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EXECUTIVE SUMMARY OF THE THESIS

Experimental testing and validation of a full-scale high-bandwidth morphing aileron demonstrator

LAUREA MAGISTRALE IN AERONAUTICAL ENGINEERING - INGEGNERIA AERONAUTICA

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1. Introduction

To address the aviation sector's sustainability challenges, the European Union is driving the development of disruptive technologies to mitigate CO₂ and non-CO₂ emissions. Within the Clean Aviation framework, the HERWINGT project aims to develop innovative wing technologies for the future Hybrid-Electric Regional Aircraft (HERA), targeting a 50% reduction in fuel burn and a 90% reduction in net emissions by 2035 [2].

This thesis supports the manufacturing, assembly, and experimental validation and testing of a full-scale morphing aileron demonstrator, a key component within the HERWINGT framework. Addressing the "morphing paradox", the requirement for low in-plane stiffness for low actuation efforts and high out-of-plane stiffness for load-bearing, this prototype employs a compliant S-glass fibre skin driven by electromagnetic actuators via a modified Scott-Russell linkage. To provide a solid background, the thesis introduces various types of morphing technologies in aviation and categorises them based on their application areas. Furthermore, it includes a clear distinction between active and passive morphing materials, alongside an analysis of the main

state-of-the-art technological solutions in morphing aileron applications.

To provide the necessary context for the experimental campaigns, the thesis outlines the design and functionality of the prototype, previously developed by the research team [1].

The purpose of this executive summary is to outline the results in a structured manner. The document begins with a concise section explaining the main objectives and the overall functionality of the demonstrator. Following this, the summary presents the Coulomb-viscous friction model developed during the thesis, before discussing the results of the static and dynamic ground tests, performed to verify the alignment with numerical predictions and to explore the feasibility of adopting such a device for active control purposes. The wind tunnel tests are then outlined, with the preliminary results presented with the aim of replicating static evaluations under aerodynamic loads while formally assessing the overall aerodynamic performance. Finally, the conclusion reviews the achieved milestones and briefly highlights future research developments.

2. Demonstrator overview and objectives

The morphing aileron demonstrator comprises two independent S-glass fibre ailerons integrated into a dummy wing box, as illustrated in Figure 1.

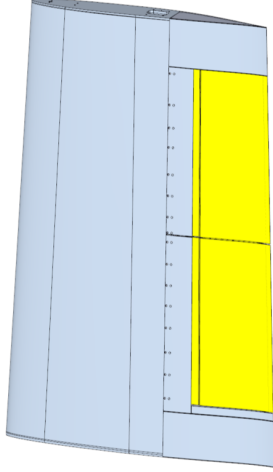


Figure 1: Pressure-side view of the morphing aileron demonstrator 3D model.

The complete model spans 2.5 metres, with each active surface covering a span of 1 metre. These ailerons are driven by two electromagnetic linear motors installed spanwise within the wing box. The actuators connect to the lower skins via two Scott-Russell kinematic mechanisms per aileron. A detailed view of this internal actuation system is provided in Figure 2. Conversely, the upper skin is clamped at 70% of the chord length, marking the start of the deformable portion of the aileron.

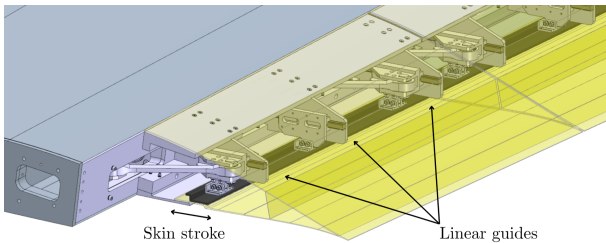


Figure 2: Detailed view of the internal actuation mechanism.

This prototype aims to exceed the performance of classical hinged ailerons by improving aerodynamic efficiency, reducing actuation forces and increasing structural efficiency. Specifically, the morphing structure must provide a lift incre-

ment equivalent to a reference deflection of $\pm 30^\circ$ on a conventional control surface [1]. The continuous and gapless profiles minimise parasitic drag and aerodynamic noise during flight manoeuvres. Furthermore, because the required lift variation can be achieved with a smaller overall deflection, the actuation system has to counteract less aerodynamic work and overcome a lower structural elastic resistance. This intrinsic mechanical advantage, combined with an optimised material distribution, decreases the required actuation effort, permitting the installation of lighter motors.

