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NUMERICAL SOLUTION OF THE NAVIER-STOKES EQUATIONS FOR ARBITRARY TWO-DIMENSIONAL MULTI-ELEMENT AIRFOILS

by

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Introduction

This research project covered a period of ten years, from 1 January 1974 through 31 December 1983. The overall purpose was to develop numerical solutions of the Navier-Stokes equations, with an algebraic turbulence model, for time-dependent two-dimensional flow about multi-element airfoils.

Fundamental to these solutions was the use of numerically-generated boundary-conforming curvilinear coordinate systems to allow bodies of arbitrary shape to be treated. This project, in fact, provided the initial support for the study of elliptic grid generation systems in two dimensions, and much of the development of numerical grid generation based on this technique has been done under this project. A general two-dimensional grid generation code for multiple-body configuration was written as a part of this project and made available through the COSMIC code library.

Numerical Grid Generation

The developments under this project in the area of numerical grid generation are summarized as follows:

(1) Elliptic grid generation with coordinate line control. This initial work was covered in the Ph.D. dissertation of Thames (1975) and was reported in Thompson, Thames and Mastin, Journal of Computational Physics (1974), and in Thames, Thompson and Mastin, NASA SP-347 (1975). Results were also reported at the AIAA 2nd Computational Fluid Dynamics Conference in Hartford, Conn. (1975). The basic techniques of elliptic generation were developed and coded, including in particular the means of user-controlled attraction of coordinate lines and/or points to other coordinate

lines and/or points to provide a priori concentration of coordinate lines in regions of expected high gradients, e.g., boundary layers.

(2) Extension to multiple-body fields: the TOMCAT code. This work culminated in the development of the TOMCAT code which generates two-dimensional boundary-conforming coordinate systems for fields containing any number of arbitrarily-shaped bodies, with a priori control of coordinate line spacing as mentioned above. This code was made available through the COSMIC code library, as reported in the NASA Tech Briefs (Spring 1978, p. 150). The code was described fully in a contractor report, CR-2729 (1977), and also was reported in Thompson, Thames and Mastin, Journal of Computational Physics (1977).

(3) Automatic coordinate line concentration in boundary layers. This allowed a prescribed number of lines to be placed within a specified boundary layer thickness on an airfoil, requiring only the specification of the Reynolds number. This technique was discussed in Thompson, et.al., NASA CP-2045 (1978); in Thompson, Computational Fluid Dynamics (1980); and in Thompson, Numerical Grid Generation (1982).

(4) Evaluation of grid-induced truncation error. Studies were made of the truncation error induced by rapid changes in coordinate line spacing, and several distribution functions were compared in this regard. Some of this work was involved in the MS thesis of D. Thompson (1980).

(5) Grids with infinity transformed to the orgin. This type of grid is particulary appropriate to double-airfoil configurations. The work was discussed in the MS thesis of Long (1977) and was also reported in Thompson, et.al., NASA CP-2045 (1978).

(6) Grid generation surveys. This project provided support for extensive coverage of the literature on grid generation over the years, contributing to the surveys given by Thompson, Warsi and Mastin, Journal of Computational Physics (1982), and that presented by Thompson at the AIAA 21st Aerospace Sciences meeting in Reno (1983).

(7) Exposition on grid generation. In the course of this long project the principles of numerical grid generation from elliptic generation systems, and the use thereof in the numerical solution of partial differential equations, were formulated and refined to the point of consistent presentation for general use. This is reflected in the expositive presentations by Thompson in Computational Fluid Dynamics (1980), and in Numerical Grid Generation (1982).

Incompressible Navier-Stokes Codes

The codes developed for the incompressible Navier-Stokes equations are summarized below. All these, except the first, were based on the velocity-pressure formulation, using the Poisson equation for the pressure. The pressure boundary condition on the body surface was obtained from the normal momentum equation, although in later work a zero normal pressure gradient on the surface was found to be sufficient because of the very close spacing of the first coordinate line off the surface, typically set at about 1% of the expected boundary layer thickness.

