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COMPARISON OF AERODYNAMIC DESIGN METHODOLOGIES FOR MORPHING UAV WINGS

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ABSTRACT

This paper details two different methodologies for the aerodynamic design of a novel Unmanned Aerial Vehicle (UAV) rectangular wing.

The first approach is a one-step optimization process with just one morphing capability: wing-twist morphing, where the sections are twisted to apply the optimum loading distribution over the wing. This is a standard approach for single-objective wing design. This methodology has the advantage of following a simple logic and of being relatively rapid.

The second approach is a two-step optimization process that considers two types of morphing mechanisms: camber morphing and wing-twist morphing. The wing is generated via cambering the baseline section in order to apply the correct loading distribution and it is then twisted to further optimize its performance. This two-step methodology incorporates changes in wing-twist and wing-camber; it is slower than the one-step type, but it significantly increases the design-space.

This paper demonstrates that different methodologies for aerodynamic design can increase wing efficiency by taking advantage of morphing wing capabilities. The resulting wings provide improved performance when compared against a baseline wing design. Between the two wings, the one generated with the two-steps optimization methodology shows better performance: lower drag; delayed separation; lower design angle of attack.

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INTRODUCTION

The CHANGE project (Combined morphing assessment software using flight envelope data and mission based morphing prototype wing development) is a European project with the aim of designing and manufacturing a UAV with wing morphing capabilities. The main objective and innovation of this project is to study and develop a novel morphing UAV which integrates up to three different morphing mechanisms into a single wing and to demonstrate this new ability in flight. This UAV would take advantage of all the aerodynamic improvements achieved by adopting its wing shape according to the mission requirements of each flight phase.

Several studies of morphing UAV have been emerging in recent years with the aim of increasing the UAV performance. [Gano and Renaud, 2002] demonstrate that UAVs with wing-morphing capabilities benefit from an increase of endurance. Several papers indicate taht the use of camber wing morphing for UAVs is beneficial, see [Lafountain et al., 2003] and [Garcia Naranjo et al., 2013]. In CHANGE the overall aim is to reduce the required power to maintain the aircraft's flight. This is achieved with a morphing-wing with three morphing mechanisms installed.

The aerodynamic design of a wing for a morphing UAV is a complex matter, since there is the need to design a different wing for different flight conditions. Moreover, an aircraft with the capability to adapt itself to each given situation is likely to achieve better performance over a range of different missions than a specific aircraft designed to conduct one specific mission. The general idea behind a morphing wing aircraft is that for each phase of the mission an optimum wing design is defined, within the limits of the morphing mechanism. In CHANGE, three types of morphing will be utilised:

- **Wing-span retraction**: The wing span can vary from a maximum of 4 m to a minimum of 3 m.
- **Camber morphing**: Camber morphing is an intentional variation of the camber of the wing section from root to tip. There is no limitation on camber morphing.
- **Wing-twist morphing**: Twist morphing is an intentional variation of the angle of twist of the local wing section from root to tip.

In CHANGE a phased mission is defined as shown in Figure 1. The mission starts with the take-off, followed by a levelled high-speed cruise. After some changes in altitude the UAV must perform a loiter and finally a landing. The UAV spends 70% of the flight time in the loiter phase, which is the main phase in this project. This paper describes two methodologies for design of the loiter wing.

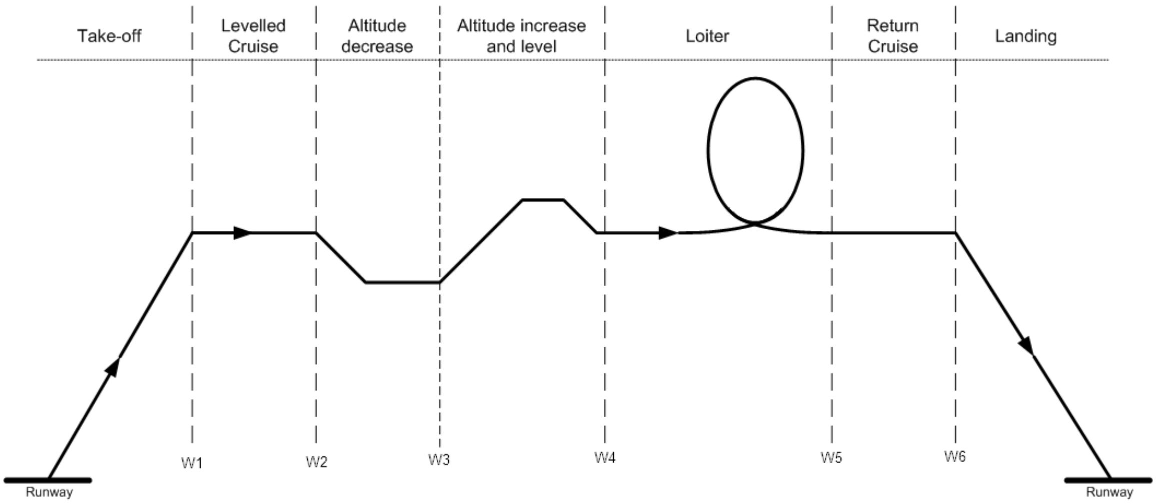


Figure 1: Mission profile

The remainder of this paper is structured as follows. In the section "METHODOLOGY" the detailed description of the two optimization processes are presented. In the section "DESIGN SPACE AND AEROFOIL SELECTION" the 2D analysis is presented. The next section is "WING DESIGN" in which wings designed with the two methodologies are presented. The section "RANS RESULTS" presents solutions of the high-fidelity RANS simulations. The last section presents the conclusions and the findings of this paper.

