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UNSTEADY FLOW AND DYNAMIC RESPONSE ANALYSES

FOR HELICOPTER ROTOR BLADES

Final Progress Report

Prepared by

Theodore Bratanow

for the

UNIVERSITY OF WISCONSIN-MILWAUKEE
Milwaukee, Wisconsin

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Theodore Bratanow*

University of Wisconsin-Milwaukee

ABSTRACT

This final report summarizes the research on the NASA-project for the period
of January 2, 1971 to June 30, 1979. Wherever possible, an effort was made
to provide a step-by-step chronological account and to note developments which
are worth mentioning. The research was directed basically in two directions:
starting with a helicopter rotor blade vibration analysis and then concentrat-
ing on two and three-dimensional analyses of unsteady incompressible viscous
flow past oscillating helicopter rotor blades. As can be seen, it was nec-
essary to cover a wide range of aspects related to the research objectives.
Very often, it was necessary to piece together whatever and how little was
known on the subject of the Reynolds number range.

A summary is presented also of the two international research collaborations
which resulted from the NASA-project: the collaboration under the auspices
of NATO between the University of Wisconsin-Milwaukee (UWM), University of
Brussels, Belgium and the Aerodynamics Research Establishment (DFVLR) in
Goettingen, W. Germany, and the collaboration under the auspices of the Na-
tional Science Foundation between UWM and the University of Hamburg and the
Ship Research Establishment in Hamburg (HSVA), W. Germany. Finally, a sum-
mary is given of the benefits from the NASA-project to UWM, the College of
Engineering and Applied Science, and the participants on the project. The
numbers in the brackets refer to reports, publications, and graduate student
theses related to the project.

*Professor

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PARTICIPANTS IN THE INTERNATIONAL COOPERATIVE RESEARCH

UNDER THE AUSPICES OF NATO

I. AT THE UNIVERSITY OF WISCONSIN IN MILWAUKEE, WISCONSIN, USA

Principal Investigator: Dr. Theodore BRATANOW, Professor
Engineering Mechanics, College of
Engineering and Applied Science

Mr. Thomas SPEHERT
Research Specialist, Engineering Mechanics

II. AT THE INSTITUTE OF AEROELASTICITY OF DFVLR IN GOETTINGEN, WEST GERMANY

Principal Investigator: Dr. Hans FOERSCHING, Professor
Director, Institute of Aeroelasticity

Associate Principal Investigators: Dr. Wolfgang GEISSLER
Head of the Theoretical Analysis
Section

Dr. Hermann TRIEBSTEIN
Supervisor of Experimental Projects

III. AT THE UNIVERSITY OF BRUXELLES-BRUXELLES, BELGIUM

Principal Investigator: Dr. Charles HIRSCH, Professor
Chairman, Department of Fluid Dynamics

Dr. Guido DE GRANDE
Research Associate

THE PARTICIPANTS IN THE COOPERATION

UNDER THE AUSPICES OF NSF

In Hamburg, West Germany

Dr. Otto Grim, Professor, Institute for Ship Research, University
of Hamburg, former director and presently member of
the board of the Hamburgische Schiffbau - und
Versuchsanstalt G.m.b.H., Hamburg

Dr. Joachim Schwarz, Head, Ice Tank Research Facility of the Hamburgische
Schiffbau - und Versuchsanstalt G.m.b.H., Hamburg

Dipl.-Ing. Franz Haeusler, Scientist, Institute for Ship Research,
University of Hamburg and the Hamburgische
Schiffbau - und Versuchsanstalt G.m.b.H.,
Hamburg

At the University of Wisconsin - Milwaukee

Dr. Theodore Bratanow, Professor, Department of Mechanics, College
of Engineering and Applied Science

Mr. Thomas Spehert, M.S., Research Associate

SUMMARY OF THE RESEARCH

1. Introduction

An effort was made to summarize the work on the project in a chronological order. A step-by-step discussion is given of the development of the analyses of the two- and three-dimensional flows which were not explained in our published work [1-22]. An explanation is given of the encountered computer difficulties. An effort was made also to assess realistically the results and the conditions under which the project was carried out.

The Navier-Stokes equations were chosen as the mathematical model for the problem of unsteady incompressible viscous flow around oscillating rotor blade airfoils and wings. It appeared that these equations contained all the features needed to represent the actual conditions and that the problem is amenable to such an approach. Above all, it appeared that this approach is the most fundamental one. As it happened a great deal could be learned in this way and some important conclusions drawn from the detailed analysis with these equations. Looking back now at the work on the project, there is very little doubt that the application of the Navier-Stokes equations was the way to go.

The vorticity-stream function formulation was applied initially for the solution of the problem at hand. The reasons for the decision to discontinue the work with this formulation are given. A new common method, suggested by Lighthill, was applied for both the two- and three-dimensional cases. It appears that this method represents efficiently the physics of the unsteady flow in a form suitable for numerical computation. See table and figure 1.

