AIRFOIL OPTIMIZATION BASED ON AN EVOLUTION STRATEGY WITH RESPECT TO AEROELASTICITY

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Key words: Airfoil design, Aeroelasticity, Transonic flow, Optimization, Evolution Strategy.

Abstract. Numerical simulations are presented in order to test airfoil optimization criteria from the aeroelastic point of view. Based on an Evolution Strategy, airfoil-shape point optimization has been performed as a lift constrained drag minimization at a given Mach/Reynolds number combination for transonic flow. Additional to the drag minimization, the propagation time of pressure disturbances from the trailing edge to the leading edge above the suction side of the airfoil has been minimized. It could be shown that this minimization influences the unsteady flow field around the airfoil positively. In particular, the phase lag of the lift response to a harmonic pitch motion of the optimized airfoil is reduced compared with the value observed at the initial airfoil. Flutter calculations indicate that this change in the unsteady airloads reduces the collapse of the flutter boundary at transonic flow conditions well known as transonic dip.
1 INTRODUCTION

The avoidance of transonic flutter is a key aircraft design problem [1]. Hence, the design of a commercial transport-aircraft wing depends on its aeroelastic properties. The aeroelastic interaction of structural deformation and aerodynamic loads may result in a stable equilibrium characterized by a static deflection of the wing, or cause instabilities leading to self-excited oscillations called flutter. Flutter at transonic airspeeds exhibits a well-known phenomenon: In the so-called “transonic dip” [2] the flutter speed shows a noticeable minimum between the critical Mach number where local supersonic regions occur in the flowfield and the Mach number where massive flow separation limits the operational flight regime. Recent experimental investigations [3, 4] revealed that the time lag of the lift response to the pitch motion of the airfoil appears to be responsible for the characteristic shape of the transonic dip. The unsteady airloads strongly depend on the steady flowfield at transonic conditions and therefore on the airfoil incidence and shape [5]. Thus, arranging the steady flowfield appropriately may provoke unsteady flow that does not lead to a pronounced dip. But, up to now criteria to be used in the design process of airfoil shapes in order to minimize the transonic dip are unknown according to the authors’ knowledge.

In order to optimize airfoil shapes for viscous transonic flow, several techniques have been tried in order to obtain reasonable results. Evolutionary algorithms [6, 7], known since the early sixties [8], have two major advantages in the context of the present paper compared with standard techniques, e.g. hill climbers and gradient based methods: firstly, these nonlinear optimization algorithms are able to capture global optima even of a noisy objective function; secondly, evolution strategies are quickly to implement. Nevertheless, these algorithms have the disadvantage that they offer arbitrary parameters, such as crossover and mutation rates as well as population size etc., which have to be optimized in order to solve a given problem efficiently [9]. However, this disadvantage is not relevant here since the objective of the present paper is to investigate criteria for optimizing airfoil shapes from the aeroelastic point of view.

Beside the structural dynamic behavior of the aeroelastic system, the unsteady airloads influence the shape of the transonic dip, in particular the time lag of the aerodynamic response to the motion of the airfoil at transonic speeds [3, 4]. The supercritical transonic flowfield of an airfoil is determined by a shock wave which generally terminates the supersonic region on the suction side. When the airfoil oscillates in the flow, this shock wave moves correspondingly but time delayed. Namely, the phase lag of the shock motion due to a harmonic pitching of the airfoil corresponds to the time required for a pressure disturbance to travel from the trailing edge to the shock wave [2]. The moving shock wave strongly influences the unsteady airloads. Therefore, in the present paper the propagation time of the sound information in the steady flowfield is used as a design criterion in order to optimize an airfoil shape. The propagation time of a sound ray above the airfoil is minimized beside the aerodynamic drag while keeping the lift at a constant level. Within the optimization procedure the steady flowfield around the airfoil is predicted by integrating the Euler/boundary-layer equations. The propagation time of sound information in this steady flowfield is analyzed on the basis of the approximation of geometrical acoustics.
Herein, we report numerical simulations in order to find and test an airfoil optimization criterion from the aeroelastic point of view. Particularly, the time required by a pressure disturbance to travel in the flowfield above the suction side of an airfoil has been minimized by changing the airfoil shape. By means of an Evolution Strategy this point optimization has been performed while simultaneously minimizing the drag at a constant lift and a given Mach/Reynolds number combination for transonic flow. Thus, both the aerodynamic performance as well as the aeroelastic behavior of the airfoil are taken into account as optimization objectives. The influence of the shape optimization on the unsteady flow field around the airfoil is evaluated by solving the Navier-Stokes equations. With respect to the base geometry the optimized airfoil exhibits a significant reduction of the phase lag of the lift response to its pitch motion. Flutter calculations indicate that this change in the unsteady airloads reduces the collapse of the flutter boundary at transonic flow conditions known as transonic dip.

