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CALIFORNIA INSTITUTE OF TECHNOLOGY

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HYDRODYNAMICS OF TURBOMACHINES

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Final Report

Submitted by
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HYDRODYNAMICS OF TURBOMACHINES

Final Report

.1 Introduction. This brief report summarizes the efforts carried out over a period of some years in the general field the fluid mechanics of turbomachines. The work began in September 1965 and (with a contract number change in 1976) has continued until January 31, 1980 at which time it was terminated. The term "turbomachines" covers many areas of application and even disciplines. The present concerns have been primarily with applications to flows of liquids in turbomachines rather than gases. Each medium has its own special problems in addition to the common basis in fluid mechanics. Liquid flows in particular are subject to cavitation when the pressure falls below the vapor pressure. Cavitation is a major element in many applications of naval hydrodynamics. Here the "turbomachine" is the propulsion system and cavitation on the components of this system, primarily the rotor or propeller, may cause intense noise, if the extent of cavitation is small, significant material erosion if there is a somewhat larger amount of cavitation, or a major performance change (loss of thrust, efficiency, etc.) when there is a large extent of cavitation. The establishment of conditions for the onset of cavitation is then an important feature in almost all naval hydrodynamic applications. Just this particular problem has been the source of much recent effort in cavitation inception research and has been a feature of some of the present work herein.

Turbomachine systems have complex three-dimensional flow systems still beyond present analytic capability. For this reason it is useful to study simpler elements such as individual hydrofoils and cascades of such hydrofoils. This has been in fact a recurring feature of much work in turbomachinery since lifting surface theory is very complex and its application to cavitating flows is not well advanced yet. Considerable attention has been directed to these kinds of problems in the present work. The intent has been to identify certain kinds of phenomena that are expected to be important in application. Where possible results are presented in a form useful for design or to help guide laboratory procedures.

The efforts of the present contract have been classified into these several groups in the next section. Some of the salient points of this work are then briefly mentioned. These together with the section on Reports and Publications form the basis of this final report.

.2 Discussion. A listing of reports and publications carried out under this effort is given in Section 3. These may be grouped into areas of study as follows.

i. Effects of cavitation on isolated hydrofoils and cascades of hydrofoils.
ii. Cascade problems in fully wetted flow.
iii. Unsteady flows.
iv. Cavitation inception.

The bulk of our work has been in catagory (i.). Here our interest has been in understanding cavitating flows past simple hydrofoils and hydrofoil cascades so that the main features of the performance change of these important applications could be understood easily. Items 1,5,8,10,15, 17,20,22,23,25 all deal with cavitating hydrofoils or hydrofoil cascades. It may be mentioned that hydrofoil cascades form a design element of pumps and turbines. More recently, supercavitating cascades have been applied to supercavitating propeller design as a direct outgrowth of No. 25. The progression of this work reflects to a great extent work in the field at that time. Linear supercavitating flow theory (developed by M. Tulin) was first applied by us to these supercavitating and partially cavitating flow configurations because it circumvented the enormous difficulties of the then exact theory of the time. The limitations of the linear theory were reviewed to a degree in Nos. 15,17,20 with a standard singular perturbation technique. But angles of attack, for example, were still limited to only a few degrees particularly for cascade flows. Furuya was subsequently able to work out a numerically stable scheme using Wu's exact non-linear free streamline theory. This has been used with great success for a wide variety of hydrofoil and hydrofoil cascade schemes and is now a preferred method for computation of these flows.

Fully wetted flows are important too; research in this area is perhaps not so important as it once was because of the great success of numerical Laplace equation solvers. There are nevertheless some interesting and subtle points connected with accelerated flow across cascades. This acceleration of the meridional flow is a common feature in many turbomachines and naval propulsion arrangements. The basic flow is not strictly two-dimensional so that two-dimensional experimental results and theories no longer apply. We have studied quasi-two dimensional flows in a large number of publications, namely, Nos. 7,9 culminating in No. 24. The results are most interesting in that the acceleration of the flow through a cascade changes the basic circulation around a given blade now (an effect to be expected) and in addition skews the symmetry of the velocity triangle. This latter effect is not at all well known in standard reference but it is apparently well known in Russian literature. The overall effect is to cause a decrease in the deviation angle for accelerating cascades proportional to the axial velocity increase.