We set out to investigate the suitability of the formulation and to produce results for suitable Reynolds number flows. Those were days of difficulty and pressure. There was a strong determination of the project group to brave out every difficulty and to make progress and to succeed. A computer terminal was acquired for our laboratory and keeping a six-day work week became standard. Good results were obtained in spite of the limitations on advanced and comprehensive computer research work in a university environment and the limitations of the UWM computer facility. We presented the results as they were obtained from the computer, letting the limitations of the applied formulation and the applied finite element technique be visible. We felt that our results were of interest to researchers and were appreciated by research engineers as samples of a first complete attempt on this complicated problem. There were over 100 requests from researchers all over the world of our many published papers. There have been already encouraging reviews of our papers.

Since UWM does not have the proper experimental facilities, we have been seeking cooperation. The two international research collaborations under the auspices of NATO and NSF were initiated and coordinated by this writer. A very good working relationship was established. The results from carefully prepared experiments contributed greatly toward our basic

understanding of flow patterns and served as a guide in developing the analyses. See figures 2-5.

2. The Work with the Stream Function Vorticity Formulation

In the first two years of the research on the flow around oscillating air-foils using the Navier-Stokes equations, we applied finite element grid-works in modelling the flow. The gridworks were composed of nonconformable third-order triangular finite elements with straight edges. These were of different sizes, usually small, closer to the airfoil, and larger, further away. Next to the stream function formulation and the velocity and pressure formulation, the stream function and vorticity formulation is one of the three formulations mostly used for incompressible viscous flow with inertia in conjunction with the finite-element method. One works here with two coupled equations of second-order in terms of the stream function and the vorticity. However, the stream function and vorticity formulation offers advantages only when applied to a two-dimensional analysis. The principal difficulty in using the stream function and vorticity formulation is that, in general, vorticity is unknown a priori along solid boundaries. Determining the values for the vorticity along the airfoil boundary required de-tailed consideration since here the no-slip boundary condition alone is not sufficient.

Variational functionals equivalent to the governing differential equations in terms of stream function, vorticity and pressure were established. For the resulting differential equations in the form of Poisson's equations, in terms of stream function and pressure as the dependent variables, the exact forms of the variational functionals were available and were used all along. No exact variational form exists for the representation of the vorticity transport equation due to the nonlinearity in the convective terms. Thus, an approximate variational functional was derived for the vorticity trans-port equation. By using the Minimum Functional Theorem and employing a Taylor series expansion of the velocity vector in terms of vorticity, an approximate minimization functional for the vorticity transport equation was obtained. The discretization process yielded two systems of algebraic equations corresponding respectively to the discretized form of the differen-tial equations for the stream function and pressure, and a system of first order ordinary differential equations in terms of the time derivative of the vorticity. The system of algebraic equations for the stream function and the system of algebraic equations for the pressure were solved at each time step of the numerical integration of the vorticity transport equation. The system of first order ordinary differential equations corresponding to the vorticity transport equation was integrated with respect to time using a first order forward difference scheme.

The stability and convergence problems associated with the integration of the vorticity transport equation with respect to time, in particula., were continuously analyzed. Sufficient criteria was established for determining the range of applicability of the applied numerical method in terms of the flow parameters related to the computational procedure; the time step, size, and shape of the distribution of finite-elements in the gridwork in

particular. The variation of the stream function over the nonconformable element was approximated by a complete cubic polynomial. Vorticity and pressure were considered to vary linearly over the triangular finite element. The method was applied first to flow around spheres and cylinders, and then to oscillating airfoils starting at arbitrary mean angles of attack. The accuracy of the boundary conditions applied for the example with the NACA 0012 airfoil and their incorporation into the finite element formulation was determined by numerical experimentation. We explained that with the nonconformable finite element, we obtained discontinuous representation of boundary values, thus causing deviations from the no-slip condition between the nodal boundary points where the no-slip condition was specified.

Close attention was paid to minute details related to the established variational functionals for stream function, vorticity, and pressure and how their discretized form affected the overall accuracy of the computational procedure. The adverse effect on accuracy due to the nonuniformity in size and shape of the applied straight edge finite elements was recognized very early in our work and continued to present difficulty with the vorticity stream function formulation. The problem conditions, factors, and parameters affecting the accuracy of our finite element solution were extensively presented and discussed in all of our papers. The question of the effect of the accuracy of the solution when defining an outer boundary of the flow around an oscillating airfoil was given attention. When we suspected inaccuracy, we changed the range of the outer boundary. With the boundary defined, we did not observe any significant inaccuracy due to the outer flow boundary. As a guide in selecting the outer boundary, we used magnified frames of the film by Professor Hazen on "Boundary Layer Control" and suitable photographs of wind tunnel experiments.

Finally, a Gordian Knot, a problem of most difficult solution in dynamics applications using the finite element method, is the discretization with respect to time. We thought that the discretization of the time variable by the finite element method would introduce disadvantages from a computational point of view. And at the time there was no proven advantage reported in the literature. This statement does not, however, mean that there are no advantages in time discretization, but rather, that there has been very little (even up to now) research done in this direction and as such the advantages have not become clear. One of the generally known advantages of discretization in time using the finite element method is that of better convergence and stability, or in other words, the possibility of using larger time step in the numerical integration. This advantage leads to less computational time for the solution of the problem.

