ANALYSES REGARDING VARIABLE CAMBERING WITH SPOILER TRACKING: EFFECT OF THE FLAP HINGE LINE LOCATION ON THE AERODYNAMIC AT TRANSONIC SPEEDS

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OVERVIEW

Variable cambering (VC) is a well proven method to help provide beneficial aerodynamics in terms of drag reduction for a wide range of the flight envelope. In combination with application of laminar flow (NLF) up to the shock VC can be even used to decrease skin friction drag. Because of the ability of VC to serve as a baseline technology providing benefits to other drag reduction technologies it is of growing interest for commercial applications again. While VC in general is fairly documented in literature its application to airfoils with shock locations at the adaptive surface providing extended laminar flow up to that point is not. This work focuses on the aerodynamic effects of flap hinge line movement with spoiler tracking at transonic speeds. The work was done within the LuFoV-1 project LDAinOp (Low Drag Aircraft in Operation). In addition to a reference configuration 8 different hinge line positions are discussed. It will be shown that, when applying VC in order to move the shock to its desired location, the hinge line position significantly affects the shock because of curvature effects at the wing/spoiler junction. Furthermore it will be shown that, if the shock is located directly at the junction at design conditions, it is even possible to reduce the wave drag by both upward and downward flap deflection. This shows the importance of taking the hinge line position into account when designing adaptive wing configurations which are utilizing movable devices as VC surfaces.

NOMENCLATURE

c = profile chord length
c_{df} = skin friction drag coefficient
c_{dw} = wave drag coefficient
c_l = local lift coefficient
D = Aerodynamic drag
L = aerodynamic lift
N = N-factor from LST
M = Mach number
Re = Reynolds number
α = angle of attack
δ_f = flap deflection angle
φ = sweep angle
LST = linear stability theory
NLF = natural laminar flow
VC = variable cambering

1. INTRODUCTION

The work presented in this paper was done within the LuFoV-1 project LDAinOp (Low Drag Aircraft in Operation). The project aims to utilize drag reduction technologies on a natural laminar flow (NLF) wing. One of the drag reduction technologies is the application of a variable camber (VC) folwer flap. VC is a well-known and well proven method to help provide beneficial aerodynamics in terms of drag reduction for a wide range of the flight envelope [1,2]. The application of variable camber trailing edge aims to increase aerodynamic performance, buffet margins and pitching moments [3,4]. First intense testing on VC was performed in the 1980s [5] and newer observations take also, like the current work, natural laminar flow into account [6].

However, transonic configurations with shock locations directly on the adaptive device are hardly documented in literature, especially in combination with natural laminar flow airfoils. The presented work analyzes the aerodynamic effects when applying VC using a Fowler flap and spoiler tracking. Hence both spoiler and flap serve as adaptive surface. The shock is located at the spoiler in most of the cases and the laminar boundary layer extends up to the shock location in every case.

2. COMPUTATIONAL SETTINGS

In addition to a reference configuration 8 different hinge line positions are discussed. The analyzed flap hinge line locations are shown in FIG. 1, they are located in a circular sector with a radius of 10% chord and a central angle of 15° centered at the reference flap hinge line location.

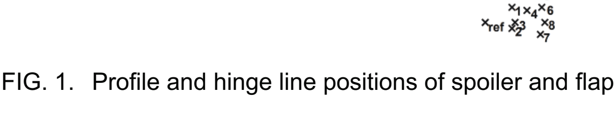

FIG. 1. Profile and hinge line positions of spoiler and flap.

The analysis is performed for 2 different Mach numbers, cruise at $M = 0.75$ and off-design of $\Delta M = +0.02$. The Reynolds numbers are $Re\backslash m = 5.89 \cdot 10^6$ at cruise conditions and $Re\backslash m = 6.05 \cdot 10^6$ in off-design. The lift coefficients are $c_l = 0.65$ at cruise and $c_l = 0.611$ at off-design conditions.

For each setting 7 flap deflection angles from $\delta_f = -3°$ (upward deflection) to $\delta_f = 3°$ (downward deflection) with $\Delta\delta_f = 1°$ are analyzed. The computations have been performed using FLOWer [7] including a sectional conical extension [8,9]. The sectional conical extension in general shows very good agreement to results obtained from three-dimensional computations. However, it is only applicable to flows where the isobar lines are parallel to the percentage chord lines.

The wave drag is evaluated using a formulation developed by *Inger* [10] and modified by *Obayashi* and *Takanashi* [11]. Additionally the formulation includes a modification considering the application of conical flow conditions:

$$(1) \quad c_{dw} = 0.02 \cdot ((Ma_{PS} \cdot \cos(\varphi_{PS}))^2 - 1)^{4.4}$$

Ma_{PS} is the local Mach number upstream of the shock and φ_{PS} is the local sweep angle upstream of the shock.

