWINGT project

the aspect ratio is extended from conventional values of approximately 12 up to values close to 16, enabling a significant improvement in lift-to-drag ratio. However, this design choice fundamentally shifts the governing constraints from purely aerodynamic considerations to a tightly coupled aeroelastic problem.

The resulting wing configuration is significantly more slender and flexible, leading to strong interactions between aerodynamic loads, structural response, and flight dynamics. As a consequence, aeroelasticity becomes a primary design driver, limiting the achievable design space due to increased structural loads, higher sensitivity to disturbances, and reduced stability margins. Overcoming this aeroelastic bottleneck requires moving beyond conventional passive approaches and adopting an integrated design strategy.

Within this context, the HERWINGT project develops a unified aeroelastic framework based on three tightly coupled technological pillars: (i) strut-braced configurations combined with physics-based aeroelastic design, (ii) morphing control surfaces with enhanced aerodynamic and dynamic capabilities, and (iii) active control methodologies for manoeuvre and gust load alleviation.

A key element of this framework is the adoption of a physics-based aeroelastic design process, in which structural mass is directly derived from load-carrying requirements and aeroelastic effects are accounted for from the early design stages. The process is structured through multiple iterative loops, progressively increasing the level of model fidelity and the representativeness of the considered load cases, from conceptual sizing to higher-fidelity multidisciplinary design optimization.

In order to consistently assess the impact of architectural choices at high aspect ratio, the aeroelastic design process is carried out in parallel on two configurations. The first one is a strut-braced wing (SBW), aimed at evaluating the potential benefits of the additional load path in reducing structural mass and alleviating aeroelastic constraints. The second one is an extended cantilever configuration, developed to systematically investigate the evolution of structural weight as a function of increasing aspect ratio within a conventional architecture.

This dual-track approach enables a direct comparison between the two concepts in terms of structural mass, aeroelastic response, and sensitivity to key design parameters, providing a consistent basis for technology assessment. The results highlight the progressive structural penalty associated with the cantilever configuration at high aspect ratio, as well as the potential of the SBW solution to mitigate such limitations.

At a defined stage of the project, a configuration down-selection is performed by the HERWINGT coordination board, with the objective of focusing subsequent activities on a single reference architecture for experimental validation. This decision is driven by the need to concentrate resources on the design and manufacturing of aeroelastic wind tunnel models dedicated to gust load alleviation (GLA) testing.

Following this selection, the SBW configuration is retained for further development and for the realization of the aeroelastic demonstrator. Consistently with this choice, morphing control surface technologies are developed exclusively for the SBW model. This decision is primarily driven by programmatic constraints, as the design, integration, and manufacturing of morphing devices require significant effort and lead time, making parallel developments on multiple configurations impractical. As a result, the integration of morphing technologies is effectively frozen a priori on the selected SBW architecture.

Within the selected configuration, the three technological pillars operate in a strongly coupled manner. The strut-braced architecture reduces structural loads and modifies the aeroelastic behaviour of the wing; morphing control surfaces provide the capability to tailor the aerodynamic load distribution while meeting stringent dynamic bandwidth requirements; and active control systems exploit these capabilities to mitigate both manoeuvre and gust-induced loads.

This interaction defines a closed-loop aero-servo-elastic design paradigm, in which structural layout, aerodynamic adaptability, and control actions are co-designed. Load alleviation reduces design loads and enables lighter structures, morphing enhances both aerodynamic efficiency and control authority, and the modified structural configuration reshapes the aeroelastic response, which is actively managed through control.

As a result, the integrated application of these technologies shifts the aeroelastic constraints that traditionally limit high-aspect-ratio wings, enabling configurations that would be infeasible within a purely passive design framework. This system-level approach constitutes the foundation for the development of active and intelligent wings for future regional aircraft.

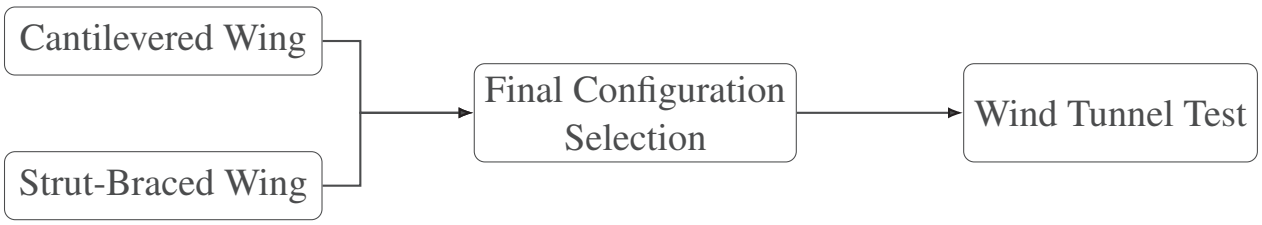

Figure 2: Selection process for the wind tunnel test configuration.

2.1 Aeroelastic Structural Design

The increase in aspect ratio leads to a significant growth in wing root bending moments, driven by the longer span and load redistribution. In conventional cantilever configurations, this results

in a substantial structural mass penalty, which can offset the aerodynamic benefits.

The adoption of a strut-braced wing (SBW) configuration provides an effective mechanism to alleviate this limitation [2, 3]. By introducing an additional load path between the wing and the fuselage, the strut reduces the bending moment along the span, enabling a lighter structural design. At the same time, this architectural change modifies the global stiffness distribution and the aeroelastic behaviour of the system, introducing strong coupling between the wing and the strut.

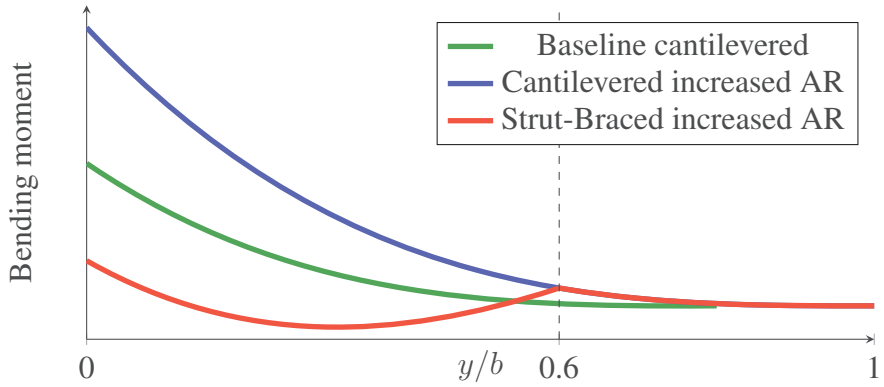

Figure 3: Out-of-plane bending moment qualitative comparison between cantilevered and strut-braced configurations.

For this reason, the SBW cannot be treated as a purely structural solution, but requires a fully integrated aeroelastic design approach. Within HERWINGT, this is achieved through a physics-based framework in which structural mass is directly derived from load-carrying requirements, and aeroelastic effects are included from the early design stages. This enables a consistent comparison between cantilever and strut-braced configurations and supports the identification of optimal solutions at high aspect ratio.

The aeroelastic design framework adopted in the present study follows a multi-fidelity and progressively refined approach, aimed at ensuring consistency between conceptual sizing, aeroelastic optimisation, and detailed structural verification.

The first stage of the process is performed using GUESS (Generic Unknowns Estimator in Structural Sizing) [4], which generates a preliminary aeroelastic stick model of the aircraft. In this framework, the structural stiffness and mass properties are derived directly from the physical characteristics of the structural components, such as panels thicknesses and stringers areas. The resulting model provides an initial estimation of the aeroelastic behaviour of the configuration and supports early-stage sizing activities.