In addition to these static benefits, the prototype targets high-bandwidth dynamic performance. Demonstrating its operational capability up to 10 Hz would enable its application for gust load alleviation or flutter suppression.

To overcome the morphing paradox introduced in Section 1, the research team employed a multi-objective optimisation process. The first phase generated target external shapes optimised to minimise both aerodynamic drag and the required actuation loads. Subsequently, the team designed an internal compliant structure capable of replicating these geometries while minimising the least-square geometric error. This design provides the necessary flexibility for shape morphing while ensuring adequate stiffness to maintain the undeformed configuration without requiring continuous power.

The dynamic behaviour was also carefully tuned. When the lower skin is free to slide, the first natural frequency is positioned within the actuation bandwidth to reduce dynamic actuation forces relative to static applications. Conversely, when the actuation is locked, the natural frequency is significantly higher. This prevents the system from acting as a low-pass filter and ensures precise tracking of control commands without phase delays.

3. Friction model identification

The characterisation of the friction acting on the kinematic system within the operational bandwidth was realised by adopting a Coulomb-viscous mathematical model, analytically expressed as:

$$F_f(v) = F_c \operatorname{sgn}(v) + F_v v \quad (1)$$

Developing this model served three fundamen-

tal purposes: configuring the motor controller's feed-forward pre-filters to improve dynamic tracking accuracy, validating numerical predictions by mathematically removing the estimated friction from experimental force measurements, and updating future numerical models with realistic non-linear damping.

To identify the Coulomb F_c and viscous F_v coefficients, dynamic tests were conducted on the bare mechanisms prior to the installation of the compliant ailerons. The system was dynamically excited using pure sinusoidal trajectories at various frequencies and amplitudes. By recording the actual kinematics (position and velocity, via an encoder mounted on the actuators) and the total motor force via the Human-Machine Interface, the pure friction force was isolated using a time-domain dynamic equilibrium approach, which subtracted inertial and gravitational contributions from the total required force. The elastic force and aerodynamic forces were inherently null in this configuration.

To establish a robust parameter identification procedure during oscillatory regimes, where hysteresis and non-linear effects can emerge, a frequency-domain harmonic approximation was implemented. By extracting the fundamental amplitudes of the isolated friction force $F_{f, fund}$ and the velocity V_{fund} via Fast Fourier Transform, a linear regression was successfully applied across all tested conditions. The slope of this fitted curve directly provided the viscous coefficient, while the Coulomb coefficient was analytically derived from the intercept. As an illustrative example, Figure 3 presents the linear regression obtained for Axis 1, demonstrating the high accuracy of the adopted model with a correlation coefficient of $R^2 = 0.9322$.

4. Static ground tests

Following the friction model characterisation, static ground tests were conducted under zero-aerodynamic-load conditions to validate the morphing capabilities of the prototype. The actual deformed shapes were acquired using a Qualisys® optical motion capture system, tracking a spanwise and chordwise grid of reflective markers. By driving the system through a quasi-steady motion across its full operational range, the physical deformation was measured and compared against theoretical targets and Fi-

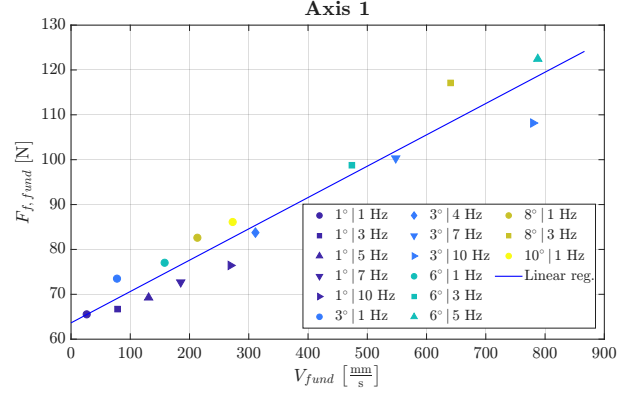


Figure 3: Linear regression of the fundamental friction force against fundamental velocity for the inner aileron (Axis 1).

nite Element predictions.