METHODOLOGY

Two different approaches are presented to generate a wing suitable for the loiter phase. Both methodologies are based on the design process presented in Figure 2.

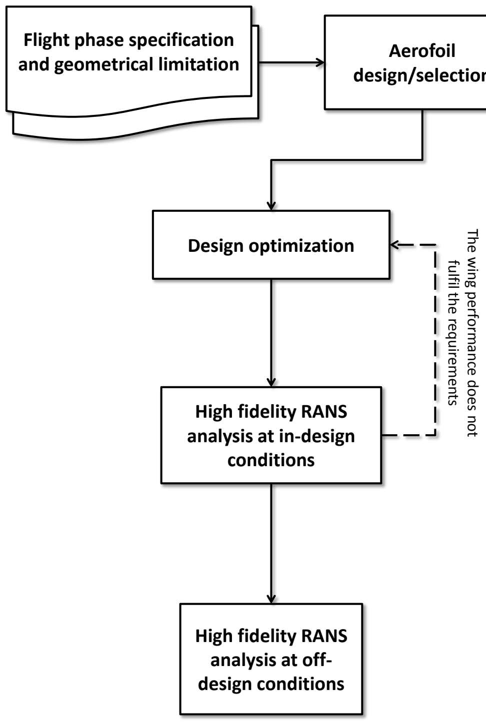


Figure 2: Design process

The first stage is the definition of the flight phase and the limitations of the shape achievable by the morphing mechanism.

The second stage is the aerofoil selection. A preliminary two dimensional analysis of aerofoils sections is performed to find the best candidate. The characteristics of the selected aerofoil depend on the flight conditions, on geometrical and manufacture limitations. The code selected for this analysis is a two dimensional Viscous Inviscid Interaction (VII) code. The VII code is ARA's in-house solver for rapid two-dimensional CFD analyses. This code is used at ARA for design and analysis of subsonic and transonic aerofoils. It combines a high-order full-potential method with an integral boundary layer method using a coupling technique.

After this stage the optimization process is performed. It is based on fast CFD analysis where a three-dimensional VII code is employed. After the optimization a high-fidelity check of the wing with Reynolds-Averaged Navier-Stokes (RANS) is performed for the design conditions. The standard tools for high-fidelity RANS simulations at ARA are SOLAR/TAU [Schwamborn et al., 2006] [Shaw et al., 2003]. SOLAR/TAU is a software widely used in European aerospace industry to solve the RANS equations for aerospace applications. If the RANS highlights problems in the design, then the wings will be optimized again until they reach the desired performance.

WING-TWIST DESIGN METHODOLOGY

The wing-twist design methodology is a design optimization process based on changing the wing-twist of wing sections in order to achieve the optimal loading distribution. The flow-chart of the wing-twist design methodology is presented in Figure 3.

The first step is defining the flight phase. Additionally, geometrical and manufacture limitations must be identified and defined in terms of achievable wing shape. The target of the optimization process, i.e. maximum endurance, must be defined at this stage.

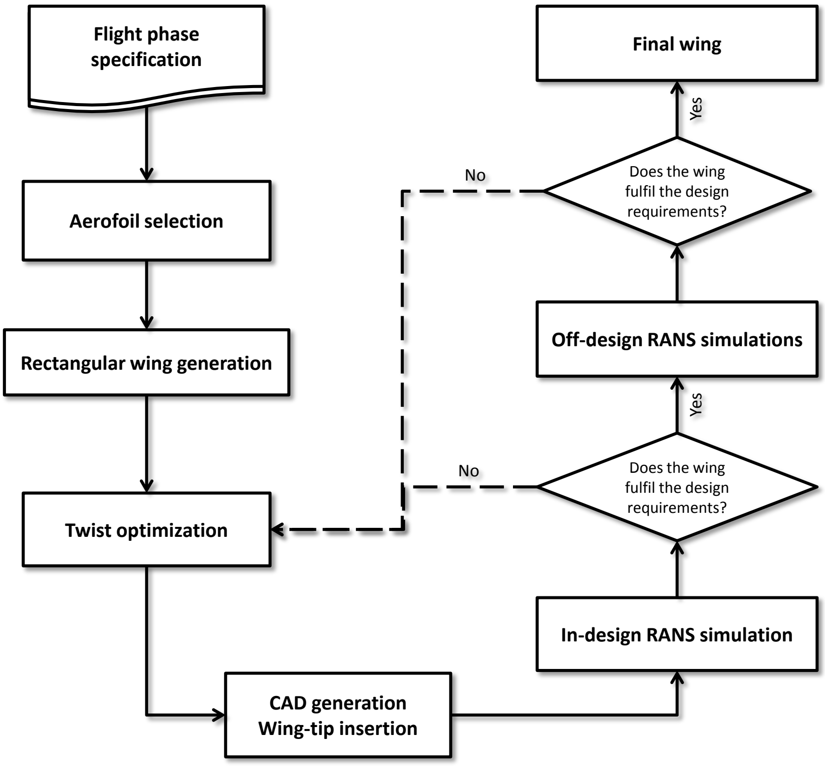


Figure 3: Twisted wing generation

The next step is the selection of the baseline aerofoil used to generate the baseline rectangular wing. The software used to select the aerofoil at the design condition is the two-dimensional VII code. The selected aerofoil is then used to generate a simple untwisted rectangular wing.

