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GENERALIZATION OF ANALYTICAL TOOLS FOR HELICOPTER-ROTOR AIRFOILS

Final Report for NASA Grant NSG 1412

by

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CONTENTS

Summary

A state-of-the-art finite difference boundary-layer program has been incorporated into the NYU Transonic Analysis Program. Some possible treatments for the trailing edge region have been investigated. One general treatment of the trailing edge region, still within the scope of an iterative potential flow, boundary layer program, appears feasible.

Introduction

The original purpose of this research was to provide improved aerodynamic predictions for helicopter-rotor airfoils by improving the viscous predictions in the NYU Transonic Analysis Program (Ref. 1). This was to be accomplished by use of finite difference boundary-layer calculations along with the existing potential-flow program. Suitable semi-empirical approximations for the trailing edge and for shock-wave/boundary-layer interactions were to be made, and predictions from the resulting program were then to be correlated with existing experimental data. The effort was intended to support a graduate student.

Following submission of the original proposal, a number of factors suggested a somewhat different emphasis. The trailing edge problem proved to be more severe than anticipated. In addition, changing interests and emphasis at NASA led to written notification that funding would not be continued for the effort. Graduate student involvement at the level intended thus became impractical.

With the viscous improvements incorporated, the program would be in a position to be a very general and useful tool provided an acceptable general trailing edge treatment could be incorporated. Such a program could provide improved predictions for a variety of airfoil types and Reynolds numbers. Another useful application would be to help distinguish between viscous and wall effects in wind tunnel data.

For the reasons indicated, additional effort was directed towards the trailing edge problem rather than an empirical correlation of data. One possibility, still within the scope of an iterative potential-flow/boundary-layer program, appears to be feasible. This, along with the rest of the effort, is described in the following sections.

Boundary-Layer Calculations

Calculations are performed for laminar, transitional and turbulent flow by numerically solving the partial differential equation form of the compressible boundary-layer equations. Turbulent flow is modeled by using semi-empirical eddy viscosity and turbulent Prandtl number (eddy conductivity) expressions in the equations. Transitional flow is modeled by multiplying the fully turbulent eddy viscosity and conductivity expressions by a streamwise intermittency function. Laminar flow is calculated by setting the turbulence expressions equal to zero, which reproduces the laminar boundary-layer equations.

The boundary-layer calculations begin at the front stagnation point and proceed downstream step by step to the trailing edge. The flow is initially laminar, then becomes transitional, and then fully turbulent. At the transition point, which can be specified by various criteria, the eddy viscosity and conductivity expressions are activated. For free transition, the streamwise intermittency function increases gradually from zero at the transition point to one for fully turbulent flow. For artificial transition (tripped boundary-layer), the intermittency function is set equal to one at the transition point. Separation, if it occurs, is predicted by the computed wall shear stress becoming zero.

With the formulation described above, the numerical solution method is the same for all cases. The numerical method, semi-empirical turbulence model, and semi-empirical transiton criteria are described in the following sections.

Numerical Method

The numerical method used is that of Harris (Refs. 2, 3). This method was selected because it has been extensively used and tested, and because it was available on the Langley Research Center computer system during the 1977 NASA-ASEE summer program. Ref. 2 describes the formulation and gives comparisons of calculated and experimental results. Ref. 3 describes the program and its usage. Some modification (not described in Refs. 2 and 3) to the details of the numerical procedure have been made by Dr. Veer Vatsa of Langley (private communication), but these do not effect the suitability or use of the method.

Briefly, Probstein-Elliott and Levy-Lees transformations are applied to the boundary-layer equations. The turbulence quantities are handled as described previously. Finite difference approximations are made in both the streamwise and normal coordinates. The streamwise grid spacing is arbitrary, while the normal grid is a geometric progression with spacing determined by three input parameters. Calculations begin at the stagnation point, where a similar solution results, and proceed downstream one grid point at a time. At each streamwise grid point, the velocity and temperature profiles are calculated by solving the finite difference equations in the normal direction. Other boundary-layer parameters follow from these profiles.

The stand-alone boundary-layer program described in Ref. 3 has been interfaced with the potential flow portion of the NYU program. The bulk of the input (eg. pressure distribution) and output (eg. displacement thickness distribution) for the boundary-layer program is handled by the interfacing. This permitted a reduction of about 400 lines of unnecessary arrays, subroutines and external functions in the boundary-layer program. All program changes were made in stages and checked at each stage. Any additional boundary-layer input (eg. grid or transition parameters) is included in the namelist input and has internally specified default values. Thus the program use is virtually identical to the previous NYU program.

Although combining existing programs is not an optimum procedure, the present program should not present problems on large computer systems. A (preliminary) sample run on the Langley CYBER 175 required about 1-1/2 minutes for 13 potential flow cycles and 3 boundary-layer calculations on both course and fine grids. The specified core for this run was 150K octal words, although no effort was made to find the minimum necessary core.

