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Design of morphing wing for aerodynamic performance considering the wing flexibility effects

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Abstract. This paper provides an insight into ongoing research aimed at designing a morphing wing with the ability to continuously adapt its aerodynamic shape. The wing is targeted at a general purpose unmanned aerial vehicle. The morphing wing concept outlined in the paper is based on continuous camber changes of the wing leading and trailing edges, allowing optimal performance in different flight regimes. The aeroelastic tailoring method is used to design the load carrying structure of the wing in order to define the optimal stiffness and strength of the structure, which are considered as fixed in subsequent design steps. The research proposes a novel modular design approach that combines aerodynamic shape optimisation and aeroelastic considerations for designing morphing wing surfaces.

1. Introduction

The current challenge in aircraft design is the reduction of the environmental impact of aircraft, particularly in terms of greenhouse gas emissions. Considering the classic tube-wing aircraft concepts, shape morphing is currently a widely investigated possibility for aerodynamic performance improvement. It is a continuous adaptation of the aerodynamic shape of the wing, which can serve as an alternative to the commonly used aerodynamic control surfaces and high-lift devices, where the elimination of air leaks and gaps can increase the efficiency [1]. This effect can be advantageous when applied to the natural laminar flow wing of regional aircraft [2] or high performance gliders [3] to improve their low speed performance using a droop nose leading edge. More advanced concepts envisage the implementation of wing morphing for spanwise lift distribution control to provide manoeuvre and gust load alleviation capabilities [4]. Trailing edge morphing of a flexible wing presents an opportunity to enhance the multi-objective performance of an aircraft by adapting the shape of the wing to reduce drag and optimise wing loading during manoeuvres or gusts [5]. Achieving the shape change necessary for the required aerodynamic effect requires a complex mechanism or compliant structure that must ensure wing morphing capability even under flight load induced deformation. This is a multidisciplinary optimisation problem requiring the integration of aerodynamic and structural design [6].

The aim of our research is to explore the use of advanced meta-materials for morphing wing structures. In this work, we focus on the initial stage of the morphing wing design. This involves the detailed aerodynamic shape design of the morphing wing surfaces for a general purpose unmanned aerial vehicle (UAV). For this purpose, we propose a novel modular design tool that uses established design tools and high-fidelity solvers. The tool is based on the gradient-based aerodynamic shape optimisation technique, which is complemented by fluid-structure interaction iterations to consider the effect of wing deformation on the aerodynamic properties of the wing in specific flight conditions. Wing morphing is achieved by continuously varying the camber along the span and chord of the wing. The baseline wing has a rectangular planform. The aeroelastic tailoring approach was used to create the wing structure in order to define the optimal stiffness and strength of the structure, which are considered as fixed in the subsequent shape optimisation of the wing morphing surfaces.

2. Morphing wing concept

The wing morphing capability investigated in the project focuses on the adaptation of the wing shape to specific flight conditions. The correct adaptation of the wing shape should lead to an improvement of the aerodynamic performance. Figure 1 shows the idea of the morphing wing. It consists of an aeroelastic tailored wing box structure and the morphing capability is enabled by a compliant leading and trailing edge ribs located at several positions along the wing span. The ribs feature a metamaterial structure, discussed in [7], which is expected to provide the state sensing and structure health sensing capabilities.

