JOURNAL OF AIRCRAFT
Vol. 42, No. 3, May–June 2005

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Passive Shock Control Concept for Drag Reduction in Transonic Flow

G. Dietz*
DLR, German Aerospace Center,
D-37073 Göttingen, Germany

Nomenclature

c	=	chord length, m
c_d	=	drag coefficient
c_l	=	lift coefficient
c_p	=	pressure coefficient
Ma	=	Mach number
p	=	pressure, Pa
Re	=	Reynolds number
v	=	velocity, m/s
x, y, z	=	Cartesian body axes, m
α	=	angle of attack, deg

Subscripts

0	=	stagnation
∞	=	freestream

Introduction

THE European Aeronautics Vision for 2020[1] demands an ambitious 50% cut in CO_2 emission per passenger kilometer, that is, a 50% cut in the fuel consumption for future transport aircraft operating close to the speed of sound. The concept of flow laminarization, which promises considerable fuel savings, will lead to lifting-surface-pressure distributions, which exhibit strong wing-suction-side shock waves. However, even for turbulent-flow wings the design and off-design properties, in particular the total drag, are strongly affected by the development of the boundary layer on the wing and its interaction with the wing-suction-side shock wave. Shock control is expected to improve the flight performance in terms of decreasing the total drag and hence the fuel consumption as well as delaying the onset of loss of lift caused by boundary-layer separation[2] or buffet.[3,4] The wave drag increases with increasing shock-wave strength. Additionally, the viscous drag increases as a result of a thickening of the boundary layer. Moreover, a strong shock wave can provoke the boundary layer to separate, which can lead to buffet. Thus, shock control also means boundary-layer control and is assumed to have a large potential for meeting the environmental goal of the European Aeronautics Vision for 2020.

Several shock control concepts have been investigated in the past.[5] Indirect methods, for example, flaps or trailing edge devices, may adjust the pressure distribution such that for a given lift the shock strength is minimized.[5,6] Direct methods attempt to affect the shock wave where it occurs.

Two-dimensional approaches, denoting concepts that are applied homogeneously in spanwise direction, were investigated in two European projects, namely, EUROSHOCK I and II.[3,4] Several types of passive and/or active shock and boundary-layer control concepts were assessed. It was shown that the most effective device is a well-placed adaptive, variable-height contour bump. Numerical simulations for a laminar-type airfoil predicted drag reductions up to 23%. Based on this type of device, implementation studies for an Airbus A340 Hybrid Laminar Flow (HLF) wing assumed an average aircraft total-drag reduction for a typical North Atlantic flight mission of 3% (Ref. 7). For a typical Airbus A340-type aircraft wing of existing turbulent-flow design, maximum drag reduction at off-design conditions were found to be about 5% (Ref. 8). In both cases cash-operating-cost (COC) reductions were determined to be $\Delta COC = -1.3\%$ for the HLF wing and $\Delta COC = -0.4\%$ for the turbulent-flow wing, respectively. For the turbulent-flow wing, higher gains are expected to be achieved at off-design flight conditions, which are generally unavoidable.[4] However, the weight penalty of about 0.2 to 0.5 tons and an increase of the maintenance costs of approximately 0.5% as a result of the installation of such a complex adaptive device decrease the potential benefit in the COC to about 0.1%.

A major disadvantage of the two-dimensional approaches is the fact that the devices need to be placed and dimensioned very accurately according to the flow conditions. Thus, in order to gain benefits in real applications these concepts must be implemented as heavy and maintenance-intensive adaptive devices. More recent three-dimensional methods such as streamwise slots and grooves,[2] three-dimensional bumps,[9] spikes,[10] or vortex generators[5] show promise to overcome these problems by acting quasi-auto-adaptively. One recently proposed[11] passive shock control concept for drag reduction on swept wings called D-Strips is presented here.

The objectives of the present Note are to introduce the operating principle of D-Strips and to summarize results of a first experimental proof of concept of this passive shock control technique. A wind-tunnel test with tripped boundary-layer transition was conducted at transonic airspeeds using the airfoil VC-Opt,[6] which has 9.2% relative thickness. The flow around the clean airfoil is compared to data obtained with several D-strip modifications applied to the same airfoil. Schlieren pictures indicate that the operating principle of D-Strips indeed works. Wake measurements demonstrate a drag rise in the wake of the D-Strips but also a beneficial drag reduction in spanwise direction next to the D-Strips at supercritical flow conditions. Further investigations have to be performed in order to quantify the potential benefit for transport aircraft. However, because of its operating principle an application of a small number of D-Strips to a swept wing promises considerable improvements in transport aircraft performance.

