Geometric Functional Specification for a lifting Airfoil

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Abstract. This paper presents a possible functional geometric specification for a lifting airfoil including the definition of functional tolerance limits (tolerance synthesis) and an associated inspection procedure. The proposed specification scheme is derived from the analogy between the mating of the airfoil with a fluid field and the consolidated example of the mating of a prismatic element in its site. The airfoil thickness is defined as a non-constant size with non-constant tolerances and the airfoil shape is prescribed with a non-constant profile of a line tolerance applied to the median airfoil line. The tolerance synthesis is based on XFLR5 software and Computational Fluid Dynamics (CFD) simulations. The inspection procedure uses the data acquired with a laser probe elaborated in Geomagic Wrap, GOM inspect and MATLAB. The overall process has been applied to a case study allowing to define limits and proposing a set of possible improvements regarding, particularly, the geometric specification of the leading and trailing edges of the airfoil.

Keywords: Geometric Specification, Airfoil, Tolerance Synthesis, Geometric Inspection.

1 Introduction

Airfoils represent the cross-section of any object moving through a fluid aiming to generate lift. They can be divided into two main classes: blades, whose motion is determined by the mounting on a rotating shaft; and lifting airfoil that freely moves in the fluid.

For blades, the geometry influences the performance, meaning that a geometric deviation from its nominal – location, orientation, and form – will influence the fluid motion around the blade determining a change in performance. Furthermore, since they are physically mounted on a shaft a reference system for comparing the actual geometry with the nominal can be easily determined. For these reasons the golden standard to check blade conformity is the check for a line profile tolerance over the airfoil's upper and lower surface. At the same time, the literature provides a deep overview of the effect of geometric deviations on blades. Liu et al. statistically studied the effects of manufacturing deviations by performing CFD analysis based on the 3D scan of 35 actual blades [1]. However, the number of blades used in this study is limited; Garzon et al. suggest using the Principal Component Analysis (PCA) to model the geometric variations based on a limited sample simulating a larger sample with congruent deviations to statistically analyze the geometric effect on performances [2]. If a set of actual blades is not available, Melin et al. propose a method based on the perturbation of the Bézier curve control points for low-frequency deviations and perturbation of the actual curve coordinate for high-frequency deviations [3].

All these methodologies require high computational effort due to the high number of CFD analyses required; a solution is the use of surrogate models. Y. Wang et al. propose a surrogate model based on a multi-point Taylor expansion (MTE) using the Adjoint method [4]. X. Wang and Zou present a method based on the Non-intrusive Polynomial Chaos Expansion (NIPC) coupled with the Kriging surrogate model [5].

Other studies also investigate the effect of specific geometrical parameters, such as chord, stagger angle, leading-edge radius, etc., on the performances [6, 7].

These models create a relationship between the geometric variations and the performance, therefore can be used as a starting point for robust optimization methods aiming to obtain nominal designs non heavily influenced by the manufacturing deviations. Examples of applications based on the NSGA-II genetic algorithm [8, 9] and Gradient-Based method SQP (Sequential Quadratic Programming) [10] are proposed. Nevertheless, none of them answers the question of which is the admissible geometric deviation ensuring the targeted performance.

On the other hand, for lifting airfoils the performance influences the geometry: the airborne system is characterized by its flight envelope describing the admissible velocity-angle of attack configurations and, at a given velocity, the system will find its equilibrium (in steady flight) changing the angle of attack (α). Therefore, for lifting airfoils there is no intrinsic functional geometric alignment to check for geometric deviation, and the functional comparison among two different airfoils, e.g., the nominal and the actual one, can be only derived by its dynamic behaviour, as, for instance, the maximum lift that can be generated.

Even though robust optimization is a valuable design solution it requires a deep understanding of manufacturing deviation. For blades, literature can provide useful data to start with. For lifting airfoils, literature is lacking contributions regarding the geometric deviation effects. Therefore robust optimization is not a useful tool.

