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BASIC HYDRODYNAMICS - FINAL REPORT

G.C. Lauchle

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Abstract: Basic hydrodynamic studies in turbomachinery and hydrodynamic drag reduction have been conducted at the Applied Research Laboratory (ARL), Penn State University under Contract Number N00014-87-K-0196 which covers FY 87 through FY 90. This research has resulted in seven refereed journal articles and several proceeding articles. In the turbomachinery thrust area, the overall objective is to develop an improved understanding of the complex three-dimensional flows typical of incompressible rotor and stator flows; this effort has been primarily computational in nature. The principal investigators for these tasks are S. Abdallah and M. L. Billet. The second thrust area is axisymmetric turbulent flow drag reduction through microbubble injection; the efforts are headed by S. Deutsch and are primarily experimental in nature. The third thrust area objective is to assess experimentally the effects of wall suction on turbulent boundary layer skin friction with possible applications to drag reduction; H. L. Petrie is the principal investigator. A fourth thrust area was initiated under the subject contract by H. L. Petrie and P. J. Morris and continues under a new contract (Number N00014-91-J-1646). This is a combined analytical and experimental study on laminar boundary layer/particle interaction physics. The significant findings of these investigations are summarized in this report.

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INTRODUCTION

Under the sponsorship of the ONR AHR Program, ARL Penn State conducts basic research in the hydrodynamics of internal turbomachinery flows and of boundary layer flows over bodies and surfaces with emphasis on drag reduction. The general goals of the turbomachinery research are to develop an improved understanding of the fluid mechanics and acoustics of low-speed turbomachines and marine propulsors, to develop computational methods to analyze such flows, and to employ this knowledge and computational methodology to the design and development of improved underwater propulsors and propulsor components. The primary goals in the drag reduction thrust area are to develop a fundamental understanding of the mechanisms that cause drag on bodies and surfaces and to suggest, implement, and demonstrate novel methods to reduce drag.

The subject basic research program evolved from a previous block-funded research program under the same title but sponsored by NAVSEA using 6.1 Navy monies. Individual projects in the two thrust areas are now determined through the standard ONR review process, so several different principal investigators have participated in the program over the performance period. In most instances, Penn State graduate assistants have been assigned to the approved projects which results in the publication of theses.

The purpose of this report is to summarize the research conducted over the period of performance, to list significant publications and reports, and to indicate any transitions of this research.

TURBOMACHINERY RESEARCH

The internal flow field of a wake adapted turbomachine is dominated by three-dimensional and unsteady effects. The three-dimensionality of the flow field is demonstrated by strong secondary flows which have been observed experimentally. The unsteadiness of the flow is due to the interaction of downstream blade rows with the wakes shed from upstream rows. The development of computational tools to accurately predict these types of flow fields is the objective in this research area. **Professor Shaaban Abdallah**, now at the University of Cincinnati, has been the principal investigator of this project.

In Abdallah, Smith, and McBride (1987), and Abdallah and Henderson (1987) incompressible blade-to-blade flow solutions for stators and rotors were obtained using an approach which combines the equations of motion into a single elliptic, second-order partial differential equation for the streamline field. This unified equation is obtained by modifying the momentum equation with a stream function that satisfies the continuity equation exactly. The equation is solved numerically through use of finite difference techniques. The method is similar to the streamline curvature method employed for many years in turbomachinery design. However, the ellipticity of the flow field is preserved and the solutions are extremely stable. Body-fitted curvilinear coordinates are generated naturally by the solutions, which means that the need for curve fitting and strong smoothing under-relaxation used in classical streamline curvature methods is eliminated. The unified equation approach allows the prediction of the stagnation streamline directly.

The pressure Poisson equation plays two distinct roles in the formulation of the incompressible Navier-Stokes equations. First, when given the velocity field as in the streamfunction-vorticity formulation, the Poisson equation is used to calculate the pressure. Second, when the pressure equation is solved iteratively with the momentum equations, the Poisson equation is used to calculate the pressure and to enforce the continuity equation. In Abdallah and Dreyer (1988) Poisson equation solutions are examined with respect to boundary conditions; in particular, the Neumann vs. Dirichlet conditions. The model problem considered is the inviscid stagnation point flow problem. The Dirichlet boundary condition is obtained by integrating the tangential component of the momentum equation along the boundary while the Neumann condition is obtained by applying the normal component of the momentum equation to the boundary. It is shown that for the Neumann condition, a solution exists only if a compatibility condition is satisfied. A consistent finite-difference procedure is developed which satisfies this requirement on non-staggered grids. In a test case, the velocity field is given from an analytical solution and the pressure is recovered from the solution of the Poisson equation. It is shown that identical results are obtained for either the Neumann or Dirichlet boundary conditions which is expected. The Dirichlet problem converges faster, however. In a second test case, the velocity field is specified from solutions of the momentum equations obtained through iterative calculations with the Poisson equation. In this case, the Neumann problem converges faster than the Dirichlet problem.

