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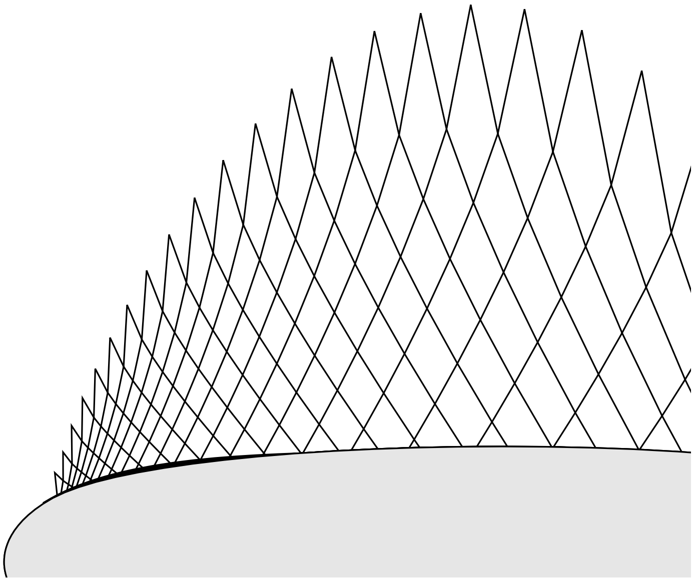

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EXPANSION SHOULDER BUMP FOR WING SECTION VISCOUS / WAVE DRAG CONTROL

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1. Introduction

This is an attempt to use a systematic, theory-based method to design supercritical airfoils for the development of variable geometry wing sections with practically feasible mechanical surface deformations. The goal is, especially in this effort, to present results for airfoils with only local deformations which can be obtained by mechanical devices and which still should result in attractive aerodynamic performance improvements in varying transonic operating conditions.

During the past years, progress in aerodynamics included systematic work to add local surface modifications on transonic airfoils to influence flow quality, by reducing the negative effects of interaction between a shock wave and the boundary layer, see the related presentations in this book. Surface deformations, therefore, usually are located in the shock foot point domain, to spread recompression over a certain interval of the airfoil chord.

In this contribution surface modifications are proposed to be located far upstream of the shock, in the airfoil nose area. The concept derives from earlier developed systematic design methods to remove recompression shocks altogether: the knowledge base of transonic flow physics has given us an idea how to create typical ‘transonic’ airfoils and wings, and also theoretical concepts how to ‘adapt’ airfoils to maintain shock-free conditions if operating conditions change within a limited domain of flight Mach number and lift, see Sobieczky (1979). In the following, the route from an arbitrary airfoil, via a ‘shock-free’ modification, toward simply an ‘improved’ airfoil, is illustrated. Finding the associated shape modifications to be spread over a large portion of the upper (suction) surface of the modified airfoil, we subsequently will ask about a trade-off between more local changes and reduced improvements.

2. Transonic knowledge base for shock-free design

Thirty years ago, airfoil design methodology prior to the advent of large scale computers heavily relied on experiment and mathematical modeling of the physical background. The reduction of shocks and the related viscous losses through refined shaping of the airfoil became a ‘knowledge base’ before optimization strategies were proposed to attack such tasks with numerical methods. Today such knowledge may contribute to a reduced effort in selecting the essential parameters of mathematically defined geometry models of aerodynamically favorable configurations.

A method used for systematic design of shock-free configurations has become known as 'Fictitious Gas (FG) Method' referring to a helpful physical interpretation of the mathematical manipulation of the governing set of flow differential equations. For a recent review of this method see Sobieczky (1997a). A part of this method consists of the inverse method of characteristics, a linear method based on potential theory and applied to the supersonic part of transonic flow past a 2D configuration. Characteristics (Mach waves) are essential for understanding the propagation of perturbations in the flow, see the illustration in Fig. 1: For a focussing on the structure of supersonic flow patterns we present a typical result of the F.G. method, discussing the shape changes between the baseline and resulting airfoil, and the characteristics pattern for shock-free flow.