Turbulence Model

The turbulence model used in the boundary-layer program is that of Cebeci and Smith, which has been widely used and tested for a variety of flows. The eddy viscosity model is a two layer one. The outer eddy viscosity is based on a kinematic displacement thickness, while the inner eddy viscosity is based on mixing length theory with the Van Driest damping factor. The turbulent Prandtl number may be taken as a variable or as a constant.

Some modifications to this formulation have been developed for various effects. These are described in Ref. 4 (Chap. 6). In general, any differences in the formulation between that given in Ref. 2 and Ref. 4 have been updated in favor of Ref. 4. The reason is that the current application considers adiabatic transonic flow with pressure gradients, while Ref. 2 is primarily concerned with high speed flow with heat transfer. Principle modifications are for low Reynolds number effects, pressure gradient effects in the damping factor, and the use of a constant (0.90) turbulent Prandtl number. The streamwise intermittency factor for transitional flow has also been updated to the more general form given in Ref. 4.

Transition Criteria

The location of free transition is determined by a number of factors, as discussed in Ref. 2 for example. In practice, transition is usually assumed to occur when some Reynolds number reaches a critical value. The actual magnitude of the critical value may vary considerably from case to case.

The vorticity Reynolds number transition criteria used in Refs. 2 and 3 has been replaced for the present application since large heat transfer rates are not a consideration. Instead, transition criteria are based on momentum thickness Reynolds number. The criteria used are actually for low speed flow, but are still appropriate for the present application. The change was made because the present criteria have been more thoroughly correlated with experiment, and presumably are more familiar to the user.

The default transition criteria uses Michel's method to determine the transition momentum thickness Reynolds number as a function of the local streamwise Reynolds number. This is given by Eq. (9.2.1) of Ref. 4, and is compared to experimental data in Fig. 9.3 of Ref. 4 or Fig. 17.9 of Ref. 5. This criteria is appropriate for smooth surfaces in low turbulence free streams, and thus tends to give an upper limit.

An option allows the default value to be overridden by a namelist input value or values (separate values for favorable and adverse pressure gradients can be used if desired). This option is useful in cases where the flow environment is unlikely to permit much laminar flow. The minimum transition value of momentum thickness Reynolds number is usually considered to be about 320. A value of 640 for favorable pressure gradients is common, and other values in this range are also used frequently.

A different option allows the transition points to be specified in the namelist input. This is the same procedure as in the original NYU program except that the specified transition points may be for either free transition (transitional boundary-layer calculations included) or fixed (abrupt) transition.

A final (internally controlled) transition criteria is to treat a laminar separation point, if one occurs, as a fixed transition point. This is necessary in order to be able to continue the boundary-layer calculations.

Trailing Edge Region

Special precautions are required for the calculations near the trailing edge of rotor-type airfoils. An inviscid pressure distirbution always leads to boundary-layer separation, and the boundary-layer calculations cannot simply be continued past the separations point. Initially, it was expected than an extrapolated pressure distribution for the first boundary layer calculations would circumvent this problem. For a subcritical flow test case, an experimental pressure distirbution did lead to well-behaved boundary-layer calculations. However, the next potential flow calculation was virtually unchanged by the presence of the boundary-layer displacement thickness, ie, an essentially inviscid pressure distribution again resulted near the trailing edge.

Following this discovery, a trial and error investigation was performed. This involved potential flow calculations using displacement thickness distributions believed to cover the feasible range of boundary-layer behavior. None of the resulting pressure distributions were in satisfactory agreement with experiment.

The calculated pressure distributions ranged from nearly inviscid to ones similar to the results reported in Ref. 6. Hindsight suggests that this should be expected since the pressure drag (excluding wave drag) is zero. A feasible empirical approach would be to fractionally extend the airfoil chord. Such a procedure could be forced to work, but considerable correlation would be needed before the generality could be trusted.

A more fundamental approach is perhaps more promising. The principle is similar to that of Ref. 7, although the details would be considerably different in the present method. Ref. 7 computes the flow about an actual airfoil plus a displacement thickness and wake. Established potential flow methods for incompressible flow along with measured displacement thicknesses, are used. Results are in suitable agreement with experiment, including the region near the trailing edge.

A roughly analogous procedure would not require drastic changes in the present calculations. Basically, the change would be to replace the computed surface pressure distribution by the distribution a displacement thickness away from the surface. In practice, this change would probably only be required for the last few percent of the airfoil chord. Since the "outer" airfoil is treated as an inviscid problem, typically with a finite trailing edge angle, this should approximate the solution for a smoothly varying effective surface that would occur in a viscous flow.

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