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CONCEPT OF A MORPHING SHOCK CONTROL BUMP SPOILER WITH TWO ACTUATORS

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Abstract. The overall goal of reducing greenhouse gas emissions in commercial aviation can be approached in many ways. One of them is the reduction in fuel consumption by reducing aerodynamic drag. Morphing can be used to adapt the shape of surfaces to gain aerodynamic benefits such as drag reduction under specific flight conditions. Among other things, drag reduction can be achieved by transonic shock control. In this work, the concept of a morphing spoiler which can form a shock control bump is investigated. This bump is shape adaptive and can shift its crest to different locations on the spoiler as well as retract the bump entirely. While the upstream bump crest position is optimized for drag reduction, and thus performance increase, the downstream position is optimized for delaying the buffet onset. This position-variable functionality is realized by using a second actuator in addition to the main spoiler actuator. A structural finite element optimization considering aerodynamic loads in form of pressure distributions is performed. The load cases cruise, with and without deployed bumps as well as the airbrake configuration are investigated. The structural concept of the spoiler is described as well as its optimization process that is based on the Nelder-Mead method. For this purpose, the finite element software ANSYS is coupled to MATLAB in which the optimization is controlled. In the end, it is shown that a morphing spoiler with two actuators can form a position variable shock control bump under realistic aerodynamic loads.

Key words: Shock Control Bump, Adaptive Aircraft Structures, Wave Drag Reduction, Buffet Onset Delay, Variable Contour Bumps, Morphing Spoiler.

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1 INTRODUCTION

Conventional transport aircraft in general fly with transonic velocities. During these conditions, transonic shocks emerge in the flow field around aircraft wings. These shocks create wave drag, and thus increase the overall drag of the aircraft. Reducing drag is key to reducing fuel consumption and corresponding emissions. Transonic shock control by the use of SCBs has been investigated for more than thirty years, starting with the introduction of such a bump in 1992 by Ashill et al. [1]. Deeper investigations have been carried out in the two European projects EUROSHOCK [2] and EUROSHOCK II [3] and a review of this technology is given by Bruce and Colliss [4] in 2015. According to these studies, SCBs can mitigate the negative effects of transonic shocks, especially in terms of drag. In addition to their drag reduction potential, SCBs can delay the buffet onset to higher lift coefficients [5]–[8]. However, an SCB that can reduce drag is not necessarily able to delay buffet at the same time. Consequently, the position of the bump respectively of its crest as well as its height are different in both scenarios. For this purpose, position and height variable morphing SCB concepts have been introduced.

A review of adaptive shock control systems and concepts can be found in [9]. A major challenge of morphing aircraft components is to implement a functionality that for example optimizes a shape in terms of aerodynamic behavior, and simultaneously to not increase the complexity of the overall system or its weight too much. Therefore, in the present work, the comparatively simple concept of a morphing spoiler has been selected that uses a flexible structure with a pre-bent region to hold the spoiler on the flap against aerodynamic loads. This concept is based on [10]–[13] and uses two actuators, similar to Kintscher and Monner [14]. However, in the present work, the morphing spoiler is enabled to form two SCB target shapes independently, of which one is optimized for drag reduction while the second delays the buffet onset under the investigated flow conditions.

According to Mayer et al. [15], the most important parameters of an SCB are the position with respect to the location of the shock and the ramp angle. The latter is coupled to the height of the bump crest in [15]. Since in the present work the SCB is formed on an aircraft spoiler, the start and end points of the bump are defined by the spoiler dimensions. In this work, the structural optimization process of a morphing spoiler is presented and a brief description about how the aerodynamic 2D SCB target shapes are created is given. These target shapes are compared to the resulting shapes which the morphing spoiler can achieve. An outlook for future work is then given as concluding remarks.

2 STRUCTURAL OPTIMIZATION OF THE MORPHING SPOILER

In this work, the morphing spoiler concept in [16] is expanded to include a second actuator. This spoiler is made of the glass fiber reinforced polymer (GFRP) HexPly®913. For the spoiler, shell elements are used in the finite element (FE) model which is shown in Figure 1. The spoiler consists of a stiff sandwich structure and a flexible section downstream of the larger main spoiler actuator attachment. The sandwich structure has the same ply stacking in its top and bottom laminates that comprise a honeycomb core. Downstream of this sandwich structure, the main actuator is mounted with a contact-based joint condition.