Subsequently, the stick model is identified and refined within the NeOPT environment [5], which enables a higher-fidelity geometrical representation of the wingbox structure. In this phase, composite materials and laminate-based structural definitions are introduced into the design process, allowing for a more realistic assessment of structural performance. In addition to conventional trim conditions, the optimisation framework accounts for dynamic load cases as well as aeroelastic stability and performance requirements, including the verification of flutter constraints and dynamic response characteristics.

Finally, through the meta-model generation capabilities implemented in NeOPT, a detailed fi-

nite element model (FEM) of the wingbox and strutbox structures is automatically generated. These high-fidelity FEM components are then substituted into the corresponding stick-model representations within the global aeroelastic model. The structural sizing is therefore verified through the analysis of the critical load cases using a refined aeroelastic representation of the aircraft, ensuring consistency between low-fidelity conceptual design assumptions and detailed structural assessments.

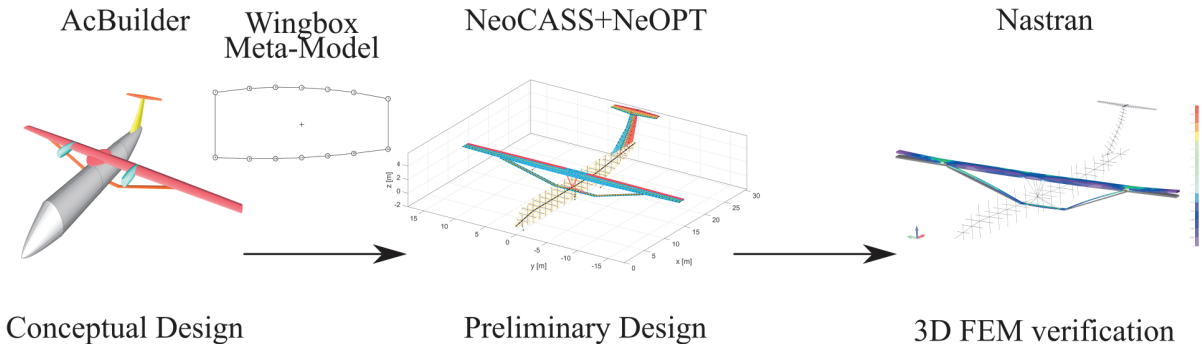

Figure 4: Increasing fidelity design process adopted for the SBW concept development

A key aspect of this approach is the early inclusion of aeroelastic effects within the design loop, enabling the evaluation of relevant phenomena such as load redistribution, dynamic response, and stability constraints already at the conceptual and preliminary design stages. This allows identifying the most promising architectural solutions based on a consistent aeroelastic assessment. The results of this process indicate that, for the targeted increase in aspect ratio, the strut-braced configuration represents a viable solution to mitigate the structural mass penalty while maintaining compatibility with aeroelastic constraints.

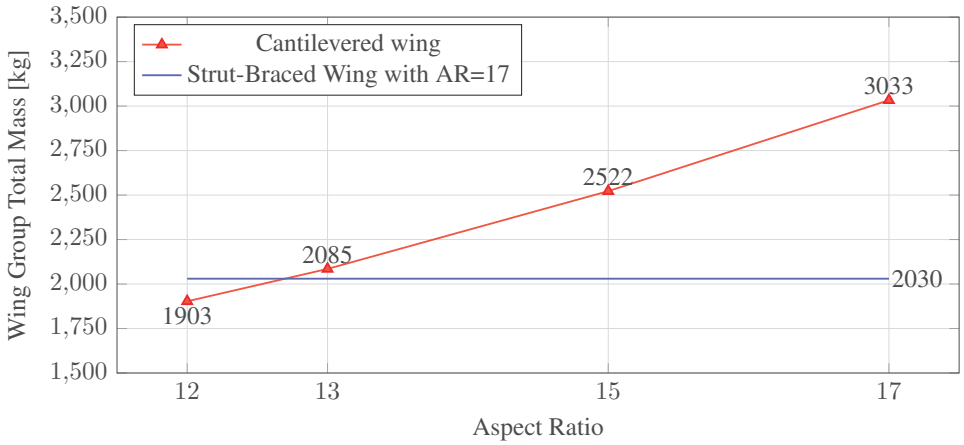

Figure 5: Wing + strut structural mass as a function of aspect ratio. Cantilever configurations are compared with the Strut-Braced AR17 solution.

2.2 Morphing Control Surfaces: Load Tailoring and Dynamic Requirements

While the strut-braced configuration mitigates the structural mass penalty, high-aspect-ratio wings remain highly sensitive to load redistribution and external disturbances. In this context, morphing control surfaces provide a key enabling technology for aerodynamic load tailoring and aeroelastic performance enhancement.

Unlike conventional hinged devices, morphing ailerons enable smooth and continuous shape variations, reducing aerodynamic discontinuities and allowing a more efficient spanwise redistribution of loads. This capability directly contributes to lowering peak structural loads and improving overall aeroelastic behaviour.

The design of a morphing aileron is a strongly multidisciplinary problem, involving aerodynamic, structural, actuation, and control-related requirements. Accordingly, the proposed concept was developed through an integrated design methodology, whose details and main outcomes are reported in [6]. The methodology is inspired by the two-level design approach originally developed at Politecnico di Milano for morphing compliant structures [7], which has been successfully applied over the years to several morphing prototypes, including a full-scale morphing droop nose [8].

Within this framework, aerodynamic performance is first evaluated in terms of drag reduction under equivalent lift conditions. In particular, the morphing deformation is assessed against a conventional hinged reference configuration by considering the same lift coefficient generated by a traditional aileron deflected by 25°, based on two-dimensional CFD analyses. Figures 6 and 7 show a comparison for the two aileron configurations (hinged and morphing) at $\alpha = 2°$, the aileron is deflected of $\delta = 30°$, while the morphing aileron is deformed to have the same lift coefficient of the hinged aileron at its maximum deflection of $\delta = 30°$. Flight condition is at aircraft V_A at sea level, for a Mach number of 0.29.

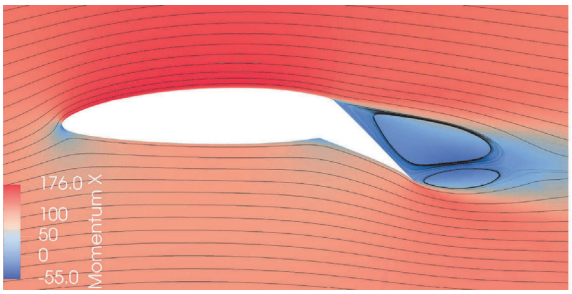

Figure 6: 2D hinged aileron CFD analysis

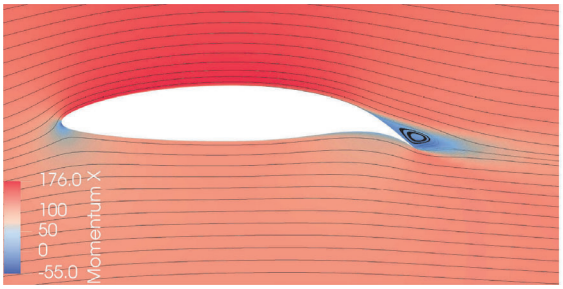

Figure 7: 2D morphing aileron CFD analysis

For this condition, the target drag reduction of 25% with respect to the reference configuration is defined at project level. The results obtained within the present work show a significantly improved performance, with a drag reduction of approximately 42% with respect to the same reference. This highlights the effectiveness of the continuous camber variation in reducing profile losses compared to discrete control surface deflections.