In all these codes, provision was made for the use of artificial viscosity proportional to the divergence of the velocity, and hence analyticaly zero, to control the solution during the initial transients. The start was through continuous acceleration, instituted through the inclusion of ficticious body force terms during the period of acceleration. The Baldwin-Lomax algebraic turbulence model was used in all cases.

(1) Stream function-vorticity. This code used point SOR iteration for the vorticity equation and the stream function Poisson equation. This work was discussed in the Ph.D. dissertation of Thames (1975) and was reported in Thames, Thompson and Mastin, NASA SP-347 (1975), and in Thames, et.al. Journal of Computational Physics (1977). Results for application to boundary layers were discussed in the MS thesis of Walker (1974), also being reported in Thompson, et.al., Symposium on Unsteady Aerodynamics (1975), and in Thames, et.al., (1977) cited above. Applications to airfoils at higher Reynolds numbers were discussed in the MS thesis of Bearden (1977) and were reported in Thompson, et.al., NASA CP-2045 (1978).

(2) Point SOR. This code was based on point SOR iteration with under-relaxation, using a variable acceleration parameter field calculated from the local velocity. This code was discussed in Thompson, et.al., NASA CP-2045 (1978); in Thompson, Computational Fluid Dynamics (1980); and in the MS thesis of D. Thompson (1980).

(3) Approximate factorization. This code used approximate factorization on the two momentum equations and line SOR iteration on the pressure Poisson equation, thus requiring only one pass of the momentum equation at each time step, although the pressure equation still was iterated. This work was discussed in the Ph.D. thesis of Bernard (1981), and results were presented at the AIAA/ASME 3rd Joint Thermophysics, Fluids, Plasma and Heat Transfer Conference in St. Louis (1982) and also in Mueller,

et.al., Computers in Flow Predictions and Fluid Dynamics Experiments (1981).

(4) Vectorized checkerboard SOR. This code was based on checkerboard SOR iteration in all equations, and was fully vectorized on the CYBER 203. The vectorization was explicit using the vector FORTRAN with bit vectors to control the manipulation of the arrays. This code was discussed in the Ph.D. dissertation of Patel (1983), and a paper has been submitted for presentation at the AIAA 17th Fluid Dynamics, Plasmadynamics, and Lasers Conference in Snowmass,Colorado (1984). This was the most promising of the incompressible codes, showing considerable speed advantage because of the vectorization.

Compressible Navier-Stokes Codes

The compressible Navier-Stokes codes are summarized as follows. All used backward-time and central-space differences and were second-order in time and space. Again the Baldwin-Lomax turbulence model was used.

(1) Point SOR. This code used point SOR iteration of all equations at each time step, with a variable acceleration parameter field calculated from the local velocity. Since these parameters proved to be very small for the continuity equation,this code was unreasonably slow. The code was discussed in the Ph.D. dissertation of Turner (1979).

(2) Density Gradients as dependent variables. A small investigation of the use of density gradients as dependent variables was made, as reported in the MS thesis of Kwon (1977), but little promise of advantage was found.

(3) Approximate factorization. This code was based on approximate factorization in the delta form for all equations and was discussed in the Ph.D. dissertation of Cooper (1980). Results were presented at the AIAA 14th Fluid and Plasma Dynamics Conference in Palo Alto (1981).

Incompressible Potential Code

In addition to the Navier-Stokes codes, an incompressible potential flow code for multiple-body fields was developed in the early stages of the project. This solution was also discussed in the Ph.D. dissertation of Thames (1975). Some results were reported in Thames, et.al., Journal of Computational Physics (1977), and more extensive results were collected later in the MSU report of Thompson and Thames (1982).

Conclusion

The major accomplishments of this long project were the fundamental development of elliptic grid generation and the establishment thereof as a basic component in the numerical solution of partial differential equations, particularity in computational fluid dynamics. A significant additional accomplishment was the development of a vectorized code for the incompressible Navier-Stokes equations. Finally, perhaps the real significance of this project was the basic support it provided over the years for the development, correlation and dissemination of ideas on numerical grid generation and the graduates it produced.