2 PROBLEM FORMULATION

In order to test airfoil optimization criteria from the aeroelastic point of view the optimization problem has to be formulated. The problem of optimizing an airfoil shape can be described by determining the values of design variables, such that a given objective function $F$ is minimized. The parametrization of the airfoil shape constitutes the design space. In the objective space, the flowfield evaluation and the method for predicting the sound propagation in the flowfield yield integral parameters which contribute to the objective function.

The airfoil shape is represented by a number of control points which are connected by natural parametric splines. Typically 32 control points are distributed over the base-airfoil surface, such that in principal their density is reciprocally proportional to the curvature of the base-airfoil shape. As the optimization progresses, these control points are perturbed by moving them perpendicular to the base-airfoil shape. The perturbation amount of the control points constitutes the design space parameters. The scaling of the perturbed airfoil shape perpendicular to the chord is adapted in the optimization procedure according to three different modes: Firstly, the area of the perturbed airfoil is kept constant compared with the base airfoil (CA mode). Secondly, the thickness of the airfoil is kept constant compared with the base airfoil (CT mode). Thirdly, the airfoil shape is changed with no such constraints (NC mode).

The numerical methods described briefly in section 3 are used for evaluating the fitness of a given airfoil shape. Within the flowfield evaluation for a given inflow Mach $Ma/\infty$/Reynolds $Re/\infty$ number combination, the angle of attack $\alpha$ of the airfoil is adapted, such that the lift coefficient $c_l$ remains constant at a prescribed value. On the one hand the flowfield evaluation yields the integral parameter drag coefficient $c_d$ which is part of the objective function. On the other hand it describes the steady flow around the airfoil and provides the input for the prediction of sound propagation. The nondimensional time $t$ a pressure impulse needs to propagate from the trailing edge at $x/c = 95\%$ to either the leading edge at $x/c = 5\%$ or in the vicinity downstream of a shock wave on the suction side of the airfoil is also used for determining the fitness. The propagation time $t$ is made nondimensional by the free-stream velocity and the chord length of the airfoil.

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In this work the objectives are a lift-constraint drag $c_d$ and sound-propagation time $t$ minimization. Different formulations of objective functions e.g. the weighted-sum method have been tested in order to combine the two objectives into a single one. The tests revealed that the fitness of an airfoil given by the objective function $F$ which reads

$$ F = t^2 \cdot c_d $$

is appropriate. The properties of the airfoil shape optimized according to this objective function, particularly, its aeroelastic behavior will be evaluated separately.

3 NUMERICAL METHODS

Evolution Strategy

A generational genetic algorithm [10] is used as Evolution Strategy. The implementation of [10] provides crossover and mutation operators that are applied on exploited chromosomes in order to produce the next generation. Several ranking and selection techniques are available to select chromosomes.

In the present paper a floating point chromosome representation is used. For each chromosome of a population in a generation the airfoil shape is derived as phenotype. In order to evaluate the fitness of equation (1) for each phenotype, the flowfield evaluation described below is used. Linear ranking is performed according to the obtained fitness. The chromosomes yielding the best fitness replace the worst parents’ chromosomes before a new generation is produced by crossover and mutation. A population consists of 16 individuals, the generation gap amounts 80%. The probability of mutating a variable of an individual, the mutation rate, is lower than 7% while the crossover rate is 70%. The mutation range shrinks as the optimization progresses without success and vice versa.