Operating Principle

In the classical interaction[12] of a shock wave of moderate strength with a boundary layer, the boundary layer starts thickening upstream of the position of the shock wave. This thickening of the boundary layer in the shock foot region leads to a ramp effect for the outer

Received 16 July 2004; revision received 15 October 2004; accepted for publication 15 October 2004.

*Research Scientist and Head of Department Aeroelastic Experiments, Institute of Aeroelasticity; Guido.Dietz@dlr.de.

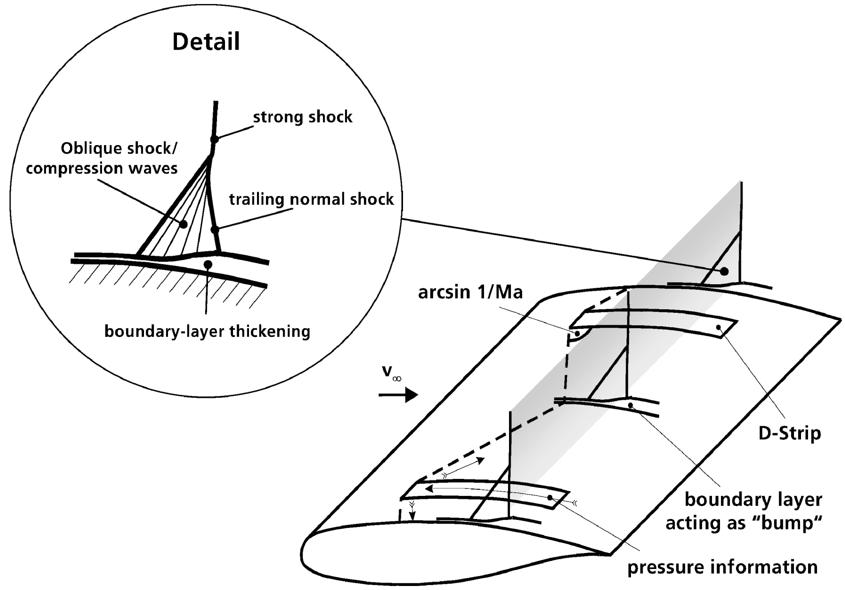

Fig. 1 Operating principle of D-Strips.

supersonic flow and provokes a formation of compression waves (compare Fig. 1 detail). The resulting small triangular region of still supersonic flow is terminated by a normal shock. The compression waves and this trailing shock meet above the airfoil to form a single strong shock. Along streamlines passing through the triangular region, the pressure gradients and the entropy production are lower than along streamlines passing through the single shock. Thus, increasing the extent of this triangular region provides two benefits: First, the entropy production across the height of the triangle is lower than above, and thus the wave drag is lower than without the interaction. Second, the streamwise pressure gradients, which are imposed on the boundary layer, decrease. This avoids a rapid and strong thickening of the boundary layer and the associated increase in viscous drag. Furthermore, the decrease in the streamwise pressure gradient can lower the risk of boundary-layer separation.

The moderate thickening of the boundary layer upstream of the shock wave is caused by the subsonic region in the boundary layer, which extends from the nonslip wall to the wall distance where the local velocity is equal to the speed of sound. The first basic idea of D-Strips is to introduce additional nonslip surfaces above the airfoil in order to increase the height of the subsonic region of the boundary layer. Thus, the high-pressure information can be passed from downstream of the shock wave further upstream than on the clean configuration. Therefore, the streamwise and the wall-normal extent of the triangle is increased. However, the viscous drag will probably increase close to the D-Strips. The second basic idea of D-Strips is based on the fact that typical local supersonic Mach numbers for transport aircraft wings are less than 1.4. Hence, the pressure information in front of the shock wave is distributed in wide-splayed characteristics. Therefore, an arrangement of D-Strips as shown in Fig. 1 promises a local increase of the viscous drag but a more global decrease of the total drag in spanwise direction. On a swept wing where 90-deg arcsin $1/Ma$ is close to the sweep angle, the positive impact of D-Strips in spanwise direction toward the wing tip will be even stronger than for a two-dimensional airfoil.

