DEPARTMENT OF COMPUTER SCIENCE
COLLEGE OF SCIENCES
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

SOLUTIONS OF 3D MID-FREQUENCY ACOUSTO-ELASTIC SCATTERING ON DISTRIBUTED MEMORY MASSIVELY PARALLEL MIMD COMPUTERS

By

M. Zubair and C.E. Grosch

Final Report
For the period March 25, 1993 through March 30, 1996

Prepared for
Naval Research Laboratory
4555 Overlook Ave., S.E.
Washington, D.C. 20375-5326

Under
Research Contract N00014-93-K-2023
Dr. Susan K. Numrich, Scientific Officer

Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, VA 23508-0369

September 1996

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	SEPTEMBER 1996	FINAL REPORT-1993 MARCH 30-1996 MARCH 30

4. TITLE AND SUBTITLE
SOLUTIONS OF 3D MID-FREQUENCY ACOUSTO-ELASTIC SCATTERING ON DISTRIBUTED MEMORY MASSIVELY PARALLEL COMPUTERS

5. FUNDING NUMBERS
C-N00014-93-K-2023

6. AUTHOR(S)
C. E. GROSCH, T. AGARWAL, AND M. ZUBAIR

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
OLD DOMINION UNIVERSITY RESEARCH FOUNDATION
P.O. BOX 6369
NORFOLK, VA 23508-0369
DEPARTMENT OF COMPUTER SCIENCE

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NAVAL RESEARCH LABORATORY
4555 OVERLOOK AVE., S.W.
WASHINGTON, D.C. 20375-5326

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
UNCLASSIFIED; UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A general purpose solver for large, sparse, banded systems of equations has been developed and tested on the CM5E. This tool can be applied to any problem arising in finite element analysis such as structures, machinery, acoustic-structure interaction among many others. For a very large problem a factorization and solution takes 10 to 12 minutes; solutions for additional right hand sides will take on the order of one minute each.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unclassified

GENERAL INSTRUCTIONS FOR COMPLETING SF 298

The Report Documentation Page (RDP) is used in announcing and cataloging reports. It is important that this information be consistent with the rest of the report, particularly the cover and title page. Instructions for filling in each block of the form follow. It is important to ***stay within the lines*** to meet ***optical scanning requirements***.

Block 1. Agency Use Only *(Leave blank)*.

Block 2. Report Date. Full publication date including day, month, and year, if available (e.g. 1 Jan 88). Must cite at least the year.

Block 3. Type of Report and Dates Covered. State whether report is interim, final, etc. If applicable, enter inclusive report dates (e.g. 10 Jun 87 - 30 Jun 88).

Block 4. Title and Subtitle. A title is taken from the part of the report that provides the most meaningful and complete information. When a report is prepared in more than one volume, repeat the primary title, add volume number, and include subtitle for the specific volume. On classified documents enter the title classification in parentheses.

Block 5. Funding Numbers. To include contract and grant numbers; may include program element number(s), project number(s), task number(s), and work unit number(s). Use the following labels:

C -	Contract	**PR** -	Project
G -	Grant	**TA** -	Task
PE -	Program Element	**WU** -	Work Unit Accession No.

Block 6. Author(s). Name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. If editor or compiler, this should follow the name(s).

Block 7. Performing Organization Name(s) and Address(es). Self-explanatory.

Block 8. Performing Organization Report Number. Enter the unique alphanumeric report number(s) assigned by the organization performing the report.

Block 9. Sponsoring/Monitoring Agency Name(s) and Address(es). Self-explanatory.

Block 10. Sponsoring/Monitoring Agency Report Number. *(If known)*

Block 11. Supplementary Notes. Enter information not included elsewhere such as: Prepared in cooperation with...; Trans. of...; To be published in.... When a report is revised, include a statement whether the new report supersedes or supplements the older report.

Block 12a. Distribution/Availability Statement. Denotes public availability or limitations. Cite any availability to the public. Enter additional limitations or special markings in all capitals (e.g. NOFORN, REL, ITAR).

- **DOD** - See DoDD 5230.24, "Distribution Statements on Technical Documents."
- **DOE** - See authorities.
- **NASA** - See Handbook NHB 2200.2.
- **NTIS** - Leave blank.

Block 12b. Distribution Code.

- **DOD** - Leave blank.
- **DOE** - Enter DOE distribution categories from the Standard Distribution for Unclassified Scientific and Technical Reports.
- **NASA** - Leave blank.
- **NTIS** - Leave blank.

Block 13. Abstract. Include a brief *(Maximum 200 words)* factual summary of the most significant information contained in the report.

Block 14. Subject Terms. Keywords or phrases identifying major subjects in the report.

Block 15. Number of Pages. Enter the total number of pages.

Block 16. Price Code. Enter appropriate price code *(NTIS only)*.

Blocks 17. - 19. Security Classifications. Self-explanatory. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED). If form contains classified information, stamp classification on the top and bottom of the page.

Block 20. Limitation of Abstract. This block must be completed to assign a limitation to the abstract. Enter either UL (unlimited) or SAR (same as report). An entry in this block is necessary if the abstract is to be limited. If blank, the abstract is assumed to be unlimited.