Flowfield Evaluation

Within the optimization procedure the flowfield about an airfoil is predicted for a given inflow Mach $M_a$/Reynolds $Re_a$ number combination by the code MSES of Drela [11, 12]. This code integrates the coupled Euler- and boundary-layer equations assuming free-flight farfield boundary conditions. The angle of attack $\alpha$ of the airfoil is adapted, such that a prescribed lift coefficient $c_l$ is obtained. The resulting drag coefficient $c_d$ is part of the objective function and the velocity distribution in the flowfield is passed to the prediction of sound propagation.

The unsteady flow about the optimized airfoil with free-flight farfield boundary conditions is evaluated by solving the Navier-Stokes equations. For that purpose the DLR-TAU code [13, 14] is applied. This flow solver is able to integrate time-accurately the Reynolds-averaged Navier-Stokes equations based on a finite-volume scheme. In the present paper the boundary layer above the airfoil is assumed to be fully turbulent and the Spalart Allmaras [15] turbulence model in the Edwards modification was used.
Prediction of Sound Propagation

Based on the linearized small-disturbance potential equation for unsteady flow the approximations of the geometrical acoustics lead to a system of differential equations. This system of equations describes the propagation of small pressure disturbances in the vicinity of airfoils in transonic flow [16]. Here this method is applied in order to predict the time it takes for an acoustic ray to propagate above the suction side of an airfoil.

Figure 1: Wave fronts (dashed) and sound rays (solid) emitted close to the trailing edge of an NLR 7301 airfoil at $x/c = 95\%$. Left: Subsonic flow conditions at $Ma_{\infty} = 0.5016, Re_{\infty} = 2.00 \times 10^6, \alpha = 0.06^\circ$; Right: Transonic flow conditions at $Ma_{\infty} = 0.7756, Re_{\infty} = 2.20 \times 10^6, \alpha = 0.87^\circ$.

Fig. 1 shows wave fronts and sound rays emitted close to the trailing edge of an NLR 7301 airfoil at $x/c = 95\%$ in a subsonic flow field compared with those emitted at transonic flow conditions. At $Ma_{\infty} = 0$ the wave fronts would occur as concentric circles with the sound source in the center. At subsonic flow conditions $Ma_{\infty} = 0.5016$ as shown on the left side of Fig. 1 the wave fronts are deformed but the sound still propagates relatively fast to the leading edge compared with the transonic case at $Ma_{\infty} = 0.7756$ shown on the right side. At the latter condition, the sound cannot pass the supersonic flow region upstream of the shock wave at $x/c = 56\%$. Hence, a pressure disturbance emitted at the trailing edge needs to travel around the supersonic flow region toward the leading edge in order to affect the flow near the leading edge. Thus, in the transonic case the propagation time of the information above the suction side of an airfoil is, in general, longer due to the longer way and the higher flow velocities along the path of the sound ray. The density of the wave fronts demonstrates this since the dimensional time difference between each two wave fronts is identical in Fig. 1.

Flutter Calculations

It is assumed that the airfoil is mounted with two degrees-of-freedom, pitch and heave, in order to analyze the improvement in the aeroelastic behavior of an optimized airfoil compared with the base airfoil. The stability of this aeroelastic system is analyzed in flutter calculati-
ons. These flutter calculations are performed according to a \( k \)-method in order to calculate the flutter-stability limit from the predicted aerodynamic characteristics of the airfoil [4]. The \( k \)-method solves an eigenvalue problem, where the unsteady airloads responses to the vibration modes are considered as complex masses. The air-load responses lift \( c_L \) and pitching moment \( c_m \) to the pitch \( \alpha \) and heave \( h \) motion of the airfoil are assumed to be harmonic. The aerodynamic response is described by complex aerodynamic derivatives \( c_{l,m,h/\alpha} \), which are here predicted by the Transonic Doublet-Lattice Method (TDLM) method [17, 18] on basis of the steady flowfield-evaluation results.