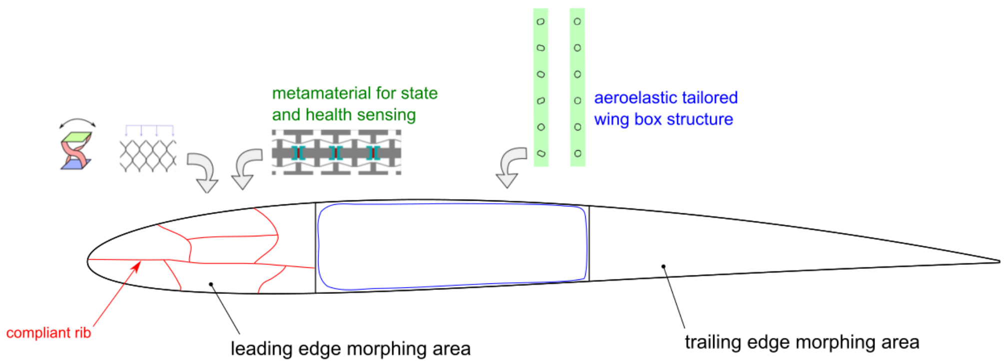

Figure 1. Wing section illustrating the morphing wing concept.

3. Design problem setup

This section defines the global design parameters which are basic parameters of target UAV, its typical mission in terms of specific flight conditions and initial considerations of the wing structural layout.

3.1. Global design parameters of the UAV

The target aircraft for which the wing is designed is a general purpose unmanned aerial vehicle with a maximum take-off weight of 50 kg. The wing planform is rectangular with span of 3.8 m and chord length of 0.6 m. The wing airfoil is NACA 2510. All parameters are summarised in Table 1.

The flight conditions considered for the aerodynamic shape design of wing morphing surfaces are shown in Table 2. These conditions have been chosen in order to create a typical mission of the UAV. The respective flight speeds have been chosen according to the recommendations of the Certification Specifications for Very Light Aeroplanes (CS-VLA, 2009).

Table 1. Design parameters of the UAV.

Parameter		Value
Maximum take-off weight	m_{TOW}	50 kg
Wing planform area	S_w	2.28 m^2
Wing span	b	3.8 m
Wing root chord	c_r	0.6 m
Wing tip chord	c_t	0.6 m
Airfoil		NACA 2510

Table 2. Design flight conditions of the UAV.

Flight regime	V [m/s]	C_L	Re_{MAC}
take-off	22.14	0.716	948755
cruise	40.0	0.219	1714125
loiter	24.0	0.609	1028475
landing	17.5	1.146	749930

3.2. Basic structural layout of the wing

The initial structural layout consists of two spars, 14 evenly spaced ribs and a load bearing skin. A unidirectional carbon fibre reinforced polymer (CFRP) laminate, specifically AS4/3501-6, was selected as the base material for all these components. Positioning of the spars was determined by dimensions of the morphing parts at the leading and trailing edge. The spars are located at the edges of these parts, effectively creating a wingbox structure between 25 and 55 percent of the chord length. Morphing parts are omitted from structural modelling to allow preliminary design of the structure without a knowledge of their parameters.

Preliminary results of the optimisation showed that skin buckling was one of the critical constraints. Buckling is affected by the size of considered skin panels which is determined by the spar and rib spacing. Therefore increasing the number of the ribs to decrease dimensions of buckling regions on a skin would allow the optimiser to reach thinner skin and decrease its weight. But it also creates a significant weight penalty caused by the mass of the additional ribs. Seven different variants of the wing were optimised, each with a different number of evenly distributed ribs. That allowed to choose a variant where the mass is most optimally divided between skin and ribs and the total weight of structure is minimised. Figure 2 shows the selected initial structural layout with 14 ribs.

4. Methodology

This section outlines the design considerations, models and methods used to design an optimal morphing wing. The first part focuses on the structural design of the wing. The second section describes in detail the proposed novel aerodynamic design tool and its components.

4.1. Structural design of the wing box

The spars and skins of the wingbox were partitioned into ten laminate regions each, as illustrated in Figure 3. A low-fidelity aeroelastic optimisation framework Proteus [8] was employed to tailor the layout and number of composite plies in these regions. The framework utilises a geometrically

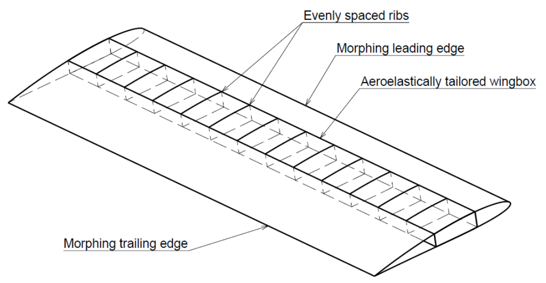

Figure 2. Initial structural layout of the wing.