To fill this gap, this contribution aims to define admissible geometric deviations for lifting airfoils to fulfil functional requirements. To do so, the geometric characteristics to be geometrically and or dimensionally controlled will be identified, therefore determining a possible geometric specification scheme for lifting airfoils, a simplified procedure to assign tolerance values (tolerance synthesis) will be presented, and an inspection procedure to check for conformity will be proposed.

1.1 The Case Study

The overall procedure is applied to the airfoil of a fixed-wing drone designed and manufactured to compete in an international student competition, Air Cargo Challenge (ACC), by the Lift UP team from the University of Padua. The wing has a tapered planform with a total wingspan of 2.1 m. The wing section is based on a custom profile, called opt06v3, designed considering the following requirements:

- $C_{l,max} \geq 1.43$
- $f = 0.7C_{d,cruise} + 0.3C_{d,climb} \leq 1.025f_{nom}$
- 11%< t_{max}/c < 14%

Where $C_{l,max}$ is the maximum lift coefficient according to the lift definition $L = 0.5\rho V^2 c C_l$ (with ρ = fluid density, V = fluid velocity, and c = airfoil chord). Similarly, the coefficient of drag C_d is defined according to the drag equation $D = 0.5\rho V^2 c C_d$. Finally f_{nom} is the nominal value of f therefore a constant and t_{max} is the maximum airfoil thickness.

2 Geometric specification of airfoils

When it comes to the geometric specification of airfoil the most used approach is the use of line profile (or surface profile, 3D) tolerances, according to ISO 1660:2017 [11], to both upper and lower surfaces. This type of geometric tolerance can effectively control the location, orientation and form of the airfoil. The standards call for a constant or linearly variable tolerance zone. Petitcuenot et al. present the application of these types of geometric tolerances to airfoils [12]. They suggest the introduction of variable tolerance zone with 3D variations and also with non-linear variability that is useful for aerodynamic requirements.

The use of such tolerances is common for blades where a functional reference system (Datum System) can be easily determined, in addition such tolerances well represent typical blades functional requirements, such as components' assemblability and proper clearance For lifting airfoils its use does not effectively represent the functional requirements: a local defect exceeding the tolerance limits may have a smaller impact on performance when compared to a global defect within limits. This implies that an actual airfoil with an out-of-tolerance local defect will be rejected even if it meets the required aerodynamic performance.

To support this statement a test case based on a NACA4412 airfoil assuming a constant line profile tolerance of 1.4% of the chord length is conducted. Two scenarios are studied: a global deviation implying a less curved camber line with a maximum deviation of 0.65% of the chord (therefore within tolerance) and a local deviation of 0.75% of the chord, therefore out of tolerance, **Fig. 1**.a).

Using the XFLR5 software which implements the 2D Interactive Boundary Layer method (IBL) developed by M. Drela et al [13], the aerodynamic performances of the two airfoils were computed, obtaining the C_l as a function of α in **Fig. 1**.b). It can be seen that the global deviation has a greater impact on the performance (the graph is further away from the baseline), compared to the local one (the graph almost overlaps the NACA4412 baseline), confirming our statement. This result suggests not using the airfoil upper and lower surface to define a geometric specification scheme when aerodynamic performance requirements are involved but identifying other geometric characteristics that are more sensitive to the airfoil aerodynamic performance changes.

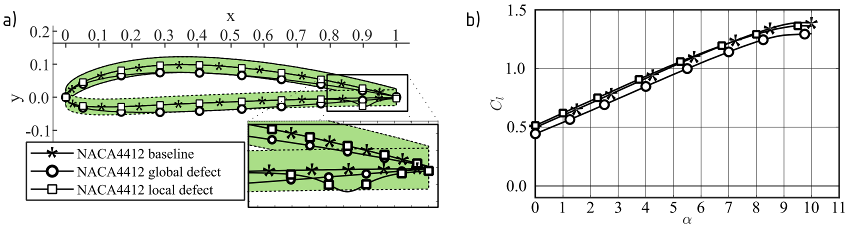

Fig. 1. Nominal NACA 4412 airfoil compared to the airfoil within tolerance with a global defect and the airfoil out of tolerance with a local defect (a), the deviations are magnified; the corresponding C_l over α graph for the three airfoil (b), it can be noted that the airfoil out-of-tolerance with a local defect is closer to the baseline compared to the one with a global defect.

