AN OPTIMIZATION PROCEDURE FOR THE OPTIMAL DESIGN OF MORPHING DEVICES

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ABSTRACT

In the present work an optimization procedure is proposed for the design of morphing devices based on the distributed compliance concept. Starting from the outcome of an existing two-levels approach, the integration of a mathematical toolbox with a finite element solver allows to refine morphing solutions but also to adapt topologies to different materials. Another optimization tool is employed to get the numerical solution closer to the manufacturing process stage. The procedure is applied to the design of a morphing droop nose to be installed on a reference regional aircraft. The same steps are then repeated using a superelastic material as alternative to the aluminium alloy for the compliant ribs. The results show an improvement of shape quality, but only the superelastic material allows to completely satisfy stress requirements. Finally, a detailed finite elements model is used to verify the obtained solution.

Keywords: morphing, optimization procedure, compliant mechanisms, superelastic material

1 INTRODUCTION

Morphing devices for aircraft wings represent a promising technology to improve the performances, enabling the achievement of more efficient aircraft thanks to the capability to adapt the aerodynamic shape during the mission. Indeed, the possibility to modify the airfoil geometry depending on the flight condition allows to increase the lift/drag ratio. Moreover, the replacement of classical high lift devices with adaptive ones results in lower drag and airframe noise reduction. Unfortunately, the design of morphing wings is complex due to conflicting requirements, since high deformability is requested to accomplish the shape change but at the same time the load-bearing function of the structural components mustn't be compromised [1].

One of the most promising concepts is the active camber morphing, whose aim is the variation of the airfoil camber in order to increase the aerodynamic performances, especially in take-off and landing. Different implementing solutions have been evaluated during the years. The typical concept is based on a flexible skin coupled to a rigid mechanism having levers and kinematic joints, as in SADE and SARISTU projects [2]. However, this approach suffers from the issues related to rigid mechanisms, such as high stress concentrations, wear and backlash.

An alternative to the rigid kinematics approach for the realization of variable camber wings is based on compliant structures, mechanical devices that achieve motion via elastic deformation, thanks to an efficient implementation of flexibility inside the structure [3]. The distributed compliance concept was originally proposed by Kota [4] as an alternative to the distributed actuation one. The major issue in the design of compliant structures is that conflicting kinematic and structural requirements must be simultaneously satisfied. Therefore, dedicated design procedures must be developed and specific tools like multi-objective optimization are required, in order to achieve a feasible design according to the requirements.

In this paper an optimization procedure for the design of morphing wings is proposed following the active camber concept, limited to leading and trailing–edge deflections, with an internal compliant structure. The proposed procedure is general for leading and trailing–edge devices. Since the criticalities concerning leading–edge morphing solutions are higher, application to droop nose will be shown. Many difficulties are encountered when designing a droop nose and also compliant structures can be characterized by high stress level. In this work the problem is overcome adopting superelastic Nitinol as material of the internal mechanism.

The working environment for the application of the procedure is the contribution of POLIMI in the framework of the EU funded Clean Sky 2 REG-IADP AG2 project.

2 DESIGN PROCEDURE

The aim of this work is the development of a procedure for the optimal design of morphing devices. The general framework can be outlined in four phases:

1. An aerodynamic shape optimization with structural constraints for the definition of the optimal shape according to the performance requirements.
2. A multi-objective genetic algorithm optimization for the definition of the topology of the internal compliant structure.
3. An SQP optimization to optimize the sizing variables of the selected topology.
4. A shape optimization of the compliant mechanism to reduce local peaks of stress.

The background of the procedure is the two-levels approach proposed by De Gaspari [5], whose capabilities are expanded here developing dedicated tools whose potentialities are:

- the possibility to change the materials or the geometric scale even if the topology has already been defined;
- the versatility of FEM simulations, in terms of material constitutive laws and modelling;
- the achievement of a solution almost ready for manufacturing process.

2.1 Morphing shape optimization

The first level of the procedure consists in an aero–structural optimization of the morphing shape to obtain the most efficient aerodynamic shape while minimizing the strains in the skin. The morphing shape optimization is performed by means of a Knowledge-Based Engineering (KBE) framework that revolves around an object-oriented code named PHORMA [6].

2.2 Multi-objective Genetic Algorithm

The topological synthesis of the internal compliant mechanism is based on the Load Path Representation method [7] and aims at obtaining the best internal structural configuration able to achieve the target optimal shape. The main tool used in the second level is SPHERA [5,8]. Topology and size design are simultaneously faced. The compliant mechanism must be able to satisfy the kinematic and structural requirements, for all the considered load conditions. This is a multi–objective problem that can be incorporated into the genetic algorithm. The optimal solution is a trade–off between the objectives of deformability and load-carrying capability.