3. The Application of the Lighthill Procedure

In light of the already discovered facts and from their correct interpretation, there were indications where revisions in the formulation and in the numerical procedure should be made. From the arbitrariness and the uncorrelated pressure distributions of some of the results, in particular, there were unmistakable clues that something about the oscillating airfoil was

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either not properly done or was not represented at all. The decision to discontinue using the vorticity-stream function formulation was based, also, on the realization that the up-to-date development of the techniques and procedures involved with the application of this formulation were still inadequate, as well as the limitations of the straight edge finite elements, and the inadequacy of the available computer and software. Finally, the amount of the computer storage needed reached the maximum analysis for higher Reynolds number flows. And then, the computer programs were specially segmented in order to meet capabilities of the 1106 Univac computer.

The two most important and obvious components of the analysis to improve on were the formulation and the applied finite element. All along we were alert on introducing improvements and refinements in the package of computer programs because around the end of the year 1974, our university introduced a computer with inferior overall capability than we had until then. Namely, the state-wide Univac 1110 computer system used was replaced by our own Univac 1108 computer installed on our campus. This change then worked against our aspirations to increase the overall size of solution procedure in order to increase accuracy of our results. This simple fact continued to plague us almost until the end of November 1975.

The vorticity transport equations were cast in a form convenient for computation. The computation is considered unsteady in the sense of being suitable for time-stepped solutions. A statement for these equations was written using the method of weighted residuals and applying the Galerkin criterion. From the discretized form of the equations, finite-element equations were assembled and summed over all elements forming thus the global system of equations for the complete flow region. The discretization in finite-element form of the vorticity transport equations resulted in a system of differential equations with respect to time. These equations can be solved with respect to the time variable using a finite difference technique. Finite-elements in the fluid region contain vorticity, since vorticity will be found only in that portion of the fluid region which is discretized by finite-elements.

An integral representation of the induced velocity at finite-element nodes due to the vorticity distribution was applied on the basis of the Biot-Savart law. The numerical procedure developed by Hess and Smith and then refined by Argyris and Scharpf was used in computing vortex sheets over the curved wing surface. The refinement introduced by Argyris and Scharpf involved curvilinear elements, in place of the plane elements used by Hess and Smith. A Hermitian interpolation model was used to approximate the geometry of curvilinear elements between nodes defining the elements. A Lagrangian interpolation model was used to describe vortex sheet intensity over finite-elements. Two types of finite-elements were applied in representing the flow region under investigation: isoparametric triangular and isoparametric quadrilateral finite-elements. Surrounding the curved wing surface are quadrilateral finite-elements, with the remainder of the fluid region divided into triangular finite-elements of varying sizes, becoming smaller and smaller near the wing surface. Quadratic shape-functions were utilized for both isoparametric triangular and isoparametric quadrilateral finite-elements.

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ANALYSIS OF THREE - DIMENSIONAL UNSTEADY FLOW
AROUND OSCILLATING WINGS

Mathematical Background

$$\frac{\partial \underline{\omega}}{\partial t} + (\underline{u} \cdot \underline{\nabla})\underline{\omega} = (\underline{\omega} \cdot \underline{\nabla})\underline{u} - \nu \nabla^2 \underline{\omega} \tag{1}$$

$$\underline{\nabla} \times \underline{u} = \underline{\omega} \tag{2}$$

$$\underline{\nabla} \cdot \underline{u} = 0 \tag{3}$$

$$\nabla^2 p = -\rho \nabla \cdot [\underline{\nabla} \cdot (\underline{u}\,\underline{u})] \tag{4}$$

Numerical Integration of the Vorticity Transport Equations

$$\phi = \int_V \omega_i \frac{\partial \omega_i}{\partial t} \, dV + \frac{1}{2} \int_V \omega_i u_j \frac{\partial \omega_i}{\partial x_j} \, dV$$

$$- \frac{\nu}{2} \int_V \left(\frac{\partial \omega_i}{\partial x_j}\right)^2 dV - \frac{1}{2} \int_V \omega_i \omega_j \frac{\partial^2 u_i}{\partial x_j^2} \, dV \tag{5}$$

$$u_i = u_i \Big|_o + \frac{\partial u_i}{\partial \omega_j}\Big|_o \Delta\omega_j + \frac{1}{2} \frac{\partial^2 u_i}{\partial \omega_j \partial \omega_k}\Big|_o \Delta\omega_j \Delta\omega_k + \cdots \tag{6}$$

$$\omega_j(x,y,z) = A^i(x,y,z)w_j^i \tag{7}$$

$$\underline{S}_\omega \frac{dW_j}{dt} = -[\underline{T}_c(\underline{U}) + \underline{T}_v] W_j + \underline{T}_d^j(\underline{W}_k) \tag{8}$$

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INTERNATIONAL RESEARCH COLLABORATIONS RESULTING FROM THE NASA-PROJECT

1. Introduction

The NASA-research program truly combines several specialized disciplines for
a common purpose. The research approaches had to involve team activities.
The collaboration aspect of the program was considered to have been impor-
tant for its success. It was founded on the conviction that more significant
contributions can be made when working together. The collaborations are
judged to have been of special significance because they coupled university
research at UWM, Brussels, and Hamburg, and applied research resources of
Goettingen and Hamburg. They gave an added dimension to our capability and
they gave us an opportunity to participate in a research on a larger scale.
The specialized resources and capabilities in Goettingen, Brussels, and
Hamburg, in a way, became available to us. The established collaboration
offered an exciting opportunity for a contribution on a wide front in the
emerging field of Unsteady Aerodynamics.

