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PARAMETRIC STUDY OF HOMOGENEOUS BLOWING AND SUCTION ON THE TRANSONIC AIRFOIL RAE2822

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INTRODUCTION

Civil aviation is responsible for about 3% of the global CO_2 emissions [4]. A decrease in the total drag of an airplane leads to an increase in efficiency and thus a reduction of fuel consumption and emissions. Viscous losses related to the skin friction at the surfaces are responsible for roughly half of the overall drag, thus reducing them promises potentially large performance improvements.

One method to achieve a skin-friction drag reduction is the control of the turbulent boundary layer. Active flow control requires additional energy compared to passive methods but promises a higher drag reduction. One active control method is wall-normal homogeneous blowing and suction. A small mass flow rate is injected or extracted from the flow to control the turbulent boundary layer formation and thus the drag generation. Early investigations of Prandtl and Beck [7] on a flat plate showed that suction can prevent the boundary layer from separation. Later studies showed the great potential of this control technique which results in a friction drag reduction of up to 50% in the subsonic and up to 80% in the transonic regime [5]. So far most studies considered the zero-pressure gradient boundary layer or other canonical flows. If an airfoil is considered the geometry is more complex and thus skin-friction drag is not the only drag component anymore. Fahland et al. [3] investigated the effect of homogeneous blowing and suction on a NACA4412, where none of the addressed configurations resulted in a drag reduction when the costs of the actuation are taken into account. A Bayesian optimization of the flow control on a NACA4412 in the incompressible regime showed, that there indeed are blowing and suction distributions where a drag reduction is reached, especially in high lift configurations [6]. When considering civil aviation the flow around the airfoil becomes transonic, which leads to the occurrence of a weak shock wave on the suction side of the airfoil. The occurrence of such a nonlinear effect leads to changes in the flow and thus affects the potential for homogeneous blowing and suction to generate a drag reduction.

In the present study, the effect of uniform blowing and suction on the aerodynamic efficiency as well as the effect on the shock characteristics are investigated via a parametric study of the transonic airfoil RAE2822.

METHODOLOGY

The flow around the transonic airfoil RAE2822 is simulated via Reynolds-Averaged Navier-Stokes equations (RANS). The simulations are conducted with the open source solver SU2 [1] with a density-based steady-state solver. As a turbulence model, the $k-\omega-$SST model was employed. At $x/c = 0.1$, with c as the chord length, a fixed transition via a semi-explicit scalar source is implemented. The grid consists of hexahedral cells and has a 2D block pattern. The C-radius is $50c$ and the outlet distance is $75c$. A validation of the RANS data with well-resolved LES simulation is being performed.

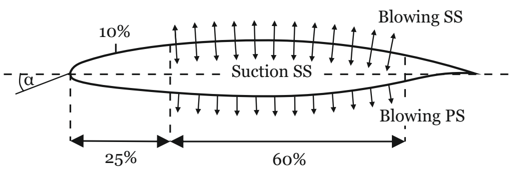

Figure 1: Sketch of the control areas and the configurations.

The surface of the airfoil where no control takes place is simulated as adiabatic walls with the no-slip condition. In the areas where control takes place a homogeneous wall-normal mass flow is prescribed. The control regime spans from 25% up to 85% of the chord length. Three different control configurations are investigated: blowing on the suction side, blowing on the pressure side and suction on the suction side. All configurations are studied individually and no combination of different configurations is considered. A sketch of the airfoil and the control configurations is shown in figure 1.

Since fluid is expelled in or removed from the system the costs e.g. accelerating the fluid which is blown into the system need to be taken into account when the overall drag component is calculated. For the analysis of the results of the parametric study the inclusive drag $c_{D,inc}$ is considered

$$c_{D,inc} = \begin{cases} c_{D,body} = c_{D,wake} + c_{BLC} & \text{for suction} \\ c_{D,wake} = c_{D,body} + c_{BLC} & \text{for blowing} \end{cases} \tag{1}$$

with the body $c_{D,body}$ and the wake drag $c_{D,wake}$. The boundary layer penalty is calculated from

$$c_{BLC} = \left| 2 \frac{u_{BLC}}{U_\infty} \frac{l_{BLC}}{c} \frac{\rho_{BLC}}{\rho_\infty} \right| \tag{2}$$

with the velocity magnitude of the control fluid u_{BLC} and the freestream flow U_∞, the length of the control area l_{BLC} and the density of the control fluid ρ_{BLC} and freestream fluid ρ_∞. For a detailed description of the concept of the inclusive drag see Fahland et al. [2].

The boundary layer penalty accounts for the costs that result from the non-zero mass flow, additionally, the power that is required to run the active control needs to be considered in the final analysis.