PUBLICATIONS

Journal Articles

J. F. Thompson, F. C. Thames, and C. W. Mastin, "Automatic Numerical Generation of Body-Fitted Curvilinear Coordinate System for Fields Containing any Number of Arbitrary Two-Dimensional Bodies," Journal of Computational Physics, 15, 299, (1974).

F. C. Thames, J. F. Thompson, C. W. Mastin, and R. L. Walker, "Numerical Solutions for Viscous and Potential Flow about Arbitrary Two-Dimensional Bodies Using Body-Fitted Coordinate Systems," Journal of Computational Physics, 24, 245 (1977).

J. F. Thompson, F. C. Thames, C. W. Mastin, "TOMCAT" - A Code for Numerical Generation of Boundary-Fitted Curvilinear Coordinate Systems on Fields Containing any Number of Arbitrary Two-Dimensional Bodies," Journal of Computational Physics, 24, 274 (1977).

Joe F. Thompson, Z. U. A. Warsi, and C. W. Mastin, "Boundary-Fitted Coordinate System for Numerical Solution of Partial Differential Equations - A Review," Journal of Computational Physics, 47, 1 (1982).

Joe F. Thompson, "Elliptic Grid Generation", Applied Mathematics and Computation, 10-11, 79, (1982).

J. F. Thompson, "General Curvilinear Coordinate Systems", Applied Mathematics and Computation, 10-11, 1, (1982).

J. F. Thompson, "A Survey of Grid Generation Techniques in Computational Fluid Dynamics," accepted for publication in AIAA Journal.

Conference Presentations

F. C. Thames, J. F. Thompson, and C. W. Mastin, "Numerical Solution of the Navier-Stokes Equations for Arbitrary Two-Dimensional Airfoils," Proceedings of NASA Conference on Aerodynamic Analyses Requiring Advanced Computers, Langley Research Center, NASA SP-347, (1975).

J. F. Thompson, F. C. Thames, R. L. Walker, and S. P. Shanks, "Numerical Solutions of the Unsteady Navier-Stokes Equations for Arbitrary Bodies Using Boundary-Fitted Curvilinear Coordinates," Proceedings of Arizona/AFOSR Symposium on Unsteady Aerodynamics, University of Arizona, (1975).

J. F. Thompson, F. C. Thames, C. W. Mastin, and S. P. Shanks, "Use of Numerically Generated Body-Fitted Coordinate Systems for Solution of the Navier-Stokes Equations," Proceedings of the AIAA 2nd Computational Fluid Dynamics Conference, Hartford, Connecticut, (1975).

J. F. Thompson, F. C. Thames, S. P. Shanks, R. N. Reddy, and C. W. Mastin, "Solutions of the Navier-Stokes Equations in Various Flow Regimes on Fields Containing any Number of Arbitrary Bodies Using Boundary-Fitted Coordinate Systems," Proceedings of V International Conference on Numerical Methods in Fluid Dynamics, Enschede, the Netherlands, Lecture Notes in Physics, Springer-Verlag, (1976), Vol. 59, p. 421.

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Joe F. Thompson, "Numerical Solution of Flow Problems Using Body-Fitted Coordinate Systems," Lecture Series in Computational Fluid Dynamics, von Karman Inst. for Fluid Dynamics, Belgium, 1978. Published in Computational Fluid Dynamics, W. Kollmann (ed), Hemisphere, 1980.

Joe F. Thompson and C. Wayne Mastin, "Progress in the Use of Boundary-Fitted Coordinates for the Numerical Solution of Partial Equations", 17th Society of Engineering Science Meeting, Atlanta, 1980.

G. Kyle Cooper and Joe F. Thompson, "A Panasonic Navier-Stokes Solver", AIAA Paper 81-1195, AIAA 14th Fluid and Plasma Dynamics Conference, Palo Alto, 1981.