Unsteady flows (category iii.) are common in naval hydrodynamics (propeller-wake interference, hydrofoils in waves etc.). We have been concerned with some features of unsteady (primarily) cavitating flows because of the close connection to hydrofoil problems and propulsion. This work has mainly theoretical (No. 12,16,18,21,27) but we do report some experimental work in No. 13 (supported largely by another agency of the U.S. Navy). These unsteady cavity flows have had an historical problem addressed by many workers, namely, the singular pressure caused in two-dimensional flow by a time-varying cavity volume. It is important to permit the cavity volume to vary with time in unsteady flows as this is the observed behavior but some cavity models do not do that or if they do allow other unphysical deformations of the cavity boundary to occur. This point is addressed in No. 27 to show that Tulin's original theory leads to a consistent unsteady behavior. Unsteady flows in hydraulic systems have in recent years achieved considerable attention (following at least the ideas contained in No. 16).

The remaining area (iv.) has to do with understanding the relation between the normal viscous fully wetted flow and the onset of cavitation. We were fortunate here in this context to have the opportunity to adapt an existing experimental technique, schlieren photography, to study the onset of cavitation in flows past simple bodies (No. 14). Earlier inception observations and cavity flows past two-dimensional hydrofoils had been made (No. 11) which showed strong real fluid effect scaling. Axisymmetric bodies are easier to observe. These and the schlieren technique developed in this work were to prove of great importance in subsequent studies of the mechanics of inception. This subject together with other topics in developed cavitation are touched upon in summary articles 25, 28. (Research in cavitation inception because of the large experimental support needed has generally been supported by other branches of the Navy.)

This completes this rather brief resume of the main topics of the work supported under the contract. Additional small publications are listed in the references.

Acknowledgement. Many people have contributed to the work listed in the references whose names do not appear as co-authors. Many of these were undergraduate students who helped with experiments or computations. A most important contribution however was made by the loyal and dedicated office staff headed by Mrs. Barbara Hawk whose help we would now like to gratefully acknowledge.

.3 Reports and Publications

1. "Investigations on Cavitating Hydrofoils", R.B. Wade, Ph.D. Thesis, C.I.T., 1965.

2. "Investigations of Cavitating Cascades, R.B. Wade, A.J. Acosta, Trans ASME 89, Sec. D, No. 4, pp. 693-704.

3. "Quasi Two-Dimensional Flows Through Cascades", Ph.D. Thesis by Ramani Mani, C.I.T., 1967.

4. "Note on an Airfoil in a Slightly Non-Uniform Stream" by A.J. Acosta and Ramani Mani, Applied Scientific Research 18, pp. 21-27, 1968.

5. "Linearized Theory of a Partially Cavitating Cascade of Flat Plate Hydrofoils", R.B. Wade, Applied Scientific Research 17, pp. 169-188, 1967.

6. "Quasi Two-Dimensional Flows Through a Cascade", R. Mani and A.J. Acosta, Trans ASME, J. Powers, pp. 119-128, 1968.

7. "A Method for Calculating Quasi Two-Dimensional Flow Through Cascades, C.I.T. Div. of Eng. & App. Sci., Report E-79.10, 1967.

8. "Liniarized Theory of a Partially Cavitating Plano-Convex Hydrofoil Including the Effects of Camber and Thickness", R. B. Wade, J. Ship. Res. 11, No. 1, pp. 20-27.

9. "The Effects of Axial Velocity Ratio on the Performance of Cascades", M. Wilson, A. J. Acosta, C. I. T., Div. of Eng. & App. Sci., Report E-79-11, 1969.

10. "Cavitation Effects in Turbomachinery", A. J. Acosta, Discussion of ASME Symposium, "Cavitation State of Knowledge", 1969.

11. "Water Tunnel Investigations of Scale Effects in Cavitation Detachment from Smooth Bodies and Characteristics of Flow Past a Bi-Convex Hydrofoil", V. H. Arakeri, C. I. T., Div. of Eng. & App. Sci., Report E-79A.12, 1971.