3 Materials and methods

3.1 Tolerance specification

For lifting airfoils, given the functional requirements in subsection 1.1, the most important geometric characteristics are the camber line, affecting the coefficient of lift and its maximum value, and the thickness, conditioning the functional equation f. Moreover, any airfoil can be uniquely described by the camber line and thickness over the chord coordinate. For these reasons, the two geometric characteristics that are controlled by means of ISO GPS tolerances are the camber line and the thickness of the airfoil. To define the tolerance specification scheme for such geometries we start with a consolidated case: the mating of a prismatic element with its site (in 2D). To guarantee the assemblability, the width of the prismatic element is controlled by a size tolerance with the envelope modifier or a combination of a local size and a linearity tolerance to the median line. If we consider the second option, a local size can be defined as the distance between to opposite point (LP) or it can be defined by the size of a perfectly inscribed sphere (LS). The meaning of this specification can be seen in **Fig. 2**. The combination of a size and a linearity tolerance defines a boundary condition that can be used to assess the functional requirements. It is then possible to describe the actual geometry by graphing the actual thickness and the actual linearity deviation as a function of the axis' coordinate and comparing them to the tolerance zone, **Fig. 2**.c).

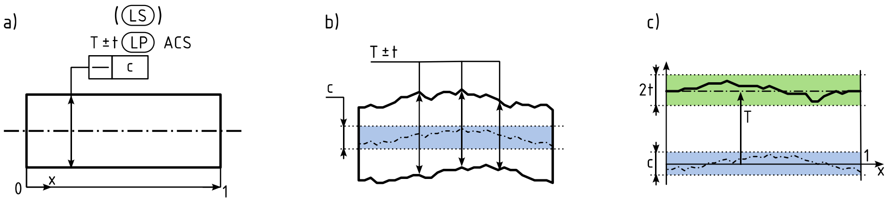

Fig. 2. – Possible specification scheme for a prismatic element in 2D (a), its interpretation (b), and a possible interpretation with the thickness and median line division mapped into a cartesian plane (c).

Looking at the airfoil, we have a mating between the airfoil itself and a fluid field. Furthermore, the geometric characteristics that were chosen, resemble the ones used for the prismatic elements. For these reasons, we have opted to adapt the specification schemes in **Fig. 2** to our case, see **Fig. 3**. The airfoil thickness, point by point, is defined through a linear size between the upper and lower surface, orthogonal to the chord. The camber line is, by definition, the derived geometry (median line) between the upper and lower surface of the profile, the same surfaces defining the thickness, therefore it can be considered as the median line of the prismatic element. The linearity tolerance has now no sense for the camber line and needs to be replaced by a "profile of a line" tolerance. According to ISO 1660:2017 "profile of a line" tolerances can be assigned also to derived geometries [11].

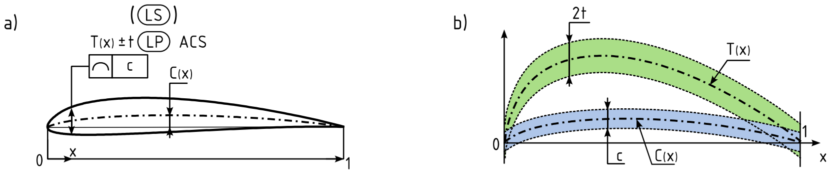

Fig. 3. – Proposed specification scheme for a lifting airfoil with constant tolerances (a), and its interpretation (b).