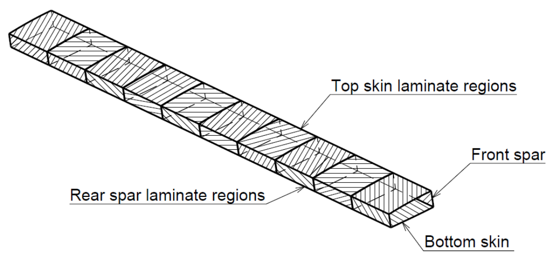

Figure 3. Laminate regions of the wingbox.

nonlinear Timoshenko beam model coupled with a vortex lattice method to simulate the wing aeroelastic behaviour. Using a gradient optimiser, the framework finds optimal stiffnesses and thicknesses of the laminate regions for given conditions and constraints. The wingbox structure was optimised for minimum weight, considering constraints on optimal wing cruise shape, structural strength and strain, buckling, aeroelastic stability and control effectiveness. Four load cases in Table 3 represent the flight envelope of the aircraft and were analysed during the optimisation.

Table 3. Design load cases.

Load case	V [m/s]	Load factor
1	40	1
2	40	4.16
3	55	3.8
4	55	-1.5

4.2. Aerodynamic shape design of the morphing wing

A design process shown in the Figure 4 was used for the high-fidelity aerodynamic shape design of the wing morphing surfaces. The design process consists of the an inner and an outer loop and is designed to be modular, using well established design components. The inner loop contains the pure aerodynamic shape optimisation method, while the purpose of the outer loop is to include the effect of the wing flexibility on its aerodynamic properties - it is the fluid-structure interaction iteration.

The particular modules of the proposed design approach are briefly described in the following text.

Aerodynamic and shape sensitivity analysis: The aerodynamic shape optimisation part of the design process utilises the capabilities of the SU2 CFD suite [9]. This open-source computational fluid dynamics (CFD) software can solve compressible and incompressible Euler and Navier-Stokes flow equations. Turbulence is modelled using, among others, various variants of Spalart-Almaras (SA) and Shear Stress Transport (SST) turbulence models and the software allows for parallel processing.