In addition to aerodynamic performance, structural efficiency represents a key requirement. The morphing concept aims to reduce the structural mass of the control surface with respect to traditional solutions, while simultaneously limiting the actuation effort. By improving aerodynamic efficiency, the morphing aileron is also expected to enhance aircraft controllability and maneuverability, yielding a more effective control response. A reduction of approximately 20% in structural mass is targeted, while the lower actuation effort enables the use of more compact and lightweight servo-actuators integrated within the wing. This represents a major advantage of the proposed concept, supporting the feasibility of lightweight, efficient, and highly integrated actuation systems for morphing control surfaces.

The aerodynamic loads were then introduced as external contributions in the structural design of the morphing aileron, which was carried out through a multi-level optimization strategy. The resulting structural response is illustrated in Figure 8, which shows the principal strain distribution in the deformed morphing aileron under combined actuation and aerodynamic loads for the two maximum upward and downward deflection configurations.

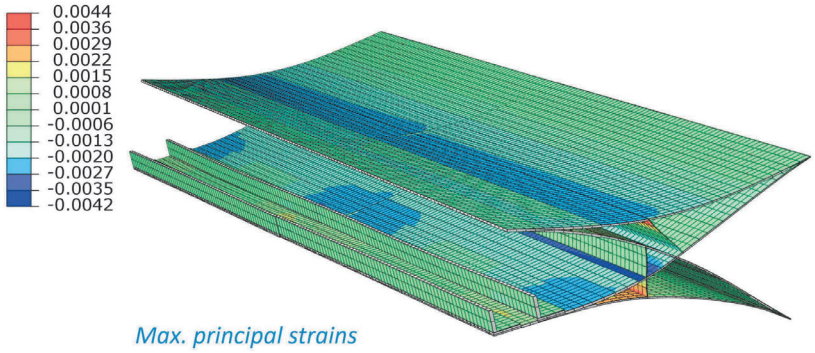

Figure 8: Principal strains for the deformed morphing aileron under actuation and aerodynamic loads

However, the role of morphing control surfaces extends beyond quasi-static load control. For high-aspect-ratio flexible wings, dynamic load alleviation becomes essential, particularly for gust-induced loads. This introduces specific requirements on the dynamic behavior of the integrated actuation system. In this context, the morphing aileron contributes to achieving a target closed–loop bandwidth of approximately 10 Hz, which is relevant for next-generation aircraft active control applications. This is enabled by the dynamic coupling between the servo-actuator and the structural response of the morphing aileron, which behaves as a flexible structure with its own dynamics. As a result, its structural layout can be tailored to provide the required compliance for shape adaptation, sufficient stiffness to withstand external aerodynamic loads, and suitable dynamic characteristics to support the desired bandwidth of the servo–control, actuator, and flexible-aileron system.

These requirements define a fundamental design trade-off: morphing devices must combine structural compliance and reduced actuation effort, which are beneficial for weight and aerodynamic performance, with sufficient dynamic bandwidth and control authority. Achieving this balance is essential to enable their integration within active aeroelastic control frameworks and to fully exploit their potential for both static and dynamic load alleviation. The performance of the morphing aileron is assessed through a set of key performance indicators (KPIs), defined with respect to a conventional hinged reference configuration and summarized in Table 1. The target values are established at project level, while the achieved values correspond to the current status obtained from the developed demonstrator.

Table 1: Morphing aileron key performance indicators (relative values)

KPI	**Target vs Ref**	**Achieved vs Ref**
Structural weight	-20%	-32%
2D C_D for a C_L equivalent at 25° aileron rotation	-25%	-42%
Roll moment coefficient	0%	+10.5%
Aircraft C_D at same roll coefficient	-10%	-26%
Actuation force	-33%	-54%
Bandwidth	10 Hz	10 Hz

2.3 Active Control of Manoeuvre and Gust Loads

The increased flexibility of high-aspect-ratio wings leads to amplified responses to both manoeuvre and gust loads, which represent primary drivers for structural sizing and fatigue design. Passive design approaches typically address these effects through increased stiffness and conservative margins, resulting in additional mass penalties.
Active control systems provide a direct means to alleviate these loads by generating real-time aerodynamic responses through available control surfaces. In this context, two complementary objectives are considered: manoeuvre load alleviation (MLA), which reduces limit loads and structural sizing requirements, and gust load alleviation (GLA), which mitigates dynamic loads and contributes to fatigue life extension.
Within the HERWINGT project, the development of active control technologies is carried out after the high-level configuration down-selection, which identifies the cantilevered wing as the reference architecture for control-oriented investigations. As a consequence, the control design and assessment are consistently performed on this configuration.
In the present study, the control design and assessment are performed using conventional hinged control surfaces. However, in order to ensure consistency with the targeted high-performance architecture, the bandwidth constraints adopted for the development of the GLA controllers are not derived from conventional actuators, but from the expected performance of the high-bandwidth morphing aileron device.
This modelling choice is intentionally adopted to isolate the contribution of active load alleviation from that of morphing technologies. In particular, it enables the assessment of the load reduction achievable using conventional control strategies, without introducing additional benefits associated with morphing-induced aerodynamic load tailoring. In this way, the respective contributions of control and morphing remain clearly separated.
The combined exploitation of morphing devices and active load alleviation, and the potential synergies between them, are therefore not addressed in the present work and are identified as a key direction for future investigations.

Manoeuvre Load Alleviation The manoeuvre load alleviation (MLA) strategy is implemented through the combined use of the ailerons and the load control tabs [9], which are symmetrically deflected in order to redistribute the aerodynamic loads along the wing span and reduce the resulting wing root bending moment. The control action is based on a quasi-static approach, in which the surface deflection is directly scheduled as a function of the load factor according to a proportional law of the form

$$\delta = k(n-1) \tag{1}$$

where n represents the instantaneous load factor and k is the control gain. Since the controller acts on the low-frequency rigid-body response of the aircraft, the MLA action can be consistently simulated through trimmed manoeuvre conditions in which the control surface deflections are prescribed and not treated as free trim variables.

From an implementation perspective, the MLA controller is separated from the dynamic gust load alleviation (GLA) controller through the use of low-pass frequency filters within the flight control computer architecture. This filtering strategy allows the quasi-static MLA action, associated with low-frequency manoeuvre dynamics, to remain effectively decoupled from the higher-frequency GLA controller, which is specifically designed to act on the elastic modes of the flexible aircraft structure.

The development of the MLA controller is performed considering the cantilevered wing configuration and is extended to a family of wing layouts with aspect ratios ranging from 13 to

16. This parametric investigation is carried out in order to assess how the control action must progressively increase with wing flexibility and structural loading in order to effectively limit the sizing loads associated with higher aspect ratio configurations.

The aspect ratio increase is obtained by extending the wing span while preserving both the wing planar form and the outboard taper ratio, as shown in Figure 9. This approach enables a consistent comparison between configurations, isolating the effect of span increase on the aeroelastic response and on the required manoeuvre load alleviation authority.