4 RESULTS AND DISCUSSION

The main objective of the present paper is to find and test an airfoil optimization criterion from the aeroelastic point of view which is suitable for the airfoil design. The motivation to formulate the fitness for the optimization process as stated in equation (1) can be found in Fig. 2: The lift response to the airfoil pitch motion is described by complex aerodynamic derivatives \( c_{l,\alpha} \). The phase lag of this lift response seems to be responsible for the shape of the transonic dip [4]. Fig. 2 compares the measured phase distributions \( \Phi(c_{l,\alpha}) \) versus Mach number \( \text{Ma}_{\infty} \) for forced harmonic pitch oscillations of an NLR 7301 airfoil at a fixed reduced frequency \( k \) with theoretically obtained derivatives. These aerodynamic derivatives are determined for an infinitesimally thin flat plate in inviscid subsonic compressible flow by solving the Possio equations.
integral equation [19] with the method described in [20]. At transonic Mach numbers \( \text{Ma}_\infty \approx 0.73 \) the measured airfoil phase distributions clearly differ from the flat plate slope which causes the characteristic shape of the transonic dip [4]. This phase lag of the lift response to the airfoil pitch motion has to be reduced in order to minimize the collapse of the flutter boundary at transonic flow conditions.

The unsteady flow field above the airfoil at transonic airspeeds and thus the phase lag of the lift response is determined by a shock wave which generally terminates the supersonic region above the suction side. The time lag of the shock wave motion to the pitching of the airfoil corresponds to the propagation time \( t \) required for a pressure disturbance to get from the trailing edge to the shock wave [2]. Fig. 2 compares the derivatives’ phase distributions with phase differences \(-kt\) based on this sound-propagation time \( t \). The slope of the measured airfoil phase distribution matches qualitatively well to the phase differences \(-kt\) based on the time \( t \) a pressure disturbance travels from the trailing edge (TE) to the shock wave (SW). But, this \(-kt\) slope exhibits an ambiguity with respect to the Mach number caused by the fact that the higher the Mach number the stronger the shock wave and thus the lower the flow velocity downstream of this shock wave. Numerical tests using the sound-propagation time \( \text{TE}\rightarrow\text{SW} \) in the fitness function according to equation 1 reveal that the ambiguity makes this time \( t \) difficult to be used in the optimization process. In Fig. 2 also a phase difference \(-kt\) is shown for a sound ray from the trailing edge to the leading edge (LE). This curve does not exhibit an ambiguity and matches quite well to the previous discussed slope up to Mach numbers where that one shows a local minimum. Due to the ambiguity of the traveling time \( \text{TE}\rightarrow\text{SW} \) with respect to Mach number, in the present paper the sound-propagation time \( \text{TE}\rightarrow\text{LE} \) from the trailing edge to the leading edge is minimized (cf. equation (1)) in order to reduce the collapse of the flutter boundary in transonic flow.

| Mach number | \( \text{Ma}_\infty \) | 0.7245 |
| Reynolds number | \( \text{Re}_\infty \) | \( 2.21 \cdot 10^6 \) |
| Lift coefficient | \( c_l \) | 0.4961 |
| Transition location | \( x_{\text{tr.suct./pres.}}/c \) | 7%/14% |

Table 1: Design conditions.

In the present investigation the supercritical NLR 7301 airfoil has been selected as base airfoil since many data regarding its aerodynamic and aeroelastic properties at transonic airspeeds are available [2, 3, 4]. The applied airfoil shape is given in [21] except that this geometry was cut off at \( x/c = 1 \). Thus, the trailing edge of the airfoil is blunt with approximately 0.1% chord as in the experiments of NLR and DLR [2, 3, 4]. The design conditions for the optimizations with the NLR 7301 as initial base airfoil are listed in Table 1.

Fig. 3 and Table 2 summarize the results of the optimization. Fig. 3 compares pressure distributions \( c_p(x) \) and airfoil shapes according to the CA mode and CT mode as well as according to the NC mode with the base airfoil NLR 7301 results. All the pressure distributions of the optimized shapes are a little bit bumpy. This is probably due to the fact that in the design space
the airfoil shape is represented by natural parametric splines instead of B-splines as commonly used in pure aerodynamic optimization [6, 7]. In the present investigation natural splines have been chosen in order not to limit the design space since this representation is also able to capture local bumps. However, from the shape of the airfoil with the best fitness value NCopt a new geometry NCoptsmt was derived by smoothing the NCopt pressure distribution and predicting a new shape using MSES in inverse mode [11, 12]. The pressure distribution and the airfoil shape of the resulting NCoptsmt is shown on the right side of Fig. 3. Shape and pressure distribution of NCoptsmt are very close to those of NCopt, but fairly smoother.

