Design of a Supercritical Airfoil

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This article treats the development of several transonic airfoils. The initial design, NPU2, was based on a specified shockless pressure distribution at given design conditions which were Mach number, Reynolds number, and lift coefficient. Wind-tunnel tests substantiated the design. They showed up, however, weak shock waves. In a second step further optimization has been performed by Sobieczky's method. It led to the NPU2M airfoil. Finally, by introducing nonlinear recompression shapes on the upper surface these modifications resulted into two wing sections—NPUBS1 and NPUBS2—which had superior aerodynamic characteristics than the former one.

Introduction

As a base, a supercritical airfoil NPU2 was designed by specifying shockless pressure distributions that were determined by modifying those of a known airfoil at the design point (M,C_L,Re). Weak shock waves could be observed, however, in wind-tunnel tests. In fact, they also have been detected by the more accurate analysis methods that had been used after the tests. It has been observed that the differences of the results between design and analysis come from the use of 1) different grid sizes, or 2) different boundary-layer routines at the same grid sizes.

In a second step, a modified airfoil NPU2M was designed by Sobieczky's optimization method.[10] Finally, further modified airfoils, NPUBS1 and NPUBS2, have been obtained based upon newly specified pressure distributions. The aerodynamic characteristics of these airfoils have been predicted. It has been found that the aerodynamic characteristics of NPUBS1 and 2 are better than those of NPU2M, even though NPU2M is an optimized one. The reason is that the optimization method can be applied only for modifying a part of a given airfoil contour. Naturally, one may find better airfoils without this restriction.

Design of Airfoil NPU2

The transonic design method available for this study was that of Carlson.[5,6] Reasonable pressure distributions have been specified. One approach to specify reasonable pressure distributions is to modify pressure distributions of a known reference airfoil at its design condition for given Mach number, angle of attack, and Reynolds number. Airfoil DFVLR-R2[9] at $M = 0.75$, $\alpha = 1.5$ deg, and $\mathrm{Re} = 3 \times 10^6$ was selected as the reference. The aim at modifications is to avoid shock waves on the airfoil or to weaken them at the design condition. There are several ways to achieve this. Two-step isentropic compression was used in the supersonic region, decelerating the flow from a lower supersonic speed to a subsonic one and hoping the shocks, if any, would be weak. It was expected to get gentle pressure gradients near the sonic point (Fig. 1). In order to increase the lift, the starting point of the subsonic recompression on the upper surface was pushed downstream, and higher pressures on the lower surface were specified. The designed airfoil was named NPU2.[11]

Experimental results of NPU2 at the design condition are shown in Fig. 2.[8] Weak shocks can still be noted, which by Carlson's analysis method[4,6] with a medium grid (69 points on the airfoil) have not appeared. Through use of a fine grid (133 points), however, the waves could have been detected[12] (Fig. 3). It is regretted that the fine grid was not originally used, but the necessary computer time could not be afforded. Calrson's method uses Cartesian coordinates for engineering convenience, but it leads to very few points in the leading and trailing regions. Therefore, it cannot predict drag accurately without time-consuming corrective calculations.

On the other hand, the analysis method of Bauer-Garabedian-Korn-Jameson (BGKJ)[1-3] requires less computer time. Predicted pressures (see Fig. 2) and even predicted drag seem to be more reliable.[13] The drag rise Mach number boundary received by the criterion $dc_d/dM = 0.1$ shows fair agreement with experiment at moderate lift, and it is conservative at high lift (Fig. 4).

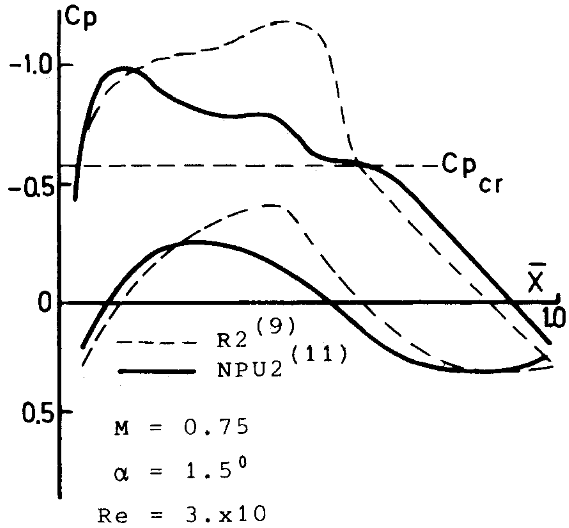

Fig. 1 Measured pressures of airfoil and specified pressures for designing airfoil NPU2.