Special comments can be made on the relation between the participants in the
collaborations. They rested on a solid foundation of confidence and deter-
mination to contribute to the development of basic science. The projects did
more than just stimulate collaboration between the scientists. The up-to-
date record of the collaborations show that the research teams brought about
an exchange of ideas, experience, and capability as well as research contri-
butions which are truly more significant than the total of individual nation-
ally supported projects.

The collaborators adopted a long-term far-reaching comprehensive approach
to the goals of the research. Substantial national support was obtained for
the basic costs. Existing experimental facilities were expanded. New equip-
ment was procured. Elaborate models were built. A new and unique high-
pressure wind-tunnel in Goettingen is nearing completion.

The following, then, is a summary of the collaboration activities, of the
work already accomplished, and of the work in progress. A complete list
[23-45] is included of the papers and reports related to the collaborations
under the auspices of NATO and the National Science Foundation in Washington,
D.C. Several of the papers listed presented results of far-reaching impor-
tance from both fundamental and applied aspects.

2. Summary of the Collaboration under the Auspices of NATO

The objectives of the conducted research program can be summarized as follows:
For the example of oscilatory motion, during operational conditions, of
helicopter rotor blades, through a coordinated systematic theoretical compu-
tational and experimental research, a method of analysis will be developed
for: forces and unsteady pressure distributions on the oscillating wing
surfaces; nature and details of the unsteady viscous flow around blade tips;
the manner in which the oscillatory motion affects the turbulence structure

of the unsteady flow around the oscillating wing. The example of the os-
cillating helicopter rotor blade was chosen because it represents the most
interesting and most complete example of the three-dimensional unsteady
aerodynamics for which fundamental knowledge is needed.

The distribution of work-load continued along the following lines: at the
University of Wisconsin-Milwaukee, theoretical and computational analyses of
unsteady viscous flow and unsteady pressure distributions around oscillating
two-dimensional airfoils and blades; at DFVLR in Goettingen, both experimen-
tally and theoretically, research with prime emphasis on unsteady pressure
measurements on two-dimensional airfoils and blades in their subsonic and
high Reynolds number wind-tunnels; at the University of Brussels, determining
effects of the oscillatory wing motion on the flow separation and turbulence
structure of the unsteady flow around oscillating two-dimensional airfoils
and blades; both experimentally and theoretically.

3. The Early Period of the Collaboration with Goettingen

For a coordinated and concentrated attack on the overall problem of the
oscillating blade, this writer sought and succeeded in laying out the
ground work for a collaboration with the Institute of Aeroelasticity of
DFVLR - Goettingen. The first contact in September of 1973 was made pos-
sible with the help of Dr. Wolfgang Geissler. He made the introduction to
the Director of the Institute, Professor Hans Foersching, who came out to
be an alumnus of mine. It happened that they were seeking to establish
contacts in the U.S.A. too. They were delighted that in this context they
were to establish collaboration with NASA - Langley. Upon return to the
U.S., a report was submitted to Mr. John F. Ward, then of NASA - Langley.
Initial details of a mechanism for starting a collaboration were discussed.
On my second visit to Goettingen in January of 1974, I presented an outline of
a suitable testing program related to my work. Professor Foersching
agreed to carry it out. It was intended on their part to be a goodwill
gesture toward NASA - Langley. In June of 1974, Dr. Geissler and I visited
Langley and then he came to UWM. We became familiar with each other's work.
Further details of the collaboration were worked out, and the prospect for
experimental correlation of results came closer to reality.

In April of 1975, Goettingen carried out, at the expense of 100,000 German
Marks, a very interesting experimental measurement program on a full-scale
helicopter blade tip (see Fig. 2). The blade is still referred to as the
"Bratanow Wing". Unsteady three-dimensional pressure distributions were
measured and documented (see below). In June of 1975, Professor Foersching
visited Milwaukee and Langley. Dr. Geissler spent three months in the
summer of 1975 at UWM. The UWM - Graduate School helped in the undertaking
and supported his family during their visit in Milwaukee. It was a very
good occasion for a meaningful cooperation and exchange of ideas.

4. The Measurement Program of 1975 [41]

Measurements were made of pressure distributions on the harmonically

oscillating rotor blade wing in low subsonic speed. The measurements were carried out in the 3×3 m-subsonic wind-tunnel of the DFVLR in Goettingen. Pressures were measured at five sections of the wing in a way that the three-dimensionality of the pressure distribution could be well observed. The flow speed was 45 m/s. The oscillation frequencies were 2, 4, 6 Hz; with reduced frequencies $\omega^* = \pi f l / V = 0.07$, 0.14, and 0.21. The oscillation amplitudes ranged from $B = 1°$ to $3°$, and the angles of attack were $\alpha = 0°$, $3°$, $6°$, $9°$, and $12°$. Comparisons with theoretical and experimental results were made. The calculated predictions were found to agree well with the measured data. At the wing tip, however, the agreement was not uniform. A description of the test-facility used is also presented in [41].