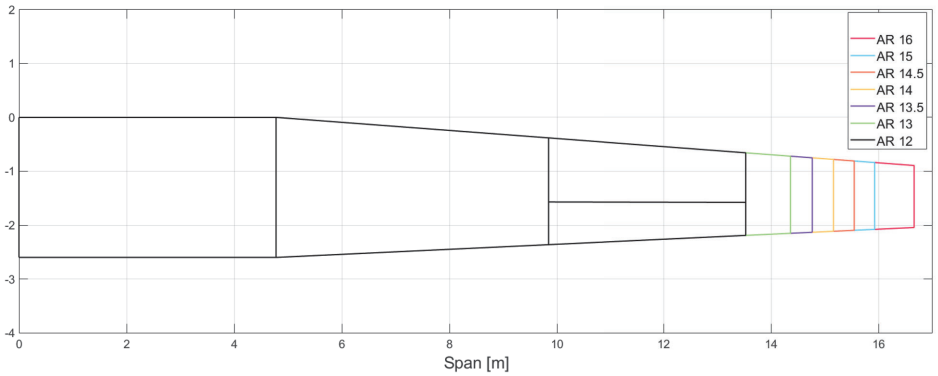

Figure 9: Wing AR increase by extending the wing

The result of the sensitivity study are illustrated in Figure 10 and reported in Table 2.

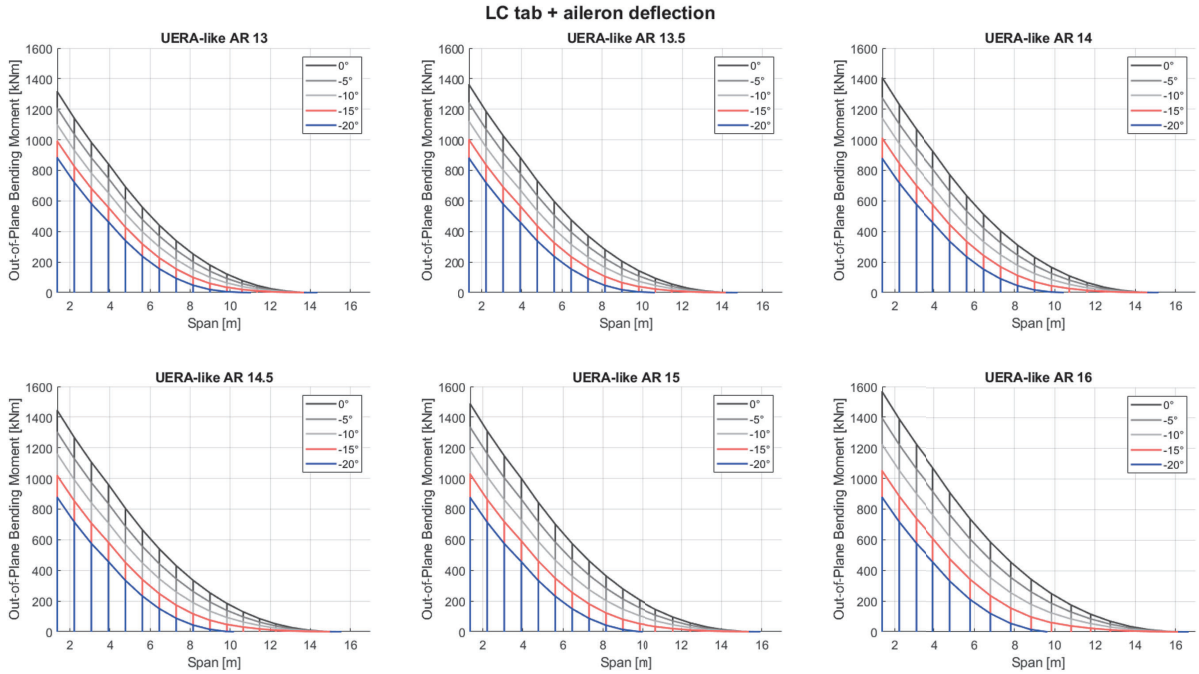

Figure 10: Out-of-plane bending moment distribution vs. different combination of LC tab and aileron deflections vs. aspect ratio

Table 2: WRBM difference w.r.t. the UERA-like baseline configuration with AR12 [%]

AR/Def.	No MLA	LC tab				Aileron				LC tab + Aileron			
	0	-5	-10	-15	-20	-5	-10	-15	-20	-5	-10	-15	-20
13.0	7.1	5.9	4.6	3.4	2.0	-0.4	-7.6	-15.2	-22.9	-1.6	-10.4	-19.0	-28.1
13.5	10.9	8.4	6.0	3.8	1.8	3.5	-3.8	-11.4	-18.9	1.2	-8.6	-18.4	-28.2
14.0	14.5	11.1	8.5	4.8	0.6	7.2	0.0	-7.1	-14.5	3.8	-6.8	-17.6	-28.3
14.5	17.8	13.2	10.0	5.0	-0.2	10.5	3.4	-3.8	-11.1	6.0	-5.1	-16.8	-28.4
15.0	21.3	15.7	10.3	5.3	-0.8	14.2	7.2	0.2	-6.5	8.7	-3.5	-16.1	-28.4
16.0	27.7	20.5	12.8	5.7	-2.2	21.1	14.3	7.7	1.1	13.6	-0.2	-14.5	-28.5

Gust Load Alleviation

NeoCASS has been employed to generate a state-space representation of the aeroelastic aircraft model [10], to be used for the development of the Gust Load Alleviation (GLA) control laws. The approach is based on a physics-based formulation in which the structural dynamics, represented in modal coordinates, are coupled with unsteady aerodynamic forces approximated through a rational function approximation. This results in a reduced-order, control-oriented state-space model that consistently captures the relevant aeroelastic dynamics of the system. The control laws are designed on this model and subsequently validated on a high-fidelity Simulink environment, in which actuator dynamics, sensor characteristics (including resolution effects), and the flight control computer are explicitly modeled, with a sampling frequency of 1 kHz.

$$\begin{cases} \dot{\mathbf{x}}_{ae} = \mathbf{A}\mathbf{x}_{ae} + \mathbf{B}_g\mathbf{v}_g + \mathbf{B}_c\boldsymbol{\delta}_c \\ \mathbf{y} = \mathbf{C}\mathbf{x}_{ae} + \mathbf{D}_g\mathbf{v}_g + \mathbf{D}_c\boldsymbol{\delta}_c \end{cases} \tag{2}$$

The GLA control law is designed starting from the control-oriented state-space representation of the aeroelastic system. A Static Output Feedback (SOF) architecture is adopted [11], in which the control input is expressed as a linear combination of measurable quantities, including centre of gravity and wing spanwise measured accelerations, their numerically integrated velocities, and pitch rate signals.

$$\boldsymbol{\delta}_c = -\mathbf{G}\mathbf{y} \tag{3}$$

The controller synthesis is formulated as a constrained optimization problem [12], where the gain matrix is tuned to minimize selected performance metrics associated with structural loads under gust excitation. In particular, the objective function is defined in terms of the ratio between the peak values of relevant load quantities in closed-loop and open-loop conditions, thus directly targeting load alleviation while preserving a consistent reference to the uncontrolled response.

$$f(G) = \sum_{i=1}^{n} w_i \frac{\max|z_{i,CL}(t)|}{\max|z_{i,OL}(t)|} \tag{4}$$

$$\begin{aligned} \mathbf{G}^\star = \arg\min_{\mathbf{G}} \quad & f(\mathbf{G}) \\ \text{s.t.} \quad & g(\mathbf{G}) < 0 \end{aligned} \tag{5}$$

The optimization is subject to stability constraints, enforced through minimum damping requirements on the aeroelastic modes, together with actuator-related limitations such as maximum surface deflection rate. This formulation leads to a low-order, physically interpretable

controller, well suited for preliminary design applications and consistent with integration within the aeroelastic sizing process.

$$\begin{aligned} \xi &< 1\% \\ \dot{\delta}_c &< 100^\circ/\mathrm{s} \end{aligned} \tag{6}$$

Finally, the designed controller is tested in a high-fidelity Simulink environment, where multiple mass configurations, flight conditions, and gust gradients are simulated to assess its robustness and performance.