T. J. Mueller, B. J. Jansen, Jr., R. S. Bernard, and Joe F. Thompson, "Experimental and Numerical Studies of the Incompressible Viscous Flow Over a Two-Dimensional Airfoil", in Computers in Flow Predictions and Fluid Dynamics Experiments, ASME, 1981.

Joe F. Thompson, "Elliptic Grid Generation", in Numerical Grid Generation, Joe F. Thompson (ed.) Elsevier, 1982.

J. F. Thompson, "General Curvilinear Coordinate Systems", in Numerical Grid Generation, J. F. Thompson (ed.) Elsevier, 1982.

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J. F. Thompson, F. C. Thames, and C. W. Mastin, "Boundary-Fitted Curvilinear Coordinate System for Solution of Partial Differential Equations on Fields Containing any Number of Arbitrary Two-Dimensional Bodies," NASA CR-2729 (1977).

Joe F. Thompson and F. C. Thames, "Numerical Solution of Potential Flow About Arbitrary Two-Dimensional Multiple Bodies", MSSU-EIRS-ASE-82-2, Mississippi State University, 1982.

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R. L. Walker, "Numerical Solution of the Navier-Stokes Equations for Incompressible Viscous Laminar Flow Past a Semi-Infinite Flat Plate," M.S. Thesis, Mississippi State University, (1974).

John H. Bearden, "A High Reynolds Number Numerical Solution of the Navier-Stokes Equations in Stream Function-Vorticity Form," M.S. Thesis, Mississippi State University, August 1977.

W. Serrill Long, "Two-Body Coordinate System Generation Using Body-Fitted Coordinate System and Complex Variable Transformation," M.S. Thesis, Mississippi State University, August 1977.

Jang-Hyuk Kwon, "Numerical Solution of the Compressible Navier-Stokes Equations Using Density Gradients as Additional Dependent Variables," M.S. Thesis, Mississippi State University, December 1977.

David S. Thompson, "Numerical Solution of the Navier-Stokes Equations for High Reynolds Number Incompressible Turbulent Flow", M.S. Thesis, Mississippi State University May, 1980.

Dissertations

F. C. Thames, "Numerical Solution of the Incompressible Navier-Stokes Equations about Arbitrary Two-Dimensional Bodies," Ph.D. Dissertation, Mississippi State University, (1975).

Louie Turner, III, "Numerical Solution of the Navier-Stokes Equations for Laminar, Transonic Flows," Ph.D. Dissertation, Mississippi State University, May 1979.

G. Kyle Cooper, "An Approximate Factorization Solution of the Navier-Stokes Equations for Transonic Flow Using Body-Fitted Coordinates with Application to NACA 64A010 Airfoils", Ph.D. Dissertation, Mississippi State University, August 1980.

Robert S. Bernard, "Approximate Factorization for Incompressible Flow," Ph.D. Dissertation, Mississippi State University, August 1981.

Nisheeth Patel, "A Fully Vectorized Numerical Solution of the Incompressible Navier-Stokes Equations," Ph.D. Dissertation, Mississippi State University, December 1983.

List of Graduates Supported

	Degree	Date	Present Affilation
Ray L. Walker	M.S.	1974	CIA
Frank C. Thames	Ph.D.	1975	NASA Langley Research Center
John H. Bearden	M.S.	1977	Cabot Corp. (entering Ph.D. program at Georgia Tech)
W. Serrill Long	M.S.	1977	United Airlines
J. H. Kwon	M.S.	1977	unknown (last known as Ph.D. student at Cornell)
Louie Turner	Ph.D.	1979	Boeing
David S. Thompson	M.S.	1980	Ph.D. student at Iowa State
G. Kyle Cooper	Ph.D.	1980	Sverdrup Corp.
Robert S. Bernard	Ph.D.	1981	U.S. Army Engineer Waterways Experiment Station
Nisheeth Patel	Ph.D.	1983	U.S. Army Ballistic Research Laboratory

Of these ten graduates, all but two were U.S. citizens.