2.3 SQP optimization

The third step is a sizing optimization aimed at the specialization of the topology to the actual structural configuration, in terms of materials or geometric scale. The problem is formulated as the minimization of the Least Square Error (*LSE*) between the deformed shape and the target shape, subject to: i) a stress constraint on the actuated mechanism; b) a constraint on the skin deformation under the aerodynamic loads of a non-morphing critical condition. The design variables are the widths of the mechanism, the thicknesses of the skin, the position of the internal points of the mechanism. The optimization problem is set up in Matlab with *fmincon* function, and Sequential Quadratic Programming (SQP) algorithm is chosen. Objective function and constraints are evaluated as results of non-linear finite element analyses performed by Abaqus. The model consists in a beam-elements rib located at the middle of a plate-elements skin whose spanwise length is equal to the rib pitch. Two different analyses are required:

1. analysis of the model when the compliant mechanism is actuated, under the aerodynamic loads of the morphing condition, for instance take-off or landing;
2. analysis of the model when the compliant mechanism is fixed, under the aerodynamic loads of a critical flight condition, such as Cruise or Dive Speed condition.

The model is the same in the two cases, apart from loads and boundary conditions. A dedicated Python script automatizes model generation during the optimization analysis.

2.4 Compliant mechanism shape optimization

The last step faces the transition from a beam-elements model to the actual drawing of the device, performing a shape optimization of the compliant mechanism aimed at the minimization of local stresses. A CAD model of the mechanism is created, exhibiting the actual internal points positions and the load path thicknesses of the found optimal solution. A planar sketch is imported in Abaqus and it is finely meshed with two-dimensional solid elements.

The optimization analysis is implemented by means of Tosca shape. It is used to find the optimal position of the surface nodes for the minimization of the maximum principal stress. The static analysis performed at each iteration consists in imposing the displacements and the in-plane rotation at the points of the rib attached to the skin and applying the actuation force at the input point. The displacement history is extracted from the output of the previous step.

3 DROOP NOSE

3.1 Reference wing

In the framework of EU funded Clean Sky 2 REG-IADP AG2 project, one of the developed concepts is a morphing Leading Edge able to guarantee high lift requirements as well as Natural Laminar Flow (NLF) wing. The reference aircraft is a 90 pax, twin prop Regional Aircraft. The reference wing has been provided by ONERA. The adoption of a morphing LE is needed to delay the stall in take-off and landing. In order to achieve this goal a seamless and smoothed surface is required so that no anticipated loss of laminarity occurs.

3.2 Topological synthesis results

After the definition of the optimal shape able to satisfy the performance requirements, the topological synthesis of the compliant ribs takes place. The solution is selected as good compromise between the conflicting kinematic, structural and stress requirements. This solution, shown in Figure 1, is the starting point for an example of application of the last steps of the procedure. The purpose is the validation of the benefits in terms of solution improvement.

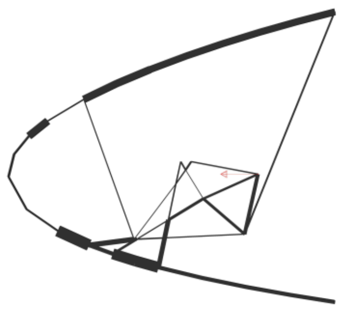


Figure 1: Topological solution

The selected solution, when actuated, displays a maximum stress of 550 MPa. The choice of accepting such high level of stress was dictated by the need of achieving the 16° droop angle of the aerodynamic target. However, this stress value is not allowable for the aluminium alloy of the mechanism. This fact suggests the need of materials able to provide high recoverable strains, a potentiality found in the superelastic behaviour of Nitinol. Both aluminium elastic material and superelastic Nitinol will be subjected to the proposed optimization tools.

3.3 Nitinol

NiTiNOL is the most common among shape memory alloys. In addition to the shape memory effect, another property they show is superelasticity: at relatively high temperatures it can happen the recovery of large deformations due to mechanical stress induced transformation.

A numerical model to simulate superelastic behaviour is available in Abaqus. The required data characterize the start and the end of the phase transformations. Some parameters (Young moduli and Clausius-Clapeyron coefficients) are taken from Qidwai and Lagoudas [9]. The other values result from setting the transformation temperatures so that superelasticity occurs for an operative range between 263 K and 313 K. Computations will be performed at the reference temperature T_0 = 293 K. Then verification at limit temperatures will be executed.