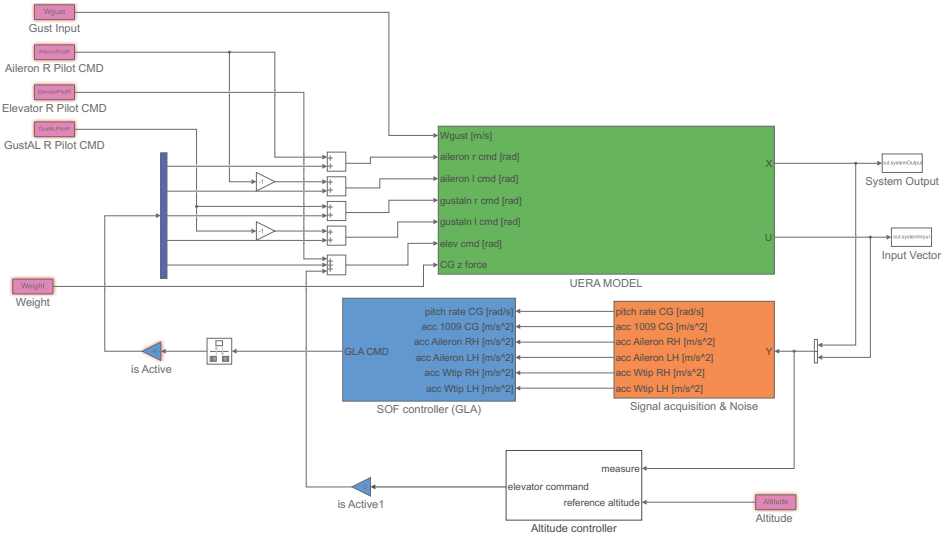

Figure 11: Simulink model of the virtual aero-servo-elastic simulator used to simulate the gust response

The resulting load alleviation is summarized in the envelope shown in Figure 12, demonstrating numerically the capability to achieve the 20% reduction in wing root bending moment (WRBM) required by the project.

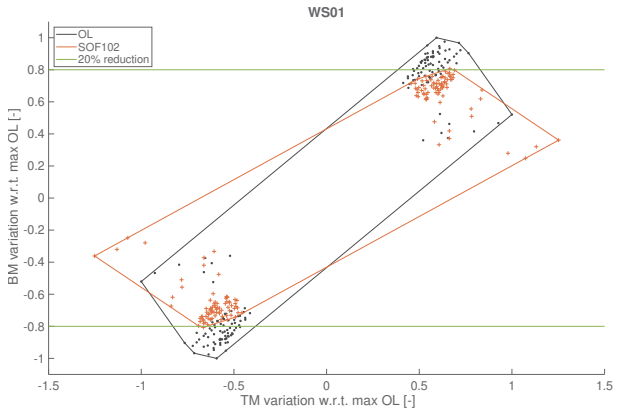

Figure 12: Gust load bending-torional moment envelope: comparison between open and close loop results

The effectiveness of the active control systems for manoeuvre load alleviation (MLA) and gust load alleviation (GLA) is evaluated in terms of reduction of the wing root bending moment (WRBM), which represents a primary driver for structural sizing. For the MLA system, the control action can be parameterized through different values of the gain coefficient k introduced in Eq. 1, allowing the achievable load alleviation to be tailored to specific design requirements.

In the case of the AR16 configuration, a combined LC tab and aileron deflection of approximately 7° is sufficient to achieve the target load reduction required for the present design study, while a deflection of approximately 9° yields a WRBM reduction of about 20% with respect to the same configuration without MLA activation. Limiting the MLA controller action to lower alleviation levels than the theoretical maximum preserves adequate residual aileron authority for roll control.

Table 3: MLA and GLA performance indicators (relative values)

Condition	Target vs Ref	Achieved vs Ref
Manoeuvre load alleviation (2.5g pull-up)	-15%	-20%
Gust load alleviation (critical gust case)	-15%	-19.4%

The results show that both MLA and GLA strategies exceed the target requirements, providing a significant reduction of the wing root bending moment under the most critical manoeuvre and gust conditions. This confirms the effectiveness of the adopted control approach in mitigating both static and dynamic loads, directly contributing to improved structural efficiency and fatigue performance.

2.4 Integrated Aeroelastic Synergy

The three technological pillars are not independent solutions but elements of a single coupled system. The strut-braced configuration reduces structural loads but alters the aeroelastic behaviour; morphing control surfaces provide load redistribution capabilities but require sufficient dynamic performance; active control systems exploit these capabilities to reduce both static and dynamic loads.

This interaction defines a closed-loop aero-servo-elastic design paradigm, in which structural layout, aerodynamic adaptability, and control actions are co-designed. Load alleviation reduces design loads and enables lighter structures; morphing enhances both aerodynamic efficiency and control effectiveness; and the modified structural configuration reshapes the aeroelastic response, which is actively managed through control.

As a result, the integrated application of these technologies shifts the aeroelastic constraints that traditionally limit high-aspect-ratio wings, enabling configurations that would be infeasible, or energetically inefficient, within a purely passive design framework. This system-level approach constitutes the foundation for the development of active and intelligent wings in future regional aircraft.

3 EXPERIMENTAL VALIDATION STRATEGY TOWARDS TRL5

A key objective of the HERWINGT project is the maturation of the proposed technologies up to Technology Readiness Level 5 (TRL5), which requires their validation in a relevant environment. Within this framework, a comprehensive experimental strategy is developed by Politecnico di Milano to assess both the functionality and the aeroelastic performance of the proposed solutions.

The validation approach is based on the development and testing of two main demonstrators, addressing complementary aspects of the wing concept: a full-scale structural demonstrator for morphing technologies and a dynamically scaled aero-servo-elastic model for the validation of active load control strategies.

3.1 Validation Philosophy

The experimental campaign is structured in two main phases, aimed at progressively increasing the level of representativeness and complexity of the tests.

The first phase consists of laboratory testing, focused on the characterization and verification of the individual demonstrators. This includes ground vibration tests (GVT), calibration of measurement systems, and functional tests of the morphing devices and actuation systems. These activities are essential to ensure that the structural and dynamic properties of the models are well understood and that the systems operate as expected before proceeding to more complex testing conditions.

The second phase consists of wind tunnel testing, where the demonstrators are tested under aerodynamic loading conditions representative of real operational scenarios. This phase is essential to satisfy the TRL5 requirement of testing in a relevant environment, allowing the assessment of the interaction between aerodynamics, structural dynamics, and control systems.

This two-step approach ensures a robust and controlled validation process, bridging the gap between component-level testing and integrated aeroelastic behaviour.

3.2 Full-Scale Morphing Aileron Demonstrator

A full–scale wing portion is developed to experimentally validate the morphing aileron technology. The demonstrator consists of a representative wingbox structure integrating two morphing aileron segments, each approximately 1 meter in spanwise extension.

The test article is designed to reproduce realistic structural boundary conditions and stiffness characteristics, enabling a meaningful assessment of the integration of morphing devices within a wing structure. The experimental campaign focuses on the evaluation of the device functionality, structural behaviour, actuation requirements, and deformation capabilities under representative loading conditions.

From an aeroelastic perspective, this demonstrator provides key information on the achievable shape control, load redistribution capability, and dynamic response of the morphing aileron. In particular, it supports the verification of the compatibility of the device with the bandwidth requirements associated with active load alleviation.