Test Setup

The first proof-of-concept study of D-strips was performed in the Transonic Wind tunnel Göttingen operated by the Stiftung Deutsch-Niederländische Windkanäle. This is a continuous run facility with a 1×1m adaptive test section. The ratio of the tunnel height to the chord of the investigated airfoil model is 2.5. The top and bottom walls of the test section are adapted to the steady flow around the airfoil. The wall interference is minimized by a one-step method of wall adaptation based on a Cauchy-type integral.[13] The displacement thickness of the turbulent wind-tunnel wall boundary layer is predicted by Head's method[14] and is added to the wall shapes; top and bottom wall displacement thicknesses are obtained according to the measured pressure gradients at each wall while the gradient is neglected for the sidewalls. (Jacobs, M., "Treatment of the Wall Boundary Layer in the Wall Adaptation Procedure and Steady Wall Adaptation for Dynamic Tests," DNW BU GuK, private communication, Göttingen, Germany).

The transonic airfoil model VC-Opt[6] with a 9.2% relative thickness, 1-m spanwidth and 0.4-m chord length is manufactured from high-tensile steel. It is mounted to a rotating mechanism on each side of the adaptive test section, which allows the adjustment of the angle of attack α with an accuracy of ± 0.02 deg. The airfoil is fitted with static-pressure taps in three spanwise rows each having 42 orifices on the suction side. In the middle row are additionally 28 orifices on the pressure side. Laminar-turbulent boundary-layer transition is forced at 10% chord on the suction and on the pressure side by disks with a height of 0.032%, a diameter of 0.250%, and a distance from each other of 0.635% chord length. The effectiveness of the transition tripping has been verified in previous tests using zig-zag tape with a height of 0.025% chord length.[6]

Beside the static pressures at the airfoil surface, static pressures at the wall as well as total and static pressures in the wake are measured using a multichannel pressure sensor system. The wake rake consists of 136 total and eight static tubes with a total rake height of 125% chord length and is mounted 150% chord length downstream of the model trailing edge in the center plane of the test section. The accuracy of the measured pressures at the airfoil surface is estimated to be $\pm 0.5\%$ and for the pressures at the wall and at the wake rake $\pm 0.35\%$ relative to a typical stagnation pressure of the present test. No corrections for displacement effects have been applied to the wake pitot measurements. The lift coefficient is calculated using integration of the measured airfoil surface pressures. The drag coefficient is calculated from the wake rake data by integration across the model wake. Data repeatability of lift and drag coefficients was examined by comparison of the present data at the clean airfoil with data obtained at the same flow conditions in two other test campaigns using the VC-Opt airfoil model. The repeatability of c_d is approximately 0.0002 and of c_l 0.02, respectively. The measured data points per channel are obtained by averaging 255 samples.

A schlieren system is used in the present investigation in order to visualize the impact of the D-Strips on the flowfield close to the wing-suction-side shock wave. It is set up in a standard Z arrangement. The light source is provided by a xenon light with 150-W

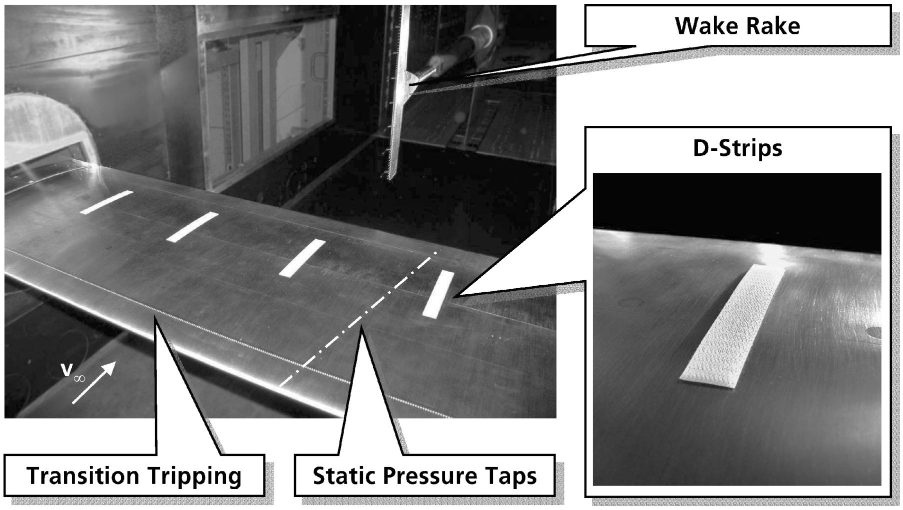

Fig. 2 VC-Opt airfoil with D-Strips applied and wake rake mounted in the DNW-TWG.

power. A slit diaphragm is placed in front of the light source. Two 594-mm-diam parabolic mirrors with a focal length of 5 m are used to collimate the light through the test section and to refocus it onto the schlieren edge provided by a razor blade. The schlieren pictures are recorded by a 1280 × 1024 pixels charge-coupled-device camera.