The rectangular wing is then divided along the span-wise direction into n sections to perform the optimization process with the three-dimensional VII code. The number of and the distance between sections are selected according to the complexity of the design. For the loiter wing, 10 equidistant sections have been used. The wing-twist is modified in the VII code in an iterative process to reach the optimum loading distribution.

After completing the optimization process the CAD model is generated and a wing-tip is added to the design. The wing-tip is added to the wing geometry to improve the quality of the RANS results. The new CAD is used to perform a simulation with SOLAR/TAU at the design conditions. If the wing fulfils the design requirements, off-design simulations with SOLAR/TAU are performed to analyse stall characteristics and off-design performance. The result of the design process is a CAD model and the aerodynamic parameters of a wing suitable for the flight phase.

WING-CAMBER DESIGN METHODOLOGY

The wing-camber design methodology is a two-step design optimization: in the first step the camber is modified, in the second the wing-twist is optimized. The flow-chart of this methodology is presented in Figure 4.

After defining the flight phase as for the wing-twist design methodology, the appropriate aerofoil is selected. The selected aerofoil will be used only in the central part of the wing, whereas other profiles are designed for the remaining wing sections.

In the second stage, an un-twisted rectangular wing is generated from the base aerofoil. The wing is made of 10 equidistant sections. The first optimization step is to use the VII code to reach the optimal loading distribution via cambering the wing sections. As for the wing-twist design methodology this is an iterative process.

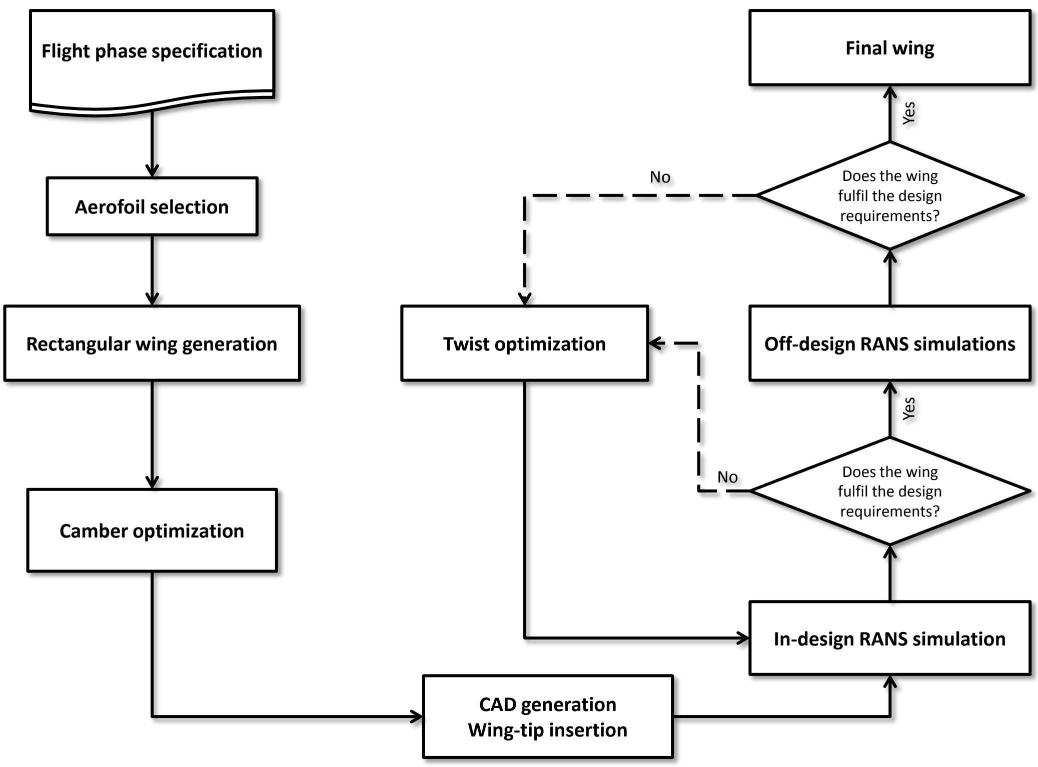


Figure 4: Camber wing generation

After finding the optimum camber distribution the wing CAD model is generated and a wing-tip is added to the design. The cambered wing is then tested at the design conditions with SOLAR/TAU. If the wing does not fulfil the requirements, the second stage of optimization is performed. In the second stage, the cambered wing sections are not modified, but the VII code is used to twist and improve the performance in an iterative optimization process. The new twisted and cambered wing is then generated. If the wing fulfils the design requirements, off-design simulations with SOLAR/TAU are performed to analyse stall characteristics and off-design performance. The result of the design process is a CAD model and the aerodynamic parameters of a wing suitable for the flight phase.

