CONTINUUM ELECTROMECHANICS GROUP

Department of Electrical Engineering

Massachusetts Institute of Technology

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Final Report

ational Aeronautics and Space Administration

for

Research in Electrohydrodynamics

Grant NGL-22-009-014#6 June 1, 1973

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I. INTRODUCTION

This report summarizes work on NASA Grant NGL-22-009-014#6 (previously NsG 368). By means of references to formal publications and material currently in publication it is possible to give an overview of activities and developments.

II. Classification of Work

Research can be placed in one of five catagories taken up in the following sub-sections.

A. Basic Electrohydrodynamics

Electrohydrodynamics can be regarded as a branch of fluid mechanics concerned with electrical force effects. It can also be considered that part of electrodynamics involved with the influence of moving media on fields. Actually it is both of these areas combined, since many of the most interesting problems in electrohydrodynamics involve both an affect of the fluid motion on the fields and an influence of the fields on the motion. The word "electrohydrodynamics" is relatively new; the area it represents is not. The related literature is as venerable as that for the subject of electricity itself. Even more to generate an engineering interest there is no need to emphasize the great technological promise of the area, since applications already form the basis for major industries.

The center of attention in almost any discussion of this subject is the lack of reproducability in experiments and the inadequacies of theoretical models. Electrostatic effects in fluids are known for their vagaries; often they are so extremely dependent on electrical conduction that investigators are discouraged from carefully relating analytical models and simple experiments. Yet the foundations of fluid mechanics are formed from work that relates carefully designed experiments to analytical models. Under the first and primary classification of work completed under this NASA grant has been basic work in electrohydrodynamics with this objective.

Articles which have been published in the formal literature summarize much of what we have done on basic electrohydrodynamics. These are as follows:

1. Devitt, E. B. and Melcher, J. R., "Surface Electrohydrodynamics with High Frequency Fields", Physics of Fluids, 8, #6, June, 1965.

2. Crowley, J. M., "Growth and Excitation of Electrohydrodynamic Surface Waves", Phys. Fluids 8, 1668 (1965).

3. Melcher, J. R., "Traveling-Wave-Induced Electroconvection", Physics of Fluids, 9, #8, August 1966, pp. 1548-1555.

4. Melcher, J. R. , "Charge Relaxation on a Moving Liquid Interface", Physics of Fluids, 10, #2, February, 1967, pp. 325-332.

5. Melcher, J. R. and Firebaugh, M. S., "Traveling-Wave Bulk Electroconvection Induced Across a Temperature Gradient", Physics of Fluids, 10, #6, June 1967, pp. 1178-1185.

6. Smith, C. V. and Melcher, J. R., "An Electrohydrodynamically Induced, Spatially Periodic Cellular Stokes Flow", Physics of Fluids, 10, #11, November 1967, pp. 2315-2322.

7. Ketterer, F. D. and Melcher, J . R., "Electromechanical Costreaming and Counterstreaming Instabilities", Physics of Fluids, 11, #10, October, 1968, pp. 2179-2191.

8. Melcher, J. R., and Schwarz, W. J., Jr., "Interfacial Relaxation Overstability in a Tangential Electric Field", Physics of Fluids, 11, #12, December, 1968, pp. 2604 - 2616.

9. Ketterer, F. D., and Melcher, J. R., "Electromechanical Stream-Structure Instabilities", Physics of Fluids, 12, #1, January 1969, pp. 109-119.

10. Turnbull, R. J., and Melcher, J. R., "Electrohydrodynamic Rayleigh-Taylor Bulk Instability", Physics of Fluids, 12, #6, June, 1969, pp. 1160-1166.

11. Calvert, R. T., and Melcher, J. R., "Stability and Dynamics of Rotating Dielectrophoretic Equilibria", Journal of Fluid Mechanics, 38, part 4, 1969, pp. 721-742.

12. Melcher, J. R. and Smith, C. V., Jr., "Electrohydrodynamic Charge Relaxation and Perpendicular-Field Interfacial Instability", Physics of Fluids, 12, #4, April 1969, pp. 778-790.

13. Turnbull, R. J., "Electroconvective Instability with a Stabilizing Temperature Gradient. I Theory", Physics of Fluids, 11, 2588 (1968).

