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BIBLIOGRAPHY ON TECHNIQUES FOR SOLVING PARTIAL DIFFERENTIAL EQUATIONS BY HYBRID COMPUTATION AND OTHER METHODS

By David L. Finn

Prepared for
George C. Marshall Space Flight Center
Huntsville, Alabama

Contract No. NAS8-2473

(Development of New Methods and
Applications of Analog Computation)

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ABSTRACT

References in this bibliography are related to the numerical solution of partial differential equations. The references are listed under three headings: Hybrid Computer Methods, Analog Computer Methods, and General Methods. Brief comments are given for most of the references on Hybrid Computer Methods.

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I. INTRODUCTION

This bibliography lists references related to the numerical solution of partial differential equations. References are listed under three headings: Hybrid Computer Methods, Analog Computer Methods, and General Methods. The primary objective of the literature search on which this bibliography is based was the finding of papers related to the solution of partial differential equations by hybrid computation techniques. References on analog computer methods and general methods are included because hybrid techniques necessarily represent an integration of analog and digital methods utilized within the framework of general numerical analysis.

Brief comments are included for most of the references listed under the Hybrid Computation Methods heading.

Most of the references listed in this bibliography are concerned with the solution of partial differential equations of the types classified by mathematicians as elliptic, parabolic, and hyperbolic. These three classifications include most of the partial differential equations that are of importance in scientific and engineering problems.

The elliptic equation classification includes as its most important members the equations of Laplace and Poisson. In general, these equations describe equilibrium processes. Laplace's equation describes systems that do not contain internal sources. Poisson's equation describes systems in which sources are present.

Laplace's equation characterizes free space potential fields in electrostatics, magnetostatics, and gravitation. It also characterizes steady-state heat transfer in a homogeneous, isotropic medium, and the stationary flow of homogeneous, incompressible fluids.

Poisson's equation characterizes the same type phenomena as Laplace's equation except that, as was mentioned previously, it is applicable in regions containing sources.

The class of parabolic partial differential equations contains the diffusion equation. The diffusion equation characterizes equilization processes. This equation describes non-equilibrium heat-transfer fields. It also characterizes diffusion processes that involve the equilization of material particles or electric charges.

The most widely occuring hyperbolic partial differential equation is the wave equation. This equation describes wave motion in lossless systems and, in general, characterizes oscillating processes. It governs the behavior of lossless transmission lines, the adiabatic flow of a compressible fluid, and the undamped vibration of strings and thin elastic membranes.

II. HYBRID COMPUTER REFERENCES

This chapter gives an alphabetical listing of references pertaining to the solution of partial differential equations using hybrid computers. A brief summary is included for each reference.

1. Allen, P. H. G., and D. J. Allan, "The Solution of a Complex Thermal Problem by Hybrid Computation," Fourth International Analogue Computation Meetings, Brighton, 14-18 September, 1964, Actes Proceedings, page 500.

This paper considers the analysis of the thermal system of a layer-type transformer winding. The analysis, using a resistance network analogue with nodal currents calculated by a digital computer, is described.

2. Ashley, J. R., "Iterative Integration of Laplace's Equation Within Symmetric Boundaries," Simulation, Vol. 9, No. 2, August, 1967, page 60.

A solution of Laplace's equation in two dimensions is discussed. In the computation system, a technique is effected in which the analog integrators are utilized in two distinct groups. When one group of integrators is operating the second group is placed in "hold" and vice versa.

3. Bryant, L. T., L. W. Amiot, and R. P. Stein, "A Hybrid Computer Solution of the Co-Current Flow Heat Exchanger Sturm-Liouville Problem," AFIPS Proceedings, Vol. 29, 1966 Fall Joint Computer Conference, page 759.

This paper discusses the solution by hybrid computation of the boundary value problems associated with the analysis of a co-current laminar flow double-pipe heat exchanger.

4. Carling, L. N., "A Study of the Solution of an Initial-Value Problem with a Hybrid Computer," Computer Journal, Vol. 7, April, 1964, Page 40.