The optical measurements confirmed an excellent overall geometric agreement. The positive deflection successfully reached the 14° target, accurately following the theoretical shape. Conversely, the maximum negative deflection was limited to -14° , marginally relaxing the original -15° kinematic constraint. Figure 4 and Figure 5 present the comparison between the target, numerical and experimental shapes for these extreme deflections, validating the structural design and the manufacturing process.

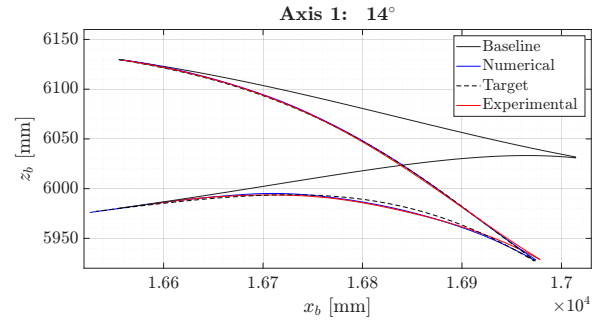


Figure 4: Maximum deflection comparison.

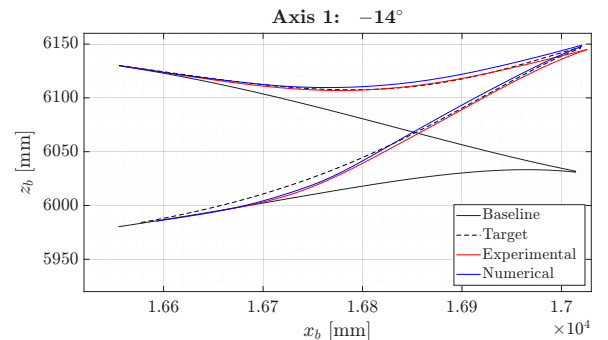


Figure 5: Minimum deflection comparison.

This quasi-static tracking also allowed for the derivation of direct and inverse polynomial laws, mapping the aileron rotation to specific motor stroke displacements. Implemented into the Human-Machine Interface, these laws enable closed-loop control and real-time angular feedback. However, this kinematic mapping is strictly valid for static or quasi-static movements. At this preliminary stage of the research, the high-frequency dynamic response of the compliant structure was not yet fully characterised, as the focus remained on defining the static baseline. Consequently, the specific structural attenuation and phase delays between the motor stroke and the true aileron deflection were addressed and quantified only in the subsequent dynamic testing phase.

Finally, the static tests evaluated the required actuation forces. Sweeping, in a quasi-static manner, the mechanism from the minimum to the maximum deflection and back revealed a force hysteresis driven by mechanical friction. Applying the previously developed friction model successfully eliminated this hysteresis for small deflections around the neutral 0° position. However, at larger deflections, the aileron exerts higher transverse forces on the linear guides, which locally increases the frictional loads. As the friction model underestimates these normal forces, the mathematical friction compensation does not completely eliminate the hysteresis at the edges of the cycle. Figure 6 compares the experimental motor force, both with and without the mathematical friction compensation, against the numerical data.

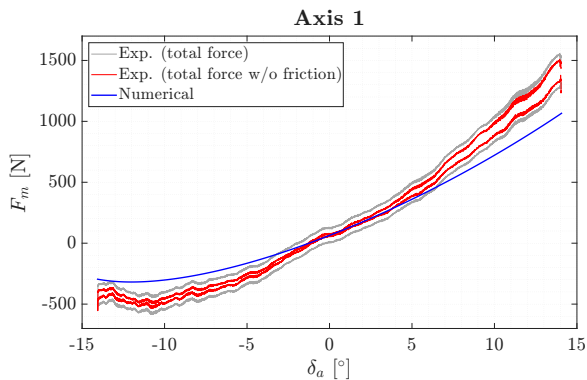


Figure 6: Axis 1: motor force comparison with and without friction compensation.