14. Turnbull, R. J., "Electroconvective Instability with a Stabilizing Temperature Gradient. II Experimental Results", Physics of Fluids, 11, 2597 (1968).

15. Wong, J., and Melcher, J. R., "Thermally Induced Electroconvection", Physics of Fluids, 12, #11, November, 1969, pp. 2264-2269.

16. Melcher, J. R., and Warren, E. P., "Electrohydrodynamics of a Current-carrying Semi-insulating Jet", J. of Fluid Mechanics, 47, part 1, (May 1971), pp. 127-143.

17. Zelazo, R. E., and Melcher, J. R., "Dynamic Interactions of Monomolecular Films with Imposed Electric Fields", Submitted for publication, Physics of Fluids.

18. Zuercher, J. C., and Melcher, J. R., "Double-Layer Transduction with Imposed Temporal and Spatial Periodicity", (in publication, Journal of Fluid Mechanics).

Basic research on electrohydrodynamic phenomena served as background for the remaining classifications of research.

B. Management of Liquids in Zero Gravity Environments

An important example of a practical objective requiring an understanding of electrohydrodynamic phenomena is the orientation, expulsion and general management of cryogenic liquid in zero gravity environments. References which summarize research in this area are as follows:

1. Melcher, J. R., and Hurwitz, M., "Gradient Stabilization of Electrohydrodynamically Oriented Liquids", Journal of Spacecraft and Rockets, 4, #7, July, 1967, pp. 864-881.

2. Melcher, J. R., Guttman, D. S., and Hurwitz, M., "Dielectrophoretic Orientation", Journal of Spacecraft and Rockets, 6, #1, January, 1969, pp. 25-32.

3. Melcher, J. R., Hurwitz, M., amd Fax, R. G., "Dielectrophoretic Liquid Expulsion", Journal of Spacecraft and Rockets, 6, #9, September, 1969, pp. 961-967.

4. Jones, T. B., and Melcher, J. R., "Dynamics of Electromechanical Flow Structures", Phys. Fluids, 16, 393, (1973).

Included in the applications of polarization forces to the management of zero gravity fluid flows is work currently in progress elsewhere on electrically augmented heat pipes. This work has been an outgrowth of that reported in reference 4 above.

C. Continuum Feedback Control

The considerable interest in the subject of feedback control for plasmas, as recently indicated by specialized conferences, has made work done on this subject under the NASA grant rewarding. The work in this area, begun under the grant almost ten years ago, was of a pioneering nature. It was the first to dilineate the requirements for the use of feedback control to stabilizing hydromagnetic equilibria. It wasn't until several years after this work had been completed that the spate of papers in this country on the subject began following the announcement of the stabilization of a fusion machine by the Russians. Our work has had an impact on experiments which are now being conducted at Los Alamos and at Cullem in England. References are as follows:

1. Melcher, J. R., "Stabilization of a Continuum Electromechanical Instability", Proceedings of IEEE, May 1965, pp. 460-473.

2. Melcher, J. R., "An Experiment to Stabilize an Electromechanical Continuum", Transactions on Automatic Control of the IEEE, AC-10, 1965, pp. 466-469.

3. Melcher, J. R., "Continuum Feedback Control of Instabilities on an Infinite Fluid Interface", Physics of Fluids, 9, #10, October 1966, pp. 1973-1982.

4. Melcher, J. R., "Continuum Feedback Control of a Rayleigh-Taylor Type Instability", Physics of Fluids, 9, #11, November, 1966, pp. 2085-2094.

D. Magnetohydrodynamics and Ferrohydrodynamics

Although the larger part of our research has been concerned with electrohydrodynamic phenomena, there has nevertheless been a continuing interest in applying what we have learned to related areas of continuum electromechanics. As already suggested by our work on the continuum feedback control of hydromagnetic equilibria, magnetohydrodynamic interactions have also seen considerable development. Here work has been carried out in plasmas, in magnetic liquids, and in liquid metals as summarized in the following references:

1. Wilson, G. L. and Woodson, H. H., "Excitation and Detection of Magnetoacoustic Waves in a Rotating Plasma Accelerator", AIAA Jrl., 5, (1967).