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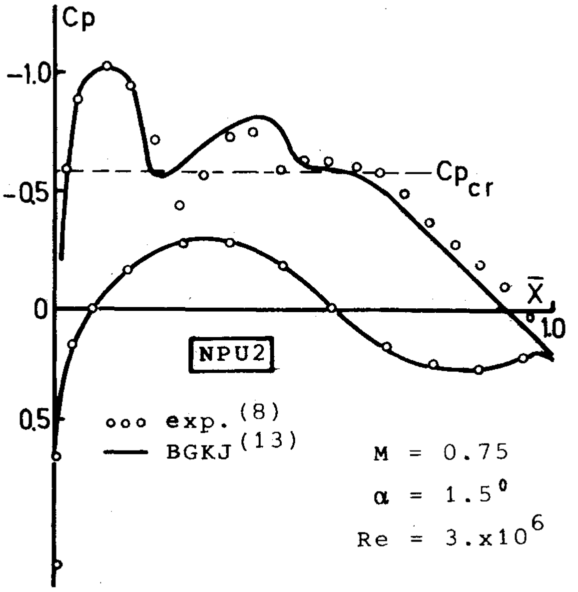

Fig. 2 Experiment and BGKJ analysis of airfoil NPU2.

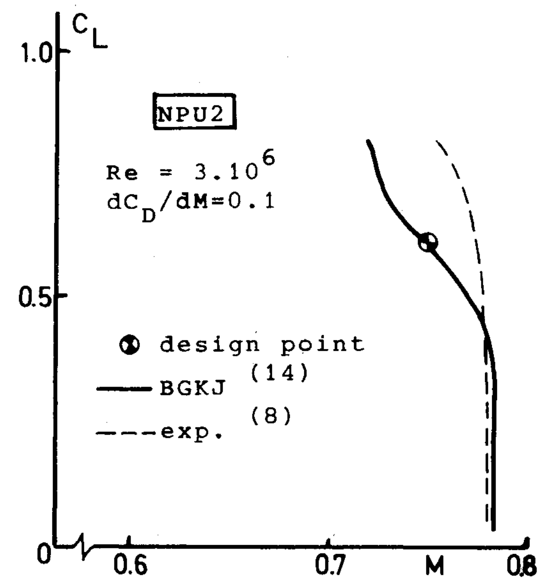

Fig. 4 Drag rise Mach number boundaries of airfoil NPU2 after experiment and BGKJ's analysis.

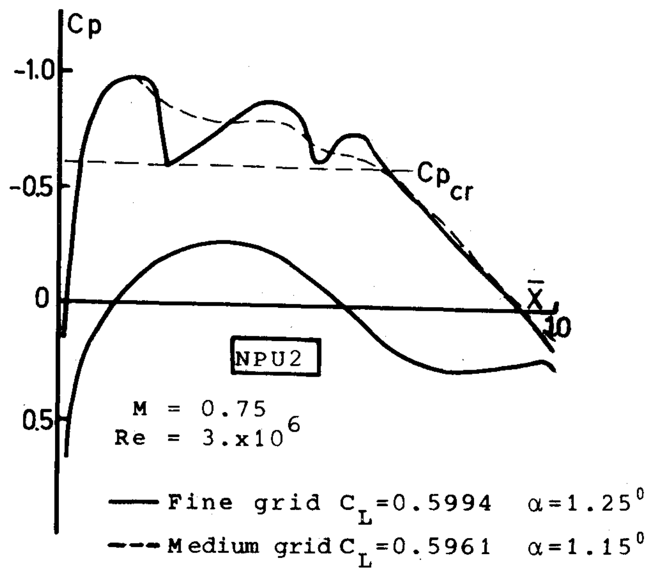

Fig. 3 Analysis of airfoil NPU2 by Carlson's method[12] with different grid sizes.