Table 2 compares optimization properties of the different airfoil shapes, i.e. CAopt, CTopt, NCopt and NCoptsmt as well as NLR 7301. The fitness values of CAopt and CTopt are somewhat lower than the fitness value of the NLR 7301 even though the sound propagation times are higher. The reason is that a strong shockwave on the NLR 7301 is reduced to weaker shock waves for the CAopt and CTopt airfoils and thus the drag coefficient decreases (cf. Fig. 3). However, the shapes are quite close to each other, and it is not to expect that the aeroelastic behavior in transonic flow is improved. Nevertheless, the fitness values of NCopt and NCoptsmt are lower than half of the value of the NLR 7301. Both, the sound propagation time $t$ and the drag coefficient $c_d$ are reduced. The relative thickness of NCopt and NCoptsmt are only 8.7% compared with the NLR 7301 having 16.5%. On the right side of Fig. 3 the pressure distributions show that only a small supersonic region is present for these optimized airfoils. This fact causes both, the reduction of the sound propagation time and the reduction of the wave
Table 2: Comparison of optimized airfoils according to the CA mode (constant area), CT mode (constant thickness), NC mode (no shape constraints) and the smoothed NC mode airfoil with the base airfoil NLR 7301. Compared are the drag coefficient $c_d$, nondimensional time $t$, objective function $F$, lift-over-drag ratio $L/D$ and the relative airfoil thickness $d/c$.

<table>
<thead>
<tr>
<th>Airfoil shape</th>
<th>NLR 7301</th>
<th>CAopt</th>
<th>CTopt</th>
<th>NCopt</th>
<th>NCoptsmt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_d$</td>
<td>0.0151</td>
<td>0.0131</td>
<td>0.0127</td>
<td>0.0091</td>
<td>0.0091</td>
</tr>
<tr>
<td>$\Delta c_d$</td>
<td>0</td>
<td>-20DC</td>
<td>-24DC</td>
<td>-60DC</td>
<td>-60DC</td>
</tr>
<tr>
<td>$t$</td>
<td>5.70</td>
<td>5.86</td>
<td>5.84</td>
<td>4.79</td>
<td>4.78</td>
</tr>
<tr>
<td>$F$</td>
<td>0.4900</td>
<td>0.4488</td>
<td>0.4330</td>
<td>0.2078</td>
<td>0.2082</td>
</tr>
<tr>
<td>$L/D$</td>
<td>32.93</td>
<td>38.00</td>
<td>39.05</td>
<td>54.69</td>
<td>54.44</td>
</tr>
<tr>
<td>$d/c$</td>
<td>16.5%</td>
<td>16.7%</td>
<td>16.5%</td>
<td>8.7%</td>
<td>8.7%</td>
</tr>
</tbody>
</table>

The pressure level on the lower side of the airfoil is high and the lift is distributed quite constantly over the chord. The performance of NCopt compared with NCoptsmt is nearly the same as shown in Table 2. Thus, NCoptsmt was selected to be further investigated regarding its properties.

Fig. 4 compares the off-design properties of the NCoptsmt airfoil shape with those of the NLR 7301 base airfoil. The relative changes in the sound propagation times by changing the angle of attack $\alpha_{OD} = \alpha \pm 0.5^\circ$ or by changing the Mach number $Ma_{\infty \, OD} = Ma_{\infty} \pm 0.1$ are similar. Also the changes in the lift coefficient are comparable except that the lift breaks
down due to flow separation at $Ma_{\infty} + 0.1$ for the NLR 7301. The changes of the lift-over-drag ratio $L/D$ with the inflow parameters depend on the occurrence of shock waves in the flowfield. However, its values are fairly higher at the NCopt compared with the lift-over-drag ratios of the NLR 7301. Summarizing, NCoptsmt shows a better aerodynamic performance than the NLR 7301 although its off-design properties are comparable. Furthermore, due to the lower time a pressure disturbance needs to travel from the trailing to the leading edge, it is to expect that NCopt exhibits a more favorable unsteady aerodynamic behavior in transonic flow than the NLR 7301.