DESIGN SPACE AND AEROFOIL SELECTION

The aim of the design process for the loiter wing is to maximize the endurance, defined as the maximum time that the UAV can spend flying at the defined conditions. It has been shown [Traub, 2011] that endurance for electrical powered UAV can be calculated as a function of the required power given by [Anderson, 1999]:

$$P_R = Dv = \frac{C_D}{C_L^{3/2}}\sqrt{\frac{2W^3}{\rho_\infty S}} \tag{1}$$

where: P_R is the required power, D is the drag, v is the flight speed, ρ_∞ is the free-stream density, C_D is the drag coefficient, C_L is the lift coefficient, W is the Weight and S is the wing surface. Hence, minimum power is required when the airplane is flying at minimum $C_D/C_L^{3/2}$. The loiter phase is a fixed lift mission. Therefore minimizing $C_D/C_L^{3/2}$ means minimizing the drag. In general terms, the drag can be written [Pankhurst, 1958] as:

$$Drag = Wave\,drag + Profile\,drag + Induced\,drag \tag{2}$$

The first component is zero because of the subsonic flow regime. The profile drag is the sum of form drag and skin friction drag and it is associated with losses in total pressure and total temperature in the shear layer. The profile drag is the smallest component of the drag in the loiter flow phase whereas the induced drag is the dominant drag component. The minimum induced drag is achieved for an elliptical loading distribution [Anderson, 2001]. Therefore, the aim of the design is to achieve the optimum loading distribution over the wing at the design conditions.

Within the CHANGE project one of the morphing capabilities is the wing-span retraction. The induced drag is inversely proportional to the wing aspect ratio [Anderson, 2001]:

$$AR = \frac{b^2}{S} \tag{3}$$

where AR is the Aspect Ratio, b is the Wingspan and S is the Wing area. In order to reduce the induced drag, the maximum allowable wing-span of 4 m must be used in the design. Generally, thin aerofoils generate less profile drag than thick aerofoils.

Before starting the aerofoil analysis some geometry and manufacture restrictions imposed on the design are presented:

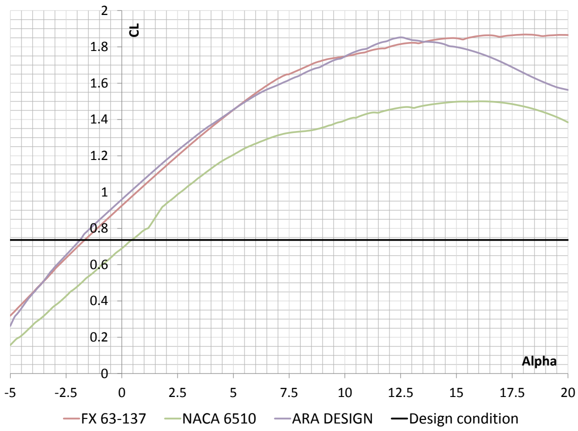
- The trailing edge thickness is fixed at a value of 0.4% of the chord (2.4 mm) for manufacture reasons.
- There is a limitation on the minimum thickness. A value of 10 % of the chord (60 mm) is defined because thinner aerofoils could not accommodate the morphing mechanism.

The main design constraints for the loiter phase are presented in Table 1. The flight speed is 55 km/h, the UAV weight is 25 kg, the chord is 0.6 m, the altitude is 1000 ft, the Mach number is 0.0451 and the Reynolds number is 605,067

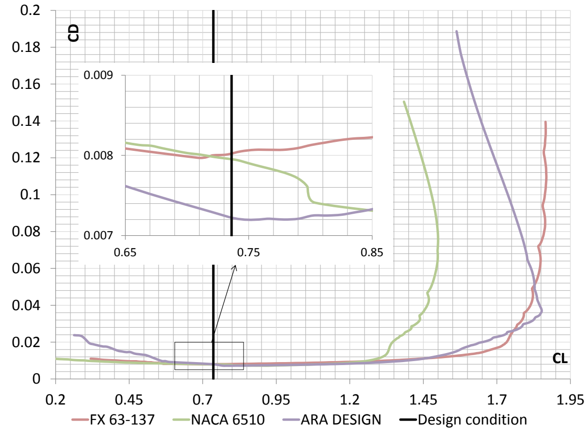
Speed[km/h]	**Weight**[kg]	**Chord**[m]	**Altitude**[ft]	**Mach number**	**Reynolds number**
55	25	0.6	1000	0.0451	605,067

Table 1: Loiter design parameter

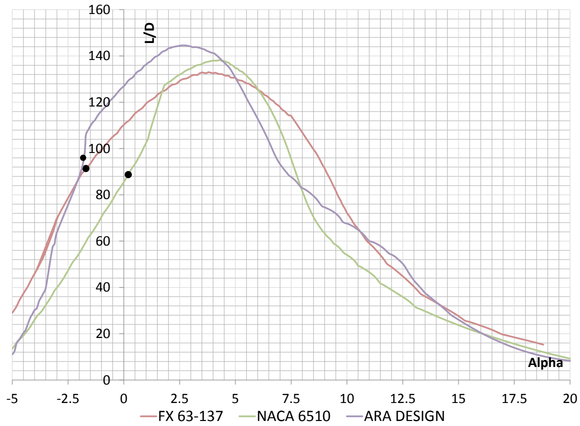
The performance of several aerofoils at the design conditions have been evaluated to find the optimal candidate and are presented in Figure 5. The software used in this analysis is the two-dimensional VII code. Figure 5(a) shows the lift coefficient from -5 degree to 20 degree angle of attack. Among the standard aerofoils [Selig et al., 1995] the NACA 6510 [Jacobs et al., 1933] has been selected for the wing-twist design methodology. Another candidate was the FX 63-137, but it was discarded because of the higher drag than the NACA 6510, see Figure 5(b). Figure 5(c) shows the lift over drag ratio curve, where the points indicate the design conditions. It is possible to note that the aerofoil design point is not where the maximum lift over drag is positioned. However, for three-dimensional wing the required angle of attack is higher than the two-dimensional ideal wing



(a) Lift coefficient - alpha curve



(b) Drag coefficient - Lift coefficient curve



(c) Lift over drag - alpha curve

Figure 5: Aerofoil selection

because of the presence of three-dimensional effects, e.g. downwash, that reduce the local angle of attack seen by the wing sections.