5. Dynamic ground tests

To assess the prototype's suitability for high-bandwidth applications, dynamic testing was conducted over a frequency range of 0 to 10 Hz. The morphing aileron was excited using sine sweep signals at various target deflections to verify the robustness of the results across different operating amplitudes. A primary objective was to empirically demonstrate the reduction in actuation effort induced by structural resonance, a phenomenon predicted during the design phase. To ensure the safety of the experimental setup during these preliminary campaigns, excitation amplitudes were limited: sweeps up to 10 Hz were performed with amplitudes of 1.5° , while larger deflections of up to 3° were restricted to frequencies below 7 Hz.

As mechanical friction introduces non-linear damping that masks this dynamic benefit, the friction component was mathematically subtracted from the total motor force using the previously derived Coulomb-viscous model. The frequency response analysis revealed a distinct anti-resonance peak in the required friction-deducted motor force at approximately 5.4 Hz. At this specific frequency, structural flexibility and inertia act in synergy with the actuation, significantly reducing the dynamic forces compared to static holding requirements. To confirm that this force reduction is a physical characteristic of the compliant aileron assembly, the bare actuator was tested in isolation; as shown in Figure 7, the response of the bare system lacks this anti-resonance notch, proving that the observed load reduction is driven by the dynamic coupling of the compliant structure with the actuation system. This result confirms that having an eigenmode within the dynamic bandwidth effectively lowers the actuation loads, a behaviour consistently observed across all tested excitation amplitudes.

Furthermore, the system exhibited excellent kinematic tracking. The dynamic response demonstrated no significant phase delays or magnitude deviations (i.e., amplification or attenuation) between the commanded motor stroke and actual aileron rotation across the entire 0 to 10 Hz bandwidth (Figure 8). The structure reacted accurately to high-frequency inputs without instability, confirming its potential for active control strategies.

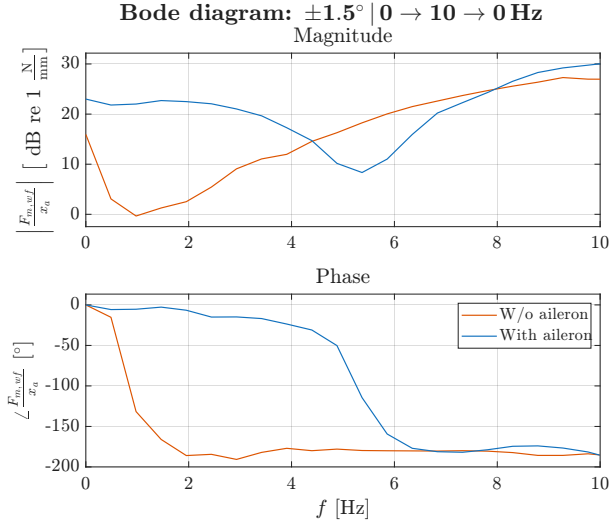


Figure 7: Frequency response of the actuation force without friction, highlighting the attenuation near the 5.4 Hz structural resonance.

6. Wind tunnel tests

The final experimental phase comprised wind tunnel testing within the GVPM facility. This campaign aimed to validate the morphing aileron's performance under aerodynamic loads. The demonstrator mounted in the test section is illustrated in Figure 9.



Figure 9: Morphing aileron demonstrator at minimum deflection, viewed from the pressure side.

The thesis reports the preliminary results of the testing campaign, focusing primarily on the aerodynamic characterisation and the quasi-

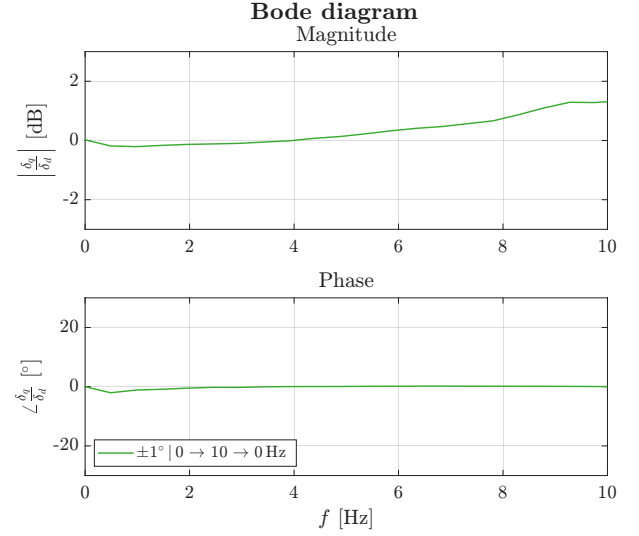


Figure 8: Dynamic tracking performance: relationship between the commanded stroke and actual aileron deflection across the 0–10 Hz bandwidth.

static actuation loads. Initially, the lift and drag coefficients, alongside the aerodynamic polars, were evaluated across various angles of attack and aileron deflections. The free stream velocity was specifically selected to ensure all structural configurations safely remained within the load limits of the aerodynamic balance.

