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Destination(s) and Dates for

Which Trip Report Being Submitted: Sweden, Norway, Italy, England

Name of Traveler: L. J. Gray

Joint Trip Report ☐ **Yes**

☒ **No**

If so, Name of Other Traveler(s): _____

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ORNL

FOREIGN TRIP REPORT

ORNL/FTR-3817

DATE: November 9, 1990

SUBJECT: Report of Foreign Travel by L. J. Gray, Senior Research Staff Member and Mathematics Group Leader in the Mathematical Sciences Section of the Engineering Physics and Mathematics Division of ORNL.

TO: Alvin W. Trivelpiece

FROM: L. J. Gray

PURPOSE: To hold technical discussions at four sites related to environmental and geophysical modeling, fracture mechanics, and boundary element methods; to attend and present a paper at the International Association for Boundary Element Methods Conference at Rome, Italy, October 15 - 19, 1990.

SITES VISITED:	10/2-3/1990	Aeronautical Res.Inst.of Sweden Stockholm, Sweden	J. Thesken
	10/5-11/1990	IBM Bergen Sci. Centre Bergen, Norway	A. Kamel, N. Odling
	10/15-19/1990	Conference Rome, Italy	F. Rizzo, T. Cruse
	10/19/1990	IBM Rome Sci. Centre Rome, Italy	P. Sguazzero, F. Dellagiacoma
	10/23-24/1990	Univ. of Bath Bath, England	A. Spence, I. Graham

ABSTRACT:

Technical discussions at the various sites visited centered on application of boundary integral methods for environmental modeling, seismic analysis, and computational fracture mechanics in composite and "smart" materials. The traveler also attended the International Association for Boundary Element Methods Conference at Rome, Italy. While many aspects of boundary element theory and applications were discussed in the papers, the dominant topic was the analysis and application of hypersingular equations. This has been the focus of recent work by the author, and thus the conference was highly relevant to research at ORNL.

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II. Report

A. Purpose

The purpose of the trip was to hold technical discussions and present seminars at four sites in Europe: the IBM Scientific Centers in Bergen Norway and Rome Italy, the Swedish Aeronautical Research Institute (FFA) in Stockholm, and the University of Bath, England. In addition to exchange of technical information, the goal was explore possible areas for collaborative research work. The development and application of boundary integral equation techniques for solving physical problems was the central topic in all site visits. The discussions in Norway and Rome centered on applications to flow in fractured media and seismic analysis. Flow in fractured media is of direct relevance to the Applied Mathematics Research Project in the Mathematical Sciences Section, Engineering Physics and Mathematics Division, of ORNL; this project, sponsored by the Applied Mathematical Sciences Subprogram of the DOE Office of Energy Research (KC0701) has as its objective the development of mathematical and computational techniques for solving problems arising in environmental analysis and remediation. The discussions pertaining to seismic wave propagation are of potential benefit in the analysis of data to be obtained from *in situ vitrification* experiments to be conducted by the Environmental Sciences Division (Gary Jacobs), ORNL.

The discussions at FFA centered on computational fracture mechanics. The mathematical problems arising in this area are relevant to the above mentioned research project, in that both involve hypersingular integral equations. In addition, DOE and NRC sponsor several research projects, at ORNL and elsewhere, in fracture; improved computational modeling capabilities should be beneficial for this work. The principal subject discussed was the extension of existing boundary integral techniques to transversely isotropic materials; this is related to fracture problems in composite and "smart" materials and is therefore likely to be of interest at ORNL. It is also of potential benefit in the nondestructive testing of mirrors being fabricated at Y-12.

The discussions at the University of Bath focused on the mathematical analysis of boundary element approximations (e.g., accuracy, convergence), and in particular, the behavior of first kind integral equations. This is directly related to some current research work, supported by the Applied Mathematics project, being carried out by the author.

A paper, *The Evaluation of the Boundary Stress Tensor* (coauthored with E. Lutz and A. Ingrassia, Cornell University) was presented at the International Association for Boundary Element Methods Conference. A total of 64 papers were delivered, covering a wide range of boundary element theory and application. As indicated above, boundary element methods for solving partial differential equations are applicable to various DOE and NRC programs.

