DESIGN OF A SUPERCRITICAL AIRFOIL

ICAS-86-1.1.2

Z. Y. Zhang
Professor, Aircraft Engineering Department
X. T. Yang
Lecturer, Aircraft Engineeing Department
Northwestern Polytechnical University
Xi'an, The People's Republic of China

and

B. Laschka
Prof. Dr.-Ing., Institute for Fluid Mechanics
Technical University of Braunschweig
3300 Braunschweig, FRG

Abstract

A supercritical airfoil NPU2 was designed by specifying shock-less pressure distributions at design point (M, C_L, Re). Weak shock waves still occurred in the wind tunnel test. A modified airfoil NPU2M was then designed by Sobieczky's optimization method. Later, modified in another way, new airfoils NPUBS1 & NPUBS2 have been obtained. It has been found that the aerodynamic characteristics of these airfoils are better than NPU2M. This is because that the optimization method is under the restriction of modifying only a part of a given airfoil contour, one could find better airfoils without this restriction.

I. Introduction

A supercritical airfoil NPU2 was designed by specifying shock-less pressure distributions which were determined by modifying those of a known airfoil at the design point (M, C_L, Re). Weak shock waves still occurred in the wind tunnel test, and, in fact, they could have been detected by sophisticated analysis methods, which had been used after the test. It has been noticed that the discrepancy of the results from design and analysis methods comes from the different estimation routines of the development of the boundary layer flow.

A modified airfoil NPU2M was then designed by Sobieczky's optimization method. Later, another new modified airfoils NPUBS1 and NPUBS2 based upon newly specified pressure distributions have been obtained. The aerodynamic characteristics of these airfoils have been estimated. It has been found that NPUBS1 & 2 are better than NPU2M, even though NPU2M is an optimized one. This is because that the optimization method is under the restriction of modifying only a part of a given airfoil contour, and, naturally, one could find better airfoils without this restriction.

II. Design of Airfoil NPU2

Carlson's transonic airfoil design

method(5,6) was used to design a supercritical airfoil by specifying pressure distributions on it. The important question is how to specify the reasonable pressure distributions. Probably, one method is to modify pressure distributions of a known reference airfoil at design condition --- given Mach number, angle of attack and Reynolds number. Airfoil DFVLR-R2(9) at $M=0.75, \alpha=1.5^\circ$ and $Re=3.\times10^6$ was selected as the reference. But how to modify the pressure distributions still remains as a question. The aim is to avoid shock waves on the airfoil or to weaken them at the design condition. There are many ways to do that. Two-step isentropic compression was used in supersonic region in hoping that the flow would decelerate from a lower supersonic speed to subsonic and the shocks, if any, would be weak. It was the same hope to keep flat pressure distributions above and below the sonic point, Fig.1. In order to get higher lift coefficient, the start point of subsonic compression on upper surface was pushed backward and higher pressure on lower surface was specified. The designed airfoil was named NPU2.(11)

Experimental result of NPU2 at design condition is shown in Fig.2,(8) where weak shocks can still be noted. But Carlson's analysis method(4,6) with crude grid (69 points on the airfoil) could not detect them; however, if we had used fine grid (133 points on the airfoil), shock waves could have been detected,(12) Fig.3.

It is regretted that fine grid had not been used, because it would take much more computer time than could be afforded at that time. BGKJ's method(1-3) can predict aerodynamic characteristics of a transonic airfoil in less computer time, Fig.2, the predicted drag coefficients are reliable,(13) and Carlson's method can not predict them without time-consuming correction calculations. The drag-rise-Mach-number-boundary ($dC_D/dM = 0.1$) predicted by BGKJ's method is compared with experiment in Fig.4.(14) It shows that the predicted result is safer than the experimental one near the design point.

Remarks:

1. It is not sufficient to use crude grid by Carlson's method in designing and analysing a supercritical airfoil. The design work of NPU2 was limited by available computer time. The results are not completely satisfied.
2. It is difficult to ensure isentropic compression in two-step manner in supersonic region. Experiment and later design experiences support the conclusion.

The discrepancy of the results from design and analysis methods comes from the different estimation routines of the development of the boundary layer flow. In the design mode, according to the specified pressure distributions, inviscid airfoil contour is designed and the boundary layer thickness is calculated; then the latter is subtracted from the former to obtain the final designed airfoil shape. And in the analysis mode, according to the final designed airfoil shape, inviscid pressure distributions are calculated first, then boundary layer thickness is calculated according to this inviscid pressure distributions. This boundary layer thickness is different from that in the design mode, because they are calculated according to different pressure distributions. It is this boundary layer thickness that is added to the designed airfoil shape and inviscid pressure distributions are calculated again to allow for viscid effects. This resulted pressure distributions sometimes will be far different from the specified pressure distributions in the design mode. Therefore, analysis work should be taken after the designed airfoil has been obtained.