5. On the Collaboration with the University of Brussels, Belgium

Professor Charles Hirsch, Head of the Department of Fluid Dynamics of the University of Brussels, is the other principle investigator in the collaboration under the auspices of NATO. He has a strong theoretical and experimental background in Fluid Dynamics and Aerodynamics.

The period of July, 1975 to April 1, 1976 in several ways was a decisive period in the course of the project. Changes in the conduct of the research program were made and proved to be very beneficial for the overall outcome of the project. Looking back to the experience, I realize now that in that period I actually put my determination to successfully finish the project above everything else. When confronted with the enormous complexity of the computational undertaking with the vorticity-stream function formulation for the two-dimensional analysis, I forgot my personal pride and secured the cooperation of Professor G.M.L. Gladwell of the University of Waterloo, Ontario, Canada and Professor Hirsch from the University of Brussels, Belgium. It was thus possible to develop a new, unified, and from a physical point of view, more complete, yet simpler, method of attack for both the two- and three-dimensional analysis of unsteady flow around oscillating wings.

Professor Hirsch visited UWM in September of 1975 and then for about one week in March of 1976, to familiarize himself with our work. He not only assisted in our work but also expressed a desire to contribute to our further, down-stream, efforts to analyze the effects of the oscillating wing on the transition and turbulence patterns of the unsteady flow. A comprehensive contribution in this area would have involved efforts beyond the ones expected in this research program.

After reviewing the iteration procedure, prepared by my research associate at UWM Mr. Thomas Spehert, Professor Hirsch was of the opinion that the procedure developed by Thomas is sound and that it ultimately will lead to a significant reduction in computational difficulties. Professor Hirsch inserted several features in the iteration procedure to increase the convergence. A proposal for funding of the mechanism for the cooperation between Brussels, DFVLR and UWM was submitted on September 15, 1976 to the NATO Research Office in Brussels, Belgium.

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6. On the Assistance from Professor Gladwell

When I felt a need for an effective consultation regarding our numerical computational difficulties, Professor G.M.L. Gladwell, a mathematician and friend, agreed to assist. Professor Gladwell is from the University of Southampton, England, and is now at the University of Waterloo, Ontario. He has an outstanding reputation as an expert in numerical analysis. He was very eager to get involved with the project and help me out. Such consultation is actually something which I should have secured much sooner.

In the second half of August, 1975, I sent Mr. Thomas Spehert to see Professor Gladwell. He agreed that Thomas was on the right track; the procedure was to be a common procedure for both the two- and three-dimensional analyses. Professor Gladwell also gave a good set of recommendations and guidelines. Thomas accepted the challenge and engaged in a further detailed research. At the end of October, 1975, Professor Gladwell came here to discuss the progress Thomas had made and there was then a useful exchange and coordination of ideas. At the end of November, 1975, Thomas went to see Professor Gladwell again. Professor Gladwell has helped us, also, in adapting the use of curvilinear (isoparametric) finite elements for improved representation of the wing boundary. In the first week of March, 1976, Thomas went again to see Professor Gladwell and by then the iteration procedure of the oscillating wing analysis was finalized.

7. On the Collaboration under the Auspices of N.S.F.

The research collaboration under the auspices of N.S.F. between UWM, the University of Hamburg, and HSVA of Hamburg, West Germany represents the other major benefit of the NASA - research project. The objectives of the conducted research program will now be summarized.

We have been working on a more consistent and generally applicable drag resistance analysis for ships. The impetus for this work has its origin in the problem of drag resistance to motion in a dense mixture of fluid and solid particles around an actual ship in a shipping channel clogged with broken (mush) ice. The example of the conditions in the St. Marys River in the peninsula of Upper Michigan during the winter months offers a unique opportunity for an application of the developed concept.

The specific objective of the research program is to carry out systematic investigation for the development of a theoretical method for determining the portion of the total encountered resistance by an icebreaking ship moving in unbroken plate ice which is due only to the broken ice particles around the ship hull. In particular, efforts were made to develop mathematical models and computational procedures toward the solution with the three-dimensional equations for viscous flow motion. Efforts have been directed toward the analysis of viscous flow characteristics and the drag resistance to continuous steady motion of a solid body of arbitrary geometry in a dense mixture of fluid and solid particles.

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For the proper modelling of the more difficult problem of determining the flow motion at lower Reynolds numbers, we use the steady state nonlinear Navier-Stokes equations. Such a treatment is an interesting approach for constructing the numerical solution in the three-dimensional case. The equations allow for a systematic investigation. An analysis with the Navier-Stokes equations can be formulated with any slip condition at the hull surface; with either no-slip, intermediate slip, or variable slip. Iteration can be carried out either up to the prescribed percentage of the no-slip condition or with a variable function. It appears that under low Reynolds number conditions the internal viscosity of the mush ice is large enough to render a conventional boundary-layer analysis invalid. Finally, such an analysis is better able to represent the trailing vorticity in the wake than any boundary-layer approach would. See figures 3-5.

The analytical method has the potential for direct application to more efficient design of ship hulls and aircraft fuselages and for reducing the amount of presently required testing in model tanks and wind tunnels. Of special consideration affecting the research program is the demonstration test case of ship motion in a channel clogged with broken ice blocks. It is expected that the research will result in answers to questions which are of special significance to this fundamental phenomenon.