This paper looks into the possibility of the use of a hybrid computer for the solution of a particular type of initial-value problem involving partial differential equations: namely, reactor fault studies on a single channel in the flattened zone of a nuclear reactor. Two methods of solution that could

be used on a hybrid computer are assessed and compared with corresponding methods that would be used on a digital computer.

5. Carlson, A., "Hybrid Simulation of a Control System for a Tubular Chemical Reactor," EAI Education and Training Memo No. 65-2, Electronics Associates, Inc., Princeton, New Jersey, January, 1965.

This report describes the transient simulation of a tubular chemical reactor, its product separator, and its control system.

6. Chan, Shu-Kwan, "A Study on Certain Hybrid Techniques for the Solution of the Heat Equations," MIT Electronic Systems Lab., DSR 9128, Memo 11, Dec. 1965.

7. Electronic Associates, Inc., "Analog and Hybrid Computers in the Solution of Partial Differential Equations," Electronic Associates, Inc., Princeton, N. J., 1966.

This is a collection of six technical reports on the subject of applications of analog and hybrid computers in the solution of partial differential equations.

8. Elzas, M., "An Iterative Hybrid Computing Method for the Solution of Boundary Value Problems," Fourth International Analogue Computation Meetings, Brighton, 14-18 September, 1964, Actes Proceedings, page 166.

This paper considers the use of methods of successive approximations in the solution of boundary value problems of ordinary differential equations and partial differential equations.

9. Fadden, E. J., "Determination of the Normal Modes of a Two-Point Boundary Value Problem," Annales de l'Association Internationale pour le Calcul Analogique, April, 1965, page 92.

Many two-point boundary value problems are included in the class of problems for which trial and error techniques must be used in obtaining solutions.

Searching operations for solution of these problems can be performed automatically on a hybrid computer. This paper discusses the use of a hybrid computer for the determination of the first N normal modes of a one-dimensional heat flow problem.

10. Fadden, E. J., "Hybrid Computer Solution of Two-Point Boundary Value Problems," Applied Dynamics, Inc., Ann Arbor, Michigan, paper presented at 55th National Meeting, American Institute of Chemical Engineers, February, 1965.

In this paper an iterative procedure is devised for the solution of a two-point boundary value problem involving one-dimensional flow of heat in a slab. A computer for implementing the procedure is described. Numerical results obtained in the solution of this problem are presented.

11. Foreau, A. E., "Etude di la Stabilite et de la Precision Dans la Resolution d'Equations aux Derivees Partielles par Calcul Hybrid Analogique et Logique," International Analogue Computation Meetings, Brighton, 14-18 September, 1964, Actes Proceedings, page 129.

12. Frank, A., and L. Lapidus, "Hybrid Simulation of Chemical Engineering Systems," Chemical Engineering Progress, Vol. 62, No. 6, June, 1966, page 66.

A discussion is given of the feasibility of using hybrid computation in three different classes of problems. These include initial and boundary-value problems involving ordinary differential equations and initial-value problems involving partial differential equations. These problems are all nonlinear and are of interest to chemical engineers. The problems include the analysis of two lumped-parameter systems and one distributed parameter system.

13. Handler, H. "High-Speed Monte Carlo Technique for Hybrid-Computer Solution of Partial Differential Equations," Ph.D. Thesis, University of Arizona, 1967.

This thesis discusses a hybrid computer implementation of the Monte Carlo Technique of solution of elliptic and parabolic partial differential equations. The hybrid computer is capable of taking statistics over 1,000 two or three-dimensional random walks each second. The Monte Carlo method has been extended

to a wide class of boundary conditions especially applicable to heat-conduction, diffusion problems.

14. Handler, H. "Monte Carlo Solution of Partial Differential Equations Using a Hybrid Computer," IEEE Transactions on Electronic Computers, Vol. EC-16, No. 5, October, 1967, page 603.

