Final Progress Report for

NASA Grant 1262

I. Summary of Progress

The support provided by this grant has contributed to the development of a vortex-lattice method that can accurately model general unsteady lifting and nonlifting flows and to the partial development of a continuous-vorticity panel method. Applications of these methods to lifting surfaces are not restricted by planform, camber, twist, or angle of attack as long as separation occurs only along sharp edges and vortex-bursting does not occur near the lifting surface.

The initial goal under this support was to develop a method for modelling steady lifting flows over highly swept delta wings at large incidence. The experimental observations of Peckham[1] and Marsden, Simpson, and Rainbird,[2] among others, showed the aerodynamic characteristics to be independent of Reynolds number, suggesting an inviscid model would be adequate. After making an exhaustive review of literature that included the innovative, but inadequate, attempts of Brown and Michael[3] and Mangler and Smith,[4] we decided to attempt development of a vortex-lattice method. To demonstrate the feasibility of using such a method, we modified an existing code developed by Giesing, Kalman, and Rodden.[5] We added a system of vortex lines to simulate the leading-edge wake. This work is described in the M.S. thesis of S. A. Maddox[6] and in the Journal of Aircraft.[7] The coefficients predicted by the modified code were in good agreement with experimental data. And it was found that in a Trefftz plane the centroid of the circulations in the leading-edge vortex system nearly coincided with the experimentally determined

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core of the leading-edge wake, indicating that the geometry of the wake is adequately represented.

Though these results were generally in good agreement with the experimental data, the scheme of Giesing et al. for placing elements on the wing was not well-suited for low-aspect delta wings. Moreover, the geometry of the wake attached to the trailing edge had been ignored. Consequently, several entire new codes were developed. These treated delta, rectangular, and swept wings. This work was reported in the Ph.D. thesis of O. A. Kandil[8] and in the Journal of Aircraft.[9] Subsequently, the capability of modelling steady aerodynamic interference was demonstrated by Kandil, Mook, and Nayfeh.[10,11]

The success of the method for steady flows led us to attempt development of a general unsteady, vortex-lattice method. The first progress in this area was described in the M.S. thesis of E. H. Atta[12] and in references 13 and 14. Originally, the problem was posed in terms of a ground-fixed reference frame, a scheme that proved to be awkward. Subsequently the method was modified so that the problem was posed in terms of a body-fixed reference frame. This progress was reported in the M.S. thesis of D. F. Thrasher,[15] and in reference 16 flows past rectangular wings were treated. Kandil, Atta, and Nayfeh[17] used the body-fixed formulation and treated flows past delta wings.

Subsequently, the method was considerably refined in the M.S. thesis of P. Konstadinopoulos.[18] The final version has been used to treat flows past helicopter rotors, rolling and pitching wings, with, and without, flaps. A manuscript has been submitted to the AIAA and is now under review.

In an attempt to treat small oscillations of wings about arbitrary angles of incidence, Nayfeh, Mook, and Yen used perturbation theory to obtain an easily solved linear problem for the real and imaginary parts of the fluctuating loads. This work was reported in reference 19. It was found, however, that the general method is just as efficient at treating this problem. The results obtained by the general method agreed with those obtained by the perturbation method.

The method was then extended to treat bodies and wing-body combinations. Progress was reported in the M.S. thesis of K. R. Asfar,[20] in the Ph.D. thesis of E. H. Atta[21] and in references 22 and 23.

The next and final effort under this grant is being directed toward the development of a continuous-vorticity panel method. With this method the strong, undesirable algebraic singularities associated with the Biot-Savart law are removed. However, continuous panels lead to a noticeable increase in complexity and place more demands on the capabilities of the computer and the programmer; the price is high. Progress in this area was recently reported in the Ph.D. thesis of A. Yen[24] and in reference 25. Continuous, triangular panels of vorticity were used to model a delta wing and its leading-edge and trailing-edge wakes, and to model a rectangular wing and its wing-tip vortex systems. The results for total loads are in excellent agreement with previous solutions and experimental data. The calculated vorticity field lines are realistic, and most importantly, the flow field is nearly devoid of singularities. When the continuous panels become tightly rolled in the wake, they are merged into a concentrated vortex core. The locations and strength of the entire wake, including the vortex core formed by the merger, are obtained as part of the solutions.

More recently, M. Kim has used the continuous-panel method (now using both sources and vorticity for comparisons of complexity, accuracy, etc.) to obtain solutions for flows around three-dimensional nonlifting bodies. These preliminary results agree with exact solutions and other solutions obtained numerically by the Douglass-Neumann program. A two-dimensional, thick airfoil has recently been treated, and preliminary designs of computer codes for general unsteady flows over airfoils and thick, three-dimensional wings have been completed. this work will be contained in Mr. Kim's doctoral dissertation.

II. Summary of Graduate Students Receiving Support

1. S. A. Maddox, M.S. 1973, after graduation worked several years for Lockheed, and currently is an attorney in the State of Washington.
2. O. A. Kandil, Ph.D. 1974, after graduation remained at VPI as an assistant professor, and currently is an associate professor at Old Dominion University.
3. E. H. Atta, M.S. 1976 and Ph.D. 1978, has worked at Lockheed Marietta since graduation, recently spent a year at NASA-Ames, and currently is doing research in transonic flows.
4. S. G. Kelley, M.S. 1978, systematically examined the influence of panel shape, size, etc. on the accuracy of the vortex-lattice method, and currently is an assistant professor at University of Notre Dame.
5. K. R. Asfar, M.S. 1978, is currently an assistant professor at Yarmouk University, Irbid, Jordan.

6. D. F. Thrasher, M.S. 1979, is currently completing his Ph.D. while working at the David Taylor Naval Ship Research and Development Center, and is applying the vortex-lattice method to model separated flows past submarines making turns.
7. P. Konstadinopoulos, M.S. 1981, is currently completing his Ph.D. requirements.
8. A. Yen, Ph.D. 1982, is currently working for General Motors. (Due to problems with citizenship, security, etc. Dr. Yen had difficulty finding employment in the aerospace industry.)
9. M. Kim will complete his Ph.D. in 1983.

III. Applications of the Method Outside the Aerospace Community

D. Thrasher is applying the technique to treat submarines, eventually hoping to obtain loads on the hull, sail and diving planes during a maneuver.

D. F. Greely, in a recent Ph.D. thesis at MIT*, used the vortex-lattice method, giving reference to publications cited here, to model the flow through the propeller of a ship, finding excellent agreement with experimental data for thrust and torque.

IV. Acknowledgement

We take this opportunity to express our appreciation and gratitude to NASA for supporting the research described above. A special word is due Dr. E. C. Yates, the grant monitor; his support and contributions made through numerous technical discussions are gratefully acknowledged.

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*"Marine Propeller Blade Tip Flows," Ph.D. Thesis, Dept. Ocean Engineering, Massachusetts Institute of Technology, January 1982.

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