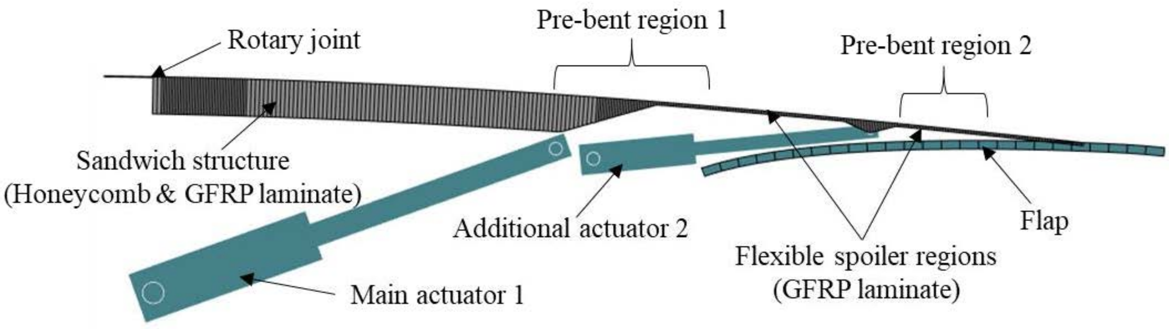

Figure 1: Finite element model of the morphing spoiler made of a glass fiber reinforced polymer (GFRP) using shell elements with two actuators that can form a position and height variable shock control bump

To enable the position variation of the SCB crest, the second actuator has been implemented, also with joint conditions in ANSYS. On its upstream side, actuator 2 is contacted to the sandwich structure, while on its downstream end this actuator is connected to a reinforced part on the flexible spoiler section. The trailing edge (TE) of the spoiler has a sliding contact to the flap. The flap itself is assumed to be rigid in the FE simulation. The upstream end of the spoiler sandwich – the spoiler leading edge (LE) – has a rotary joint condition to the rigid wing body so that the spoiler can rotate freely in this simplified hinge.

2.1 Aerodynamic optimized SCB shape

Combining aerodynamic target shapes with the consideration of structural requirements is essential to design morphing devices. Regarding the morphing spoiler that can form an SCB, Goerttler et al. [17] describe aerodynamically optimized SCB shapes under consideration of structural constrains. The same approach is used in the present work and has been further improved.

The sandwich structure makes this spoiler region comparatively stiff. One important boundary condition of the overall optimization is the agreement of the morphing spoiler contour with the clean profile within specified tolerances. This is why the shape of the stiff sandwich section consists of a similar contour as the spoiler in its undeployed state. This requirement is implemented into the aerodynamic shape optimization by using a linear ramp approach for the upstream bump flank which is introduced in [17]. On the other hand, the flexible spoiler section downstream of the stiff sandwich consists of a curved shape and not a linear ramp. Thus, the form-variable section is created by a spline of 4th order. This is an improvement in terms of structural feasibility to the linear ramp approach in [17], since in that work it is assumed to have a second stiff sandwich structure on the descending bump flank.

Two aerodynamic SCB target shapes have been optimized independently from each other. Both have the same start and end points which are equal to the spoiler LE and TE. The shape with the further upstream bump crest position represents the drag reduced bump (referred to as “PerfoSCB”). The further downstream located bump (“BuffetSCB”) is optimized for buffet onset delay. The goal of the structural optimization as well as for the actuator design is to meet both SCB target shapes as well as enabling the clean spoiler shape and airbrake load case. Thus, in total four load cases including the respective aerodynamic loads are used in the FE simulations and structural optimization.