BENEFITS FROM THE NASA-PROGRAM AT OUR UNIVERSITY

1. Introduction

The University of Wisconsin-Milwaukee (UWM) appreciates the benefits which have accrued both to the NASA-research goals and to UWM from the NASA sponsored research program. The period of duration of the NASA program here has coincided with the period of significant growth of UWM. Recent years have seen a rapid increase in the number of under-graduate and graduate students as well as faculty members on the Milwaukee campus. This growth in enrollment has coincided with corresponding growth in research activities. The NASA-program has provided a strong technological orientation of these activities.

The Graduate School of UWM, for instance, has been enthusiastically encouraging this research activity of ours. Since the commencement of the project, it has been effectively supporting us in several ways; by partly paying salaries of people working on the project and by paying the salary of visiting scholars like Dr. Kiciman and Dr. Geissler to contribute to our program; by partially paying the expenses connected with presenting papers at international meetings overseas and particularly by supporting us with computer funds.

2. Contributions of the NASA-Program to our College

The College of Engineering and Applied Science is relatively new on the UWM campus since about 15 years now. It is an ECPD accredited school and it has a notable responsibility and opportunity to produce highly competent engineers. The college has provided education on Master's and Doctoral levels. The NASA-project was primarily instrumental and helpful in the process of establishing the Doctoral degree program in the college. Because of its unique nature, this research project has helped strengthen the overall research capability of the college. Above all, the project has helped enhance the national and international reputation of our college when one considers that there have been about 100 requests for our papers from the U.S. and all over the world.

There has been a sizeable aeronautically oriented industry and a well known commercial aircraft activity in the state of Wisconsin. They have provided a career destination for our graduates. Finally, this project has helped our department to gain a valuable experience in a vital branch of transportation.

3. Benefits to the Participants on the Project

The NASA-sponsored research program has been very beneficial to the participating students, faculty members, and visiting scientists. It has contributed toward their professional development. They have acquired an excellent experience with aerodynamics, numerical computational methods, applied

mathematical analysis, fluid dynamics, and hydrodynamics [46-52].

The following participated on the project:

Students; 1. Gary Driesen, now with Westinghouse Electric Company
2. Michael Kobiske, Eaton Corporation
3. Thomas Spehert, Harley-Davidson
4. Joseph Eichers, Aqua-Chem Corporation
5. Gerald Baker, McDonnell-Douglas Corp.
6. Kenneth Rademacher, Wisconsin Electric Power Co.
7. Robert Farchione, Harley-Davidson
8. Dean Kaja, professional engineer
9. Frederic Chudy, United Aircraft Corporation
10. Gary Exner, professional engineer
11. Huseyin Aksu, professional engineer
12. Perry Kirsop, presently graduate student at UWM

In addition, a good number of undergraduate students participated as part time assistants and typists, and benefited from the project in their pursuits of higher education.

The grant has also contributed toward the professional development of the participating visiting scientists:

1. Dr. M.O. Kiciman, now president, University of Ankara, Ankara, Turkey
2. Dr. H. Foersching, Aerodynamics Research Establishment, Goettingen, W. Germany
3. Dr. W. Geissler, Aerodynamics Establishment, Goettingen, W. Germany
4. Dr. C. Hirsch, University of Brussels, Brussels, Belgium
5. Dr. G.M.L. Gladwell, University of Waterloo, Waterloo, Canada

Dr. Kiciman contributed for three months in the summer of 1973 as visiting professor on the project at no expense to the project and was paid by the Graduate School of UWM. Dr. Kiciman helped in developing the optimization technique applied in our three-dimensional flow analysis. Dr. Akin Ecer is a practicing scientist in Cincinnati, Ohio.

Finally, the NASA-project contributed greatly toward the professional development of the Principal Investigator. In the past he has been repeatedly invited to present papers at international conferences and to present lectures at universities and aircraft companies on the work related to this project.

PUBLICATIONS AND REPORTS GENERATED UNDER THE GRANT

1. Bratanow, T., Ecer, A. and Kobiske, M., "Finite Element Analysis of Unsteady Incompressible Flow Around an Oscillating Obstacle of Arbitrary Shape", AIAA Journal, Vol. 11, No. 11, Nov. 1973, pp. 1471-1477; presented also as paper 73-91 at the AIAA - 11th Annual Aerospace Sciences Meeting in Washington, D.C., Jan. 10-12, 1973.

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At the University of Brussels - Belgium

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27. Hirsch, C. with Kool, P. and DeRuyck, J., "The Three-Dimensional Flow and Blade Wake in an Axial Plane Downstream of an Axial Compressor Rotor", Paper No. 78-GT-66, ASME Publication.