4 RESULTS AND DISCUSSION

In this section, starting from the result of genetic algorithm, an optimized solution is found by means of the SQP optimization. Then, the new compliant mechanism is subjected to Tosca shape optimization. The whole procedure is applied twice, for different materials of the mechanism: aluminium alloy (E = 72 GPa, ν = 0.33) and Nitinol. In both cases, the skin is made of composite material, modelled as an equivalent isotropic material (E_{skin} = 40 GPa, ν = 0.12).

4.1 Aluminium alloy

4.1.1 SQP optimization

First, the features of the model and the set-up of the optimization are discussed. The rib pitch is equal to 130 mm and it is used as spanwise length of the skin. The rib thickness is equal to 35 mm. The chord extension of the model is 467 mm. The actuation force has vector components (-468.2 N, -40.96 N). The aerodynamic conditions for the evaluation of objective and constraints are landing condition (α = 10°, q_d = 2561 Pa) and dive speed condition (α = 0°, q_d = 5000 Pa) at sea level. The model corresponding to the initial solution is depicted in Figure 2. It shows the starting design variables, that are the result of the genetic algorithm.

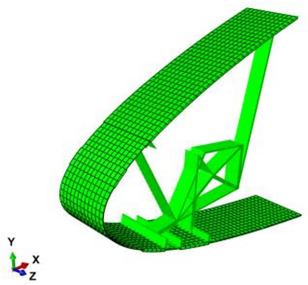
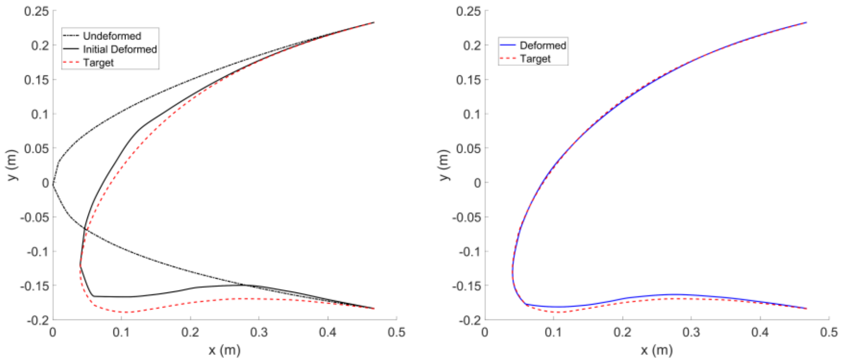


Figure 2: Abaqus model corresponding to the initial variables

Concerning the admissible stress for aluminium, the 550 MPa value already discussed is considered. The sizing variables must belong to [0.5 mm, 7 mm]. The internal points position can vary of ±5 mm. The optimization analysis converges to an optimal solution, decreasing the

LSE from 10.2 mm to 2.2 mm. Maximum stress in the rib is 549.9 MPa. Figure 3 illustrates the initial shape, the optimal shape and their comparison with the target.



(a) (b)

Figure 3: Aluminium alloy: SQP optimization. (a) Initial solution; (b) Optimal deformed shape

The results show the improvement of the kinematic requirement. The optimal solution shows a greater droop angle and a smoother skin surface with respect to the initial solution. Concerning the stress constraint, it is satisfied within the optimization analysis; however, it must be remembered that the selected admissible value is overestimated. Therefore, the obtained solution isn't feasible, in the absence of elastic materials with a sufficiently large elastic range.

4.1.2 Shape optimization

Shape optimization of the compliant mechanism is applied to the optimal solution previously found. First, a static analysis with imposed displacements at the boundary is performed to observe the mechanism behaviour and to identify the most critical regions. The result is shown in Figure 4. In addition to the global deformation, the most stressed regions are highlighted.

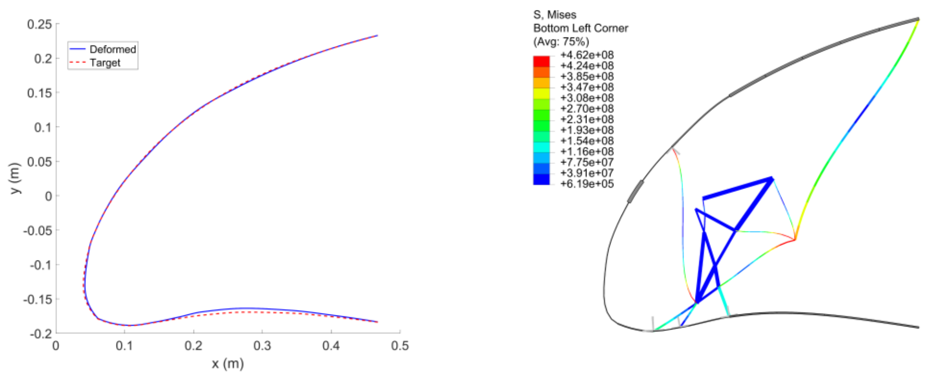
Figure 4: Aluminium alloy: static analysis of the compliant mechanism