3. Keeping flat pressure distributions above and below the sonic point in order to prevent strong shock waves probably is a good idea.

III. Modifications of Airfoil NPU2

Airfoil NPU2M

Sobieczky's optimization method (fictitious-gas method)$^{(10)}$ was used to modify the contour of NPU2, and airfoil NPU2M was obtained. The modified pressure distributions and the shape are shown in Fig.5 & Fig.7.$^{(12)}$ The predicted wave drag coefficient can be reduced from 0.0030 to 0.0004 at design condition.

Airfoils NPUBS1 & NPUBS2

According to the idea of reference 7, new pressure distributions have been specified. Curvilinear pressure distributions at the rear-part on the upper surface, and nose-loading have been used. Two-step compression in the supersonic region has been replaced by one-step compression to avoid shock waves predicted by the followed analysis work. 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. Drag-rise-Mach-number-boundaries have been determined by BGKJ's method for these obtained airfoils and airfoils NPUBS1 & NPUBS2 have been selected from them.

The pressure distributions and shape of NPUBS2 are shown in Fig.6 & 8. Drag-rise-Mach-number-boundaries of NPU2, NPU2M and NPUBS2 are compared in Fig.9. It can be seen that NPUBS2 are better than the optimized airfoil NPU2M.

Remarks:

1. Sobieczky's optimization method can be used for modifying a given airfoil.
2. Over-all change of pressure distributions may result in better airfoils than what might be obtained by optimization method. It is because that the optimization method is under the restriction of modifying only a part of a given airfoil contour; one could find better airfoils without this restriction.
3. Wind tunnel test models of airfoils NPUBS1 & NPUBS2 have been prepared. Further remarks could be made when the testing is completed.

IV. Conclusions

1. It is convenient to use Carlson's design method, fine grid should be taken in the calculation.
2. BGKJ's method can be used to predict aerodynamic characteristics of the designed airfoils and select some promising ones from them for wind tunnel testing.
3. Sobieczky's optimization method can be used to modify a given airfoil to obtain shock-less flow at design condition.
4. At present stage, the design of a supercritical airfoil largely depend upon how to specify suitable pressure distributions, and accumulating experiences is still the most important thing in designing an airfoil.

Acknowledgements

This work was supported in part by the Chinese Aeronautical Establishment (CAE), and the German Aerospace Research Establishment (DFVLR) and Carl Duisberg Gesellschaft e.V. (CDG), Landesstelle Niedersachsen, FRG. The support of Prof. Dr.-Ing. F. Thomas, Dr.-Ing. H. Körner and Dr.-Ing. G. Redeker to this work is greatly helpful.

References

1. Bauer,F.,Garabedian,P. and Korn,D., Supercritical wing sections I, Lecture notes in economics and mathematical systems, Vol.66. Springer Verlag, New York (1972).
2. Bauer,F.,Garabedian,P.,Korn,D. and Jameson,A., Supercritical wing sections II, Lecture notes in economics and mathematical systems, Vol.108. Springer Verlag, New York (1975).