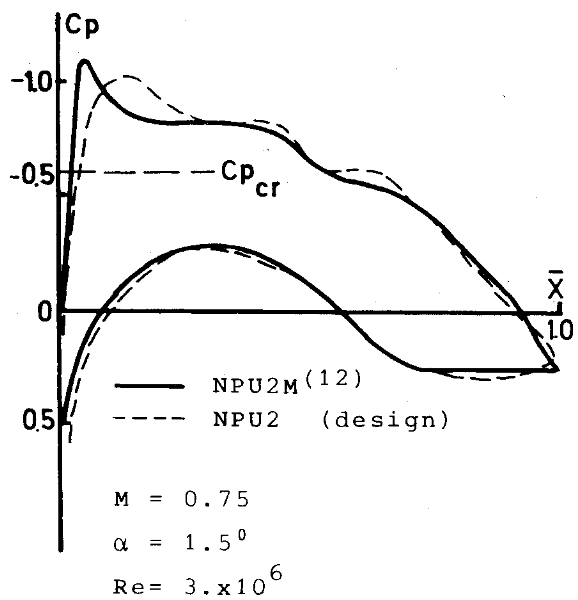

Fig. 5 Pressures for the Sobieczky optimized airfoil compared with those of airfoil NPU2.

Conclusions are:

1) Design and analysis of supercritical airfoils with Carlson's method should be performed with the fine grid only in order to resolve shock waves sufficiently. The NPU2 design made with the medium grid was therefore not completely satisfactory.

2) Isentropic compression in a two-step manner in supersonic regions is difficult to ensure. Experiment and later design experiences support the conclusion.

The redesign of NPU2 with a fine grid still reveals shock waves by the analysis method. The difference here between the design and analysis method at the same grid size is due to different boundary-layer calculation routines. In the design mode the airfoil shape first results from inviscid calculation for a specified pressure distribution. The final shape is obtained by reducing thickness according to the boundary layer.

In the analysis mode the calculation is the other way around. The inviscid flow around the final shape is determined first and the airfoil thickness is increased afterwards due to the

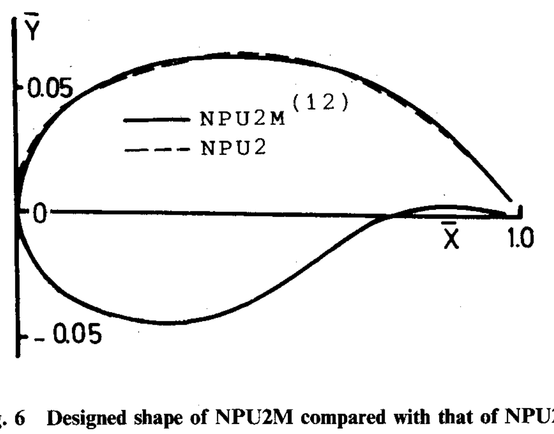

Fig. 6 Designed shape of NPU2M compared with that of NPU2.

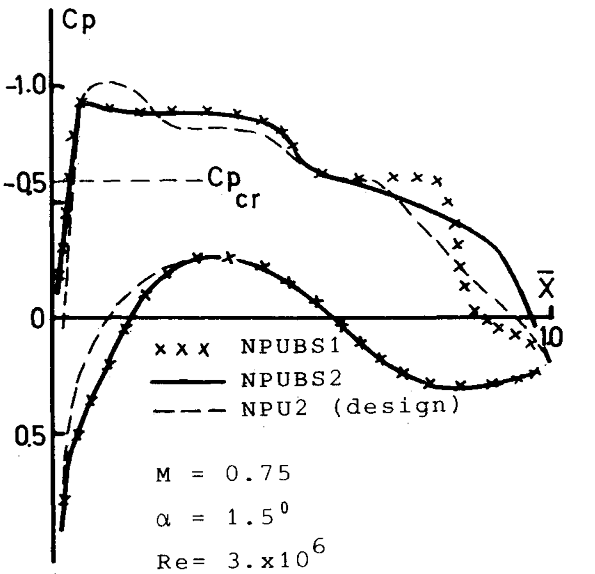

Fig. 7 Specified pressures for designing NPUBS1 and NPUBS2 compared with those of NPU2.