The tests are conducted both in laboratory conditions, for detailed characterization, and in wind tunnel environment, where the aerodynamic performance and aero-structural interaction of the morphing device can be assessed. Figures 13 and 14 show the assembled morphing ailerons mounted on a dummy rear spar in the Polimi's structural test laboratory, where an extensive experimental campaign assessed the functionality of the items. Their capability of reaching the desired deformed shapes was measured with a Digital Image Correlation (DIC) system by SIEMENS.

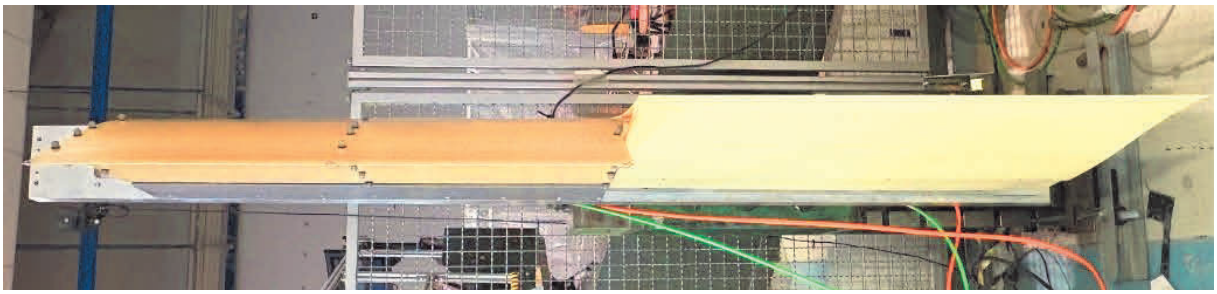

Figure 13: Morphing ailerons deflected in upward (right) and downward (left) direction. Markers are used for camera stereography preliminary shape reconstruction



Figure 14: Morphing ailerons with markers patterns used for shape and deformation reconstruction via Digital Image Correlation

The servo–actuated morphing aileron system was experimentally tested to assess the achievement of the project bandwidth requirement of 10 Hz. In conventional control surfaces, the movable surface is generally assumed to behave as a rigid body and affects the servo-control bandwidth mainly through its inertia. Accordingly, in the aeroelastic demonstrator described in Section 3.3, the bandwidth of the rigid aileron results from the combined contribution of the servo-control system and the inertia of the rigid control surface. In that Aero–Servo–Elastic Scaled Model, a dedicated servo-control law based on a double-loop architecture with high–order integral actions is adopted [13].

For the morphing aileron, the bandwidth is instead governed by the dynamic coupling between the servo–controller, the actuation kinematics shown in Figure 15, and the structural dynamics of the flexible morphing surface. The measured transfer function between the commanded and actual position of the linear actuator used to deform the aileron is reported in Figure 16: the excitation is a sine sweep with bandwidth limited to 10Hz, therefore above 10Hz only measurement noise is present. The transfer function has a unit gain up to 10Hz and the phase is $0°$. This assesses the capability of achieving a 10 Hz bandwidth in dry conditions. Further assessment will be carried out through wind tunnel tests.

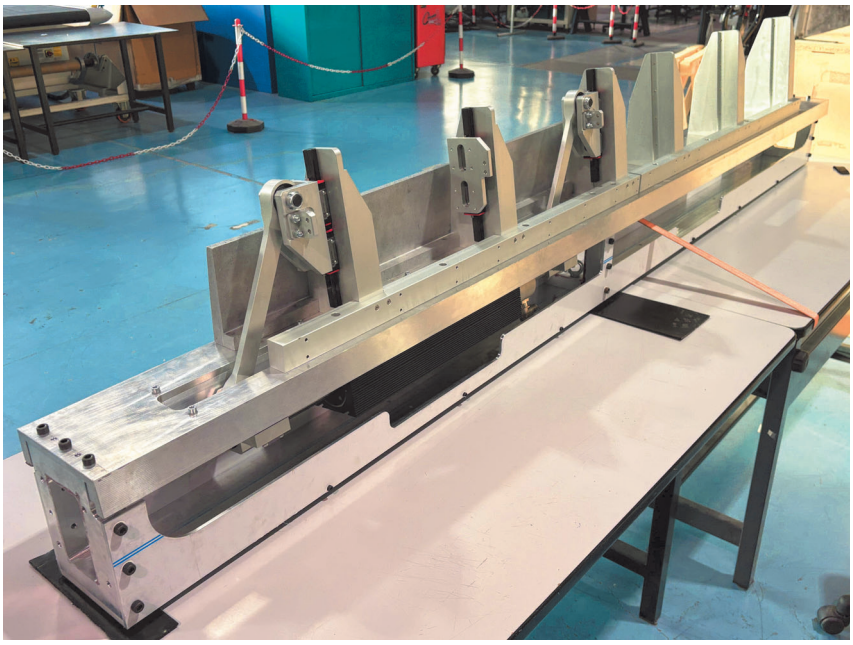

Figure 15: Actuation system for morphing ailerons

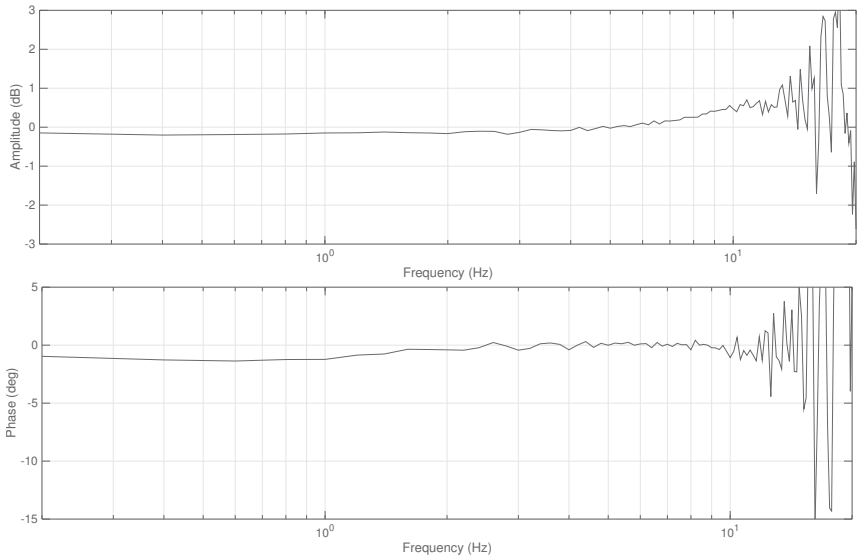

Figure 16: Experimental transfer function between the commanded and actual position of the morphing aileron actuator

3.3 Aero-Servo-Elastic Scaled Model for Load Control Validation

In parallel with the full-scale morphing aileron demonstrator, a dedicated aero-servo-elastic model, named D1-9, is developed for the validation of active control strategies for manoeuvre load alleviation (MLA) and gust load alleviation (GLA).

The model is realized as a half-wing configuration with a geometric scaling factor of 1:6 and is designed according to isofrequency scaling criteria, ensuring that the relevant dynamic characteristics, such as natural frequencies and mode shapes, are representative of the full-scale system and suitable for aeroelastic and control investigations.

A key advantage of the adopted isofrequency scaling approach is the direct applicability of con-

trol laws developed at full scale to the wind tunnel model. In particular, the gust load alleviation (GLA) controller designed for the full aircraft can be implemented on the scaled model without any modification to its structure or tuning. This is possible because the dynamic similarity ensured by isofrequency scaling preserves the relevant time scales, reduced frequencies and modal characteristics of the system. As a consequence, the control law operates on a dynamically equivalent system, allowing a consistent evaluation of its performance in the experimental environment. Only a scaling of the measured signals is required: structural displacements and accelerations obtained from the wind tunnel model are multiplied by the geometric scaling factor (equal to 6) to match the corresponding full-scale quantities. This straightforward scaling preserves the physical meaning of the signals used by the controller, enabling a direct and meaningful validation of the control strategy.