The maximum Von Mises stress is 1200 MPa, higher than the value obtained from the beams model. Indeed, a beams model can't give accurate estimates of the stress in singular points like its extremities or the intersections. The application of shape optimization to the region on the right decreases maximum stress from 877 MPa to 598 MPa, however it is still too high. A similar analysis is carried out on the left region but failing. Therefore, the optimization tool is able to modify the junction region in such a way to reduce stress peaks, however it can't overcome the intrinsic limitation of a conventional linear material for the compliant mechanism.

4.2 Nitinol

4.2.1 SQP optimization

Nitinol is adopted in the same optimization analysis previously performed with the aluminium material. 500 MPa is considered as admissible stress: this value is just below the stress level at the end of the loading plateau. The SQP optimization converges to an optimal solution, decreasing the *LSE* from 10.2 mm to 1.4 mm. Figure 5 illustrates the comparison between the optimal shape and the target one, and the stress level inside the mechanism.



(a) (b)

Figure 5: Nitinol: SQP optimization. (a) Optimal deformed shape; (b) Von Mises stress in the rib

The results show a significative *LSE* reduction, better than with aluminium. The maximum stress is 462 MPa and the corresponding strain is 0.018, which is in the range of the recoverable strains. These results reveal that materials able to provide large strains are preferred for compliant structures. Moreover, the existence of the stress plateau allows to limit the stress values. Therefore, the use of Nitinol in combination with the SQP optimization, allows a meaningful enhancement of the aerodynamic performance. Moreover, the following results will show that Nitinol may assure the structural feasibility that aluminium alloy can't guarantee.

4.2.2 Shape optimization

The 2D solid elements model of the optimal compliant mechanism made of Nitinol is created. The result of the static analysis with imposed displacements is shown in Figure 6.

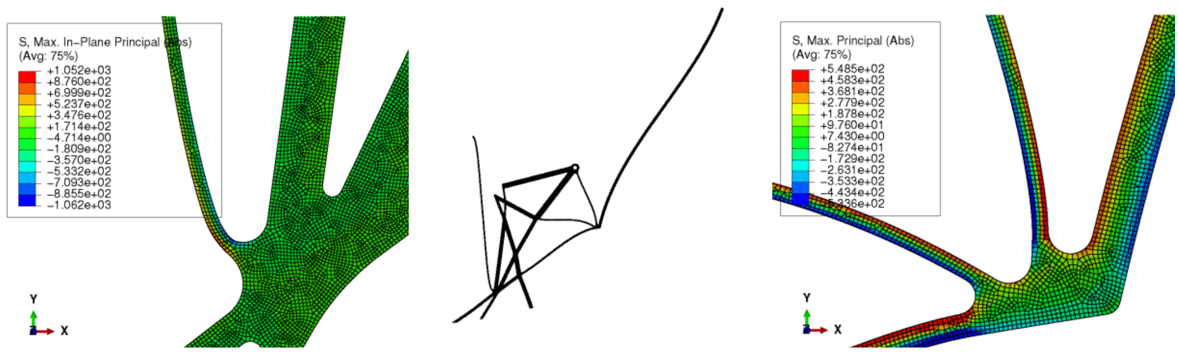


Figure 6: Nitinol: static analysis of the compliant mechanism

Also in case of Nitinol the refined finite element model shows stress concentrations and the critical regions are the same of the previous case. Shape optimization is applied to the left region, where maximum stress is 1052 MPa. The optimization provides a redistribution of stress reducing it to 541 MPa. The comparison between initial and optimized solutions is in Figure 7.