2. Zelazo, R. E. and Melcher, J. R., "Dynamics and Stability of Ferrofluids: Surface Interactions", Journal of Fluid Mechanics, 39, part 1, 1969, pp. 1-24.

3, Schaffer, M. J., "Hydromagnetic Surface Waves With Alternating Field", Journal of Fluid Mechanics, (1968), vol. 33, part 2, pp. 337-351.

E. Reviews

For an overview of our research the following references are particularly helpful. In the area of basic electrohydrodynamic research are reviews and summaries of research as follows:

1. Melcher, J. R., and Taylor, G. I., "Electrohydrodynamics: A Review of the Role of Interfacial Shear Stresses", Chapter in the First Review of Fluid Mechanics, Annual Reviews, Inc., Palo Alto, California, pp. 111-146.

2. Melcher, J. R., "Review of the IUTAM-IUPAP Symposium on Electrohydrodynamics", J. of Fluid Mechanics, 40, Part 3, 1970, pp. 641-655.

3. Melcher, J. R., and Cheng, T. C., "Prospects of Electrogasdynamic Power Generation", invited paper, Paper No. 70 CP 210-PWR, IEEE Winter Power Meeting, New York, N. Y., Jan. 25-30, 1970.

4. Melcher, J. R., "Electrohydrodynamics", chap. in Proceedings of 13th International Congress of Theoretical and Applied Mechanics, in publication, Springer-Verlag.

As the chapter in a book covering a conference on feedback stabilization of plasmas, a useful summary of work on the continuum feedback control is

5. Chu, T. K., and Hendel, H. W., eds., "Feedback Stabilization of Hydrodynamic Continua: Review and Prospects", Proceedings of the Symposium on Feedback and Dynamic Control of Plasmas, American Institute of Physics, New York, 1970, pp. 38-53.

Much of what we have learned about interactions between electric fields and fluids is readily demonstrable in easily visualized experiments. Thus one biproduct of our work has been experiments which are useful for the teaching of basic electromagnetic and electromechanical theory. A film, generally available for educational purposes, is based primarily on experiments developed under this NASA grant.

6. Melcher, J. R., "Electric Fields and Moving Media" film produced for the National Committee on Electrical Engineering Films by the Educational Development Center, 39 Chapel St., Newton, Mass. 02160. (Distributed by Coronet Films, Coronet Bldg., 65 E. South Water Street., Chicago, Ill. 60601.)

F. General Bibliography

As a matter of general interest a summary is given now of the patents, theses, and presentations which were an outgrowth of work on this NASA grant.

Patents

1. "Electrohydrodynamic Apparatus and Method", U. S. Patent #3,463,944, August 26, 1969.

2. "Electrohydrodynamic Induction Flowmeter and Conductivity Measuring Device", U. S. Patent #3,528,287, September 15, 1970

3. "Electrohydrodynamic Generator", U. S. Patent #3,529,186, September 15, 1970.

Ph.D. Theses

1. "Feedback Control of a Convective Instability", J. M. Crowley, 1965.

2. "Excitation and Detection of Magnetoacoustic Waves in a Rotating Plasma" G. L. Wilson, 1965.

3. "Electromechanical Streaming Interactions", F. D. Ketterer, 1966.

4. "Hydromagnetic Surface Waves with an Alternating Magnetic Field", M. J. Schaffer, 1966.

5. "Electroconvective Instabilities with a Stabilizing Temperature Gradient", R. J. Turnbull, August, 1967.

6. "Cellular Electric Convection in the Presence of a Free Surface", C. V. Smith, Jr., January 1968.

7. "Dynamics of Electromechanical Flow Structures", T. B. Jones, Jr., August, 1970.

8. "Dynamics of Charged Fluids", M. Zahn, August, 1970.

9. "Video Techniques in the Feedback Control of an Electromechanical Continuum", J. L. Dressler, January, 1972.

10. "Dynamic Interactions of Monomolecular Films with Imposed Electric Fields", R. E. Zelazo, August, 1971.

11. "Electromechanics of Fluid Double-Layer Systems", J. C. Zuercher, September, 1971.

M.S. Theses

1. "Excitation and Growth Rate of Electrohydrodynamic Instabilities", J. M. Crowley, published, Phys. Fluids, 8, 1668 (1965).

2. "Stability of the Hydromagnetic Pinch with Ideal Feedback", R. Canales, 1965.