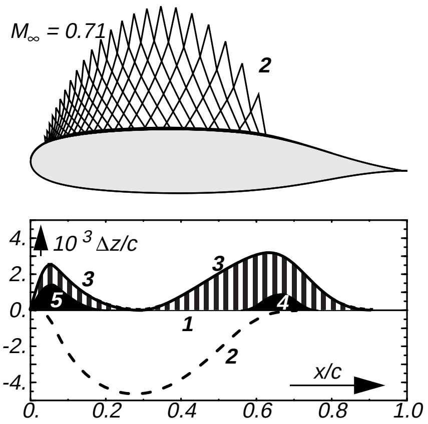

Figure 1:
Airfoil in inviscid transonic flow, (M_∞= 0.71). Shape changes of an initial airfoil (1) to become shock-free (2), and a new airfoil (3) with surface bumps to model design (2) curvature. Characteristics pattern of shock-free flow (2).
Reduced size bumps (4) and (5) to pick up part of the aerodynamic performance improvements.

The examples (1, 2, 3) illustrated here were computed using our Navier/Stokes code (see Geissler (1992)) which has been extended to serve as a design tool using the F. G. method, presented by Sobieczky, Geissler & Hannemann (1996). Fast analysis of steady airfoil flow is carried out with Drela's Euler code (MSES) for 2D airfoils, which is coupled with an efficient boundary layer method. We use this method in the software frame of a comfortable expert system, see Zores (1995).

The essential details of the shape changes resulting in shock-free flow are the curvature changes within the supersonic domain, leading to the desired balance of expansion and subsequent recompression along the characteristics in the adjacent flow field. We learn that increased curvature near the sonic expansion and recompression ('sonic shoulders') areas goes with reduced airfoil curvature within this domain, necessarily consistent with a somewhat flattened airfoil crest. Learning from this, we try to avoid the unpractical thickness ***reduction*** by obtaining similar curvatures by ***addition*** of two suitable bumps (3), see the diagram in Fig. 1, one in the expansion region and one in the recompression region. Immediately the question arises whether such an approximation of a systematic design by the simple geometry manipulation (3) leads to improvements in the lift-to-drag ratio comparable to those observed from the exact shock-free redesign (2). In Fig. 2 we compare therefore the drag polar and the drag rise curve for off-design conditions: We see that favorable properties of the redesigned airfoil (2) are not completely, but partly reached.

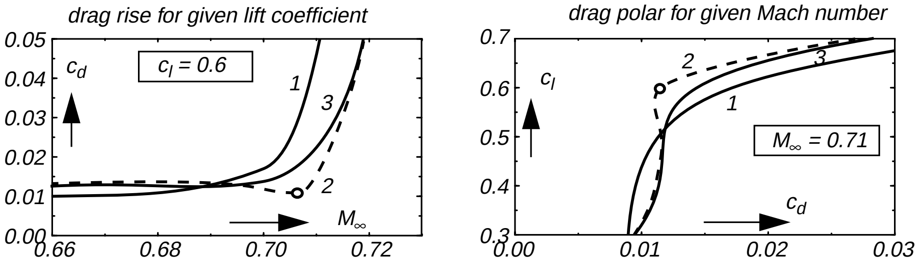

Figure 2:
Aerodynamic performance of original (1), shock-free (2) and modified (3) airfoil, Re = 20 Mill: drag rise for given lift coefficient (a) and drag polar for given Mach number (b).

3. Expansion and Recompression Shoulder Bumps

We return to Fig. 1 and observe that the dual bump (3) modeled for this example to create two curvature peaks adds up 0.3% to local airfoil ordinate z/c. Compared to the large negative bump (2) of -4.5% height, prescribed by the design method, this is desirable not only because of keeping the original airfoil thickness, but also because the substantial surface changes are required in the front and in the rear portion of the wing section, off the main wing box.