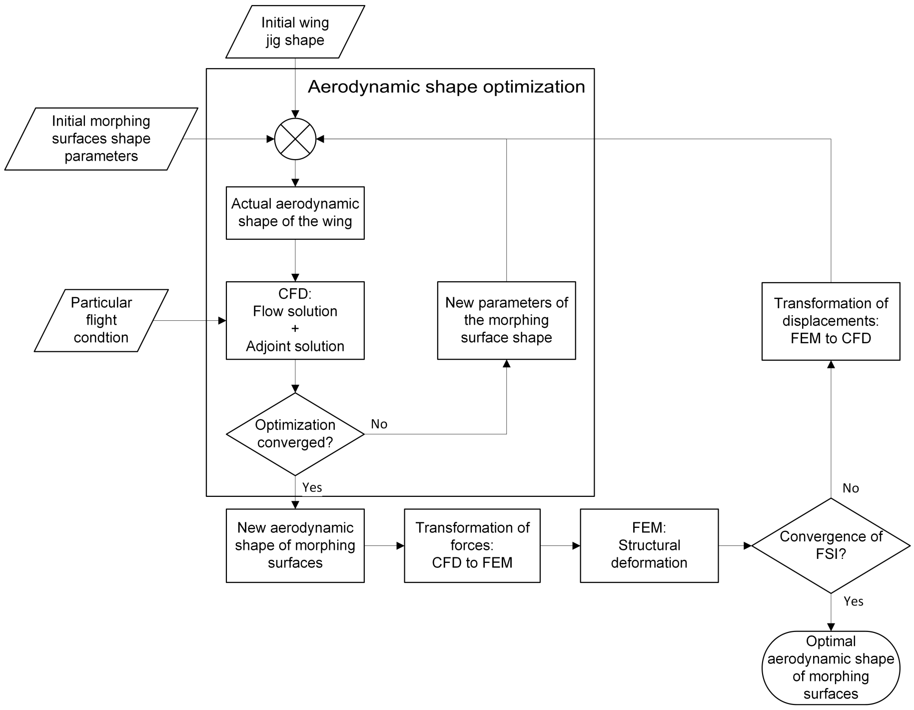

Figure 4. Schematics of the process for the morphing shapes aerodynamic design.

In this work, we employ the SU2 CFD to obtain a solution of the viscous flow around the wing. The solver solves the Reynolds Averaged Navier-Stokes (RANS) equations with turbulence modelled by Spalart-Almaras turbulence model. The shape sensitivities of the objective and constraints are obtained by solving the continuous adjoint of the RANS flow equations. The

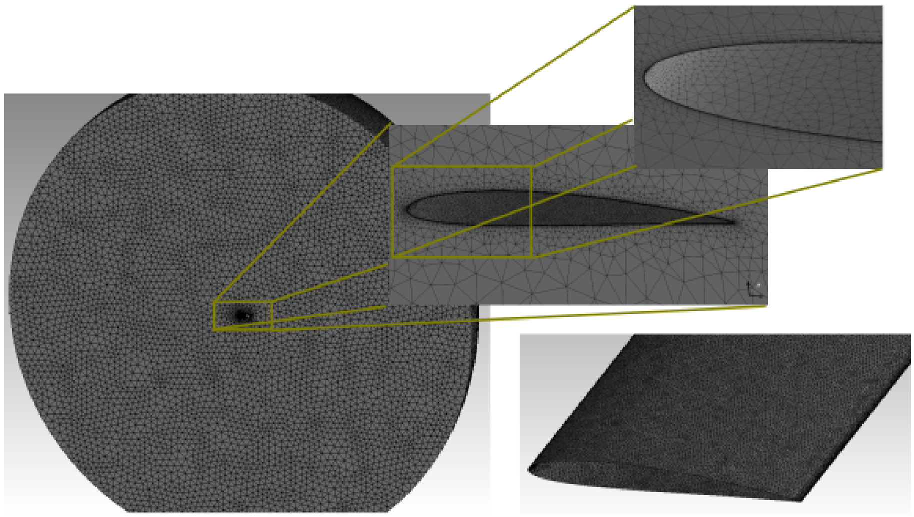

Figure 5. CFD computational domain.

CFD simulation uses a hemispherical domain for the flow domain, as shown in Figure 5. The wing surface is defined as a no-slip wall boundary condition, while the circular plane is considered as a symmetry boundary condition. The surface of the sphere creates a far-field boundary condition. The domain consists of around 7.42 million tetrahedral cells, with 18 inflation layers in the near wall area. The boundary layer is fully resolved by ensuring that the y+ values in the first inflation layer do not exceed 1 over the entire wing surface.

The optimal mesh size was chosen after conducting a mesh dependency study which evaluated four different mesh sizes at the loiter flight condition.

Aerodynamic shape parameterisation: The Free-Form Deformation parameterisation (FFD) technique [10], implemented in SU2 CFD Suite, is used to explore the design space and identify optimal wing shapes. Figure 6 shows the typical lattice of control points used in this technique. In this case, the change of the wing shape is driven by controlling the camber of the airfoil in specific spanwise sections. This is achieved by vertical displacements (along the z-axis) of pairs of control points.