For the camber-wing design the idea is to push the design further in order to achieve the maximum lift over drag ratio possible. The aerofoil designed after the two dimensional analysis with the VII code is a modified version of the FX 63-137 aerofoil with 10% thickness. This aerofoil has a higher lift over drag ratio at the design condition than the NACA 6510 and it needs a lower angle of attack than the NACA 6510 section to achieve the design lift coefficient. This choice aims to reduce the angle of attack of the wing for the given flight condition. This aerofoil is used only in the central part of the wing. The geometry of the aerofoils used in the designs are presented in Figure 6. The main difference between the NACA 6510 and the ARA design is in the thickness distribution in the second half of the chord, where the NACA 6510 is thicker than the ARA design.

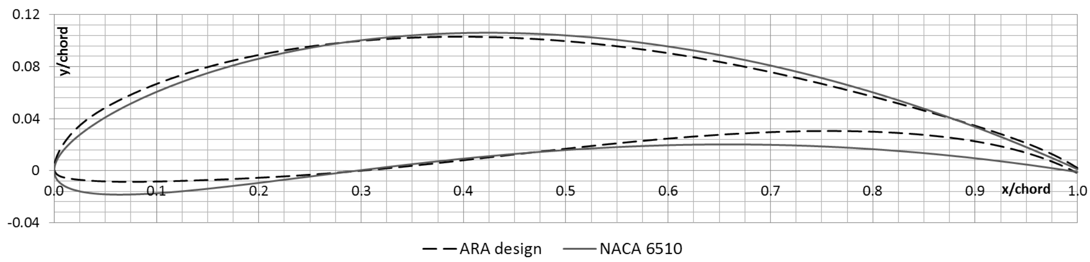


Figure 6: Aerofoil sections

WING DESIGNS

Both approaches outlined in the Methodology section lead to a wing that complies with the design parameters in Table 1 and is suitable for the loiter phase.

The optimum loading distribution for an elliptical shaped wing is presented in Figure 7 and it is compared with the RANS results of the final wings. In the region near the wing root both wings have a local lift coefficient (Cll) almost identical to the calculated one. It is possible to see that the loading distribution of the twisted wing is slightly better than the cambered wing, but the drag is lower on the cambered wing.

