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Executive Summary of the Thesis

Numerical assessment and experimental testing of a full-scale morphing aileron and its large-bandwidth actuation system

Laurea Magistrale in Aeronautical Engineering - Ingegneria Aeronautica

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1. Introduction

The aeronautical industry has always been characterized by a strong tendency to continuous improvement to satisfy all the possible needs that have been raised over the decades. Aware of the new climatic changes that are present throughout the world, in the new century more attention has been paid to the environmental sustainability of the existing and in-development-phase technologies due to the significant contribution of the aeronautical field to global emissions. Thanks to recent developments in terms of material and technology, a new opportunity to reach the final goal could be the introduction of the *morphing* concept in aircraft design, originally proposed to improve the aerodynamic performance of aircraft during take-off, landing, and cruising, and now utilized also for enhancing flutter suppression and load alleviation.

Following the trend towards greener technologies in the aviation sector, the European Clean Aviation Joint Undertaking funded the HERWINGT project, which was developed to address new wing design concepts for a subsonic Hybrid Electric Regional Aircraft (HERA) with up to 100 seats and a range of 500–1000 nautical miles [2].

Within this framework, the present thesis was carried out as part of the activities conducted by Politecnico di Milano, focusing on the experimental analysis of a full-scale physical model representing a portion of the aircraft wing equipped with a morphing aileron. These experimental investigations were followed by numerical analyses based on fluid–structure interaction (FSI) simulations, aimed at studying the aerodynamic behavior of the airfoil section under oscillatory motion of the morphing aileron. The goal was to obtain numerical results suitable for validation through future wind tunnel tests.

In addition to these activities, a numerical analysis of the airfoil equipped with the morphing aileron under off-design conditions was conducted through an optimization process in the transonic flight regime. This analysis, which focused on the methodological details, highlighted the excellent aerodynamic performance and adaptability of the airfoil under varying flight conditions.

2. State of the Art

Morphing takes inspiration from the natural world, observing birds changing their wing shapes in response to the natural instinct of seeking a configuration that demands less effort during their time spent suspended in the air. Thus, technologies have been developed to modify the aerodynamic shapes of aerial vehicles, enabling them to adapt to varying flight conditions, achieve desired aerodynamic loads, and, more broadly, enhance overall performance. These possibilities have driven researchers worldwide to study, develop, and test new solutions that incorporate morphing in various ways, as better outlined in the following paragraphs, and which potential applications extend beyond aerospace into sectors such as agriculture, medical devices, energy systems, defense, and adaptive manufacturing. In these domains, morphing technologies can be further optimized to improve production efficiency, operational reliability, and adaptability [7].

Given the wide variety of existing aerial vehicles and technical solutions, there is no single standard approach to introducing the concept of morphing in the aeronautical field. However, the most extensively studied solutions can be summarized as follows:

- *Wing planform alteration*:
  1. Wing span resizing.
  2. Chord length variation.
  3. Sweep angle change.
- *Out-of-Plane transformation of the wing* [7]
  1. Airfoil camber changing.
  2. Wing control surface morphing.
  3. Lateral wing bending.
  4. Wing twisting.
- *Airfoil profile adjustment.*
- *Tail morphing.*

The study and development of continuously changing configurations required substantial advancements in the materials and mechanisms capable of enabling such shape variations without increasing internal stresses or causing functional damage. The most relevant adopted materials are polymeric skins, Electro-Active Polymers (EAPs) skins, Shape Memory Polymers (SMPs) skins, and the most broadly applied ones—the composite material. In fact, the application described in this work considered a morphing aileron characterized by a fiber-glass skin that represents a good trade-off between expenses and overall performance. In fact, they match the most common requirements for morphing materials, such as high elasticity, mechanical strength, toughness and out-of-plane stiffness while presenting low in-plane stiffness and hysteresis [4].

3. Study Case Description

This thesis work takes place in the development of a wide European project denominated HERWINGT (Hybrid Electric Regional Wing Integration Novel Green Technologies), which develops key technologies to address new wing design for a HERA. In fact, it will conduct the manufacturing, assembly, structural concepts and processes, concept studies, configuration and architecture trade-offs for a full wing component to be applied on a HERA with up to 100 seats and a range of 500–1000 nm [2]. The design process is challenging due to the necessity to incorporate new technical solutions, relevant to the wing systems, and translated into technological objectives:

- Deliver an innovative wing design for a HERA.
- Demonstrate a minimum fuel reduction of 15% due to wing aerodynamic improvements.
- Demonstrate a structural weight reduction of at least 20% when compared to a state-of-the-art (SoA) wing through the introduction of more integrated systems and new material technologies at the component level.
- Analyze the reduction potential of CO2 and all other relevant Greenhouse Gas (GHG) emissions.