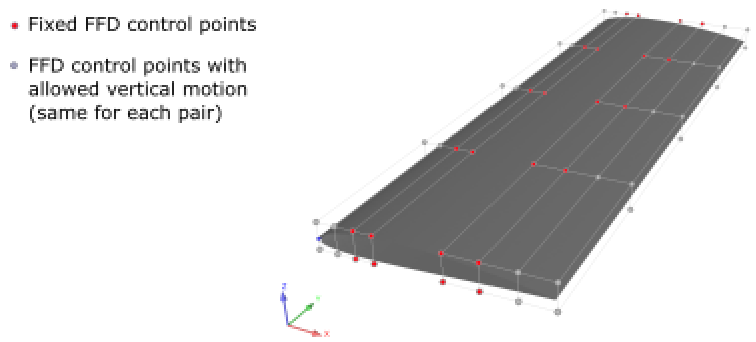

Figure 6. Lattice of control points of the Free-Form Deformation parameterisation.

Optimisation method: The aerodynamic shape optimisation in this design approach utilises the capabilities of the SU2 CFD suite. It uses the Sequential Least Squares Programming (SLSQP) optimiser, which belongs to a class of gradient-based optimisation algorithms capable of efficiently solving problems with a large number of design parameters and constraints.

Structural Analysis: The non-linear analysis using MSC. Nastran (v2022.4) solution sequence SOL 400 computes deformations of the structural model. The model, shown in Figure 7, consists

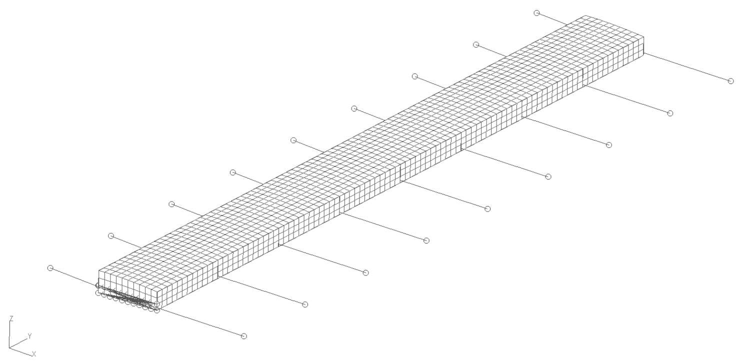

Figure 7. Finite element model of the wingbox for Nastran solver.

of shell elements that represent the skin and spars of the wingbox. The model properties were obtained from the output data of the Proteus utilising the Proteus2Nastran tool ([11]).

Fluid-structure interface: The fluid-structure interface is created using a Python-based function in SU2 as described in [12]. The interface is formulated using Radial Basis Functions interpolation, specifically the Thin Plate Spline (TPS) function. The data exchange to and from the CFD solver partly uses the capabilities of the SU2 CFD suite. In our work we have implemented a Python routine that allows direct communication with the Nastran solver via input (.bdf) and output (.h5) files.

Convergence of the solution: A converged solution of the inner loop - the aerodynamic shape optimisation - is achieved when the difference between the objectives in two consecutive iterations falls below a specified tolerance, or when the number of iterations reaches the specified maximum. The stopping tolerance and the maximum number of iterations is defined in such a way that the inner loop stops and the solution continues to the outer loop, even if full convergence has not been achieved. This approach is likely to speed up the solution of the overall design loop. The entire design loop is considered converged when the difference in structural deformation between two consecutive iterations of the outer loop falls below the specified tolerance.

5. Results

The optimised wing box structure is the first step in designing a morphing wing optimised for aerodynamic performance. The outcome of this optimisation will be used to account for flexibility in the process of aerodynamic optimisation.

The optimisation results are shown in Figure 8. The resulting relative stiffnesses of skins in the inboard sections are highly directional while in most of the outboard sections stiffness remains the same in all directions. This behaviour, which can be seen in both membrane and bending stiffness, occurs in laminate regions where the laminate reaches a minimal skin thickness limit of 1 mm. The minimum thickness level is imposed on the design to ensure its manufacturability and to avoid barely visible impact damage to the composite. This limit prevents the optimiser from reaching a lower weight of the structure in these laminate regions and thus prevents any changes in their layout.