The application of a hybrid computer to the solution of elliptic and parabolic partial differential equations is discussed. The exceptional computing speed and flexible digital control of the computing system permit direct plotting of partial differential equation solutions.

15. Hanawalt, A. J. and E. H. Hochman, "A Hybrid Computer Simulation of Ablating Bodies with Emphasis on Shape Change," Electronic Associates, Inc., Princeton, N. J., presented at the IFIP Congress, May 25, 1965.

A hybrid simulation of an ablating nose cone is discussed. This results in the provision of a time history of the ablating body shape.

16. Howe, R. M. and S. K. Hsu, "Preliminary Investigation of a Hybrid Method for Solving Partial Differential Equations," Applied Dynamics, Inc., Ann Arbor, Michigan, October, 1967.

This report summarizes the results of a preliminary investigation of the use of a hybrid computer technique that involves a continuous-time, discrete-space method for the solution of partial differential equations. A combined parallel-serial computation approach is used in which the digital computer is employed primarily for function storage and playback.

17. Karplus, W. J., "A Hybrid Computer Technique for Treating Nonlinear Partial Differential Equations," IEEE Transactions on Electronic Computers, October, 1964, page 597.

This paper describes application of a system that includes a small digital computer connected in a closed loop with a network of analog elements. The analog network consists of an array of inexpensive node modules, one for each grid point in space. The analog unit serves as a subroutine that solves a

system of difference equations whenever this solution is required by the digital program. This technique has been developed to take advantage of the fact that an analog computer, by virtue of parallel mode operation, generates solutions of simultaneous algebraic equations almost instantaneously regardless of the number of equations involved.

18. Karplus, W. J., "Analog Subroutine for Digital Computer Programs," Simulation, Vol. 4, No. 9, March, 1965, page 145.

A brief description is given of a hybrid computer system in which the analog devices act as major subroutines for the digital computer and carry out all the mathematical steps required in a specific computational task. These analog subroutines are particularly effective when a time-consuming loop in the digital flow chart can be replaced by a single "pass" through an analog system. A brief discussion is given on the application of the hybrid system to the solution of partial differential equations.

19. Karplus, W. J., "Error Analysis of Hybrid Solutions of Partial Differential Equations," Annales de l'Association pour le Calcul Analogique, No. 1, January, 1967, page 34.

This item in the correspondence section of the Annales briefly summarizes the main ideas of a talk by Dr. Karplus scheduled for presentation at a panel session of the Fall Joint Computer Conference in 1966.

20. Korn, G. A. and T. M. Korn, "Electronic Analog and Hybrid Computers, McGraw Hill Book Co., New York, 1964, Section 12-17 - Section 12-23.

21. Landauer, J. P., "Spectrum of Applications for a Modern Hybrid Computer," Computer Applications Research Department, Electronic Associates, Inc., Princeton, N. J., April, 1966.

Several typical hybrid computer applications are discussed briefly including the hybrid solution of a set of partial differential equations used in the

simulation of a tubular reactor. The solution employs the method of characteristics whereby the original partial differential equations are reduced to ordinary differential equations.

22. Little, W. D., "Hybrid Computer Solutions of Partial Differential Equations by Monte Carlo Methods," AFIPS Proceedings, Vol. 29, 1966 Fall Joint Computer Conference, page 181.

A discussion is given on the application of a hybrid computer to the solution of partial differential equations by the Monte Carlo method. The random walks required in the solution were implemented on a conventional analog computer requiring about five minutes for a thousand random walks. A digital computer controlled the analog computer operation.

23. Little, W. D., "Hybrid Computer Solutions of Partial Differential Equations by the Monte Carlo Method," Ph.D. Thesis, University of British Columbia, British Columbia, Canada, 1965.

24. Little, W. D. and A. C. Soudack, "On Boundary Generation and Detection in Random Walk Problems," Simulation, Vol. 7, No. 2, August, 1966, page 63.