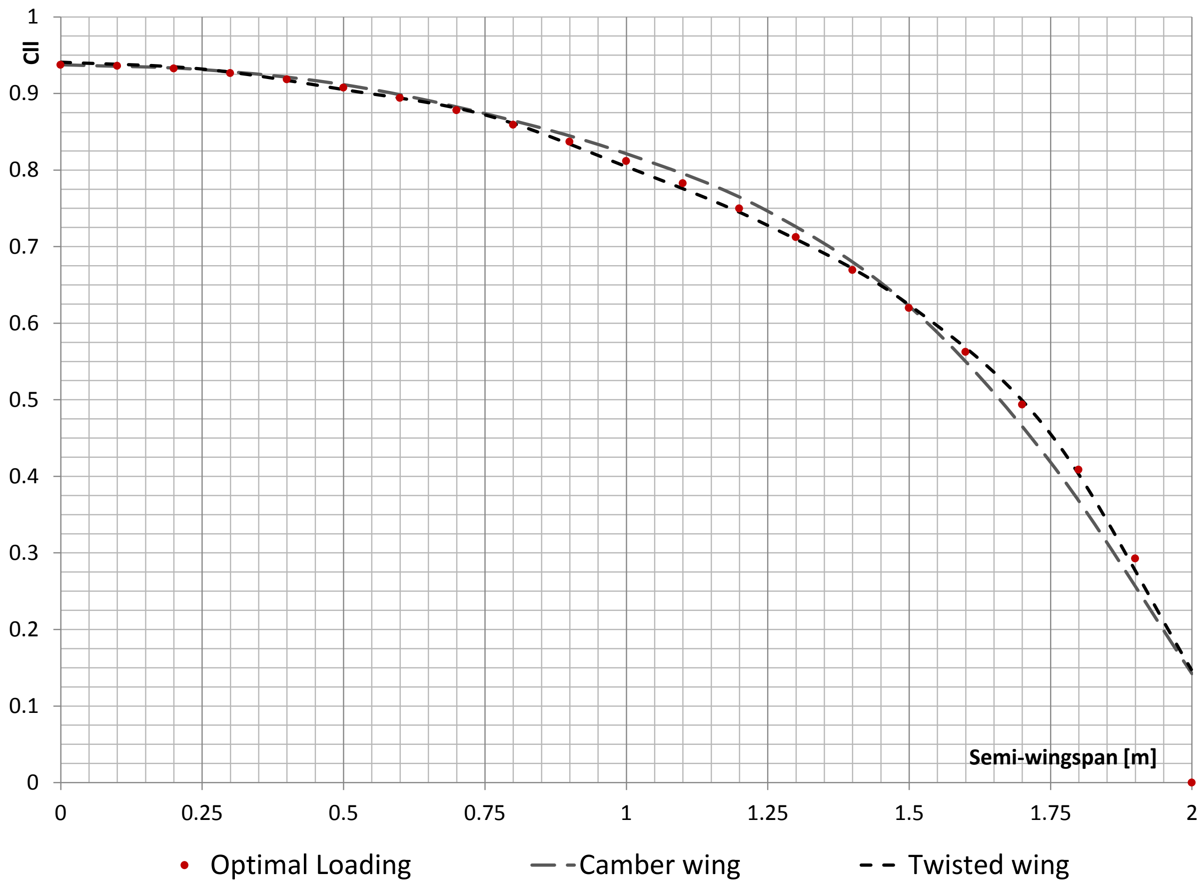


Figure 7: Spanwise optimal loading distribution

WING TWIST METHOD

The NACA 6510 profile is used in all wing sections except at the wing-tip, where a symmetric NACA 0010 is used. The main reason for a symmetric aerofoil at the wingtip is to reduce the loading in this region of the wing and to improve the performance. The optimized wing-twist from this methodology is presented in Figure 8. The wing-twist is varying smoothly from ∼ 2 degree at the wing root to ∼ -3.6 degree at wingtip.

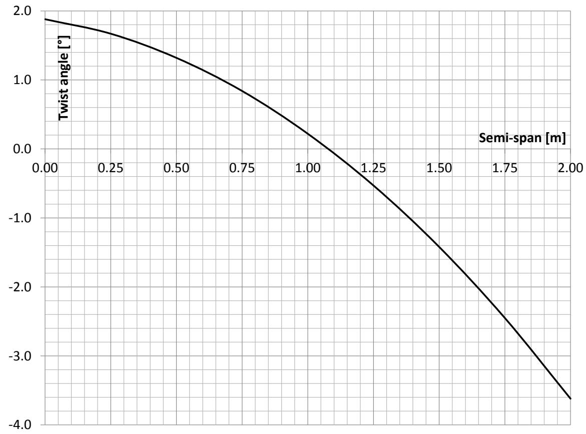
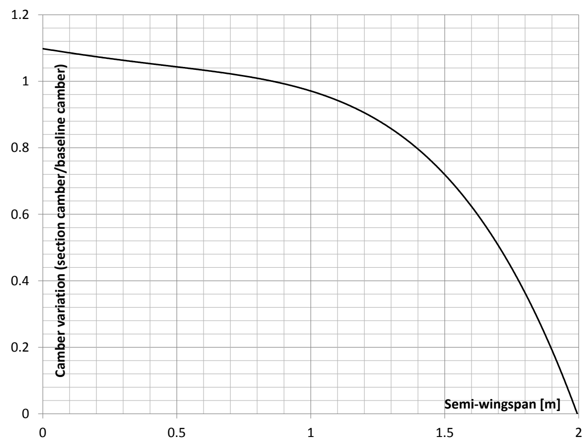


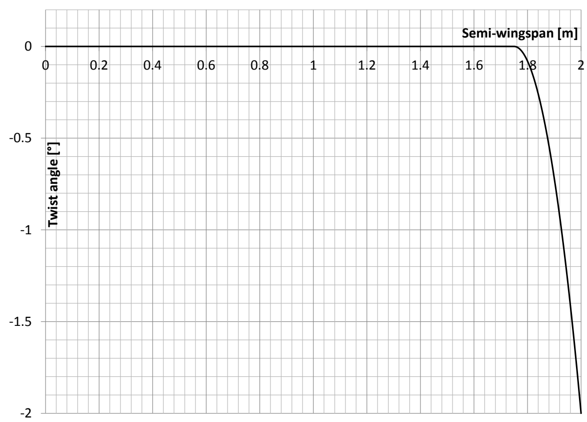
Figure 8: Twisted wing - Twist angle

WING CAMBER METHOD

The ARA designed profile is presented in Figure 6. At the wing-tip the symmetric NACA 0010 is used in this design because it shows slightly better performance than the zero camber derived aerofoil. The camber variation compared to the ARA design of the wing-camber design is presented in Figure 9(a). The original section is at 0.85 m from the root. The camber at the root section is 1.15 times the original section and the camber at the last section is zero. Figure 9(b) shows the wing-twist distribution, it is zero everywhere except at the wingtip, where is ∼ -2 degree.



(a) Camber distribution



(b) Twist angle

Figure 9: Cambered wing - Geometry

RANS RESULTS

The results presented in this section are based on high-fidelity CFD simulations performed with SOLAR/TAU for design and off-design conditions. A SOLAR mesh setup was used to generate a grid of approximately 3,000,000 elements for both designs. The mesh is unstructured with a semi-elliptical domain with radius of 50 m and a first cell height is 9.8279 10^{-6}. The solver settings are presented in Table 2.

Turbulence Model	**Reynolds number**	**Mach number**	**Target lift coefficient**
Spalart-Allmaras	605,067	0.0451	0.7361

Table 2: TAU settings for in-design simulations

The design simulations were performed to achieve the target lift coefficient. For off-design conditions, a lift polar ranging from -2 degree to 20 degree was simulated. Both design methodologies lead to a wing that complies with the design parameters in Table 1 and is suitable for the loiter phase. Compared to the baseline wing, both wings show several improvements presented in Table 3.