Here comes the Politecnico di Milano's contribution with the main goal of replacing the traditional hinged aileron with a morphing aileron capable of performing the same lift variation due to a maximum rigid rotation of $\pm 30°$ in different flight conditions, to guarantee roll performance while minimizing the aerodynamic drag and the total actuation force.

Additionally, the morphing aileron is required to achieve a maximum bandwidth of 10 Hz, so that the device can be used for active control purposes.

To meet these requirements, an aerodynamic de-

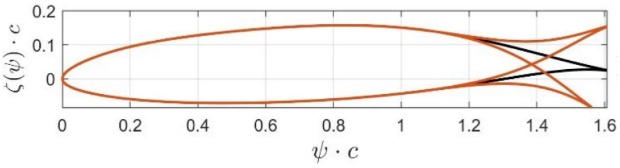

Figure 1: Final aerodynamic baseline and target shapes, i.e. maximum deflections, of the aileron wing section.

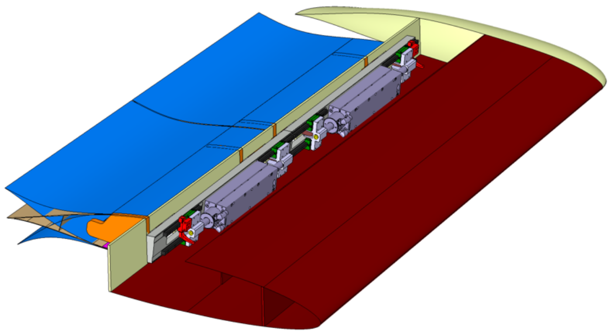

Figure 2: Wind tunnel demonstrator CAD representation.

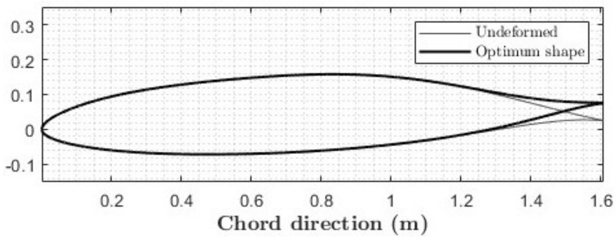

Figure 3: Final optimum shape in transonic flight.

sign process was carried out within Politecnico di Milano, resulting in the optimized airfoil profile, reported in Figure 1, capable of achieving the target performance of a conventional aileron. This phase was then followed by a structural design process aimed at fulfilling the aeronautical structural requirements, performing topology optimization in order to obtain the shapes defined during the aerodynamic design phase [1]. To verify the outcomes predicted during the design phase of the aileron skin, the full-scale experimental model, subject of this thesis, was designed in detail, achieving the geometry represented by the 3D model shown in Figure 2.

4. Airfoil Shape Optimization in Off-Design Conditions

Following the definition of the target aerodynamic shapes defined during the initial design stage of the HERWINGT project, in this thesis work a deeper geometric analysis of the airfoil profile was performed studying the off-design behavior of this 2D profile. In fact, the geometric characteristic of the airfoil developed for the HERWINGT project suggests the possibility to obtain relevant aerodynamic performance in off-design flight regimes. The optimization process was developed using a `Matlab` code integrated with the `SU2` CFD solver to perform the necessary aerodynamic investigations.
The optimization aimed to maximize the aerodynamic efficiency of the airfoil under transonic flight conditions, characterized by a Mach number $M = 0.75$ and a flight altitude of $h = 7620$ m.
An optimization constraint was imposed to maintain the lift coefficient above a minimum threshold equal to the baseline value ($C_{L_{ref}} = 0.2981$).
The optimization process was therefore performed by acting only on the parameters directly controlled by the pilot, namely the angle of attack (AoA) and the equivalent deflection of the morphing control surface (δ_{TE}), thus the baseline configuration corresponds to the airfoil profile at $AoA = 0°$ and $\delta_{TE} = 0$.
This optimization was also carried out to perform a methodological comparison between two different optimization algorithms (Sequential Quadratic Programming SQP, and Interior-Point) and among various methods used for the computation of the gradients of both the objective and constraint functions, which were needed for the optimization function. Through this optimization procedure, an optimal configuration was identified with AoA $= 4.26°$ and $\delta_{TE} = -5.89°$ (associated shape is reported in Figure 3), providing an increase in aerodynamic efficiency from an initial value of 12.573 to an optimized value of 25.320. This result highlights the excellent off-design performance of the airfoil analyzed in this thesis. Such improvement is further confirmed by the variation of the pressure coefficient (C_P) between the baseline and optimized configurations reported in Figure 4, which shows a significant reduction in the intensity of the shock wave and, consequently, in the associated drag.