3. Bauer,F.,Garabedian,P. and Korn,D., Supercritical wing sections III, Lecture notes in economics and mathematical systems, Vol.150. Springer Verlag, New York (1977).
4. Carlson,L.A., Transonic airfoil flowfield analysis using Cartesian coordinates. NASA CR-2577 (1975).
5. Carlson,L.A., Transonic airfoil design using Cartesian coordinates. NASA CR-2578 (1976).
6. Carlson,L.A., TRANDES: a FORTRAN program for transonic airfoil analysis or design. NASA CR-2821 (1977).
7. Laschka,B., Der Weg zum superkritischen Flügel. Festschrift zum 65. Geburtstag von Prof. Dr.-Ing. E.h. Erich Truckenbrodt, Technische Universität München, Institut für Strömungsmechanik (1982).
8. Puffert-Meißner,W., Tests on the NPU2 airfoil in the DFVLR-Transonic Windtunnel Braunschweig (TWB), Data Report. DFVLR IB 19111-84C29 (1984).
9. Redeker,G. and Müller,R., Messungen am Profil DFVLR-R2 im Transsonischen Windkanal Braunschweig. DFVLR IB 151-78/2 (1978).
10. Sobieczky,H.,Yu,N.J.,Fung,K.J. and Seebass,A.R., A new method for designing shock-free transonic configurations. AIAA Paper No. 78-1114, AIAA 11th fluid and plasma dynamics conference, Seattle, Wash. (1978).
11. Zhang,Z.Y.,Yang,X.T.,Zhang,L.H. and Yang,Y., The design of two supercritical wing sections --- NPU2 & NPU3. Northwestern Polytechnical University Internal Report (1983).
12. Zhang,Z.Y.,Redeker,G.,Wichmann,G. and Köster,H., Design and analysis methods for transonic airfoils. DFVLR IB 129-84/21 (1984).
13. Zhang,Z.Y., An improvement to the transonic airfoil analysis and design program,TRANDES. DFVLR IB 129-84/31 (1984).
14. Zhang,Z.Y. and Yang,Y., Evaluation of the aerodynamic characteristics of the supercritical airfoil NPU2. DFVLR IB 129-84/32 (1984).