3. "An Electrohydrodynamic Relaxation Surface Instability", W. J. Schwarz, Jr., 1966.

4. "Active Electromechanical Control of Fourth-Order Continua", J. L. Dressler, 1966.

5. "Surface-Coupled Electromechanics in Time-Varying Fields", E. B. Devitt, 1966.

6. "A Magnetoaeroelestic Energy Conversion Scheme", J. V. Burchett, 1966.

7. "Electrohydrodynamic Induction Pumping in a Closed Conduit", M. S. Firebaugh, 1966.

8. "Stability of a Distributed Parameter System Controlled by Spatially and Temporally Sampled Feedback", R. H. Thomas, 1966.

9. "Traveling-Wave Charged Particle Generation", Lance Herold, 1967.

10. "Traveling-Wave Synchronous Electrohydrodynamic Power Generation", W. F. Reeve, 1967.

11. "Traveling-Wave Induced Shear Flows", H. T. Ochs, III, 1967.

12. "Bang-Bang Electrohydrodynamic Stabilization", D. S. Guttman, 1967.

13. "Stability of Electrohydrodynamic Waves in Rotating Media", S. E. Grodzinsky, 1967.

14. "Loading Characteristics of Charge-Constrained Synchronous Generator", J. P. Regan, 1968.

15. "Thermally Induced Electroconvection in DC Fields", J. Wong, 1968.

16. "Cellular Electroconvective Instability in a Fluid Layer", D. C. Jolly, 1968.

17. "A Self-Excited Electrostatic Induction Generator", T. L. Wilke, 1968.

18. "Stability and Dynamics of Rotating Dielectrophoretic Orientation Systems", R. T. Calvert, 1968.

19. "An Electrohydrodynamic Synchronous Generator", F. A. Centanni, Jr., 1969.

20. "An AC Electrostatic Precipitator", B. E. Bennett, 1969.

21. "An Electrohydrodynamic Wick", D. L. Luck, 1969.

22. "Electromechanical Peristaltic Pumping", R. R. Burn, 1970.

23. "Electrogasdynamic Flows and Related Shock Phenomena", T. C. Cheng, 1970.

24. "Nonlinear Aspects of Electrohydrodynamic Surface Instability", D. M. Pearson, 1970.

25. "Double Layer Transduction Mechanisms", K. S. Sachar, 1970.

26. "Electrohydrodynamics of Pendent Drops", D. M. Dudley, 1971.

27. "Elastic Electricapillary Transduction", A. J. Grodzinsky, 1971.

G. <u>Oral Papers, Colloquia, Invited Seminars and Lectures</u> (J. R. Melcher)

1. "Continuum Feedback Control of a Rayleigh-Taylor Type Instability", American Physical Society, Division of Fluid Dynamics, November, 1965, Meeting.

2. "Control of a Continuum Electromechanical Instability", American Physical Society Division of Fluid Dynamics Meeting, Nov., 1964 Meeting.

3. "Gradient Stabilization of Electrohydrodynamically Oriented Liquids", American Physical Society Division of Fluid Dynamics Meeting, 1966, (co-author, M. Hurwitz)

4. "Free-Charge Instability of a Dielectrophoretically Oriented Fluid", American Physical Society Division of Fluid Dynamics, 1966 Meeting, (co-author, F. D. Ketterer)

5. "Traveling-Wave Bulk Electroconvection Induced Across a Temperature Gradient", American Physical Soc. Division of Fluid Dynamics Meeting, 1966 (co-author, M. S. Firebaugh).

6. "Interfacial Charge Relaxation Dynamics in a Tangential Electric Field", American Physical Society Division of Fluid Dynamics Meeting, 1967, (co-author, W. J. Schwarz, Jr.)

7. "Dielectrophoretic Bang-Bang Interfacial Dynamics and Stability", American Physical Society Division of Fluid Dynamics Meeting, 1967, (co-author, D. S. Guttman).

8. "Dielectrophoretic Liquid Expulsion", Joint AIAA/Aerospace Corporation Symposium on Low Gravity Propellant Orientation and Expulsion, May 21-23, 1968, Los Angeles, Calif. (co-authors M. Hurwitz, R. G. Fax, and J. R. Blutt).