B. Activities

At the Swedish Aeronautical Research Institute (FFA), materials research is focused on composites, and a new project on "smart" materials is likely to be funded in the near

future. Current experimental work, being carried out by K. Levin, is using Moire patterns to analyze impact damage in composites. The computational modeling at FFA is performed mainly by means of finite element methods; the author presented a seminar on his collaborative work with Cornell University on boundary element fracture analysis. In subsequent discussions with John Thesken, it was deemed likely that transversely isotropic materials could be treated by appropriate extension of the author's fracture techniques for the isotropic case. As the author is unaware of any boundary element analyses for these materials, this is a potentially new research area with important applications in composite materials technology. Thesken indicated that computational modeling of the interaction of a crack with an optical fiber sensor in a "smart" material is also unexplored territory. It was agreed that these research topics should be jointly pursued.

At the IBM Bergen Scientific Centre, discussions were held with A. Kamel on acoustic wave scattering problems in heterogeneous media arising in seismic analysis. In general, boundary integral techniques are not efficient for nonhomogeneous media, but for the particular applications considered, the surface to volume ratio is small enough that boundary methods are potentially very useful. There are two difficulties in applying the boundary element method to this problem. The first is the occurrence of internal corner points on the common boundary of two or more homogeneous subdomains; a recent method developed by the author should be capable of treating this problem, but has not yet been tested for this particular situation. The second problem is the determination of appropriate boundary conditions for the fictitious surface used to "close off" the semi-infinite domain; inappropriate boundary conditions causes spurious reflections from this far boundary. Kamel indicated that recent results by Keller and Givoli (*J. Computational Physics* **82**, 1989) might be applicable, but this will require further study. Kamel is working with P. Sguazzero and F. Dellagiacoma at the IBM Rome Scientific Center, and this topic was further discussed with these researchers during the author's site visit in Rome. It was decided that IBM Rome would construct a two dimensional test geometry which is simpler than the real world problem, but nevertheless contains all the complicating features. The author will then use his existing 2D Helmholtz code to solve the problem, employing approximate boundary conditions on the far surface. If these results are promising, an extension of Keller's exact boundary condition method for a nonhomogeneous domain will be investigated, and the solution technique should then be extended to three dimensions.

Discussions on flow in fractured media were held at IBM Bergen with a geologist, N. Odling, working on mapping out fracture patterns in rock formations. The author would like to use these realistic geometries to test a new boundary element method; this will hopefully lead to a better understanding of the effect of a complex fracture pattern on porous media flow. The hope is to be able to compress the fracture geometry down to a few crucial parameters which characterize the system and can be measured in the field; these parameters could then be incorporated in a model which would provide a reasonably accurate model the flow, without complete knowledge of all fracture locations. For testing the boundary element algorithm, IBM Bergen will provide a discretized model of one of the mapped regions. The possibility of modeling, via boundary integral equations, flow in a random medium was also briefly discussed; the author will pursue this topic.

At the University of Bath, discussions with I. Graham and A. Spence centered on the numerical analysis of integral equation methods. The author learned a great deal about the current state of the theory; of particular relevance to the author's work were that first kind equations, at least in two dimensions, do not present much of a problem, and that although some existing work does apply to hypersingular equations, there is apparently no analysis for crack problems. Discussions were also held with F. Sabina on integral equation methods for elastic wave propagation in media with random inclusions; Sabina is currently on sabbatical from the University of Mexico, and is working with J. Willis. They have developed a self-consistent theory for this model, and their techniques may be very useful for developing methods for flow in random media.

At the IABEM conference, the work on hypersingular integrals reported by Guiggiani (in collaboration with Krishnasamy, Rudolph and Rizzo) is the closest to the author's approach, in that a limiting process is employed to define the integral. Although the limiting procedures are different, the same answers are eventually obtained and it may just be a matter of taste as to which is preferable (Guiggiani's method deforms the surface, whereas the author moves the singular point; the author's biased view is that the latter is simpler). Professor Rizzo raised the question of whether the smoothness requirements (imposed on the function multiplying the hypersingular kernel) can be relaxed. The preliminary answer seems to be that one can get by with less than C^1 if one is willing to employ a Galerkin approximation. Aside from the papers dealing with hypersingular integrals, the most interesting (from the standpoint of possible impact on DOE/NRC programs and the author's research) development reported at the conference were two papers from Japan (N. Nishimura and S. Kobayashi (Kyoto University): *Further applications of regularized integral equations in crack problems*; M. Tanaka, M. Nakamura and T. Nakano (Shinshu University): *Identification of cracks or defects by means of the elastodynamic BEM*) on solving inverse problems related to nondestructive evaluation. While by no means complete solutions, these papers presented feasible algorithms which were capable of solving simplified (two dimensions, flat cracks), but nevertheless reasonably difficult, model problems. The Italian boundary integral community is apparently very strong in aerodynamics, and there were many papers devoted to aerodynamical flow problems.