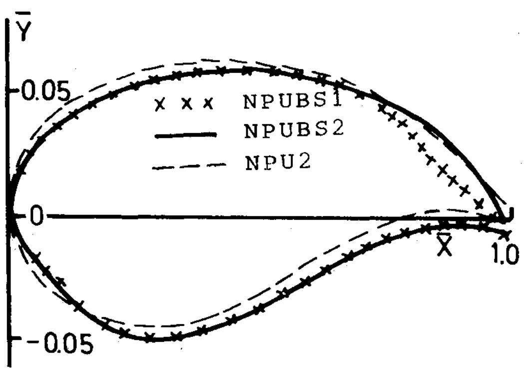

Fig. 8 Designed shapes of NPUBS1 and NPUBS2 compared with that of NPU2.

boundary layer. The two boundary layers differ as does the pressure. This is pronounced the case when steep pressure gradients have been specified. Therefore, analysis work should be taken as a check after the designed airfoil has been obtained.

3) Specifying gentle pressure changes near the sonic point, as we did for the design of NPU2 and the subsequent modifications, prevented strong shock waves from occurring at or near the design point.

Modifications of Airfoil NPU2

Airfoil NPU2M

Sobieczky's optimization method (fictitious-gas method)[10] was used to modify the contour of NPU2 and to obtain airfoil NPU2M. The resulting pressure and the airfoil shape are shown in Figs. 5 and 6.[12] The predicted pressure drag coefficient has been reduced from 0.0030 to 0.0004 at design condition.

Airfoils NPUBS1 and NPUBS2

According to the proposal of Ref. 7 (based on separation criteria), instead of linear upper surface recompression shapes, convex and concave ones and additionally, noseloading have been attempted. Two-step compressions in the supersonic region have been replaced by a one-step compression to avoid shock waves possibly predicted by the subsequent analysis.

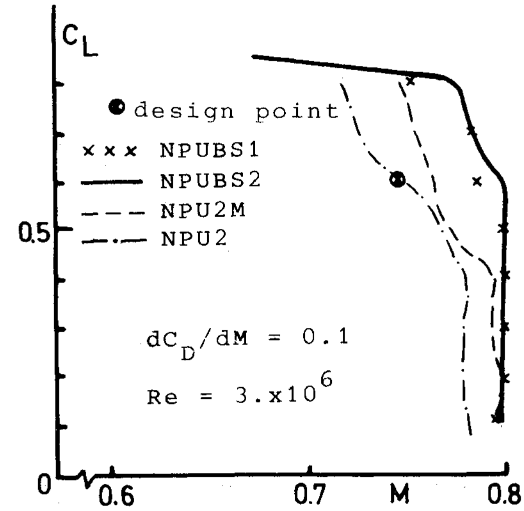

Fig. 9 Drag rise Mach number boundaries of NPU2M, NPUBS1, and NPUBS2 compared with that of NPU2.

Carlson's method with fine grid has been taken for design and then BGKJ's method for analysis. Several reasonable airfoils have been obtained for further selection. NPUBS1 and NPUBS2 have been retained from them. Their pressure distributions and airfoil shapes are shown in Figs. 7 and 8. Drag rise Mach number boundaries of NPU2, NPU2M, NPUBS1 and NPUBS2 are compared in Fig. 9. NPUBS1 and NPUBS2 are more favorable than the optimized airfoil NPU2M.

Conclusions:

1) Sobieczky's optimization method is well applicable for modifying a given airfoil.

2) Changing overall pressure distributions may result in better airfoils than an airfoil which is obtained by the optimization method, as the latter works under the restriction of modifying only a part of a given airfoil contour.

3) Wind-tunnel test models of airfoils NPUBS1 and NPUBS2 have been prepared. Further analysis will be made when the testing is completed.

Acknowledgments

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