Figure 2 shows a photograph of the airfoil model and the wake rake installed in the wind tunnel. D-Strips are applied to the airfoil ranging from 40 to 70% in chord direction. The spanwise width of the D-Strips is 4.25% chord length, and in the spanwise direction they are 50% chord length apart. In the tests two different heights of Velcro-type strips are applied: thin D-Strips with a height of 0.215% and thick D-Strips with a height of 0.570% chord length.

Proof-of-Concept Experiment

The objectives of the first proof-of-concept experiment are to validate the operating principle of D-Strips and to demonstrate its potential benefits. Nevertheless, further investigations are necessary to quantify the potential benefit for a transport aircraft with swept wings. Schlieren pictures of the flowfield above the airfoil and total-pressure distributions in the wake of the airfoil are taken in order to validate the operating principle of D-Strips. Lift and drag polars demonstrate the benefits of D-Strips with respect to airfoil performance.

Figure 3 shows schlieren pictures at flow conditions where a moderately strong shock wave occurs above the clean airfoil at $x/c = 64\%$. The angle of attack in all four cases is adjusted such that the lift force is the same. The flow visualizations present the flowfield density gradients integrated across the span. Dark and light areas indicate high gradients. The top picture reveals the flow structure for the clean airfoil as reference case. It shows a classical transonic shock-wave/boundary-layer interaction of moderate strength.[12] Because of the density gradients in the boundary layer, one can see the thickening of the boundary layer in the shock foot region, which leads to a small triangular region of compression waves. This region has a smaller extent compared with the cases where thin or thick D-Strips are applied. Here the density gradients in the flowfield above the airfoil are smaller compared to the reference case. The presence of the D-Strips causes the thickening of the boundary layer to start further upstream. Moreover, the boundary-layer thickening is spread over a longer chordwise distance, which leads to weaker density gradients in the boundary layer. Thus, from these schlieren pictures one can expect a lower wave drag and a lower viscous drag as a result of the shock-wave/boundary-layer interaction modified by the D-Strips compared to the clean airfoil. In Fig. 3 thick D-Strips "closed" with plasticine are also shown. Hence, the displacement effect of the closed version is comparable with the one of an ordinary strip, but the pressure information cannot travel upstream in

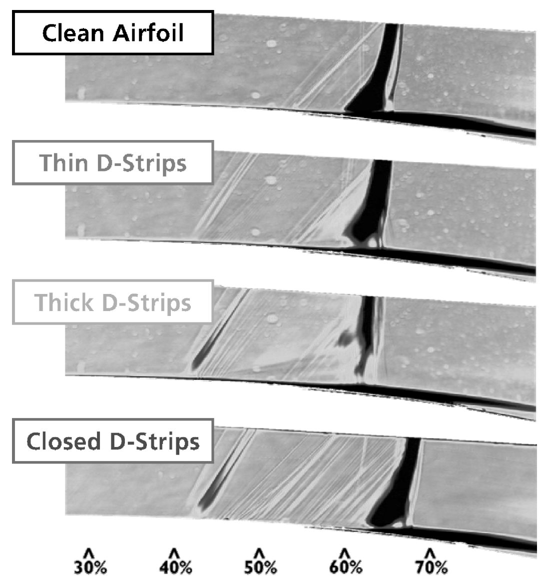

Fig. 3 Schlieren pictures at $Ma_\infty = 0.793 \pm 0.002$, $Re_\infty = 5.05 \cdot 10^6 \pm 1.2\%$, α adapted to constant lift.

the subsonic flow within the D-Strips. For this case, the flowfield is similar to that observed for the clean airfoil. Namely, the shock wave has a similar strength, and the triangular region of more isentropic compression is smaller than in the two cases with D-Strips.