C. Travelers' Role

The most significant discussions were those at FFA, IBM Bergen and IBM Rome. As described above, these discussions will likely lead to collaborative research projects in fracture analysis and seismic wave propagation. In both instances, the problem was presented to the author, and his expertise was essential in (a) assessing whether or not a boundary integral approach would be feasible, and (b) defining the specific research issues that would have to be addressed in order to obtain the solution.

At the IABEM conference in Rome, several discussions were held with M. Guiggiani (University of Pisa), T. Cruse (Vanderbilt University), and F. Rizzo (University of Illinois) on the subject of hypersingular integral equations. The author's paper was the only one to discuss the treatment of these integrals at a boundary corner point, and this attracted some interest. Discussions with Professor Rizzo covered a variety of topics (crack problems, nondestructive evaluation, first kind equations), and he provided several references and names which should prove useful.

D. Recommendations

This trip identified two specific mathematical research problems (fracture analysis in transversely isotropic media, seismic wave propagation) which are highly applicable to DOE programs, and which are of interest at European research centers. In addition, there is continued mutual interest in the area of flow in fractured media. There are obviously great benefits, both scientific and economic, to collaborative research, and the author recommends that the projects and contacts with FFA (Stockholm) and IBM Bergen/Rome be pursued.

The author was given a demonstration of a program for visualizing computational results that is currently being developed at IBM Rome. This software is specifically designed for the new IBM RISC workstations, and it would be a very tool to have. The author recommends that IBM Rome be contacted about possible release of a preliminary version of the program.

The IABEM conference was highly successful in achieving a balance between theoretical and applied papers. It was considerably smaller and the papers generally of higher quality than the annual boundary element international conference run by Computational Mechanics; as there were only a few parallel sessions, it was possible to listen to most of the papers. The conference provided the opportunity to hold discussions with the leading researchers in the field of boundary elements applied to solid mechanics (Professors Rizzo and Cruse), and to gain international exposure for ORNL research. The author recommends attendance at future conferences.

E. Significant Technical Developments

As mentioned above, FFA has submitted a proposal (joint with industry in Sweden) to establish a research program in "smart" materials. This program will include experimental work on fabrication techniques and computational computational modeling. The author suspects that this program, and the ongoing composite work at FFA, would be highly relevant to DOE materials research.

During the past year, the IBM Bergen Scientific Centre (BSC) has been named IBM's European laboratory for environmental analysis and modeling. As this has become the focus of DOE sponsored mathematical research at ORNL, work at BSC is directly related to the DOE program. While dollar levels are not known precisely, the funding at BSC is approximately 20 million kroner (3 million dollars), with a large percentage of this supporting the environmental work; at least three new people have been hired during the last year in this area. In addition to modelling, BSC carries out work in environmental databases, remote sensing, visualization, and numerical analysis. In addition to the Basic Energy Sciences program, this work is probably very relevant to global climate research sponsored by DOE.

IBM Rome has an active research group in robotics, robotic vision, and voice acquisition systems. This work should be of interest to ORNL programs in the Engineering Physics and Mathematics Division and the Robotics Division.

F. Summary Evaluation

From the standpoint of the technical interests of the traveler, the trip was highly productive. In addition to identifying several new and exciting areas of research, a great deal of technical information was obtained which will assist current research work. The conference attended provided a forum for presenting the traveler's work to the leading experts in the field, and excellent exposure for the ORNL mathematics research program. These contacts should be highly beneficial in the future.

III. Appendix

A. Itinerary for L. J. Gray

10/1/90	Travel from Oak Ridge to Stockholm.
10/2/90 - 10/4/90	Stockholm, Sweden.
10/4/90 - 10/13/90	Bergen, Norway.
10/14/90 - 10/18/90	Rome, Italy.
10/19/90	Rome, Italy.
10/20/90 - 10/22/90	Weekend - 10/20-21. Personal - 10/22.
10/23/90 - 10/24/90	Bath, England.
10/25/90	Travel home.