In the Monte Carlo solution of boundary value problems associated with partial differential equations, both the boundaries and the boundary conditions must be generated and detected. This note discusses techniques for the generation and detection of these boundaries and boundary conditions.

25. Max, S. "A Preliminary Investigation of the Analog-Digital Solution of Partial Differential Equations," MIT Electronic Systems Lab., R-108, March, 1961.

26. Mitchell, E. E. L., "Hybrid Techniques for Solution of Partial Differential Equations," SAG Report No. 19, Electronic Associates, Inc., Princeton, N. J., October, 1963.

This report examines some aspects of the mathematical stability of solutions for linear transport and diffusion equations. Also considered is the effect of finite analog accuracy on time differences together with conditions for iterative satisfaction of boundary value problems.

27. Mororey, Richard, "Solution of Laplace's Equation in Two Dimensions on a Hybrid Computer," MIT Electronic Systems Lab., DSR 9128-WP-14, December 25, 1963.

28. Paker, Y., "An Automated Direct Analog Computer - ADAC," Ph.D. Thesis, Columbia University, May, 1965.

29. Paker, Y. and S. H. Vnger, "ADAC - A Programmed Direct Analog Computer," Annales de l'Association Internationale pour le Calcul Analogique, No. 1, January, 1967, page 16.

This paper outlines the preliminary design for a hybrid computer utilizing both digital and analog techniques. In essence, it consists of a small stored program digital computer that controls and interacts with a large network of analog elements. The basic network element, corresponding to a single node, consists of a capacitor and two resistors. However, other elements, including active ones, may be used. This computer was conceived of primarily with complex heat flow problems in mind, but it is expected that it will be useful for many other kinds of problems.

30. Soudack, A. C., and W. D. Little, "An Economical Hybridizing Scheme for Applying Monte Carlo Methods to the Solution of Partial Differential Equations," Simulation, Vol. 5, No. 1, July, 1956, page 9.

This presentation considers the solution of partial differential equations by the use of a hybrid system in which random walks are accomplished and boundary conditions established on the analog computer and the walk averaging and control is done with the digital computer.

31. Vichnevetsky, R., "Method of Characteristics in the Hybrid Solution of First Order Partial Differential Equations," ECC Report No. 60, Electronic Associates, Inc., Princeton, N. J., July, 1962.

The utilization of hybrid computation is discussed in the application of the method of characteristics to the solution of first order partial differential equations.

32. Wall, Ian, "A Study of Analog-Digital Procedures for the Solution of a Diffusion Equation Problem," MIT Electronic Systems Lab., DSR 9128, Memo 2, Sept. 15, 1962.

33. Witsenhausen, Hans, "Development of a Program for the Hybrid Simulation of a Tubular Reactor," Annales de l'Association pour le Calcul Analogique, April, 1964, page 112.

A discussion is given of the conceptual details of the hybrid solution of equations arising in the study of the transient behavior of a chemical tubular reactor under various conditions when an optimizing controller is installed. Solutions are based on a function iteration scheme that utilizes digital function storage to reduce the amount of analog non-linear equipment required through the time-sharing of analog operations.

34. Witsenhausen, H. S., "Hybrid Solution of Initial Value Problems for Partial Differential Equations," MS Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, Sept., 1964.

35. Witsenhausen, H., "Hybrid Solutions of Initial Value Problems for Partial Differential Equations," Proceedings, IFIPS Congress, New York, May, 1965.

III. ANALOG COMPUTER REFERENCES

This chapter gives an alphabetical listing of references pertaining to the solution of partial differential equations using analog computers.

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2. Bayly, J. G. and R. M. Pearce, "Method of Studying Multi-Region Reactors with an Analog Computer," Nuclear Science and Engineering, 2, 352-362 (1957).

3. Bingulac, S., with L. Radanovic, M. Matansek, and B. Lazarevic, "Elimination of Undesired Sensitivity in the Analog Solution of Diffusion Equations," International Analogue Computation Meetings, Brighton, 14-18 September, 1964, Actes Proceedings, pp. 146-149.