Figure 5: Lift hysteresis loops $c_l(\alpha - \alpha_0)$ for the NC optimized and smoothed airfoil shape compared with NLR 7301 and flat plate results. $Ma_{\infty} = 0.7245$, $Re_{\infty} = 2.21 \times 10^6$, $c_l = 0.4961$, $k = 0.25$.

Fig. 5 shows the lift response to the airfoil pitch motion which has an impact on the collapse of the flutter boundary at transonic flow [4]. At a certain transonic flow condition, lift hysteresis loops $c_l(\alpha - \alpha_0)$ for the NCoptsmt airfoil shape are compared with NLR 7301 and flat plate results. The unsteady flow field about the base and the optimized airfoil is evaluated by solving the Navier-Stokes equations using the DLR-TAU code. The lift response to the pitching of an infinitesimally thin flat plate in inviscid subsonic compressible flow is predicted by solving the Possio integral equation [19]. As the area of the compared lift hysteresis loops increases, the phase lag of the lift response to the airfoil pitch motion increases. The phase lag of the NCoptsmt lift response is about 29% lower than the value predicted for the NLR 7301, and it is roughly the mean between the flat plate and the NLR 7301 value. Thus, the unsteady aerodynamic behavior of NCoptsmt is expected to be better with respect to transonic flutter compared with NLR 7301.
In Fig. 6 symbols show the measured flutter and buffeting boundary in the flutter index \( \Phi \)/Mach number \( M_{\infty} \) plane revealing the slope of a transonic dip [4]. Below the curve, the aeroelastic system is stable, i.e. small oscillations of the system are damped out. The flutter index characterizes the ratio of the aerodynamic loads to the elastic forces. The higher the flutter index of this curve the lower the risk of flutter. The measured data compare with the TDLM results for the NLR 7301 satisfactorily up to Mach numbers of \( M_{\infty} = 0.745 \). At higher Mach numbers, strong shock/boundary layer interaction and separation determines the steady flow field and the unsteady airloads. TDLM is not able to capture the measured rise in the stability boundary since the method’s assumptions are violated at these flow conditions. However, the NLR 7301 stability limit based on the TDLM results demonstrates, that this method is able to predict the stability limit sufficiently up to the minimum of the transonic dip. Fig. 6 also shows a stability limit predicted on the basis of TDLM results for the NCoptsmt airfoil shape. This curve clearly demonstrates that the flutter behavior of the NCoptsmt airfoil is more gentle than the one of the base NLR 7301 airfoil.

5 CONCLUSION

The present paper describes a numerical investigation in order to test airfoil optimization criteria for obtaining good aerodynamic performance and gentle flutter behavior.

Airfoil-shape point optimizations were performed by means of an Evolution Strategy. For a transonic design condition, aerodynamic drag as well as the propagation time of pressure
disturbances from the trailing edge to the leading edge have been minimized while keeping the lift at a constant value. The resulting airfoil shape exhibits a better steady aerodynamic performance than the supercritical base airfoil NLR 7301. The pressure level on the lower side of the optimized airfoil is high and the lift is distributed quite constantly over the chord. The flowfield about this airfoil exhibits only a small supersonic region terminated by a weak shock wave. The steady flowfield about the optimized airfoil influences the unsteady flow field around the airfoil positively in the way that the lift response to a harmonic pitch motion of the airfoil is reduced compared with the base airfoil. Flutter calculations indicate that the optimized airfoil does not exhibit such a pronounced transonic dip compared with the NLR 7301.

6 ACKNOWLEDGMENTS

Thanks are due to Prof Marc Drela for allowing the use of the MSES code in our research work. We are grateful to Dr Volker Carstens for providing the code to solve the Possio integral equation and wish to thank Dr Günter Schewe, Dr Fritz Kießling and Holger Mai for fruitful discussions and suggestions.

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