The wind tunnel dimensions limit the geometric scaling to approximately 1:12, which, under isofrequency constraints, would require a proportional reduction of the flow velocity to about 10 m/s. To avoid this limitation, a half-model configuration is adopted, consistently with previous European projects (GLAMOUR [14], AIRGREEN2 [15], U-HARWARD [16]), allowing a 1:6 scaling for both length and velocity and preserving the dynamic similarity with the full-scale aircraft. The model is mounted vertically, with gravity acting along the spanwise direction, and is connected to the wind tunnel floor through a sledge-pivot mechanism that enables free-body motion in plunge and pitch. A weight augmentation system (WAS), based on a long-stroke actuator, provides a scaled representation of the aircraft weight, allowing trimming at different load factors and enabling the investigation of manoeuvre load alleviation (MLA). The mechanism is illustred in Figure 18. Gust disturbances are generated by six vertically mounted vanes located at the test section inlet, that reproduce a 1-cosine gust profile. The gust is applied under unit load factor trim conditions, so that the resulting loads correspond to the superposition of steady and dynamic contributions, representative of in-flight gust encounters. A rendering of the model in the test section is shown in Figure 17.



Figure 17: Rendering of the D1-9 assembled in the Polimi's large wind tunnel section

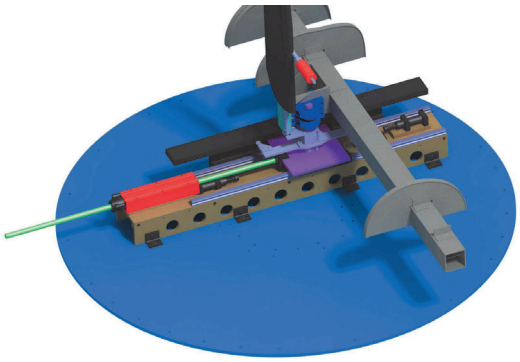

Figure 18: Detail of the pitch-plunge-WAS mechanism

The assembled model, outside the wind tunnel, is shown in Figure 19. It span reaches 2.7 meters.



Figure 19: Model assembled in Polimi's laboratory for dry tests

The test article is equipped with multiple control surfaces, actuated with servo actuator [13], and a distributed set of sensors, enabling the implementation and testing of different control laws in closed-loop conditions. The experimental campaign focuses on the evaluation of the effectiveness of load alleviation strategies, the robustness of the control systems, and the interaction between structural dynamics and active control. Experimental activities in preparation to the wind tunnel test were performed in the Polimi's structural laboratory, including strain gauges calibration for load monitoring (bending and torsional moment) as shown in Figure 20 and a ground vibration test to investigate the dynamic characteristics of the wing .

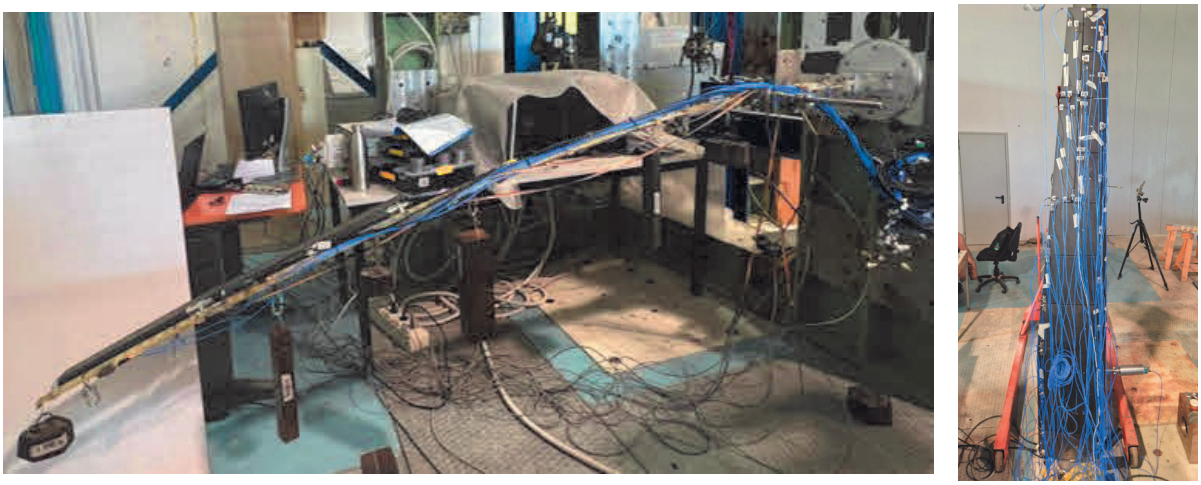

Figure 20: Wing spar during strain gauges calibration (left) and ground vibration test (right)

Wind tunnel testing of the aeroelastic model allows the reproduction of controlled aerodynamic disturbances, including gust-like excitations, providing a realistic environment for the validation of the control concepts. This enables the assessment of the reduction of dynamic loads and the overall improvement of the aeroelastic response of the wing.

The combination of full-scale structural testing and dynamically scaled aeroelastic experiments provides a comprehensive validation framework, supporting the assessment of both the techno-

logical feasibility and the aeroelastic effectiveness of the proposed active wing concept.

3.4 Wind Tunnel Facility

All wind tunnel experimental activities are carried out at the Politecnico di Milano Wind Tunnel (GVPM), a large-scale closed-circuit facility specifically designed for aerodynamic and aeroelastic testing.

The facility is equipped with multiple test sections, including a low-turbulence high-speed test section particularly suited for aeroelastic experiments. This test section has characteristic dimensions on the order of 4,m $\times$ 4,m $\times$ 4,m and allows testing at wind speeds up to 55,m/s, with low turbulence intensity.

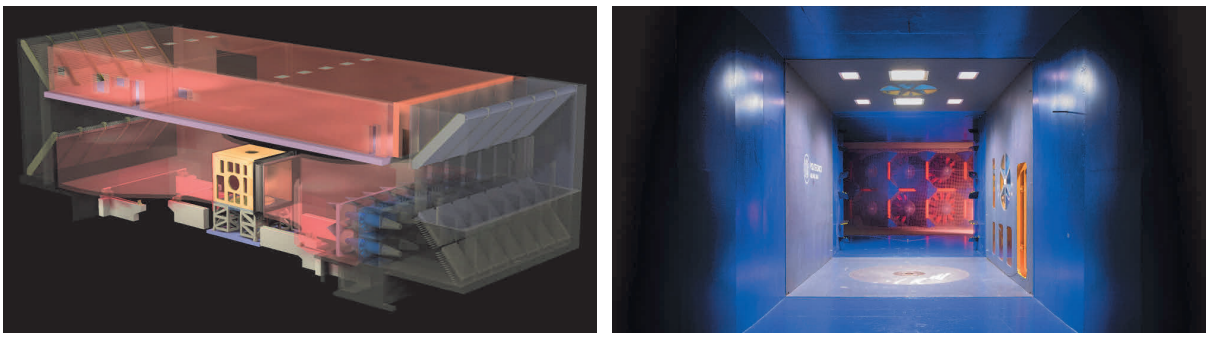

Figure 21: Politecnico di Milano large wind tunnel

The size of the test section enables the testing of relatively large-scale models, which is particularly advantageous for aeroelastic investigations where structural flexibility and dynamic similarity are critical. The facility is also equipped with advanced measurement systems, including multi-component balances, pressure measurement systems, and high-frequency instrumentation, enabling detailed characterization of both aerodynamic and structural responses.