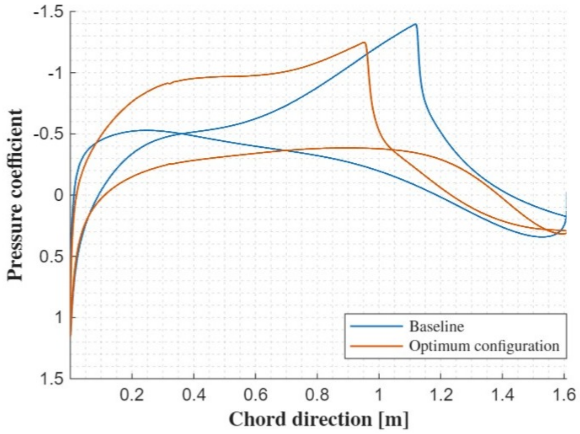

Figure 4: C_P comparison between the baseline and optimum configurations in transonic flight.

5. Experimental Tests of the Actuation System

The main part of this thesis consists of the experimental tests carried out on the full-scale physical model of the morphing aileron, focusing on the actuation system available at this stage of development. Indeed, the complete aileron model, intended for future wind tunnel tests, was not yet available; instead, only its rear portion was accessible, characterized by the actuation system and the associated mechanism, along with the electric motor for the outer section. The tests performed on this configuration also aimed to identify possible improvements to be implemented later in the production phase of the inner portion of the model, which is larger due to the wing tapering. To support this activity, the CAD model was finalized, followed by the manufacturing of several components, including the aileron skin.

In addition to a preliminary analysis of the actuation system behavior under simple imposed displacements, dynamic analyses were performed by imposing a sinusoidal oscillatory motion around a reference position, both at constant and variable frequency. For this purpose, the user interface provided by the control panel manufacturer was used, together with a `LabView` program for generating the voltage signal and the LinMot Talk software [6] for acquiring the motor motion data as well as for setting the control parameters required for the tuning of the control system.

The main objective of these experimental analyses was indeed the tuning of the motor drive control loop, schematically represented in Figure 5. The kinematic chain was analyzed in order to quantify the effective moving masses, and the motor response was investigated under imposed oscillatory motion with maximum deflections of approximately ±5° at different frequencies. In this way, both the gravitational component[1] and the frictional resistance force were compensated through appropriate feed-forward (FF) terms. The latter, according to the manual [6], is based on a Coulomb and viscous friction model, which includes the Coulomb friction F_c and the viscous coefficient F_v, multiplied by the velocity[2], as expressed in Equation 1.

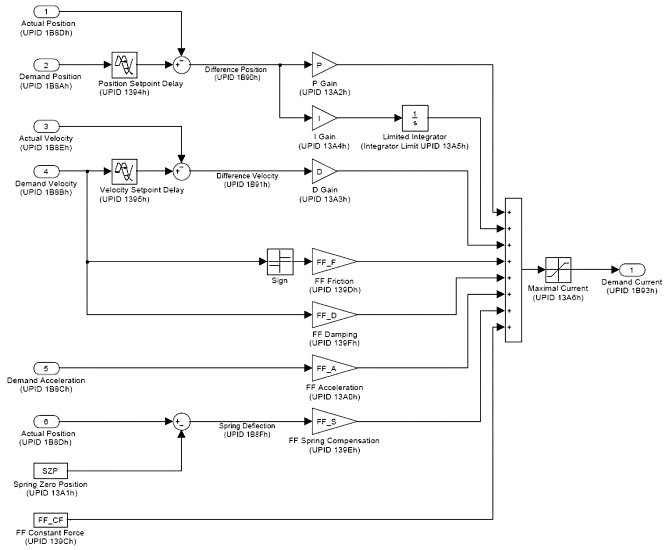

Figure 5: Control Structure of the Position Control System [5].

$$F_f(v) = F_c \operatorname{sign}(v) + F_v\, v \tag{1}$$

Then, through a frequency-domain analysis of the fundamental amplitude of the actual friction force[3], it was possible to obtain the coefficients' values $F_v = 76.08\,\mathrm{N/(m/s)}$, $F_c = 30.84\,\mathrm{N}$. After performing an experimental validation of the

[1] Gravitational component due to the vertical direction of the motor's linear motion.