Figure 4 shows pressure distributions that were recorded simultaneously with the schlieren pictures of Fig. 3. On the left side of Fig. 4, the surface static-pressure distributions $c_p(x/c)$ for the just-mentioned cases are compared. On the right side of Fig. 4, the corresponding wake total-pressure distributions $z/c(p/p_0)$ are shown. The wake rake is in between two D-Strips. The wake measurements confirm that the closed D-Strips act similar to the reference case except that there is a kink at $z/c = 0.2$. This kink is most probably caused by the displacement effect from the ramp of the upstream end of the closed D-Strips. The thick D-Strips result in an increased total pressure at $z/c = 0.1$ and a lower peak at $z/c = -0.05$ in the wake total-pressure distribution. These changes in the wake compared to the reference case result in a lower wave drag as well as a lower viscous drag at a constant lift.

In the lower incidence range, D-Strips generally have a very small effect on lift as is demonstrated in Fig. 5a. Nevertheless, one can see that the lift coefficient c_l at a constant angle of attack α is somewhat reduced when D-Strips are applied compared with the clean airfoil. However, the maximum lift tends to be increased, most likely because of the weaker shock waves and a thus delayed flow separation. This confirms the observation in Ref. 3, where tests reveal that there is an increase in the maximum lift suggesting that the buffet-onset limit is delayed by passive control.[3] Figure 5b shows drag polars $c_l(c_d)$ obtained from the wake rake data that are positioned between two D-Strips. At low lift coefficients c_l where the drag coefficient c_d is almost constant vs lift, no strong shock waves occur above the suction side of the airfoil. The drag polars in Fig. 5 show that the influence of the D-Strips is negligible at these lift coefficients. This is in contrast to the observations presented in Ref. 3: tests with passive ventilation over the span always lead to an increase in viscous drag, which generally overcompensated the reduction in wave drag except at certain conditions.[3]

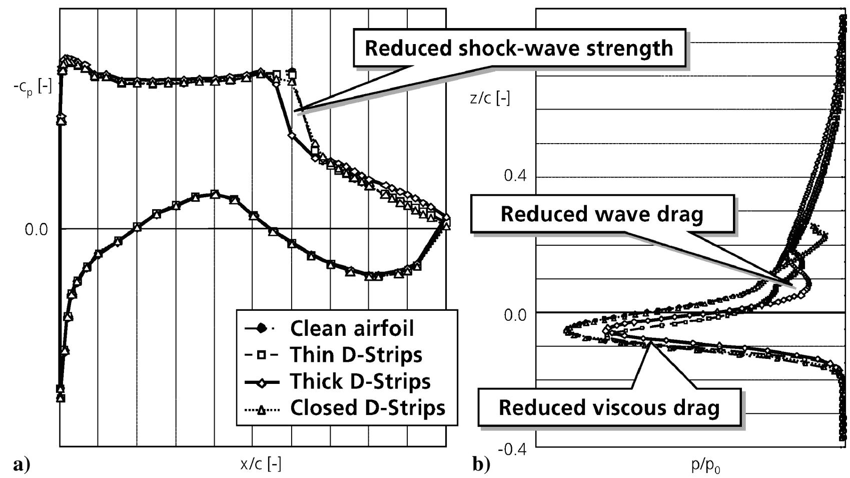

Fig. 4 Measured influence of D-Strips on: a) airfoil static-pressure distributions c_p (x/c) and b) wake total-pressure distributions z/c (p/p_0) at $Ma_\infty = 0.793 \pm 0.002$, $Re_\infty = 5.05 \cdot 10^6 \pm 1.2\%$, α adapted to constant lift.

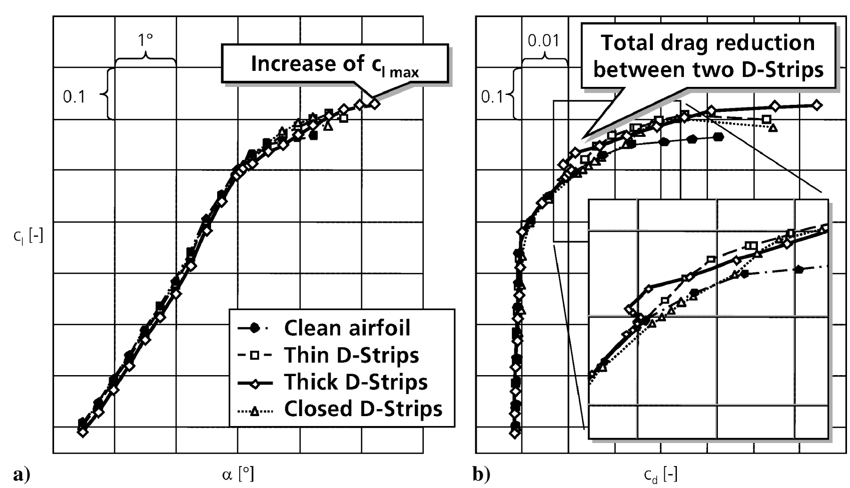

Fig. 5 Measured influence of D-Strips on: a) lift c_l (α) and b) drag c_d (c_l) polar at $Ma_\infty = 0.793 \pm 0.002$, $Re_\infty = 5.05 \cdot 10^6 \pm 1.2\%$.