Another notable part of the resulting design is a significant difference in the main direction of membrane stiffness on the top skin of the wing. Laminate regions closer to the root section are optimised to cause a wash-out of the wingtip while the layout of laminates in the central part of the wing leads to a wash-in effect. This seemingly contradictory behaviour can be explained by the presence of cruise shape constraint which ensures the wing remains untwisted along the whole wingspan while loaded with (loadcase 1) which allows the wing to keep its original aerodynamic performance in a cruise condition. Apart from these differences, the results are similar to those previously obtained for a similar case by Sodja et al.[13].

6. Conclusion

The paper presented an ongoing research effort focused on the design of the aerodynamic shape for a morphing wing, tailored for a general purpose UAV, with particular emphasis on improving aerodynamic performance under varying flight conditions. The concept of wing morphing is introduced and it is achieved by continuously adapting the leading and trailing edges of the wing. The definition of the wing stiffness was performed using aeroelastic tailoring within the Proteus design tool. This initial design activity is fundamental to obtain the optimal morphing wing, because its outcome allows to account for the wing flexibility in the subsequent aerodynamic optimisation. The core of the aerodynamic shape design for the wing's morphing surfaces lies in the innovative design tool proposed and detailed in this paper. The proposed tool uses aerodynamic shape optimisation techniques while taking into account the aeroelastic effects which can have a significant effect on the wing aerodynamic performance. The results of the application of the tool to the design of the shapes of the morphing wing surfaces will be presented

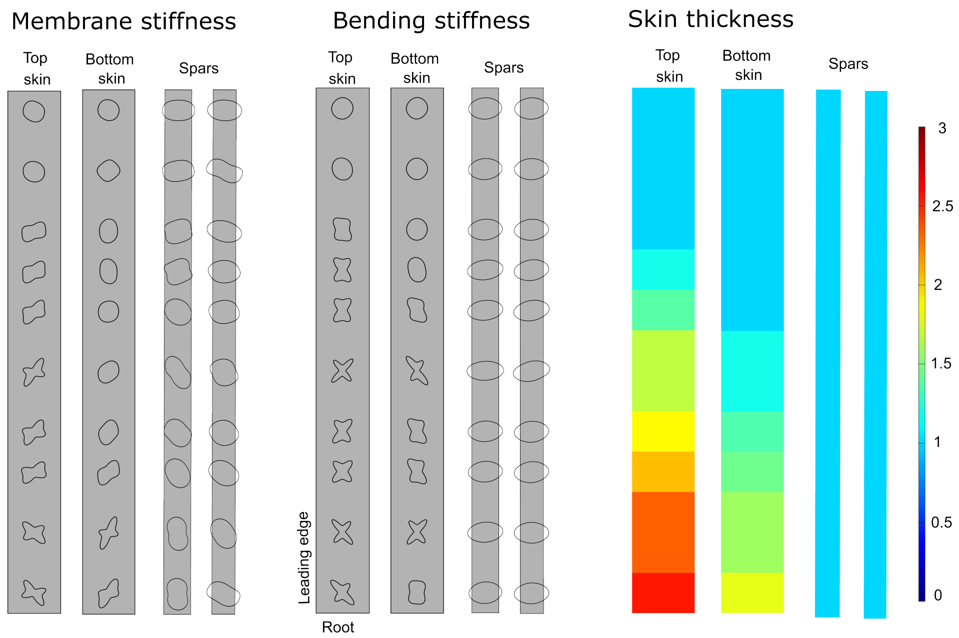

Figure 8. Thickness and relative directional stiffness of tailored parts of the optimised wingbox.

in a forthcoming paper, providing a more comprehensive view of its effectiveness in improving aerodynamic performance.

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