9. "Electrohydrodynamics", Invited general lecture for 14th British Symposium on Applied Mathematics, Spring, 1972, London, England.

10. "Electrohydrodynamics", Invited lecture given while guest of Polish Academy of Science, Summer, 1972, Gdansk, Poland.

11. "Electrohydrodynamics", Sectional lecture at 13th International Congress of Theoretical & Applied Mechanics, Summer, 1972, Moscow, USSR.

12. "Continuum Feedback Control", Los Alamos Scientific Laboratory, Los Alamos, New Mexico, June, 1969

The following lectures were all on the topic of Continuum Electromechanics:

1. Department of Electrical Engineering, University of Illinois, Urbana, Illinois. Fall, 1964.

2. Department of Electrical Engineering, Iowa State University, Ames, Iowa, Fall, 1966.

3. Sandia Corporation, Albuquerque, New Mexico, Fall, 1966.

4. Electric Power and Propulsion Workshop, U. S. Navy, Annapolis, Md., April, 1968.

5. Battelle Memorial Institute, Columbus, Ohio, July, 1968.

6. Xerox Corporation Research Laboratories, Rochester, N. Y., August, 1968.

7. Case Western Reserve University, Cleveland, Ohio, October, 1968.

8. The Mead Corporation Central Research Laboratories, Chillicothe, Ohio, May, 1969.

9. Air Force Research Laboratory, University of Cincinnati, Dayton, Ohio, August, 1969.

10. Symposium on Feedback and Dynamic Control of Plasmas, June 18-19, 1970, Princeton University, Princeton, N. Y.

11. University of Massachusetts, Mechanical & Aero. Engineering Department, Amherst, Mass., Oct. 14, 1970.

12. University of South Florida, Tampa, May 29, 1970.

III. Outgrowth of the NASA Grant Research

Although it is not possible to give a complete reference to activities which are in some measure outgrowths of the NASA sponsored research under this grant it is nevertheless helpful to site a few directions motivated by this work.

In the development of high voltage transmission lines above the 500 KV level it has been found that the audible noise generated on the transmission lines under foul weather conditions is a major constraint on determining rights of way. This noise is created by the electrohydrodynamic instability of moisture on the conductors which leads to corona breakdown and a complex electrically driven acoustical response. The utilities are presently concerned enough about understanding the fundamentals underlying this problem that research is being sponsored both in industry and among academic groups. One such project is in a group at MIT and as an example of the impact of our research on this area research summarized in the report, "Current-Driven, Corona-Terminated Water Jets as Sources of Charged Droplets and Audible Noise", Hoburg, J. F. and Melcher, J. R., presented at the IEEE PES Winter Power Meeting, New York, N. Y., Jan. 28 - Feb. 2, 1973.

The augmentation of heat transfer by means of electrohydrodynamic phenomena is yet another application of electrohydrodynamics that is currently under investigation. In the heat pipe, expecially under zero gravity conditions, the electric field can be used to augment both the condensation and evaporation as well as provide a substitute for the wicking action normally caused by capallarity. As an outgrowth of a doctoral thesis done under this grant, Jones continues to develop the electrohydrodynamic heat pipe: Jones, T. B., and Perry, M. P., "Entrainment in Electrohydrodynamic Heat Pipes", NASA CR-114499, 1972 (research under NASA grant # NGR-06-002-127).

Yet another application of electrohydrodynamics has been to the area of air pollution control. Here the use of electric fields in particle systems which have fluid-like properties has promise for innovation in the control of particulate. Sachar, K. S., and Melcher, J. R., "Electrostatic Agglomeration Processes", Pollution Measurement and Control Conference, Chema N.E.R.E.M., Boston, 1971.

There is at present considerable interest in applying the electrohydrodynamic bulk instability research to experiments to be conducted on the manned space laboratory. Here the interest is in finding new types of manufacturing processes that exploit the zero gravity conditions. It appears that continuum feedback control can be exploited to an advantage under these conditions and that any system involving an applied electric field may be subject to electrohydrodynamic phenomenon that would not be observed in 1-g conditions.

The usefullness of continuum feedback control concepts developed under this project has yet to be shown. It is our understanding that fusion projects in England and at Los Alamos incorporate these concepts and are currently testing their feasibility.