We may think of a mechanical realization of such surface modification by an adaptive device and see that surface deformation is still proposed to happen along a large part along the upper surface. This may be practically too difficult to install by some elastic, pneumatic or other device. We ask for a trade-off: If the bumps occur locally, with reduced amplitude, (4) and (5) in diagram Fig. 1, it is still possible to obtain the front and rear curvature peak, but we loose the crest curvature reduction.

At this point we realize that the idea of a rear bump (4) may be close to the concept of shock - boundary layer interaction (SBLI) control which has been investigated by various authors as reviewed elsewhere in this meeting. If this is correct, we should propose to extend this SBLI control concept by applying not only one bump (4) but another one (5) in the nose area, too. Before we further investigate such possibilities (with a necessarily doubled mechanical effort because of two bumps to be put into reality), we follow the more modest idea to install only the front bump (5) and neglect the rear bump (4).

In the following a first example of airfoil modification by such a front bump is presented with some results obtained with the above mentioned Euler and Navier/Stokes codes. Because of this bump situated amidst the above mentioned sonic expansion region, causing a concentration of wedge-shoulder type expansion waves, we call the surface modification an “Expansion Shoulder Bump” (ESB), its rear counterpart would be a “Recompression Shoulder Bump” (RSB). From the exact and approximated design case studies we are encouraged to assume that an only partial application of the surface deformation (3) may lead also to some improvements in efficiency, relative to the small and local surface changes of a baseline airfoil (1). We set the ambitious goal to start from an already aerodynamically well-designed airfoil, with the goal to improve it for some higher Mach number and higher load.

4. Improving a given transonic airfoil

Choosing a given airfoil shape and adding some of the discussed bumps gives an idea about the potential of increasing aerodynamic efficiency. As a baseline we use the transonic airfoil “OA15T”, designed at the French aerospace research establishment, see Rodde & Archambaud (1994).

The airfoil was designed for a Mach number $M_\infty = 0.73$ and a lift coefficient $c_l = 0.65$. First we used our analysis methods and verified the published experimental data to a reasonable accuracy. These methods should then suffice to show the trends toward possible improvements, before further investigations in the transonic wind tunnel will confirm the concept. Here we show only the computational results.

We set the goal to allow for a local surface modification within the first 15% of airfoil chord on the upper surface in order to improve aerodynamic efficiency, i. e. the ratio of lift to drag, for the higher Mach number $M_\infty = 0.75$ and the higher lift of $c_l = 0.7$ at a Reynolds number of Re = 6 millions. Analysis of the baseline airfoil shows a moderate shock at these operating conditions.

Choice of the surface bump function should ultimately be determined by the means of a mechanical realization: use of an elastic structure leads to modelling by spline functions but the use of materials with variable flexibility by the means of varying thickness presently suggests to study more general functions: Identifying the bump shape parameters of importance for obtaining efficient changes in aerodynamic performance will require parametric computational studies prior to an experiment. Here we still use a set of mathematical functions which can also model whole airfoil shapes, see Sobieczky (1998). Figure 3 shows the front portion of the upper airfoil surface in the nose area with the contour changed by the bump geometry. A number of bump parameters can be varied, their numerical data determine the bump geometry very precisely for any model function which observes these data:

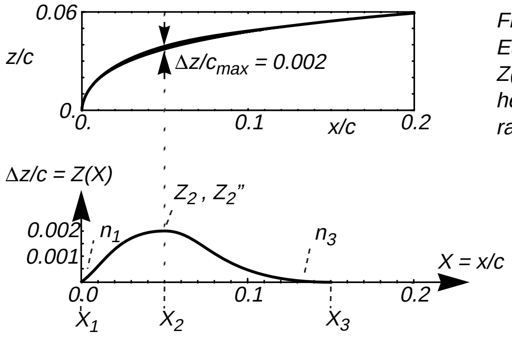

Figure 3:
ESB modeled by a parameterized function Z(X). Basic parameters defining range and height, (anti-)symmetry, crest curvature and ramp exponents.