The simulations for the parametric study are conducted at a constant Reynolds number of $Re = 5 \cdot 10^6$. The Mach number is varied between the subsonic regime ($Ma = 0.6$) up to the transonic regime ($Ma = 0.729$). A maximum control magnitude of $\dot{m}_{BLC} = 3\% \dot{m}_\infty$ is chosen with the free-stream mass flow of $\dot{m}_\infty = U_\infty c \rho_\infty$, while the angle of attack is varied between $\alpha = -1^\circ$ to 3°.

The free-stream parameters selected in this study are chosen to represent a cruise flight scenario at an altitude of 11km.

The free-stream temperature of $T_\infty = -53.5°\mathrm{C}$, the viscosity of $\mu_\infty = 1.449 \cdot 10^{-5}\,\frac{\mathrm{kg}}{\mathrm{ms}}$ and the Mach number are prescribed, while the ideal gas law is used to determine the density and pressure from the given parameters.

RESULTS

In the parametric study, three different control configurations are studied. Figure 2 shows the pressure coefficient for the three different configurations at a transonic Mach number of $Ma = 0.725$, an angle of attack of $\alpha = 2.31°$ and a control magnitude of $\dot{m}_{BLC} = 0.1\%\dot{m}_\infty$.

The uncontrolled reference case is covered by the red curve. For blowing on the suction side a strong effect of the active control on the shock characteristics can be observed. The shock position is shifted towards the leading edge and the shock magnitude is decreased. This leads to a reduction of the lift coefficient c_l compared to the uncontrolled case. As already observed in previous investigations blowing leads to a reduction of the friction drag, which is also seen in the present results. Under consideration of the increased pressure drag and the boundary layer penalty, the inclusive drag increased and a decrease of the efficiency is observed. The opposite effect can be observed for suction on the suction side, the shock is shifted towards the trailing edge and it is increased in magnitude. In this case, an increase in c_l is present. Additionally, the growth in magnitude also leads to an increase in the drag coefficient. Overall, an increase in the efficiency of suction on the suction side was observed. Blowing on the pressure side does not influence the position or magnitude of the shock.

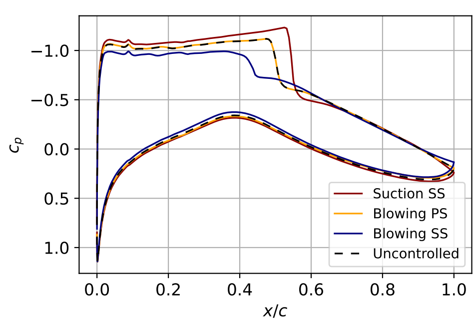

Figure 2: Pressure coefficient for the three control configurations and the uncontrolled reference case for $\dot{m}_{BLC} = 0.1\%\dot{m}_\infty$, $\alpha = 2.31°$ and $Ma = 0.725$.

The parametric study showed cases where an increase in the efficiency at a constant angle of attack is observed. For a better comparison of the effect, these cases are analysed in more detail and are rerun at a constant lift coefficient. An increase in efficiency was mainly observed for the cases with suction on the suction side at low control magnitudes. Promising cases are observed throughout the whole investigated Mach number and angle of attack regime. The most promising case of suction on the suction side is at $Ma = 0.725$ and $\dot{m}_{BLC} = 0.1\%\dot{m}_\infty$ at $c_l = 0.897$. Compared to the uncontrolled case an efficiency increase of 22.29% is observed for suction on the suction side. As already mentioned above, additional energy is needed for active control, which is not taken into account so far. Since the air intake or dumping of fluid is not explicitly defined in the investigated system, a worst-case estimation of the costs is made. Even under consideration of the costs, an increase in the efficiency of 17% is observed.

DISCUSSION

As already studied in the previous literature blowing leads to a reduction of the friction drag of up to 40% for a transonic case with a medium mass flow rate. When the inclusive drag is calculated and thus the pressure drag as well as the boundary layer penalty are included, an increase in the total drag is observed. When considering the inclusive drag the only control configuration which leads to a decrease in the inclusive drag and thus an increase in the efficiency is suction on the suction with a low control magnitude. The presence of the non-linear effect of the shock, whose characteristics are strongly affected by the active flow control, leads to the positive effects of the control which are not observed in the subsonic regime. Taking into account the energy that is needed to run the control results in a higher drag coefficient. Even though the assumptions which are made to get an estimation of the costs reflect a worst-case scenario, configurations with a maximum increase in the efficiency of 17% are found.

The results of the parametric study show that the active flow control of wall-normal homogeneous blowing and suction has potential, especially suction on the suction side at low control magnitudes in the transonic regime. Considering the non-optimal estimation of the costs and no targeted optimization is made, the potential of the control might be even larger.

In the conference talk the results of the study will be presented in detail with a focus on the cases where an increase in efficiency is observed and on validation via scale-resolving simulations. This includes a discussion of the simulation results and a more detailed look at the assumptions made to estimate the cost of the control.

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