Transition prediction is performed using the toolbox STABTOOL, which is based on linear stability theory and a 2-N-factor approach [12].

3. RESULTS

The functional principle of trailing edge devices used for VC control is well known from literature. Downward flap deflections increase camber and thus shift the maximum achievable lift to lower angle of attacks. Upward flap deflection is working vice versa, it decreases camber and thus shifts the maximum achievable lift to higher angle of attacks [4,13]. In general VC is used to increase aerodynamic efficiency and margin to buffet.

In the following the laminar boundary layer of all discussed cases extends to the shock location. For reasons of simplicity the reference hinge line position (see FIG. 1) is denoted reference.

3.1. Design case (M=0.75)

3.1.1. Upward flap deflections (δ_f<0°)

FIG. 2 shows the pressure distributions for upward flap deflections of $\delta_f = -3°$. Pressure distributions are shown for the reference and for the most backward flap hinge line (no. 8). The figure shows that the expected behavior from literature can be observed. Obviously more backward flap hinge line positions (no. 8) increase camber and the angle of attack, which is required for achieving the targeted lift, is lower. Especially the reduced acceleration at the leading edge leads to reduced overall velocities at the upper profile side and delay the shock location in comparison to the reference. Furthermore the shock strength is significantly reduced and the laminar boundary layer length is increased. Hence the lift coefficient c_l remains the same and the wave drag and skin friction coefficients c_{dw} and c_{df} are decreased. The overall aerodynamic efficiency $M * L/D$ is increased.

FIG. 2. Pressure distributions for upward flap deflection of $\delta_f = -3°$ for reference hinge line position and most upstream position no. 8 ($M = 0.75$).

3.1.2. Downward flap deflections (δ_f>0°)

For downward flap deflections an opposite behavior is expected, the reference is supposed to be the one with the best aerodynamic performance. However, FIG. 3 shows that this expectation cannot be met when the shock is moved downstream at the adaptive surface. The local curvature effects at the junction from the wing surface to the tracked spoiler surface are highly affecting the pressure distribution in the transonic regime.

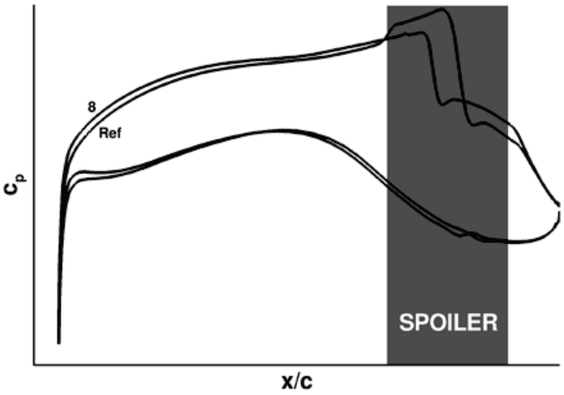

FIG. 3. Pressure distributions for downward flap deflection of $\delta_f = 3°$ for reference hinge line position and most upstream position no. 8 ($M = 0.75$).

More backward positions of the flap hinge line (no. 8) decrease camber and increase the angle of attack for achieving the targeted lift. Furthermore the shock position is moved upstream. Up to this point the VC mechanism is working as expected. Because of the reference being the one with the highest camber it should be also the one with the lowest shock strength. But in contrast to the upward deflection local curvature effects reverse the expectations considering shock strength and thus aerodynamic efficiency. Increasing camber in this case means increasing curvature effects too and thus accelerating the flow upstream of the shock. This leads to the result that, in contrast to the expectations, the case with most upstream movement of the flap hinge line position is the one with the best aerodynamic efficiency.

3.1.3. Design case summary

Because of non-negligible curvature effects at the wing to spoiler junction a backward movement of the flap hinge line is in any case beneficial to the aerodynamic performance and thus the margin to buffet. FIG. 4 and FIG. 7 show that this behavior is observed for every analyzed flap deflection angle. The reasons for this behavior are curvature effects occurring when the shock is located at the adaptive surface – here only for downward flap deflections. Furthermore FIG. 4 shows that the horizontal movement of the flap hinge line position seems to be of more influence as the vertical one for all cases.

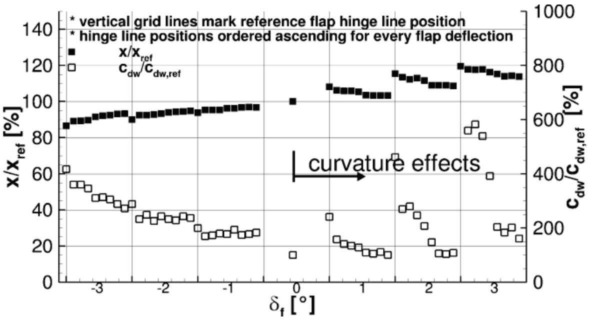

FIG. 4. Shock positions and wave drag coefficients for all analyzed flap deflections ($M = 0.75$).