Here we start the bump at the nose, x/c = $X_1 = 0$ and place its maximum at X_2 = 5% chord. Starting the bump at the parabolic nose allows a ramp exponent $n_1 = 1$ (wedge) there without curvature discontinuity around the nose, but for any $X_1 > 0$, n_1 would be cubic, like the ramp ending with a cubic ($n_3 = 3$) ramp exponent ensures smooth connection curvature at X_3 = 15% chord. Crest curvature Z_2” is an important parameter, the ratio Z_2”/Z_2 determines local flow quality substantially. A refined analysis of the role of these parameters seems worthwhile.

Flow analysis using both the MSES (Euler + boundary layer) code and the Navier/Stokes code confirms the concept nicely: Both numerical methods show good agreement in local surface pressure and give improved ratios of lift over drag. The improvement resulting from the MSES code is $\Delta(L/D)$ = 15%, from the N/S code it’s 8.3%. The discrepancies are attributed to the still imperfect computation of drag, refined analysis with comparable grid resolution in both codes will follow these first investigations.

Of main interest here are the relative changes obtainable from such surface modifications, from the preliminary CFD results we find a promising confirmation of the concept as we see here.

Next we need to know the changes in off-design performance, both codes are therefore used to vary the angle of attack at the design Mach number of $M_\infty = 0.75$. Figure 4 shows drag polars for both the baseline airfoil and the ESB-modification. We see optimal improvements at design conditions while both at lower and at higher load the gains become marginal. At this point we may compare such improvements of those which are obtainable from SBLI control using what we termed earlier as ‘RSB’: a bump added at the recompression area of the local supersonic flow field, see the related contributions in this book. It is too early to oversee the advantages of an ESB over the use of RSB, parametric studies of both concepts, and also of a use of both an ESB and a RSB seems worthwhile.

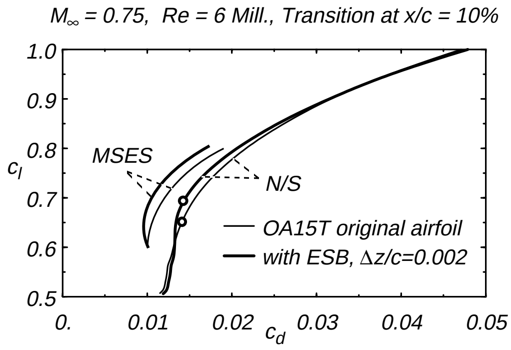

Figure 4:
Drag polars for the baseline OA15T airfoil and a modification with an ESB of 0.2% height: results of Euler + b.l. and N/S codes.

5. Toward 3D and unsteady flow applications

Our computational tools creating surfaces and their modifications are currently being used for airfoils, wings and complete configurations, see Sobieczky (1997b). Bump shapes like those introduced above, if found to be practically useful for 2D airfoils, will be tuned along span of aircraft wings and they may be used for unsteady flow control by changing bump shapes with time. Some first applications of such geometry tools are presently used for the definition of unsteady boundary conditions modeling a periodic droop of the airfoil nose, see Sobieczky, Geissler & Hannemann (1996), these are used in the low speed retreating phase of a helicopter rotor blade. Combination of this variable geometry with the ESB concept may be found useful also in the transonic, advancing phase of the rotor blade, thus prescribing periodic shape changes of rotor blades for the full cycle.

6. Conclusion

We have shown a theory-based shape modification concept for transonic wing sections which might have a potential for application in flow control in the domain of cruise conditions: A local bump in the upper surface nose region can be adapted to increase aerodynamic efficiency in varying cruise Mach numbers and aerodynamic loads and thus widen the region of optimum lift-over-drag ratio. The presented procedure to create calibrated bumps for curvature control is a ‘manual’ approach, which can be replaced later by a computer program resting on the same knowledge base. Future use of mechanical devices creating such bumps may include active control of transonic flow along wings and unsteady phenomena on rotorcraft.

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