4. Brancker, A. V., "Heat Flow and Simulation," Petroleum, July, 1956, pp. 244-250.

5. Brunner, Walter, "An Iteration Procedure for Parametric Model Building and Boundary Value Problems," Proceedings of the Western Joint Computer Conference, Los Angeles, May 9-11, 1961, pp. 519-525.

6. Brunner, W., "Serial Solution of Partial Differential Equations on an Electronic Analog Computer," PCC Report 180, Electronic Associates, Inc., Princeton, New Jersey, 1961.

7. Buist, W. S. and C. J. Rallis, "A 100-node Liebmann Analogue," NASA Report N66-14068, August, 1965.

8. Chandhuri, A. K., "Solution of Boundary Value Problems Using Electronic Differential Analyser," Journal of Science Engineering Research, Vol. 3, 1959, pp. 393-408.

9. Cheng, K. C., "Analog Solution of Laminar Heat Transfer in Noncircular Ducts by Moire Method and Point Matching", Journal of Heat Transfer, (ASME), May, 1966, p. 175.

10. Childs, D., "Modal Simulation of Undirectional Fluid Dynamics (water hammer)", Simulation, Vol. 5, No. 3, September, 1965, pp. 180-189.

11. Chuang, K., with L. S. Kazda and T. Windeknecht, "A Stochastic Method of Solving Partial Differential Equations Using an Electronic Analog Computer", Project Michigan Report 2900-91-T, Willow Run Labs., Ann Arbor, Michigan, June, 1960.

12. Corcos, G. M., with R. M. Howe, L. L. Ranch, and J. R. Sellars, "Application of the Electronic Differential Analyzer to Eignevalue Problems", Project Cyclone Symposium II on Simulation and Computing Techniques, Part 2, Reeves Instrument Corporation (under sponsorship of the U.S. Navy Special Devices Center and the U.S. Navy Bureau of Aeronautics), New York, April 28-May 2, 1952.

13. Davies, W. D. T., "Exact Simulation of a Simple Tubular Heat Exchanger", Control, Vol. 10, 1966, September, pp. 469-471.

14. DeGreef, J. F., "Cylindrical Thermal Equations for the Analog Computer", Annales de l'Association Internationale pour le Calcul Analogique, Vol. 9, No. 4, October, 1967, page 195.

15. Dekkers, D. with J. Devooght, and J. R. Thiry, "Solution Analogique de Quelques Problèmes de Diffusion de Neutrons", 2 Journees Internationales de Calcul Analogique, Strassbourg, 1958.

16. Dekler, L., "Optimizing a Diffusion Problem with the Help of a High Speed Analogue Computer", Proceedings of the Fourth International Analogue Computation Meetings, Brighton, September 14-18, 1964, page 527.

17. Dickson, A. J., A. M. Patterson, and C. J. Rallis, "Use of a Modified Liebmann Analogue for the Solution of Heat Flow Problems in Deep Mines Including Methods of Estimating Discretization Errors", Proceedings of the Fourth International Analogue Computation Meetings, Brighton, September 14-18, 1964, page 497.

18. Dorri, M. K., "Approximate Solution on an Analog Computer of Certain Partial Differential Equations of Heat Exchange", Automation and Remote Control, Vol. 27, No. 8, August, 1966, page 1445.

19. Edwards, K. H., "Design and Application of a Stochastic Analogue Computer", Proceedings of the Institute of Electrical Engineers, May, 1967, page 679.

20. Ellis, D. R., "Analog Solution of the Diffusion Equation with Continuous Space and Discrete Time Variable", Master's Thesis, Department of Electrical Engineering, Massachusetts Institute of Technology, August, 1963.

21. Fallside, F., "Network Analogue for a Flexible Hull Wave Equation". Proceedings of the Fourth International Analogue Computation Meetings, Brighton, September 14-18, 1964, Page 536.

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