3.2. Off-design case (M=0.77)

3.2.1. Upward flap deflections (δ_f<0°)

The pressure distributions near the shock of upward flap deflection of $\delta_f = -3°$ are shown in FIG. 5. In addition to the previous cases the flap hinge line position no. 4 is also plotted. From reference up to position no. 4 there are no curvature effects of the wing/spoiler junction. Like before, design case and upward deflections, the shock strength can be reduced by moving the hinge line more backward. However, moving the hinge line too far backwards increasingly causes curvature effects to occur. The shock strength is increasing again. The previously described mechanism, which is reverting the initial expectations, starts working again. However, the increase of wave drag of subsequently downstream shock movement is counteracted by the decreasing skin friction drag caused by higher laminar extent. Thus the aerodynamic efficiency will decrease less, see FIG. 7.

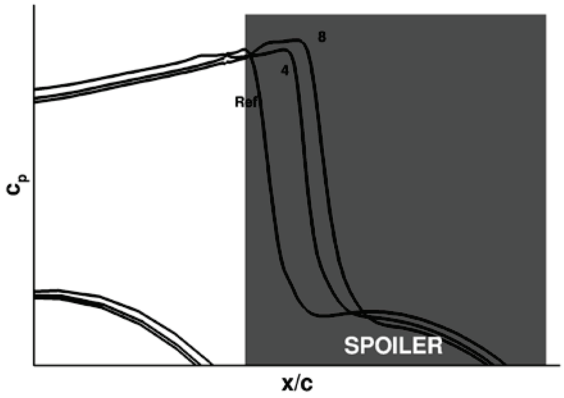

FIG. 5. Pressure distributions for upward flap deflection of $\delta_f = -3°$ for reference hinge line position and positions no. 4 and 8 ($M = 0.77$).

3.2.2. Downward flap deflections (δ_f>0°)

For downward flap deflections the behavior observed at $M = 0.77$ is equal to the one at design conditions.

3.2.3. Off-design case summary

Again non-negligible transonic curvature effects at junction from wing to spoiler are highly affecting the pressure distributions and thus the shock strengths and locations. Because of higher free stream velocity in comparison to the design case the shock is located at the adaptive surface early. Curvature effects can be observed for almost all cases, see FIG. 6.

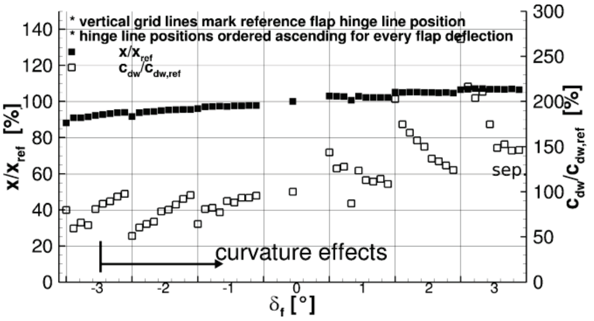

FIG. 6. Shock positions and wave drag coefficients for all analyzed flap deflections ($M = 0.77$).

For high cambering at downward deflection of $\delta_f = 3°$ and backward movement of the hinge line flow separation is observed. A general statement that far backward movement of the flap hinge line is in any case beneficial to the aerodynamic performance cannot be made. However, slight backward movement may be of more benefit because of the increasing margin to buffet. Again horizontal movement of the flap hinge line position seems to be of more importance than vertical movement.

4. CONCLUSION

The presented work shows that curvature effects occurring upstream of the shock in the transonic regime may not be neglected when applying variable cambering using trailing edge devices. The curvature effects can completely revert the expectations which are known from literature. Furthermore this work shows that it is possible to take advantage of these curvature effects. If the shock is located at the junction from the rigid to the adaptive surface, backward movement of the hinge line of the adaptive surface is in any case beneficial to the aerodynamic performance, see FIG. 7. Nevertheless this statement is only true for one speed.

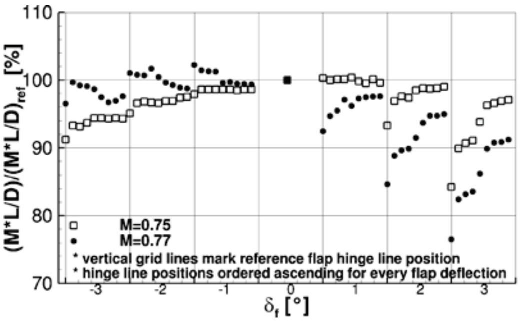

FIG. 7. Aerodynamic efficiency for all cases.

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