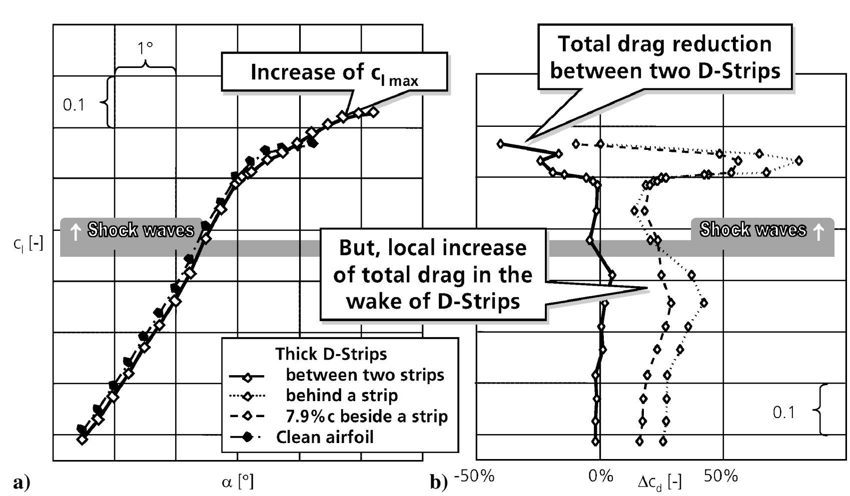

Fig. 6 Measured spanwise influence of D-Strips on: a) lift polar c_l (α) and b) drag increase Δc_d $(c_l) = c_d - c_{d\,\mathrm{clean\,airfoil}}$ at $Ma_\infty = 0.793 \pm 0.002$, $Re_\infty = 5.05 \cdot 10^6 \pm 1.2\%$.

In the wake of D-Strips, the viscous drag increases as is shown in Fig. 6. Straight behind and at a spanwise location of 7.9% chord length from the thick D-Strip, the total drag increases by about $\Delta c_d = 25\%$. However, in particular for a swept wing this increase in drag would only occur locally in spanwise direction. Globally, a net decrease of overall drag can develop by applying D-Strips if strong shock waves occur in the flowfield above the clean airfoil. Figure 6b also shows that total drag reductions of $\Delta c_d = -20\%$ can be achieved at the midsection between two thick D-Strips. For the present investigation no optimization of the D-Strips was performed either with respect to the strips' layout or to the positioning on the airfoil because the main objective of the present test is to validate the operating principle of D-Strips. Thus, only commercially available Velcro-type strips were applied as D-Strips although other configurations such as airscoop-type structures also meet the first basic idea of its operating principle. Nonetheless, at spanwise locations sufficiently away from a D-Strip measurable total drag reductions are achieved.

Summary

The operating principle of a novel passive shock control concept for drag reduction on swept wings called D-Strips[11] is introduced, and results of a first experimental proof of concept are presented. Wind-tunnel experiments are conducted at transonic airspeeds using an airfoil VC-Opt[6] (9.2% relative thickness) with forced boundary-layer transition. Schlieren pictures confirm the operating principle. Wake measurements demonstrate that, locally, in the wake of D-Strips the total drag increases. However, more globally, at spanwise locations away from these positions the total drag is measurably reduced if a sufficiently strong shock wave is present above the wing-suction-side surface. In contrast to passive control by ventilation,[3] outside of the wake of the D-Strips a wave and viscous drag reduction and observed. Furthermore, the maximum lift tends to be increased by D-Strips suggesting that the buffet-onset limit is delayed. An application of D-Strips to a swept wing at cruise conditions can yield net aircraft drag reduction because the drag rise is limited to the D-Strips and its wake, but the shock-weakening effect and the drag reduction are distributed in the wide-splayed characteristics upstream of the shock front. The effectiveness of D-Strips is less sensitive to the location of the shock wave than control concepts like two-dimensional bumps, which are only effective at the design conditions. Another application of D-Strips that can be considered is the regions with a distinct shock, for example, between engines or in the wing-root region or at the inboard engine. (Kühn, W., and Dargel, G., "Discussion About D-Strips," private communication, Bremen, Germany). However, there is a need for further investigations in order to optimize D-Strips and to quantify their impact on aircraft performance. Recent experimental results indicate that airscoop-type configurations might perform better as D-Strips than Velcro-type strips. Because D-Strips are easy to apply on existing wings, an application of D-Strips for retrofit is possible.