Wing	**CD**	**L/D**	$\mathbf{CM_x}$	$\mathbf{CM_y}$	$\mathbf{V_{stall}}$[m/s]	**Alpha**[deg]
Baseline wing	0.03975	18.518	0.67531	-0.09417	10.408	3.062
Twisted wing	0.03861	19.065	0.62679	-0.09213	10.605	3.014
Camber wing	0.03793	19.407	0.62224	-0.09757	10.074	2.370

Table 3: Loiter design performance

Comparing the camber-wing design with the baseline, the total drag is reduced by 5%, consequently the lift over drag ratio, the main parameter of endurance for UAV, is increased by 5%. The design angle of attack is reduced by 22.6%. Compared with the twisted wing, the cambered wing features a 5% lower stalling speed and the maximum lift coefficient CL_{max} is increased by 5%.

Improvement can also be seen in the pressure distribution in Figure 10, when reduced separation is observed at the wing-tip. Figure 11(a), Figure 11(b) and Figure 11(c) show the pressure coefficient profile for three

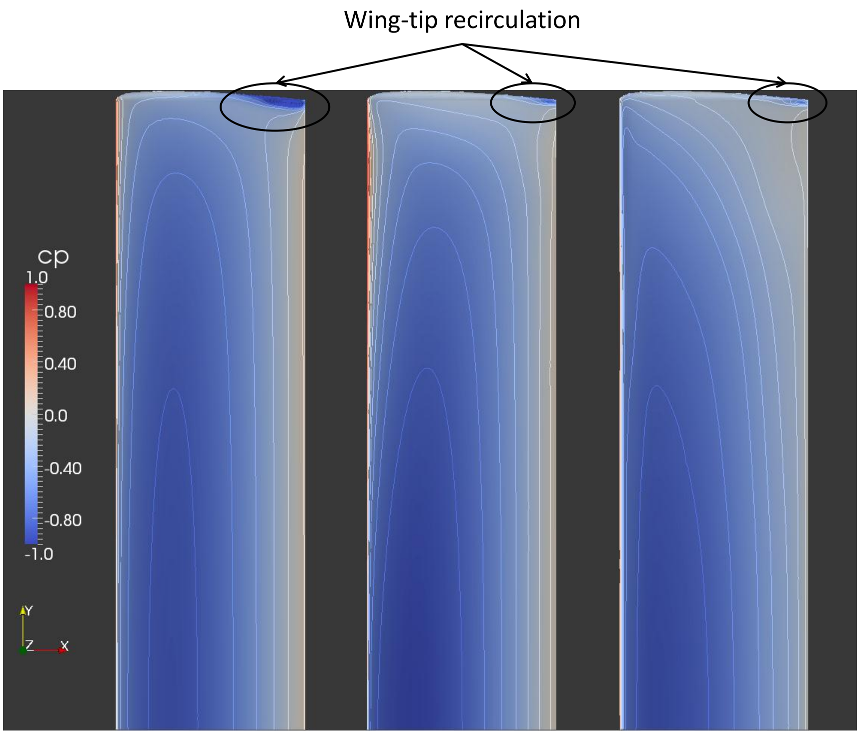
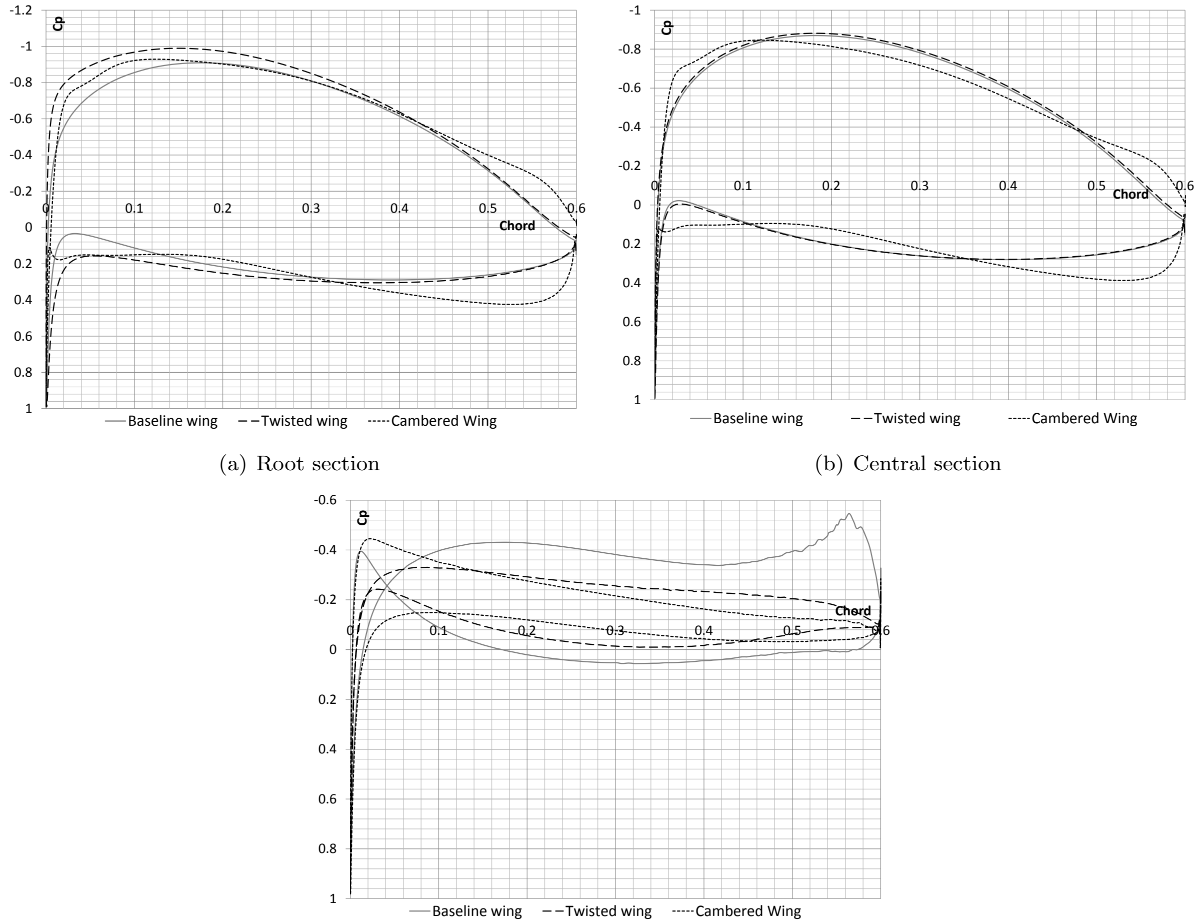