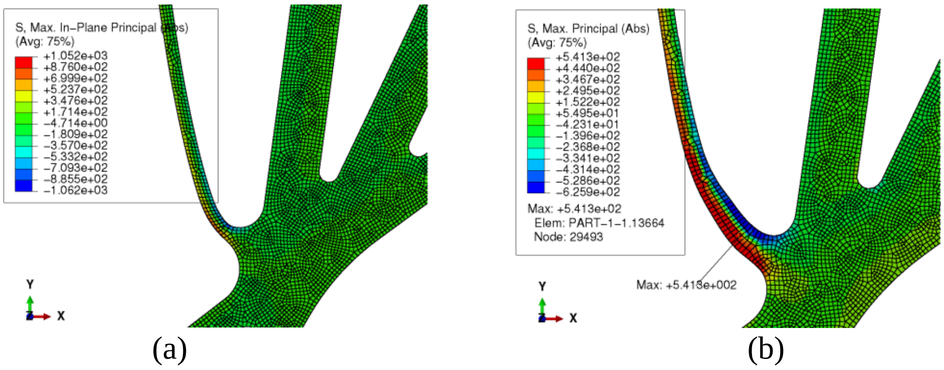


Figure 7: Nitinol: shape optimization for the left region. (a) Initial solution; (b) Optimum solution

The transformation strains are significantly reduced. The stress-strain relationship for the loading history is reported in Figure 8. It shows that the initial solution is not acceptable since the plateau is fully exploited and then the stress reaches the critical value for slip: permanent deformations would remain upon unloading. Differently, the optimized solution shows an acceptable behaviour: deformations can be recovered. Therefore, shape optimization is crucial to achieve a feasible structural solution, as well as the adoption of a superelastic material.

Figure 8: Nitinol: stress-strain curve in the left region. (a) Initial solution; (b) Optimum solution

4.2.3 Verification at limit temperatures

The analyses of the optimal solution at the limit temperatures do not show substantial differences in terms of deformed shape with respect to what obtained at reference temperature.

4.2.4 Detailed verification of the optimal solution

At the end of the procedure, the designed optimal morphing device must be verified. A 3D solid elements model of the compliant mechanism coming from shape optimization is realized. It is coupled with the shell elements skin and the displacement at the actuation point is imposed. Figure 9 shows the deformed shape and its comparison with the target.

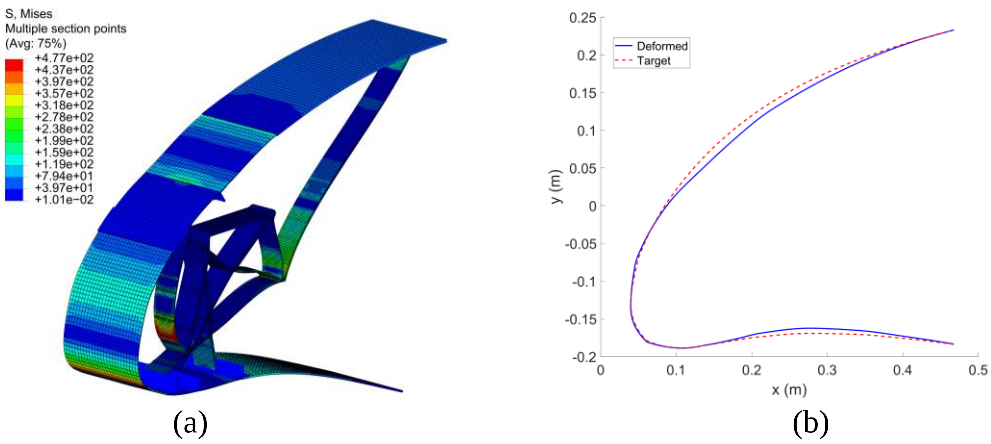


Figure 9: Nitinol verification. (a) 3D verification; (b) Deformed shape and target shape

The maximum stress in the mechanism is 477 MPa and the corresponding strain is 0.026, hence the structural feasibility of the solution is confirmed. Concerning the aerodynamic requirement, the *LSE* is 4.4 mm. Despite the worsening, the achieved result can be considered acceptable.

After the numerical design phase, manufacturing and testing are required to assess the real feasibility of the conceived solution. This includes studies of characterisation for the material and the investigation of manufacturing technologies. This is especially true for Nitinol. Due to the dependence of its mechanical characteristics on alloy composition, manufacturing process, thermal treatments and operative temperatures, a lot of work is required to understand better how to achieve the actual application of Nitinol in aeronautical structures.

5 CONCLUDING REMARKS

This paper has described an optimization procedure for the design of morphing devices. Its application to the design of a droop nose has shown the benefits in terms of fulfilment of the requirements. Sizing optimization applied to a topological solution allows an improvement of the device. Moreover, even adopting the same topology, the use of a different material is possible, and the results demonstrate a further enhancement if Nitinol is selected. Indeed, it has permitted to achieve a better kinematic requirement, as well as the withstanding of the loads within the material strength limit. The last steps of the procedure can be considered validated since they are able to improve the solution, decreasing the *LSE* and then reducing the stresses.

6 ACKNOWLEDGEMENTS

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