Acknowledgments

The author would like to thank the DLR program management for financial support of the test. Thanks also to M. Bruse and M. Jacobs for preparing, conducting, and postprocessing the experimental results, as well as to J. Berold for participating in the tests. I am grateful to K. Richter and H. Rosemann for providing the airfoil model as well as fruitful discussions and suggestions. Special thanks to P. Petrie-Repar for proofreading the text.

References

[1]European Commision (ed.), *European Aeronautics: A Vision for 2020*, Office for Official Publications of the European Communities, Luxembourg, 2001.

[2]Smith, A. N., Babinsky, H., Fulker, J. L., and Ashill, P. R., "Shock-Wave/Boundary-Layer Interaction Control Using Streamwise Slots in Transonic Flow," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 540–546.

[3]Stanewsky, E., Délery, J., Fulkner, J., and Geißler, W., "Synopsis of the Project EUROSHOCK," *EUROSHOCK—Drag Reduction by Passive Shock Control*, Notes on Numerical Fluid Mechanics, Vol. 56, Vieweg-Verlag, Braunschweig, Germany, 1997, pp. 1–81.

[4]Stanewsky, E., Délery, J., Fulkner, J., and Geißler, W., "Synopsis of the Project EUROSHOCK II," *Drag Reduction by Shock and Boundary Layer Control*, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 80, Springer-Verlag, Berlin, 2002, pp. 1–124.

[5]Rosemann, H., "Wave Drag Reduction Concepts for Transonic Wings," *Proceedings of the European Congress on Computational Methods in Applied Sciences and Engineering ECCOMAS*, 2004.

[6]Richter, K., and Rosemann, H., "Experimental Investigations of Trailing-Edge Devices at Transonic Speeds," *The Aeronautical Journal*, Vol. 106, No. 1058, 2002, pp. 185–193.

[7]Dargel, G., and Thiede, P., "Assessment of Shock and Boundary Layer Control Concepts for Hybrid Laminar Flow Wing Design," *Drag Reduction by Shock and Boundary Layer Control*, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 80, Springer-Verlag, Berlin, 2002, pp. 383–414.

[8]Doe, R., "Assessment of Bump Control and Its Application to a Long-Range Turbulent-Wing Aircraft," *Drag Reduction by Shock and Boundary Layer Control*, Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 80, Springer-Verlag, Berlin, 2002, pp. 415, 416.

[9]Holden, H. A., and Babinsky, H., "Shock/Boundary Layer Interaction Control Using 3D Bumps," *Proceedings of the CEAS Aerospace Aerodynamics Research Conference*, 2002.

[10]Rein, M., Schülein, E., and Rosemann, H., "Anordnung zur Reduktion von Verlusten, die mit einem starken Verdichtungsstoß verbunden sind," Deutsches Patent 103 05 973.3, 2003.

[11]Dietz, G., "Verfahren und Vorrichtung zum Reduzieren eines mit einem begrenzten Überschallströmungsgebiet verbundenen Wellenwiderstands," Deutsches Patent 10332655, 2003; Europäische Patent 04016283.6, 2004.

[12]Bur, R., Délery, J., and Corbel, B., "Basic Study of Passive Control Applied to a Two-Dimensional Transonic Interaction," *EUROSHOCK—Drag Reduction by Passive Shock Control*, Notes on Numerical Fluid Mechanics, Vol. 56, Vieweg-Verlag, Wiesbaden, Germany, 1997, pp. 89–111.

[13]Wedemeyer, E., Taylor, N. J., and Holst, H., "Adaptive Wall Techniques," AG 336, AGARD, Oct. 1998, pp. 10-13–10-15.

[14]Cebeci, T., and Bradshaw, P., *Momentum Transfer in Boundary Layers*, McGraw–Hill, New York, 1979.