2.2 Structural optimizer

For the optimization of the morphing spoiler structure, a workflow has been established based on a Nelder-Mead approach in MATLAB using the function *fminsearchbnd*. This is also described in [16]. The bump target shapes, the objective function and the optimization variables are imported and defined in MATLAB which also runs the FE simulation in ANSYS. In this process, one iteration consists not only of the bump simulations but also of the simulations in which the clean profile is formed. The applied structural limitations of the fiber laminate such as maximum curvature have experimentally determined in [18]. Consequently, in every iteration of the optimization two FE simulations are executed, one for the SCB shape and one for the clean spoiler shape without bump. To reduce computational effort of the optimization, the airbrake simulation is not included in these loops. However, this load case is additionally examined when the structure has been optimized.

The structural optimization of the morphing spoiler that uses two actuators is separated into two steps. As an initial optimization, the one-actuator concept described in [16] is used. Within this approach, the morphing spoiler can form a height-variable SCB, however, the crest position in chordwise direction cannot be adjusted.

Initial structural optimization with only one actuator

During this optimization, the actuator is represented by an attachment point respectively an edge on the 2D spoiler in ANSYS. The bump formation is simulated by a displacement of this attachment and remains constant during the optimization. The optimization design variables are the laminate thickness, the length of the sandwich structure and the region of the pre-bend / pre-strain. Since the location of the actuator attachment on the sandwich structure is not relevant for forming the bump, this location is also kept constant as well as the thickness of the honeycomb core.

The pre-strain is modelled in ANSYS using a thermal gradient between upper and lower layers which leads to a bending of the structure. It holds the spoiler on the flap against the aerodynamic suction pressure loads during cruise. This approach serves as an analogous model. A real spoiler would be manufactured with the curved shape that results due to the simulated pre-strain.

In the subsequent process step, the main actuator points are then optimized regarding available design space underneath the spoiler and the resulting actuator force. The driving design load case is the airbrake which loads the spoiler and consequently also the actuator with the highest forces and torques. If a suitable configuration of the actuator is found, the next structural optimization can be executed, that contains the second actuator.

Second structural optimization including the second actuator

In this second optimization, the length of the sandwich structure is not changed but taken from the first, above described optimization. In addition, the main actuator configuration stays the same. As optimization variables, the laminate of the flexible region and the locations of the second actuator attachments are used as well as a second pre-strain section. While the one-actuator concept consists of the same laminate thickness over the entire spoiler length, the two-actuator concept has two different laminate thicknesses downstream of the sandwich structure. The reason is that the laminate for the one-actuator concept has to be comparably thick, and thus stiff to resist the airbrake loads. However, in the two-actuator concept the second actuator provides stiffness to the spoiler structure. Furthermore, to reduce the necessary actuator forces the laminate between the two contact points of the second actuator should be comparably thin.

3 RESULTS

In the following, results of the structural optimization are described, beginning with the one-actuator concept. For this purpose, comparisons to the aerodynamic target shapes are drawn for the load cases cruise with and without bumps as well as the airbrake load case.

3.1 One-actuator concept

Although in [16] the downstream section of the spoiler after the bump crest does not meet the SCB target shape from the aerodynamic optimization, the aerodynamic performance in terms of drag reduction is still given. This is due to the fact that the bump crest position and height match between the structural spoiler and the aerodynamic target. In Figure 2, this old target bump shape from [16] is named PerfoSCB-07. It becomes clear that the section downstream of the bump crest consists of a linear ramp approach. Thus, the boundary conditions to create this downstream target section do not align with the demands of the structural spoiler design in which the downstream part consists of a flexible structure. Consequently, in this work the aerodynamic target shape has been re-designed. It now contains a spline of 4th order downstream of the crest to already consider structural feasibility of a form-variable laminate in the aerodynamic bump design. The resulting new SCB target shape in Figure 2 is named PerfoSCB-08 and contains this new spline approach for the downstream bump part.

The resulting spoiler deformation in the FE simulation meets this new target with high accuracy. Not only the position and height of the bump crest (0.34% of the airfoil chord length) match well, but also the overall FE shape is almost congruent to the target. Only minor deviations can be seen in the last downstream section as well as around the actuator attachment, which do not influence the aerodynamic behavior considerable.