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There were two more graduate students supported from this project who did not complete their work: Dean Kaja, and Gary Exner.
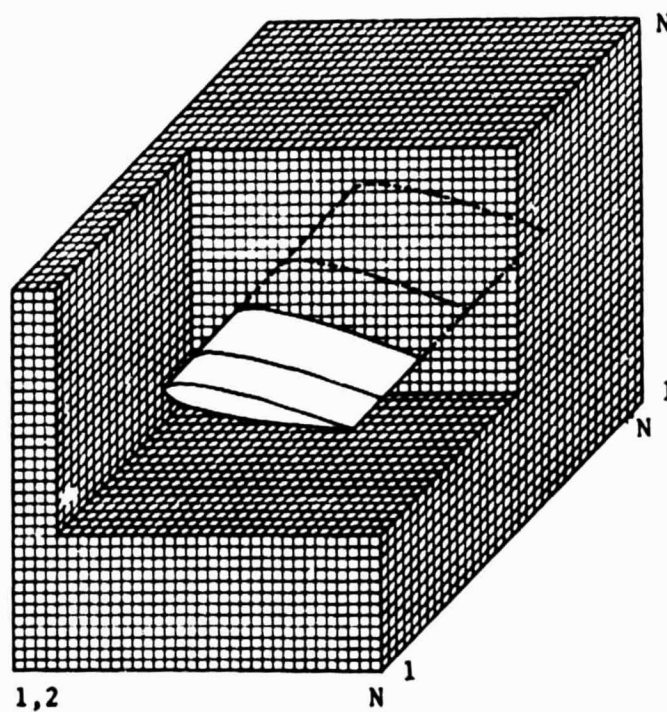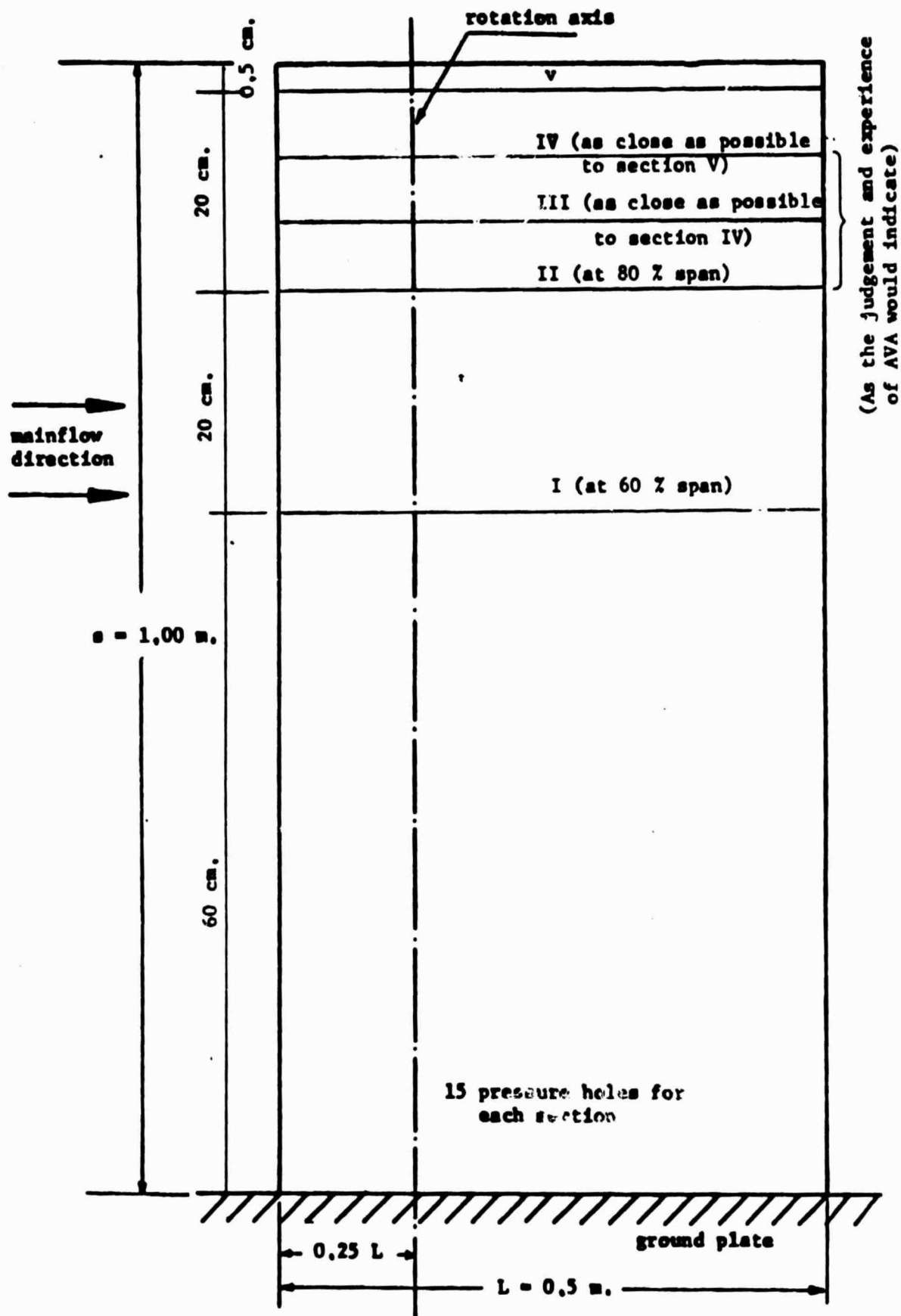
22

Fig.1. Three-dimensional finite element gridwork.