12. "The Wall Effect for Unsteady Choked Supercavitating Flows", J. H. Kim, C. I. T, Div. of Eng. & App. Sci., Report E-79A.13, 1971.

13. "Experimental Investigation of Non-Steady Forces of Hydrofoils Oscillating in Heave", A. J. Acosta and R. K. DeLong, I. U. T. A. M. Symposium on High Speed Flow, Leningrad, 1971.

14. "Water Tunnel Observations of Laminar Boundary Layer Separation Using Schlieran Technique", V. H. Arakeri, ASME Polyphase Flow Forum, 1972.

15. "Supercavitating Hydrofoils with Rounded Noses", O. Furuya, ASME Polyphase Flow Forum, 1972.

16. "Analysis of Unsteady Cavity in Internal Flows", J. H. Kim, ASME Polyphase Flow Forum, 1972.

17. "A note on the Calculation of Hydrofoils with Rounded Noses", O. Furuya, 2nd International J. S. M. E. Symposium on Fluid Mechanics, Tokyo, 1972; also Trans ASME 95, Series 1, No. 2.

18. "The Wall Effect for Unsteady Choked Supercavitating Flow", J. H. Kim, J. Ship. Res. 16, No. 4, 1972.

19. "Hydrofoils and Hydrofoil Craft", A. J. Acosta, Ann. Rev. Fluid Mech. 5, 1972.

20. "Singular Perturbation Method on Calculations of Supercavitating Hydrofoils with Rounded Noses", O. Furuya, C. I. T., Ph. D. Thesis, 1972, also C. I. T. Div. of Eng. & App. Sci, Report E-79A-14.

21. "The Unsteady Cavity in Internal Flows", J. H. Kim, C. I. T., Ph. D. Thesis, 1971.

22. "Numerical Computations of Supercavitating Hydrofoils of Parabolic Shape with Wu and Wang's Exact Method", C. I. T. Div. of Eng. & App. Sci, Report E-79A.15, 1973.

23. "Supercavitating Linear Cascades with Rounded Noses", O. Furuya, Trans ASME J. Fl. Eng. 96, Ser. 1, No. 1, pp. 35-43, 1974.

24. "A Note on the Influence of Axial Velocity Ratio on Cascade Performance", M.B. Wilson, R. Mani, A.J. Acosta, in Fluid Mechanics, Acoustics and Design of Turbomachinery, B. Lakshminarayana, W. Britsch, W.S. Gearhart (eds.), pp. 101-133, 1974 (U.S. Govt. Printing Office, Wash. D.C., stock No. 3300-00524).

25. "Cavitation and Fluid Machinery", Invited address Cavitation Conference, Edinburgh (Institution of Mechanical Engineers) 1974.

26. "Exact Supercavitating Cascade Theory", O. Furuya, ASME Symposium "Cavity Flows", W. Morgan, B. Parkin, eds., 1975. (This paper received the ASME Robert T. Knapp Award for 1976).

27. "A Brief Note on Unsteady Supercavitating Flows", A.J. Acosta, O. Furuya, J. Ship. Res. 23, No. 2, 1979, pp. 85-88.

28. "Cavitation Inception and Internal Flows with Cavitation", A.J. Acosta, 4th David W. Taylor Lecture, DTNSRDC-79/011, Oct. 1979.

29. "A Note on the Determination of Cavitation Nuclei Distributions by Holography", E.M. Gates, J. Bacon, J. Ship. Res. 22, No. 1, March 1978, pp. 29-31.

30. "Unsteady Effects in Flow Rate Measurement at the Entrance of a Pipe", A.J. Acosta, Trans ASME, J. Fl. Eng. 98, Lec. 7, No. 3, pp. 562-563.

31. "A Note on Three-Dimensional Supercavitating Hydrofoils", A.J. Acosta, O. Furuya, J. Ship. Res. 19, No. 3, Sept. 1975, pp. 164-165.

32. "Dynamic Forces on a Whirling Centrifugal Rotor", D. Chamieh, A.J. Acosta, 6th Conf. on Fluid Machinery, (Budapest), 1979.

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