One of the most important criteria of the spoiler is in general to meet the flat, clean cruise shape of the conventional rigid spoiler. In the objective function of the structural optimization, contour limitations for deviations to the clean profile are considered. If the limits are exceeded a penalty factor is increased in the objective function. The contour deviations of the final structural one-actuator design including aerodynamic pressure loads are depicted in Figure 3.

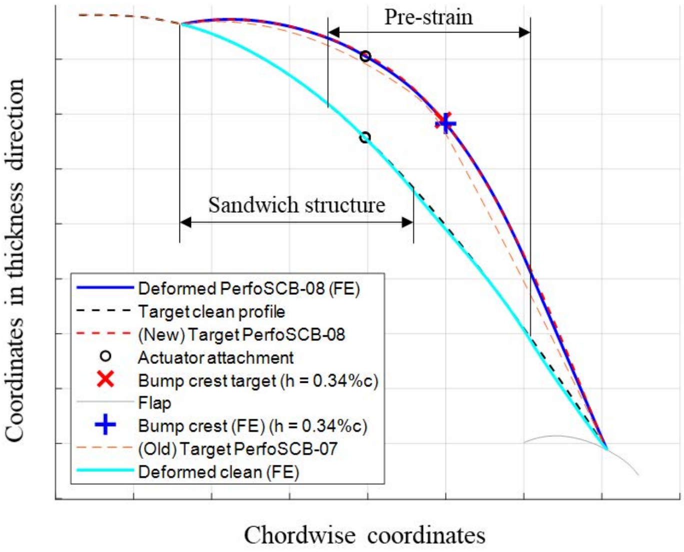

Figure 2: Resulting shapes of the morphing spoiler with one actuator after finite element (FE) structural optimization compared to the aerodynamically optimized shock control bump (SCB) target shapes (the horizontal and vertical axes differ in scale)

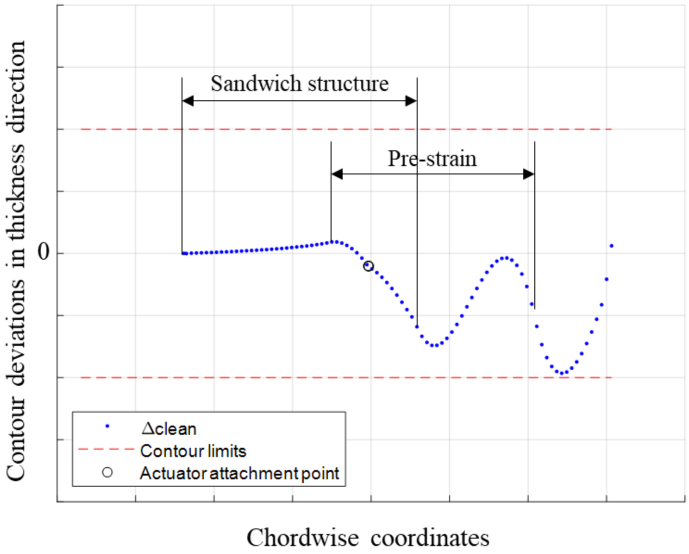

Figure 3: Resulting contour deviations of the morphing spoiler with one actuator to the clean profile target shape after finite element structural optimization (the horizontal and vertical axes differ in scale)

The deviations of the spoiler contour in clean configuration in Figure 3 stay within the given limits. The waviness of the contour is a result of the varying stiffness distribution along the chord of the morphing spoiler due to the comparatively rigid sandwich structure and the form-variable laminate section as well as the pre-bent region. The airbrake load case can also be fulfilled with the morphing spoiler design. Due to the aerodynamic loads as well as the pre-bend of the structure, the downstream part of the spoiler is curved more than a conventional, rigid spoiler. Thus, the actuator must be extended more compared to a conventional design. For the presented morphing spoiler, the actuator stroke must be delivered by additional 8%.

The laminate thickness of the flexible spoiler region amounts to 10.25 mm GFRP. This thickness could be reduced in further optimizations that explicitly use mass in the objective function and/or constraint functions. In the current optimizer setup, the top and bottom laminates of the sandwich structure are united downstream of the sandwich and form the flexible region. Consequently, these top and bottom laminates become thicker if the optimizer increases the thickness of the flexible region. However, the sandwich section does not need such thick laminates to provide sufficient stiffness. In future developments of the optimizer, the sandwich structure will be designed with the goal of reduces weight, and thus will consist of thinner laminates. Nevertheless, for all load cases (SCBs, clean and airbrake), the resulting laminate curvatures remain below the failure limits determined experimentally in [18] which utilizes the same HexPly®913 ply-stacking.