The main difference between the two cases is that for the airfoil the thickness and the camber (which is the vertical coordinate of the camber line) have different nominal values along the chord coordinate. Therefore the nominal values need to be replaced by functions as in **Fig. 3**. Regarding tolerance zone type, the ISO GPS standards only address constant tolerance zones. When evaluating the geometrical deviations between the real and actual airfoils, however, the alignment of the leading and trailing edges is required. Consequently, the allowable deviations at the leading and trailing edges must be zero, which is not the case with constant tolerance zones. Therefore, it was determined to define a non-constant tolerance zone as also suggested in [12], which ensures that the leading and trailing edges have zero allowable deviations..

The two different modifiers, (LP) or (LS), can describe two different conventions for the thickness definition: the English convention that defines the thickness as the distance between the lower and upper surface perpendicularly to the chord, (corresponding to the (LP) modifier) and the American one where the thickness is defined as the size of an inscribing sphere [14] (resulting in the application of the (LS) modifier).

3.2 Tolerance synthesis

The tolerance synthesis consists of the process of defining the tolerance limits that guarantee the fulfilment of functional requirements. To define the limits one way is to perform numerical simulation.

Different airfoils derived from the nominal one with different thickness distributions have been simulated with XFLR5 software to obtain C_d values in cruise and climb conditions so the functional equation f can be computed. Therefore, the tolerance limit for the thickness is determined by the modified airfoil that fulfils the functional requirement for f with the highest thickness increment compared to the nominal one. Similarly, the modified airfoil that fulfills the functional requirement for the maximum lift coefficient with the highest camber reduction determined the tolerance limit for the camber distribution. In this case the simulations were performed via CFD with the software Ansys Fluent using a structured mesh of 137’000 elements with wall resolved flow, and a kw-SST turbulence model and second-order upwind scheme for the spatial interpolation.Based on XFLR5 and CFD simulations the limits for the thickness and camber line are defined.

3.3 Inspection procedure

The actual wing manufactured by the LiftUP team was also inspected based on the geometric specification defined.

The geometry was acquired with a FARO® ScanArm 2 with a laser probe controlled by Geomagic Wrap®. The cloud of points was converted into a mesh and elaborated in GOM Inspect. Three different sections were sampled at 100 mm, 250 mm, and 400 mm from the wing root. The three sections were then elaborated in MATLAB® where the leading and trailing edges were geometrically defined and the profile oriented and scaled to have a unitary chord. The camber line was traced and the thickness was sampled along the chord. The actual values were then compared with the tolerance zones.

4 Results and discussion

From the tolerance synthesis - subsection 3.2 - the tolerance limit for the thickness was found to be $+7$ %, while for the camber line -7 %. Assuming symmetrical tolerances for both characteristics, both tolerances were set to be ± 7 % with respect to the nominal values. Therefore, the proposed geometric specification can be seen in **Fig. 4**.a), and the corresponding tolerance zone in **Fig. 4**.b). If the tolerance zone for the thickness is compared with the third functional requirement, subsection 1.1, no further restrictions are needed: the third functional requirement is always respected if the actual thickness is in tolerance.

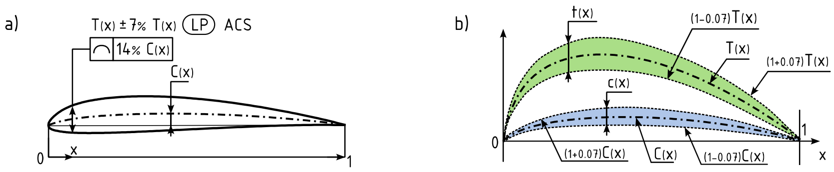

Fig. 4. Proposed specification scheme for the opt06v3 airfoil with the defined functional limits and non-uniform tolerance zones (a), and its interpretation (b).