The basic findings of Abdallah and Dreyer (1988) are extended to practical turbomachinery-type flow fields in Abdallah, et al (1989) and Abdallah and Smith (1990). In the latter study, a primitive variable formulation is used for the solution of the incompressible Euler equation. That is, the pressure Poisson equation approach using non-staggered grids is demonstrated for several rotor blade geometries. Each rotor was evaluated experimentally so that validations of the numerical procedures could be attempted. Numerical and experimental data include the internal flow velocity field and exit swirl angles. The comparisons between experiment and computation are very good. In Abdallah, et al (1988) the three-dimensional rotating flow field in a stator is computed. The unsteady form of the momentum equations are solved using an upwind differencing scheme. The incompressibility condition is used to derive a Poisson equation for the pressure which is solved using a line succession overrelaxation method. The computations agree very well with experimental data obtained on a stator of the geometry considered.

Hydroacoustic Studies

In FY 87, the first year of the subject contract, a study on measuring the aerodynamically-produced pressure field on rotor and stator blades was continued from a previous FY 86 contract. Under the direction of **Dr. D. E. Thompson** the experiments were conducted in the Axial Flow Research Fan which is a highly specialized axial flow ducted fan that permits detailed blade velocity, pressure, force, and moment measurements in the presence or absence of upstream flow disturbances. Of fundamental importance in this study was the development and use of PVDF pressure sensors in a rotating frame of reference. The sensors were found to exhibit remarkable sensitivity and a wide range of frequency response. An array of these thin film sensors was positioned on a test blade and considerable data on point pressure spectra and correlation lengths obtained. The results of this investigation have yet to be published because of some major delays in the completion of the Masters thesis being prepared by the graduate student assigned to this project.

DRAG REDUCTION

Microbubble Drag Reduction

Under the direction of **Dr. Steven Deutsch**, a major effort was undertaken to demonstrate and explain the phenomenon of drag reduction on axisymmetric bodies, in which a thin layer of air is introduced into the water turbulent boundary layer. Previous work under separate ONR contracts showed that such a technique could reduce the skin friction of a flat plate by as much as 90% locally. Thus, this project was designed to provide similar results for axisymmetric flows. The project supported two graduate students; one MS and one Ph.D.

Deutsch and Castano (1986) conducted tests on a 89 mm diameter body with a blunt nose and porous plastic gas injector near the nose. The mid-body region was a floating element skin friction force balance. Tests were conducted in the 12-inch water tunnel at speeds from 5 to 17 m/s. Length Reynolds numbers were as high as 10 million. Over this range of velocities, Deutsch and Castano found that the maximum drag reduction for the axisymmetric body increased with increasing free stream speed, in opposition to the earlier flat plate results. The maximum skin friction reduction was found to be about 80%.

The differences in maximum drag reduction velocity between the flat plate and the axisymmetric body, uncovered in Deutsch and Castano (1986), were explained using the work of Pal et al. (1988) and Deutsch and Pal (1990). In the first article, additional experiments on a flat plate were conducted with particular emphasis on the plate orientation relative to the direction of buoyancy forces. When buoyancy tends to move the microbubbles closer to the test plate, more drag reduction is observed than when the plate is reversed where the bubbles tend to migrate away from the wall. These findings support the notion that microbubbles must remain in the buffer region of the boundary layer in order to be effective drag reducers. Deutsch and Pal (1990) extended the measurement set for an axisymmetric body by measuring local skin friction with an array of flush mounted hot film probes. At speeds of 10.7 m/s and above, the data indicate a circumferential gradient in skin friction, with skin friction reduction larger at the top than at the bottom of the model. The gradient was observed to get stronger as the speed is lowered or as the volume airflow rate is increased. Higher speeds tend to drive the axial location of the asymmetry farther downstream. At speeds below 10.7 m/s the flow is dominated by a double vortex structure that entrains the bubbles at the bottom and sides and transports them to the top of the model as they progress downstream. The transport of these bubbles by the vortices is the cause of the poor skin friction reduction observed on axisymmetric bodies at low speed.

A comprehensive review paper covering all aspects of microbubble drag reduction has been prepared by Merkle and Deutsch (1991) for publication in *Applied Mechanics Reviews*. This paper, which will appear in the February issue, reviews the early Soviet work along with the flat plate and axisymmetric body work conducted at Penn State and other U.S. research institutions.