[2] The velocity v used to compute the friction force is the actual velocity measured during the experiments. It is essential to consider this value rather than the expected velocity, since the former corresponds to the actual force value.

[3] The actual friction force was computed as difference between the actual force and the theoretical one that takes only into consideration the gravitation and inertia terms.

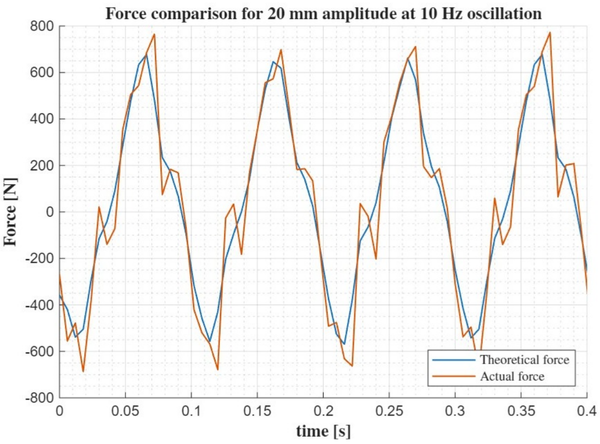

Figure 6: Comparison between the theoretical total force and the actual force analyzed, without the friction compensation enabled, for oscillation amplitude of 20 mm at 10 Hz.

obtained coefficients, it could be stated that the adopted model represents a good approximation of the actual force, as showed by the example reported in Figure 6. These values were then introduced in the drive settings. Furthermore, the tuning of the PID coefficients was performed in order to achieve the best possible motor response under imposed motion within the operating frequency range of the aileron [0 – 10 Hz]. To this end, both the amplitude and phase of the transfer function, relating the imposed motion to the actual one, were analyzed during experimental tests in which a sinusoidal motion with frequency sweep was imposed, with maximum deflections of ±5°.

These tests allowed verifying the excellent dynamic behavior of the motor and the limited influence of the PID coefficients on the actual response, given the high intrinsic performance of the system. Figure 7 shows the amplitudes of the transfer functions corresponding to the most relevant P and D coefficient values[4]. It can be observed that the deviation between imposed and actual motion remains well below the target range of ±3 dB.

Based on the evaluation of both amplitude and phase over the entire frequency range, the final tuning values were set to $P = 7.5$ and $D = 10$ for the future tests.

[4]The integral term I was always set to zero, since its increase led to a noticeable degradation of performance.

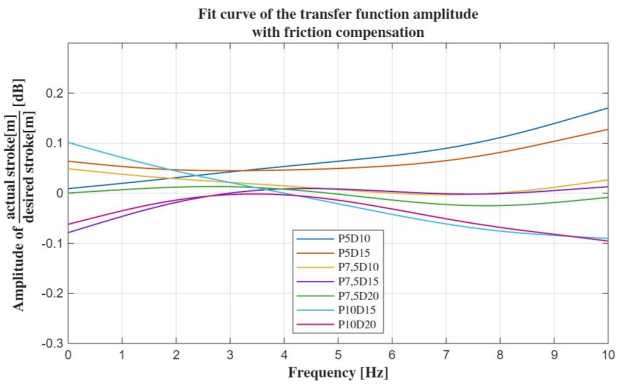

Figure 7: Fitted curves of amplitude of the transfer function for different PID coefficients values.

6. Computational Aerodynamic Analysis for Supporting Future Wind Tunnel Experiments

As support to the experimental analyses, it was decided to perform a preliminary numerical analysis aiming to obtain initial results of the structural (FEM analyses) and aerodynamic (CFD analyses) characteristics of the model to be validated through Wind Tunnel tests that will be performed at the university's facilities in the following months.

This numerical study is performed through high-fidelity simulations (i.e. FEM and CFD), which are highly demanding in terms of computational time, power and, most of all, precision in the definition of the model's properties from both the structural and aerodynamic standpoints.

Our study is limited to the wing region characterized by the morphing control surface. Therefore, 2D models of the relevant section are available for testing, i.e. the last 2 m of aileron and 2.5 m of wing (the outer wing portion including the aileron and wingtip).

Since only the 2D model of a section of the wing portion of interest was available (the last 2 meters of the morphing aileron with the corresponding 2.5 meters of the outer wing portion), a series of Fluid–Structure Interaction (FSI) analyses were performed on the airfoil.