After proving successfully that aerodynamic SCB target shapes which consider structural demands in their design process can be met by a structurally optimized morphing spoiler, the next goal is to implement a chordwise position variation of the bump crest.

3.2 Two-actuator concept

Based on the above described spoiler design and main actuator configuration, a second actuator is implemented. For this purpose, the upstream attachment of this additional actuator 2 is defined closely downstream of the actuator 1 attachment. As a new optimization variable, the location of the downstream actuator 2 attachment is defined. Furthermore, a second pre-strain section has to be implemented. While the location of the sandwich structure of the one-actuator concept stays the same, the pre-strain areas are changed and repeatedly optimized for the two-actuator concept. The results are shown in Figure 4.

It can be seen that both bump crest positions of the FE results are very close to the target crests in terms of location and height. However, in contrast to the results of the one-actuator concept in Figure 2, the sandwich section shows larger deviations. And also downstream of the crests, there are some differences to the descending flanks of the target bumps. Nevertheless, flow simulations with the resulting structural bump shapes have shown no significant changes in terms of aerodynamic performance. This leads to the conclusion that the bump formation with a morphing spoiler can be seen as successful.

Regarding the cruise without bump, actuator 2 has been simulated as locked (0 mm stroke). In Figure 5, the contour deviations of the morphing spoiler in clean configuration including aerodynamic pressure loads are depicted.

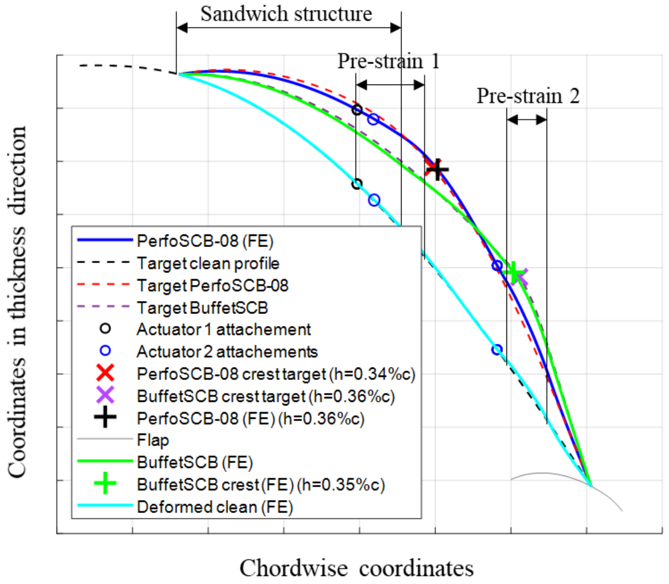

Figure 4: Resulting shapes of the morphing spoiler with two actuators after finite element (FE) structural optimization compared to two aerodynamically optimized shock control bump (SCB) target shapes (the horizontal and vertical axes differ in scale)

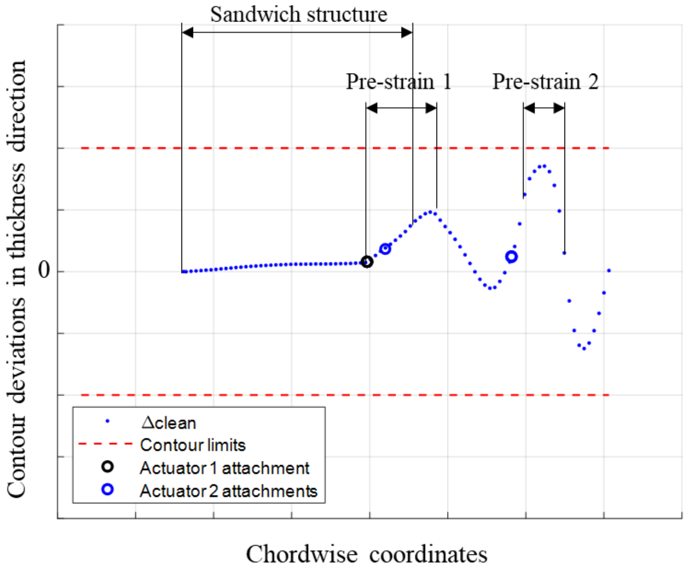

Figure 5: Resulting contour deviations of the morphing spoiler with two actuators to the clean profile target shape after finite element structural optimization (the horizontal and vertical axes differ in scale)