Figure 2. Arrangement of Pressure Measuring Points

NOTE: Distribution of the holes on sections I,II,III uniform in chordwise direction
distribution of the holes on sections IV and V use cosine type of distribution
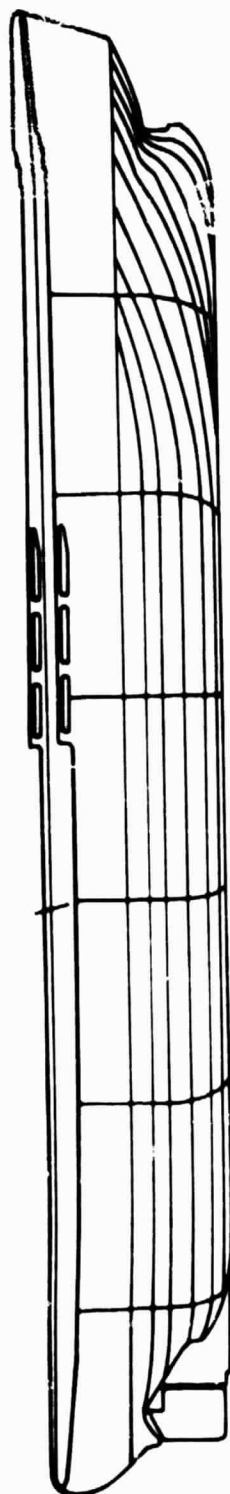(more toward the leading or trailing edge) 24

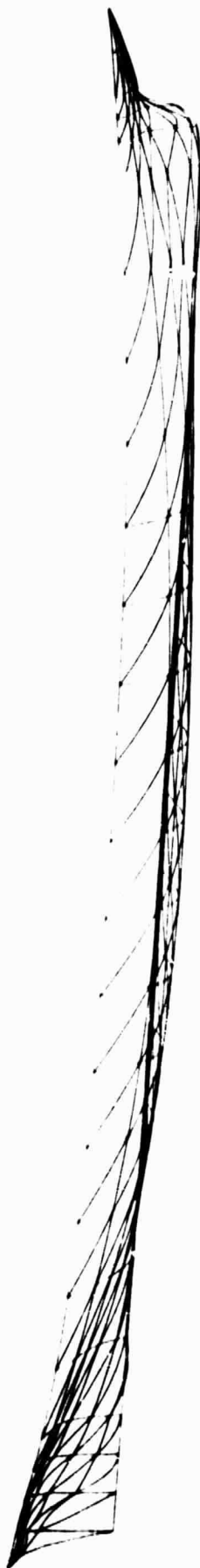Figure 3 - Schematics of Ship Hull Idealization for U.S.C.G.C. Mackinaw

Figure 4. Discretization of Entire U.S.C.G.C. MACKINAW Hull into Super-Parametric Finite-Elements - discretized portion of the hull below the design waterline.
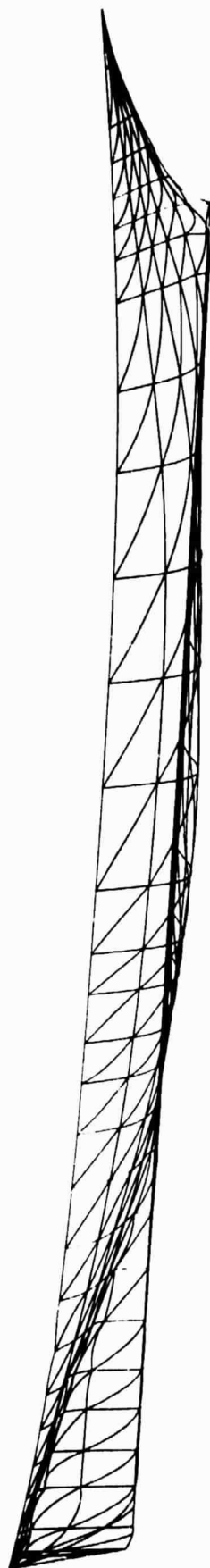
Figure 5. Discretization of Entire U.S.C.G.C. POLAR STAR Hull into Super-Parametric Finite-Elements - discretized portion of the hull below the design waterline.

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Progress Report

16. Abstract

This final report summarizes the research on the NASA-project for the period of January 2, 1971 to June 30, 1979. Wherever possible, an effort was made to provide a step-by-step chronological account and to note developments which are worth mentioning. The research was directed basically in two directions: starting with a helicopter rotor blade vibration analysis and then concentrating on two and three-dimensional analyses of unsteady incompressible viscous flow past oscillating helicopter rotor blades. As can be seen, it was necessary to cover a wide range of aspects related to the research objectives. Very often, it was necessary to piece together whatever and how little was known on the subject of the Reynolds number range. A summary is presented also of the two international research collaborations which resulted from the NASA-project: the collaboration under the auspices of NATO between the University of Wisconsin-Milwaukee (UWM), University of Brussels, Belgium, and the Aerodynamics Research Establishment (DFVLR) in Goettengen, W. Germany, and the collaboration under the auspices of the National Science Foundation between UWM and the University of Hamburg and the Ship Research Establishment in Hamburg (HSVA), W. Germany. Finally, a summary is given of the benefits from the NASA-project to UWM, the College of Engineering and Applied Science, and the participants on the project. The numbers in the brackets refer to reports, publications, and graduate student theses related to the project.

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