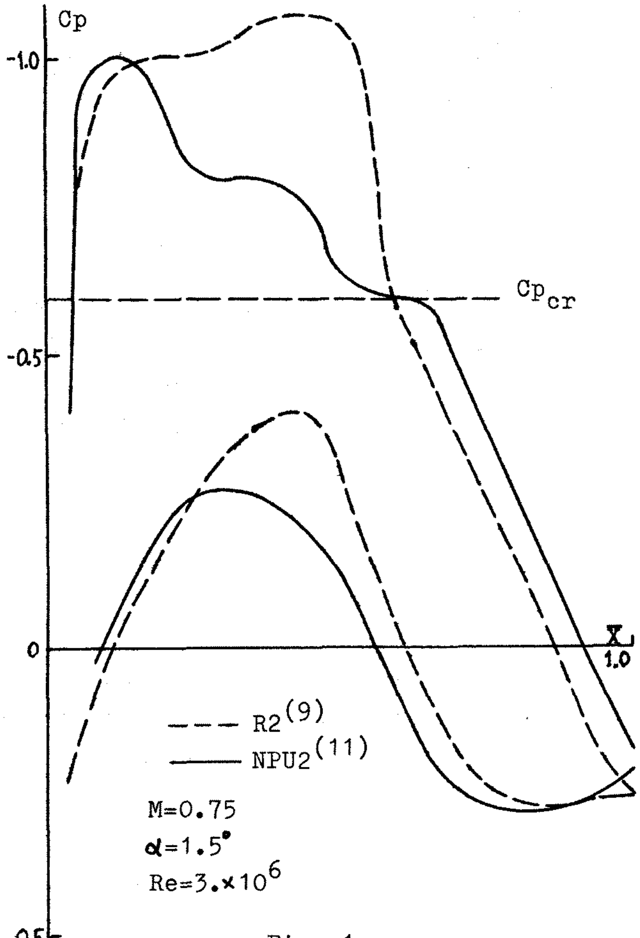

Fig. 1

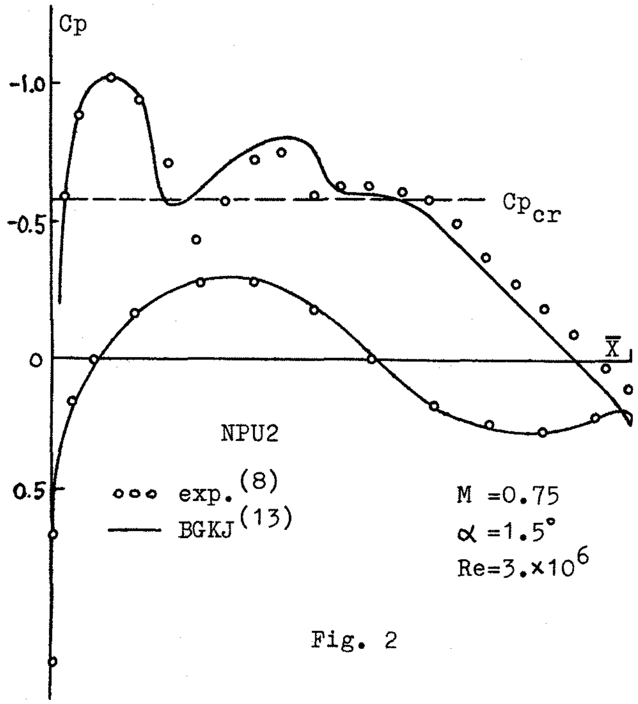

Fig. 2

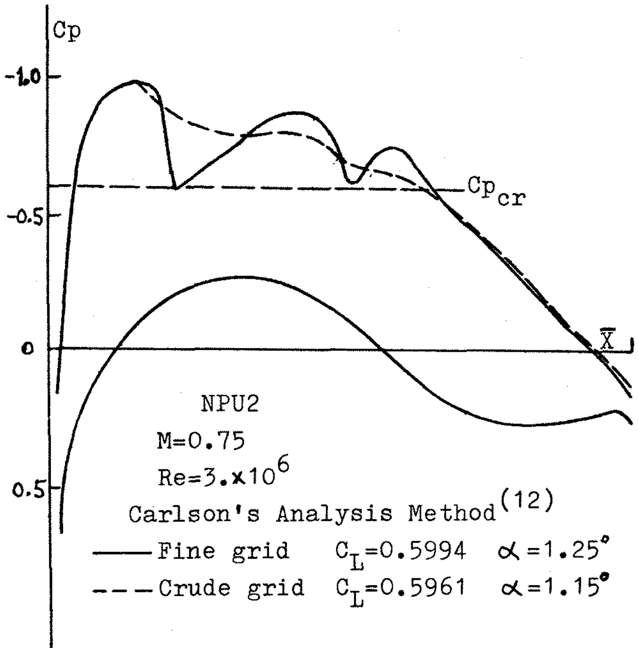

Fig. 3

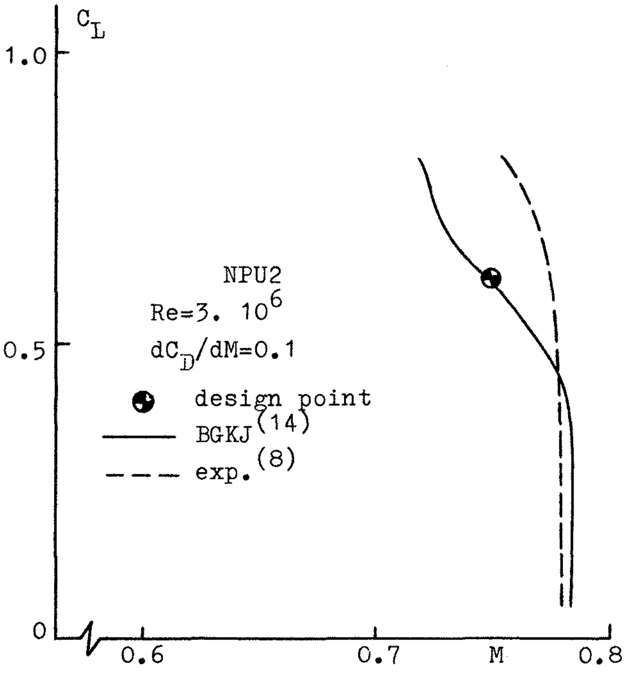

Fig. 4

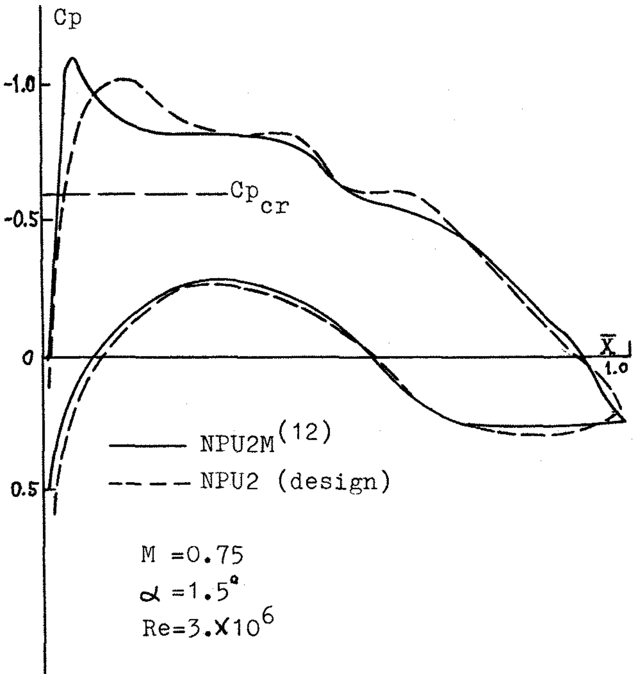