These results show that even by implementing the second actuator the contour deviations stay within the limitations. Compared to Figure 3, the contour deviations in Figure 5 show a larger amplitude in their fluctuation downstream of actuator 2. This is a result of the distinctly thinner glass fiber laminate of this spoiler region compared to the thicker laminate

(10.25 mm) of the one-actuator concept. This thickness decrease could be realized due to the provision of additional stiffness by actuator 2. The laminate between the two actuator 2 attachments has a thickness of 3.75 mm while downstream of actuator 2, the thickness amounts to only 3.625 mm. Similar to the one-actuator concept, the curvatures changes do not exceed the material limits in [18], also not for the airbrake load case.

The airbrake loads are determined at dive speed for the highest dynamic pressure occurring during an emergency descent. In Figure 6, the FE results for this load case are shown. The longer morphing spoiler is deflected by an angle of about 37°, while the ideal stiff reference spoiler is shorter and has an airbrake angle of 45°. The reason for the elongation of the morphing spoiler is an easier structural realization, since a longer bump does not face such high curvatures as if a bump of equal height is formed on a shorter spoiler. Furthermore, the aerodynamic investigations have shown a benefit in terms of drag reduction for the elongated spoiler, while the shorter spoiler/bump with an identical spoiler TE position is beneficial for buffet onset delay. One goal of the morphing spoiler for the airbrake is to reach at least the projected height of the conventional, rigid reference design to achieve a similar aerodynamic effect.

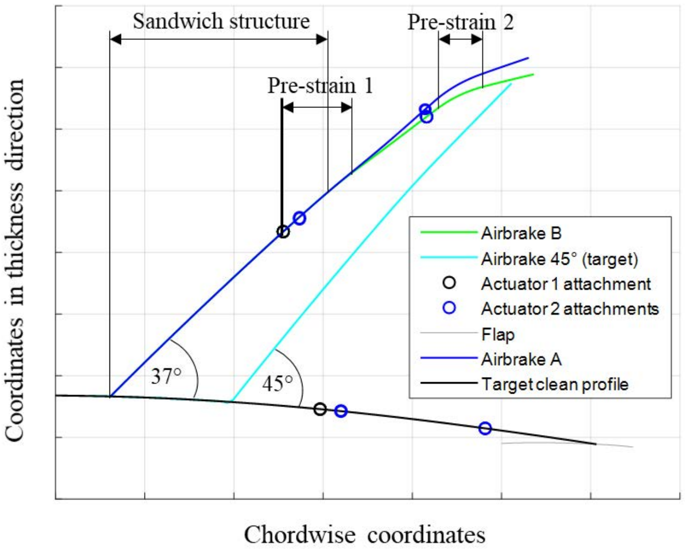

Figure 6: Resulting shapes of the morphing spoiler under airbrake pressure loads with two actuators after finite element structural optimization compared to the target shape of a shorter, rigid spoiler (the horizontal and vertical axes differ in scale)

In Figure 6 it becomes clear that the target height of the deflected spoiler is reached with the morphing design. Furthermore, when actuator 2 is locked (0 mm stroke), the respective spoiler section is straight due to the introduced stiffness of the actuator. In the following, this load case is denoted as Airbrake A. However, downstream of actuator 2 the structure is bending. This happens not only due to the aerodynamic loads but also due to the structural pre-strain 2 that deforms the spoiler. In Figure 6, an additional airbrake configuration is shown (Airbrake B) in which actuator 2 is retracted by -3.0 mm. This is done to evaluate the force decrease since in this scenario, actuator 2 must not work against pre-strain 1 anymore as it is the case for 0 mm stroke in Airbrake A.