Subsequently, the actuation forces were measured by commanding the ailerons through complete deflection cycles at a suitably low actuation speed. This quasi-static approach ensured that the flow field could be treated as steady at each instantaneous deflection angle. These force evaluations provided crucial insights into the limitations of the previously developed friction model when subjected to aerodynamic loading. Unlike the wind-off scenario, the mathematical compensation could not fully eliminate the force hysteresis, even at zero deflections where the baseline model was initially tuned. This discrepancy arises because the current formulation neglects external aerodynamic loads. To improve friction estimation, future iterations of the model must incorporate the variation in normal reaction forces based on the instantaneous position of the actuation mechanism, alongside the proportional increase in these normal reactions induced by the external pressure distribution.

Finally, the structural deformation under load was recorded using a Siemens Digital Image Cor-

relation (DIC) system, exploiting a speckle pattern applied to the aileron skin. From a static perspective, these optical measurements are essential to evaluate physical shape retention and identify any deviations from the baseline wind-off geometries. Furthermore, the DIC system tracked surface variations over time to support the dynamic evaluations in the presence of unsteady aerodynamics. However, the comprehensive data processing and analysis of these static and dynamic optical measurements fall outside the scope of this thesis due to time constraints, remaining a primary subject for subsequent research.

7. Conclusions and future developments

This thesis has demonstrated the feasibility of full-scale morphing ailerons as an efficient alternative to conventional hinged control surfaces. By integrating S-glass fibre compliant skins with electromagnetic actuators and Scott-Russell linkages, the prototype achieved target aerodynamic profiles and validated the proposed structural design principles.

Experimental campaigns provided a performance baseline for the system. A Coulomb-viscous friction model was developed to account for internal dissipative forces. This model was implemented in the control logic as a feed-forward pre-filter to improve tracking accuracy. It was also used to mathematically remove the friction contribution from the experimental motor forces, enabling a direct correlation with the numerical model, which yielded matching results. Furthermore, ground tests confirmed high-bandwidth kinematic accuracy and demonstrated that structural resonance at 5.4 Hz reduces the dynamic actuation effort. Although the structural anti-resonance was initially masked by internal friction, subtracting the modelled friction from the experimental actuation forces isolated the phenomenon, revealing the expected dynamic behaviour. This outcome highlights that to avoid offsetting the dynamic advantages of the resonant system, dissipative forces must be accounted for and mitigated during the design phase.

Finally, the wind tunnel campaign established an aerodynamic baseline and allowed the analysis of actuation forces under aerodynamic loads.

Future work will focus on achieving a comprehensive numerical-experimental correlation to refine the predictive accuracy of the numerical model. This process includes implementing the derived friction data to introduce realistic nonlinear damping, and post-processing the Digital Image Correlation data to verify shape retention under steady and unsteady aerodynamic conditions. Additionally, since the wind tunnel tests showed that external pressure distributions alter the internal mechanical friction, the current friction model requires further refinement: it must be extended to account for load-dependent normal reactions and kinematic variations as a function of the aileron rotation angle and the external aerodynamic forces. Ultimately, this research establishes a solid foundation for the industrial maturation of continuous-morphing architectures for next-generation regional aircraft.

References

- [1] Vittorio Cavalieri and Alessandro De Gaspari. Design optimization and virtual testing of a morphing aileron with high actuation bandwidth. *Aerospace Science and Technology*, 168:111110, 2026.
- [2] EASN-TIS. A pioneering wing design for a hybrid electric regional aircraft with a maximum capacity of 100 seats and a range of 500 km to 1000 km, 2023.