The deviation of the actual thickness and camber for the three sections analyzed, obtained through the procedure described in subsection 3.3, overlapped with the tolerance zones can be seen in **Fig. 5**. Assuming x is the chord coordinate ($x = 0$ corresponds to the leading edge position), all three sections are within tolerance limits in the range $0.1 < x < 0.75$, except for the camber at $x = 0.7$ in section 3. The cause of this violation is the presence of the hinge between the fixed and moving parts of the wing (namely the flaps), which causes a discontinuity in the wing surface. It shall be determined whether this single out-of-tolerance point precludes functional requirements fulfilment; if this is the case then it's necessary to improve the manufacturing quality of the flap hinge. Therefore the possibility to apply filters to the sampled data might be convenient and shall be explored. For $x > 0.75$ the deviations increase more and more getting closer to the trailing edge. This is because the nominal airfoil has a sharp trailing edge while the actual airfoil has a finite thickness at the trailing edge for manufacturing limitations.

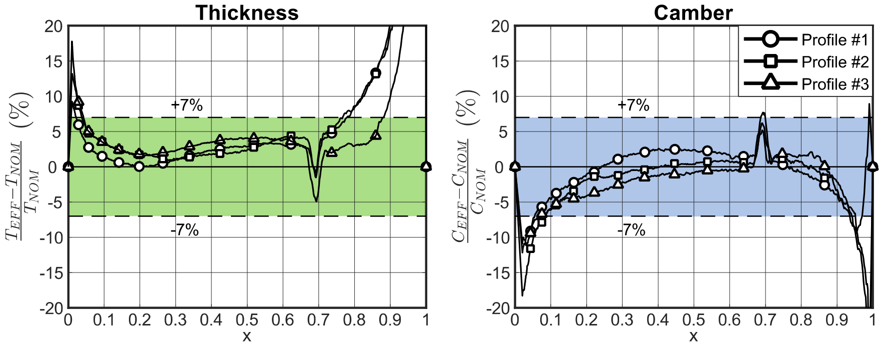

Fig. 5. – Relative deviations for all three sections analized; thickness deviation on the left and camber deviation on the right.

Two possible solutions can be identified to overcome this issue. On the first hand during the design optimization process, a constraint to the trailing edge shape could be implemented to obtain a nominal airfoil that can be actually manufactured. On the other hand, the proposed verification process could be limited only at x lower than a certain value. Similar but less extreme behaviour is also seen near the leading edge. The reason behind this can be traced back to the tolerances definition as a percentage: near the leading and trailing edges both thickness and camber have near zero values meaning that the width of the tolerance zone is near zero too. A solution can be the definition of a more complex tolerance zone being wider near the leading edge or alternatively, applying the verification only at x higher than a certain value.

5 Conclusions

This paper proposes a possible functional geometric specification scheme for an airfoil section from a fixed-wing drone and an inspection procedure. The specification scheme is based on a size tolerance to the thickness and a line profile tolerance to the camber line. The size tolerance is mapped into a line profile as explained in subsection 3.1 to fit the purpose.

The tolerances are defined based on Panel Method and CFD simulations. One of the main limits of the proposed approach is that the camber and thickness impact on performance is considered independent, while a correlation may be present. Therefore, there is the possibility to have a airfoil within tolerance limits not fulfilling functional requirements and vice versa. A statistical analysis shall be performed to validate and eventually adjust the tolerance limits as a second-level refinement.

The application to an actual case study allowed to highlight the procedure limits and at the same time it gave the opportunity to suggest a set of possible improvements. In particular, the proposed procedure performs well only far from leading and trailing edges, so it can be used in a middle range of x, for example $0.1<x<0.9$. However, since the leading-edge shape greatly affects the stall characteristics of airfoils, the proposed specification scheme should be modified including, for example, the leading-edge radius as a geometric characteristic to be verified. The extension to a 3D case may also be considered for a more comprehensive aerodynamic analysis. To conclude, the proposed specification scheme can be considered a valid first step towards the functional geometric specification of lifting airfoils when functional requirements involved the coefficient of lift and drag. Thanks to the proposed improvements, the future effectiveness of the method will increase too.

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