As depicted in Table 1, the maximum forces for both actuators are present during the airbrake. It becomes apparent, that actuator 2 is loaded with less than half of the actuator 1 force. Furthermore, when actuator 2 is retracted by -3.0 mm (Airbrake B) the force is decreased by more than 11%.

Table 1: Actuator loads and results from finite element simulations of the two-actuator concept

	Airbrake A	Airbrake B	PerfoSCB-08	BuffetSCB	Clean
Angle	37°	37°			
Actuator 1 force	109 kN	108 kN	-34 kN	-31 kN	-35 kN
Actuator 1 stroke	135 mm	135 mm	7.4 mm	5.1 mm	0 mm
Actuator 2 force	45 kN	40 kN	-19 kN	-12 kN	-22 kN
Actuator 2 stroke	0 mm	-3.0 mm	-2.5 mm	-0.1 mm	0 mm

It should be noted that the airbrake pressure loads have been determined for one rigid spoiler with 37° deflection angle. Thus, in the FE simulations, always the same pressure distribution is being used, independently of the spoiler deformation. Since this is also the case for the one-actuator concept, the respective forces stay under 110 kN as well which is a reasonable size for the main spoiler actuator. Furthermore, in Table 1 it can be seen that for the three no-airbrake load cases all actuator forces are negative, even for the cases when one of the bumps is deployed. This means that the actuators have to pull which is a result not only of aerodynamic suction pressure loads but also due to the pre-curved spoiler structure.

4 CONCLUSIONS

In this work, the concept of a morphing spoiler that can form a shock control bump with different crest positions by using two actuators is described. The spoiler consists of a sandwich structure and a form-variable glass fiber laminate. The larger actuator is the main spoiler actuator, the other is an additional component which introduces not only the capability of varying the SCB crest position but also provides stiffness to the spoiler. The two different SCB target shapes are the result of aerodynamic optimizations in terms of drag reduction for the more upstream located bump crest and buffet onset delay for the more downstream bump. The structural optimization is divided into two parts. In a first step, the region of the stiff sandwich structure to match the upstream SCB crest with only one actuator is identified. During this optimization, the laminate thickness and a pre-curved spoiler section are varied as well. This is followed by defining the main actuator configuration. The second optimization includes the additional actuator 2, while the configuration of actuator 1 as well as the length of the sandwich structure stay the same. Both approaches consist of one respectively two spoiler sections in which the structure is bended by implementing a pre-strain. These regions are different for both concepts and must be optimized as well.

While for the one-actuator concept a very good match of the aerodynamic SCB target shape is reached, minor deviations to the two bump target shapes can be seen for the two-actuator approach. However, flow simulations of the resulting FE spoiler shapes show no significant decrease in aerodynamic performance. Furthermore, in the clean spoiler configuration, the shapes for both concepts stay within the contour limitations and the airbrake load case is also fulfilled. Consequently, the SCB formation including the variation of the bump crest position on a morphing spoiler by using two actuators can be seen as successful. Although aerodynamic pressure loads have been used in the FE analyses, these pressure distributions have been determined for the target shapes, thus they do not change with changing SCB shapes in the FE model.

5 OUTLOOK

The next step is the design of a conventional spoiler which serves as a reference. This reference spoiler can be compared to both morphing concepts in terms of spoiler weight and actuator loads. To achieve a lightweight design of the morphing spoiler, the penalty factors in the structural optimizer for thicker laminates can be increased to reduce weight. In addition, a more detailed design of the spoiler structure is to be realized in terms of ply drop-offs and an accurate re-design of the spoiler trailing edge. Also, the actuator attachments are currently modeled via contact and joint conditions in the FE model, which could be done in more detail.

The resulting 2D SCB shapes of the structural design could be evaluated in fully coupled fluid-structure-interaction optimizations. Furthermore, SCBs are often investigated as a retrofit solution. However, considering morphing technologies in general and SCBs in particular from the beginning into aircraft designs would increase the efficiency of these adaptive systems, compared to retrofitted solutions.

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