From the perspective of the present work, the GVPM wind tunnel provides an ideal environment for the validation of both the full-scale morphing demonstrator and the aero-servo-elastic scaled model. In particular, the combination of high flow quality, large test section dimensions, and flexible instrumentation allows for the investigation of fluid-structure interaction phenomena under controlled and repeatable conditions.

The availability of this facility plays a key role in achieving the TRL5 objective, as it enables the experimental assessment of the proposed technologies in a relevant aerodynamic environment, bridging the gap between laboratory characterization and real flight conditions.

The test will be performed in June 2026 for both the morphing aileron and the aeroservoelastic demonstrator. The morphing aileron will be mounted on a force balance for load measures at its root, and the DIC will be used to reconstruct the deformed shape under relevant aerodynamic loads. The aeroservoelatic demonstrator will undergo an extensive validation test campaign for MLA controller, testing different MLA gain values and comparing the results with the numerical prediction. Discrete gust and turbulence will be simulated to experimentally validate the effectivness of the developed controllers in dynamic load reduction.

4 CONCLUSIONS

This work presents the results of the research activities carried out within the HERWINGT project, focused on the development of advanced aeroelastic technologies for future high-aspect-ratio regional aircraft wings. Although the investigated technological streams may appear as independent developments, the present work highlights how they are strongly interconnected and contribute to a common objective: enabling lighter, more efficient, and actively controlled wing architectures.

The increase of wing aspect ratio represents a key strategy to improve aerodynamic efficiency through induced drag reduction. However, such an approach inherently leads to increased structural flexibility and higher wing root bending moments. For conventional cantilevered configurations, this translates into a significant structural mass penalty, partially offsetting the aerodynamic benefits associated with higher aspect ratio wings.

Within this context, the adoption of a strut-braced wing configuration demonstrates the capability to limit the structural weight increase by introducing an additional load path between wing and fuselage, thereby reducing the bending loads acting on the wing structure. The presented results confirm the effectiveness of this architectural solution in mitigating the aeroelastic limitations associated with highly flexible wings.

At the same time, active load alleviation technologies demonstrate the capability to further compensate for the load increase associated with slender wing configurations. Through manoeuvre and gust load alleviation strategies, the structural loads acting on the wing can be significantly reduced, directly contributing to lower structural sizing requirements and improved aeroelastic behaviour.

The effectiveness of these active control strategies is enabled by the development of innovative morphing control surfaces. Compared to conventional hinged devices, the proposed morphing ailerons provide improved aerodynamic performance through continuous camber variation, while simultaneously reducing structural mass and actuation effort. In addition, the achieved dynamic bandwidth demonstrates the compatibility of the morphing technology with active aeroelastic control applications.

Overall, the presented results demonstrate how the combination of advanced structural concepts, adaptive aerodynamic technologies, and active control methodologies enables a new aero-servo-elastic design paradigm for future aircraft wings. The strong interaction between these technological pillars highlights the necessity of an integrated design approach, in which aerodynamic efficiency, structural behaviour, and control capabilities are addressed simultaneously rather than independently.

Finally, the experimental validation activities developed within the HERWINGT project, including both full-scale morphing demonstrators and aero-servo-elastic wind tunnel models, provide the foundation for the maturation of these technologies towards higher technology readiness levels and their future application to sustainable regional aviation.

ACKNOWLEDGEMENTS

This study is part of the Hybrid Electric Regional Wing Integration Novel Green Technologies (HERWINGT) project. This project has received funding from the Clean Aviation Joint Undertaking under the European Union's Horizon Europe research and innovation program under

grant agreement ID 101102010. Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the Clean Aviation Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them. The authors also gratefully acknowledge Hellenic Aerospace Industry (HAI), partner of the HERWINGT project, for its contribution to the design and manufacturing of the dummy wing-box structure.

5 REFERENCES

[1] HERWINGT Project (2026). Hybrid electric regional wing integration novel green technologies. `https://herwingt-project.eu/home` (accessed 2026-05-20).

[2] Ma, Y. and Elham, A. (2024). Designing high aspect ratio wings: A review of concepts and approaches. *Progress in Aerospace Sciences*, 145, 100983.

[3] Sohst, M., do Vale, J. L., Afonso, F., et al. (2022). Optimization and comparison of strut-braced and high aspect ratio wing aircraft configurations including flutter analysis with geometric non-linearities. *Aerospace Science and Technology*, 124, 107531.

[4] Cavagna, L., Ricci, S., and Travaglini, L. (2011). Neocass: an integrated tool for structural sizing, aeroelastic analysis and mdo at conceptual design level. *Progress in Aerospace Sciences*, 47(8), 621–635.

[5] Toffol, F. and Ricci, S. (2023). A meta-model for composite wingbox sizing in aircraft conceptual design. *Composite Structures*, 306, 116557.

[6] Cavalieri, V. and De Gaspari, A. (2026). Design optimization and virtual testing of a morphing aileron with high actuation bandwidth. *Aerospace Science and Technology*, 168, Part F(111110), 1 – 16. doi:10.1016/j.ast.2025.111110.

[7] De Gaspari, A. and Ricci, S. (2011). A two–level approach for the optimal design of morphing wings based on compliant structures. *Journal of Intelligent Material Systems and Structures*, 22(10), 1091–1111. doi:10.1177/1045389X11409081.

[8] De Gaspari, A., Cavalieri, V., and Ricci, S. (2024). Experimental and performance validation of a full–scale morphing droop nose design based on composite compliant structures. *Composite Structures*, 348(118502), 1 – 13. doi:10.1016/j.compstruct.2024.118502.

[9] Carossa, G. M., Roncolini, E., Cardenas-Mutis, T. E., et al. (2025). Preliminary design of an ultra efficient regional aircraft. In *Proceedings of the AIDAA Conference 2025*. Italy.

[10] Ripepi, M. and Mantegazza, P. (2013). Improved matrix fraction approximation of aerodynamic transfer matrices. *AIAA journal*, 51(5), 1156–1173.

[11] Fonte, F., Ricci, S., and Mantegazza, P. (2015). Gust load alleviation for a regional aircraft through a static output feedback. *Journal of Aircraft*, 52(5), 1559–1574.

[12] Toffol, F. (2021). *Aero-servo-elastic optimization in conceptual and preliminary design*. Ph.D. thesis, Politecnico di Milano.

[13] De Gaspari, A. and Mantegazza, P. (2024). Dual loop $pi^m pi^n$ control for an aileron positioning. *IEEE Access*, 12, 56120 – 56140. doi:10.1109/ACCESS.2024.3390557.

[14] Ricci, S., De Gaspari, A., Riccobene, L., et al. (2017). Design and wind tunnel test validation of gust load alleviation systems. In *58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*. p. 1818.

[15] Toffol, F., Marchetti, L., Ricci, S., et al. (2023). Gust and manouvre loads alleviation technologies: Overview, results and lesson learned in the framework of the cs2 airgreen2 project. In *19th International Forum on Aeroelasticity and Structural Dynamics (IFASD 2022)*. pp. 1–24.

[16] Ricci, S., Paletta, N., Defoort, S., et al. (2022). U-harward: a cs2 eu funded project aiming at the design of ultra high aspect ratio wings aircraft. In *AIAA Scitech 2022 Forum*. p. 0168.

COPYRIGHT STATEMENT

The authors confirm that they, and/or their company or organisation, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission from the copyright holder of any third-party material included in this paper to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and public distribution of this paper as part of the IFASD 2026 proceedings or as individual off-prints from the proceedings.