This work was based on the in-house FSI coupling code developed at Politecnico di Milano [3], which enables the interface between the

structural FEM model and the CFD model. In the present case — which represents only one of the possible applications of this code [3] — the tool was used to impose the prescribed motion on the morphing aileron, resulting in mesh deformation of the aerodynamic domain and the execution of unsteady CFD simulations under sinusoidal oscillation of the control surface.
Given the final purpose of these simulations, they were carried out with wind-tunnel physical parameters, namely at sea-level conditions and with a free-stream velocity of $V = 35\,\mathrm{m\,s^{-1}}$. The simulations were performed for both the morphing and rigid aileron configurations, using dedicated FEM models, and included both steady-state analyses (necessary to obtain reference conditions) and unsteady analyses with imposed motion.
The most relevant simulations, which are the focus of this section, involved sinusoidal oscillations of the ailerons with maximum deflections of 4° and 5° for the morphing aileron and 5° for the rigid one, all oscillating about the undeformed equilibrium configuration. These oscillations were performed at different frequencies to cover the entire operational bandwidth expected for the aileron, i.e. the range [0 - 10 Hz].
To allow for general observations and comparisons, the reduced frequency parameter was used, defined as $k = \frac{\omega L}{V}$ where $\omega = 2\pi f$, L is the characteristic length of the model ($L = 1.608\,\mathrm{m}$), and V is the free-stream velocity ($V = 35\,\mathrm{m\,s^{-1}}$).
The tested reduced frequencies were $k = 0.289, 0.577, 1.443, 2.309,$ and 2.887, corresponding respectively to oscillation frequencies of 1, 2, 5, 8, and 10 Hz.
For each simulation, aerodynamic coefficients were collected to obtain results suitable for future validation against wind-tunnel data, as well as to extract information that cannot be obtained experimentally, with the experimental setup adopted for the wind tunnel tests, such as the analysis of hysteresis cycles of the aerodynamic coefficients induced by the aileron motion and the comparison of performance between the morphing and rigid (hinged) ailerons. Indeed, the latter configuration was modeled numerically but no experimental prototype was available for physical testing.

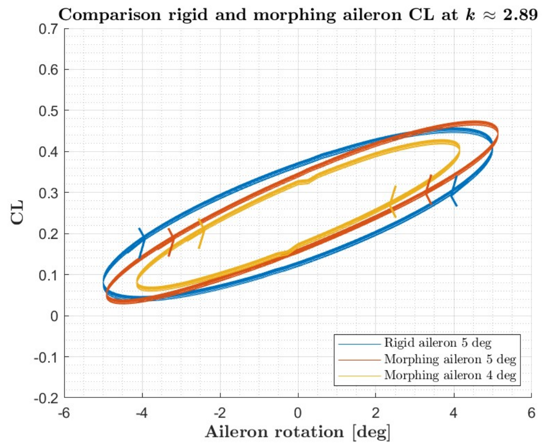

Figure 8: Comparison of C_L hysteresis cycles for both morphing and rigid aileron in the case of the sinusoidal motion at maximum oscillation frequency.

These simulations therefore provided valuable insights for future validation activities and for performance comparisons that would otherwise not be achievable experimentally.

The obtained results, visually represented by the example shown in Figure 8, highlighted the dependence of the aerodynamic coefficients on the reduced frequency. These simulations not only demonstrated an excellent agreement with Theodorsen's model [8], but also highlighted the superior aerodynamic performance of the morphing aileron compared to the rigid one, as evidenced by the higher aerodynamic coefficients achieved for the same oscillation amplitude and by the smaller performance decay with increasing k.

7. Conclusions

Considering what has been up to now reported, this thesis work focuses on a specific type of morphing solution highlighting, through both experimental tests and numerical simulations, the outstanding capabilities and potential of this technology. The tuning of the control system unlocked a dynamic behavior of the physical model that shows the capability of this solution to allow wider control frequency bandwidth.
The enhancement of the aerodynamic performance with respect to the hinged control surface was stated to be not only a design assumption, but a clear statement proven in both static and dynamic conditions with an overall increment of

the lift and moment coefficients at equal angle of attack, while decreasing the corresponding drag. Furthermore, the smooth shape variation proved its adaptability in totally different flight conditions ($M = 0.75$) with respect to the design flight regime ($M = 0.3$).
It can be concluded that morphing technologies, particularly the developed morphing aileron, could be an effective solution for decreasing the environmental impact of the aeronautical industry while increasing the achievable performance.

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