B. Persons Contacted

J. Thesken	Swedish Aeronautical Research Institute (FFA)
K. Levin	
P. Gaffney, Director	IBM Bergen Scientific Centre (BSC)
A. Kamel	
N. Odling	
C. Thompson	
T. Cruse	Vanderbilt University, USA
F. Rizzo	University of Illinois, USA
M. Guiggiani	University of Pisa, Italy
B. Annigeri	United Technologies Corp., USA
J. Dominguez	Sevilla University, Spain
J. Kane	Clarkson University, USA
J. Niedzwecki	Texas A M University, USA
P. Sguazzero	IBM Rome Scientific Center
F. Dellagiacoma	
A. Parisi	
A. Spence	University of Bath
I. Graham	
F. Sabina	
A. Stewart	

C. Literature Acquired

Crack Kinks and Crack Closure Modeled By Integral Equation Methods by Weilin Zang, Stockholm - 1990.

Iterative Solution of Linear Systems Arising from the Boundary Integral Method by Kendall E. Atkinson and Ivan G. Graham, University of Queensland - (1985 Rev.)

High-Order Methods For Linear Functionals Of Solutions Of Second Kind Integral Equations by I. G. Graham and G. A. Chandler, Anal., Volume 25, Australia - 1988.

Uniform Convergence of Galerkin Solutions To Non-compact Integral Operator Equations by G. A. Chandler and I. G. Graham, Australia - 1987.

Product Integration-Collocation methods For Noncompact Integral Operator Equations by G. A. Chandler and I. G. Graham, Australian National University, Canberra - 1988.

Extrapolation of Nystrom Solutions Of Boundary Integral Equations on Non-Smooth Domains by I. G. Graham, United Kingdom, Lin Qun and Xie Rui-feng - 1988.

Towards Automation Of Boundary Integral Methods For Laplace Equation by Juian Gold and Ivan G. Graham, United Kingdom - 1990.

A Hypersingular Boundary Integral Method For Two-Dimensional Screen and Crack Problems by E. P. Stephan, Atlanta, Georgia and W. L. Wendland, W. Germany - 1980.

On Multigrid Methods Of The First Kind For Symmetric Boundary Integral Equations Of Nonnegative Order by Friedrich-Karl Hebekker - 1988.

A Simple Self-Consistent Analysis Of Wave Propagation In Particulate Composites by F. J. Sabina, Mexico and J. R. Willis, Bath, United Kingdom - 1987.

Hierarchical Fracture Trace Model by Jun-Suk Lee, D. Veneziano, and H. H. Einstein, Massachusetts Institute of Technology - 1987.

Permeability And Simulation Of Natural Fracture Patterns by Noelle E. Odling and Itzhak Webman, Bergen Scientific Centre, Bergen, Norway - 1990.

IABEM -90 Symposium Of The International Association For Boundary Element Methods "Abstracts" Sponsored by, Consiglio Nazionale delle Ricerche, Aeritalia, Agusta, CIRA, Universita degli Studi di Roma "La Sapienza" - 1990.

On The Sloan Iteration Applied To Integral Equations Of The First Kind By Ivan G. Graham, United Kingdom and Kendall E. Atkinson, Iowa City, Iowa - 1990.

The Galerkin Method For Integral Equations Of The First Kind With Logarithmic Kernel: Applications by I. H. Sloan, Australia and A. Spence, Claverton Down, Bath - 1988, *IMA J. Num. Anal.*, 8, 123-140.

The Galerkin Method For Integral Equations Of The First Kind With Logarithmic Kernel: Theory by I. H. Sloan, Australia and A. Spence, Claverton Down, Bath - 1988, *IMA J. Num. Anal.*, 8, 105-122.

On Superconvergence Properties Of Galerkin's Method For Compact Operator Equations by A. Spence, Claverton Down, Bath and K. S. Thomas, University of Southampton - 1981.

Piecewise Constant Collocation For First Kind Boundary Integral Equations by I. G. Graham and Y. Yan, Australia - 1989.

The Effect Of Contact Area On The Permeability Of Fractures by D. W. Chen and R. W. Zimmerman, Lawrence Berkeley Laboratory, Berkley, California - 1989.

The Reflection Of Electromagnetic Waves From Very Rough Interfaces by D. R. S. Talbot, J. B. Titchener and J. R. Willis, United Kingdom - 1990.

Hypersingular Boundary Integral Equations: A New Approach To Their Numerical Treatment by M. Guiggiani, Pisa, Italy, G. Krishnasamy and F. J. Rizzo, Urbana, Illinois, T. J. Rudolphi, Ames, Iowa - 1990.

Harmonic Waves In Periodically Layered Anisotropic Elastic Composites by T.C.T. Ting, Chicago, Illinois and P. Chadwick, Norwich, England -1988.

Finite-Element Methods For Porous Media Flow, *O Bte* University of Bergen, Norway - 1990.

END

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12 / 10 / 90