Figure 10: Pressure coefficient on the upper surface comparison

different sections of the wing. Figure 11(a) is the pressure distribution at the wing root, Figure 11(b) at the central section and Figure 11(c) is at 98 % of the span. Figure 11(c) shows the improvements in the pressure coefficient distribution for the two designed wings provide additional evidence that flow separation is reduced.



(a) Root section

(b) Central section

(c) Wingtip section

Figure 11: Pressure distributions

The lift polar in Figure 12(a) shows that the cambered wing generates more lift for a fixed angle of attack than the other two one. Both wing designs show smooth stall behaviour. The lift over drag ratio in Figure 12(b) shows similar trends for the cambered wing and the twisted wing, both wings are better than the baseline wing.

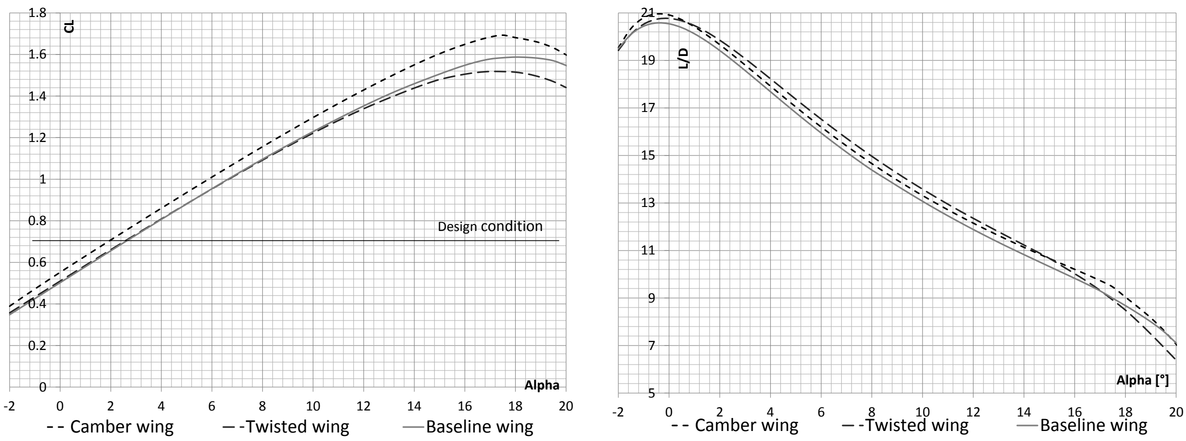
The results demonstrate how a two-step design method with twist and camber optimization can achieve better performance at design conditions than a simple twist optimization. The camber-wing design methodology can achieve better performance for multiple design points because it has a considerably larger design-space than the wing-twist design. This methodology, therefore, can be considered, if coupled with a fast response modelling method such as a look-up table, as a candidate for a live on-board controller that adjusts the wing shape dynamically according to the flight condition.

The wing-twist design methodology can be considered for single design point missions and the twist morphing can be used as an alternative, or companion, of the usual control system.

CONCLUSIONS

Two different methodologies for the design of a UAV morphing wing were presented in this paper.

The wing-twist design methodology is a one-step design optimization process that allows for morphing of only



(a) CL - Alpha comparison (b) L/D - Alpha comparison

Figure 12: Polar results

one wing parameter during the optimization: the twist. It is quick, because the optimization uses low-fidelity CFD analysis, high-fidelity is only needed at the end of the design as performance check to increase confidence in the design.

The second approach is a two-step process for optimizing the wing performance, in the first step the camber and in the second step the twist. Compared to the one-step method, it is slower because it uses high-fidelity CFD also during the design. This method shows that it is possible to improve the performance of a wing if the morphing mechanism allows for changes of the aerofoil camber and twist at the same time. Considering a morphing UAV, like the one in the CHANGE project, this method shows that, in general, camber and twist morphing have the possibility to generate a better suited wing for each flight phase. It is also clear that the aerofoil selected has a high impact on the wing performance.

The one-step wing-twist is a standard approach for single-objective wing design. This methodology has the advantage of following a simple logic and of being relatively rapid. However, wing-twist alone does not provide a sufficiently large design space to allow for multiple design points during a flight mission. In this case, the two-step methodology incorporating changes in wing-camber needs to be employed. This approach, coupled to a fast response modelling method, could also be considered for a live on-board controller that dynamically adjusts the wing shape based on the current flight condition.

ACKNOWLEDGEMENT

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