Turbulent Boundary Layer Modification by Suction

The development of long streamwise oriented streaks of low momentum fluid in the near-wall region of a turbulent boundary layer and the subsequent lifting of the streaks into violent turbulent bursts is the key to the production of turbulence in the boundary layer.

Dr. Howard L. Petrie has suggested that small amounts of wall suction applied through a tailored porous surface may efficiently and substantially reduce this near-wall turbulence. The approach involves applying suction through rows of holes that are approximately 100 viscous wall units apart. This corresponds closely with the expected mean spanwise spacing between the near-wall streaks and the premise of the method is to control these streaks by removal of fluid from them and thereby stabilize the near-wall flow. The effect is somewhat analogous to the effects of riblets. The objectives were to achieve the maximum possible effect on boundary layer turbulence at low suction levels with a minimum penalty in drag.

Special suction surfaces employing microholes approximately 100 microns in diameter were fabricated by a chemical etching process. A reference surface consisting of a uniform staggered grid of holes was also fabricated. A flat plate assembly that could accept either of the two porous surfaces was assembled. The entire suction test surface was mounted on a floating drag balance for integrated skin friction force determination. The suction rate could be controlled locally on the test plate and the plate could be instrumented with miniature static pressure transducers that were mounted flush to the surface. Laser Doppler velocimeter measurements were taken for a range of suction rates for both the uniform and tailored surfaces.

The drag balance data taken with no suction indicated that the microholes acted as roughness elements and the test surfaces were transitionally rough. The effects of roughness were less pronounced on the tailored surface than the uniform surface. The tailored surface skin friction forces agreed with expected smooth surface results within the uncertainty of the measurements but the uniform surface skin friction forces were as much as 14% larger than the expected smooth surface result. This difference is due to both the geometry of the hole patterns and the difference in the number of holes needed for each pattern. The Reynolds shear stress was the turbulent stress most affected by suction with reductions as large as 55% resulting. Overall, the effects of suction on the turbulence were larger with the tailored surface than with uniform surface. Also, the increases in skin friction due to suction were less with the tailored surface than the uniform surface. It could be argued that this indicates the tailored surface approach has merit but the surface roughness effects complicate the issue. Surface pressure fluctuations were made on a limited basis. For the low levels of suction considered, no changes were observed in the power spectrum of the static pressure fluctuations on the uniform surface but these data were not taken at a suction rate that produced large reductions in the Reynolds shear stress.

A technical report detailing this work has been written and forwarded as a letter report to the scientific officer at ONR. The report will be released as an ARL technical memorandum in the near future.

Turbulent Spot Generation by Particles in a Laminar Boundary Layer

This project was initiated under the contract of the subject report and now continues under ONR Contract N00014-91-J-1646. In FY 81 through FY 86, the block program in Basic Hydrodynamics at ARL Penn State had as a major thrust drag reduction through laminar flow control. Experiments on a large underwater heated body revealed that freely suspended particles can interact with the laminar boundary layer in a destabilizing manner; see Lauchle and Gurney (1984) and Lauchle, et al (1987). Consequently, a more fundamental analytical and experimental investigation was initiated with goals directed toward identifying the physical mechanisms of turbulent spot formation due to particles in the freestream. This effort is conducted by **Dr. H. L. Petrie** and **Prof. P. J. Morris**.

Computationally, the trajectory of particles in a laminar layer are computed and this information is coupled with linear, inviscid stability analysis. Two approaches to the problem are under study: to follow the evolution of the disturbance in time, or to compute the normal modes in the frequency domain and superimpose them. In this work, a wave packet generated by an impulse disturbance causes oscillations in the flow as the packet evolves downstream. This initial disturbance is reproduced computationally by linearly combining spatially unstable modes and summing over all wavenumbers and frequencies. Details of this approach may be found in Petrie and Morris (1991).

The experimental study is conducted in a laminar flow channel along a smooth flat plate surface. Three subtasks are in process: 1) study the transition induced by fixed particles of various diameters mounted at various positions within the boundary layer, 2) examine spot generation by particles that are free to convect (roll) along the surface, 3) examine spot generation by particles that are free to fall through the boundary layer through the action of gravity. These experiments utilize flow visualization and laser doppler velocimetry for data collection. For further details on this on-going project, see Petrie and Morris (1991).

CONCLUSIONS

Fundamental hydrodynamics research has been conducted at ARL Penn State through ONR support from FY 87 through FY 90 under contract N00014-87-K-0196. Significant publications have resulted from this research and a noteworthy portion of the results have been transitioned into applied research and engineering development programs. The computational methods developed for turbomachinery flow fields have formed basic groundwork for the development of more advanced design tools. We conclude that the contributions made in this program have had significant impact on more advanced and applied programs being undertaken by the Navy and DARPA.

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