Fig. 5

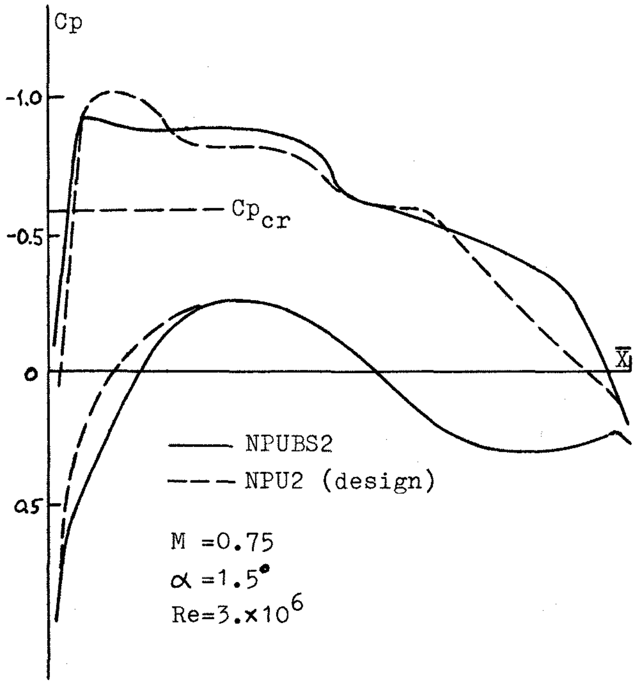

Fig. 6

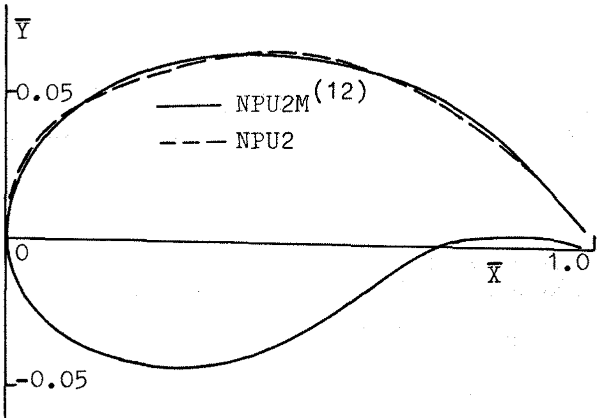

Fig. 7

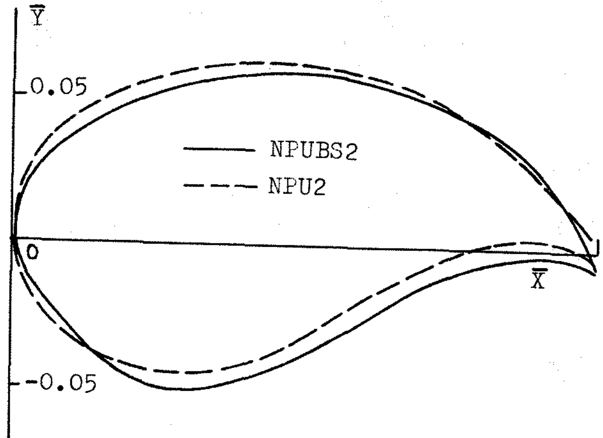

Fig. 8

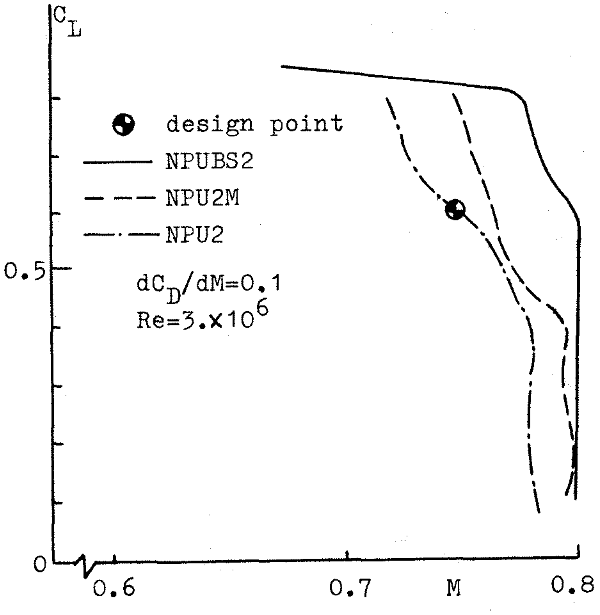

Fig. 9