Methodology

The steps in code for solving large, sparse, banded systems of equations are outlined in Table 1. The solver uses either Gaussian Elimination or Cholesky Decomposition. Figure 1 is a schematic flow chart of the solver. A complete solution has three steps: (1) factorization, requiring the updating of data in local node memory, block broadcast of data to other nodes, block receive of data from other nodes and updating of local data using the received data; (2) forward elimination, requiring updating of variables local to the node and broadcasting of update information to other nodes; (3) backward substitution, requiring solving for the variables local to each node and the sending of update information to other nodes. Multiple right hand sides can be used with a single factorization.

Implementation of this algorithm on the CM5E posed several problems. The major problem was the limitations imposed by CM FORTRAN. It is desireable to have the matrix data distributed equally to the nodes in a block round-robin fashion in order to optimize the usage of the four vector pipelines per node. As is sketched out in Figure 2, the CM FORTRAN compiler distributes a vector of N elements, a row of the matrix in this algorithm, uniformly to the four vector pipelines as N/4, N/4, N/4 and N/4. Operations on elements in any one pipeline in effect disables the other pipelines. Thus very low vector performance results. As is sketched in Figure 3, redefining a vector as an array with the second dimension parallel solved this problem. The speedup over the "natural" data distribution was as high as 80.

Results

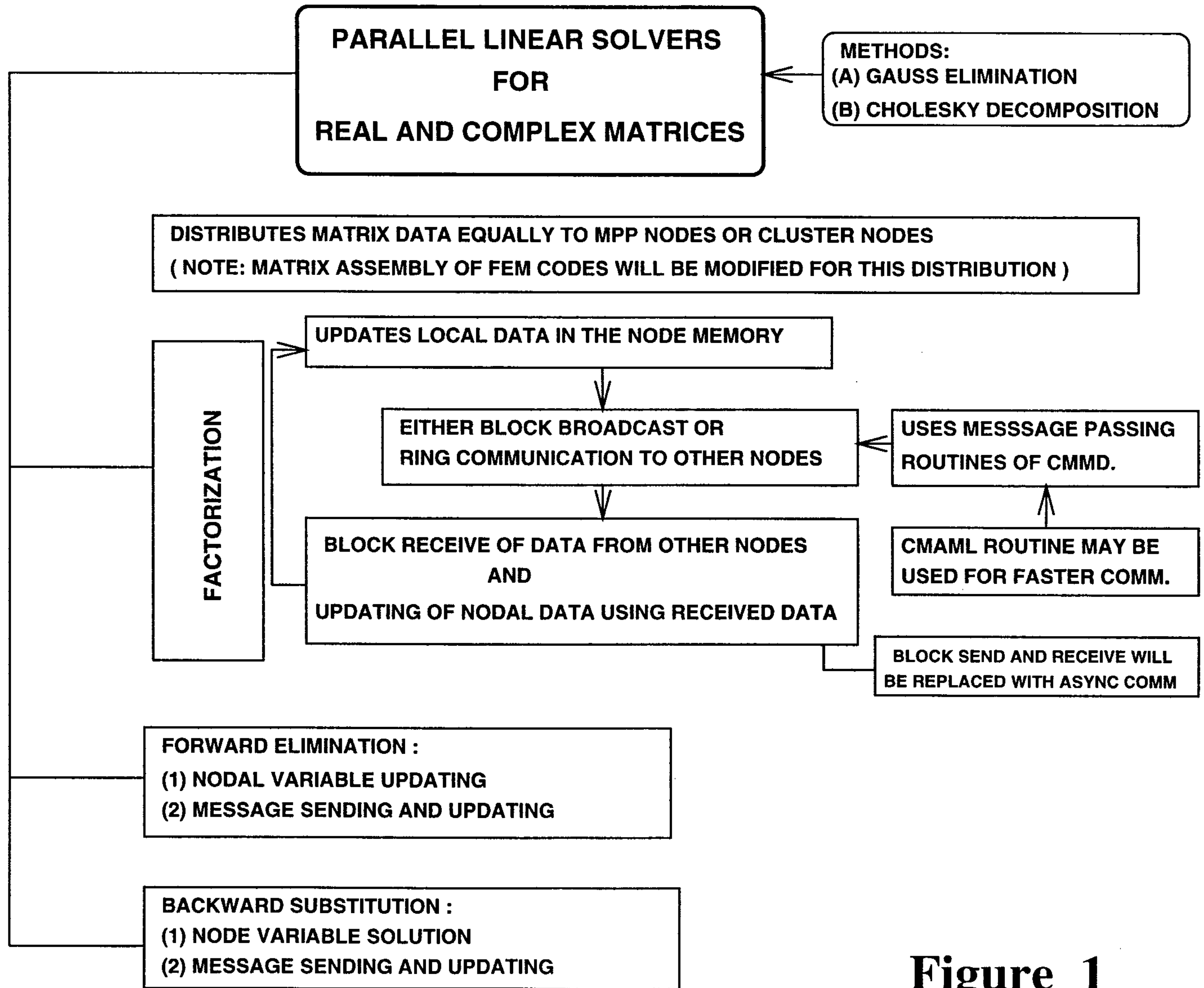
A series of test problems have been run to measure the performance of the code. The problems are: (A): 10,000 equations with an average half band width of 500. (B): 50,000 equations with an average half band width of 1000. (C): 100,000 equations with an average half band width of 4000. The results are presented in the table below. In this table (*) denotes an estimated value.

Problem	Number of CM5 Nodes	Run Time (Seconds)	Processing Rate (Megaflops)
A	1	21.0	
	4	10.1	
	16	6.5	
	64	5.5	
	128	5.5	
B	1	*1666	*30
	64	76	657
	128	65	760
	256	59	847
C	1	*40000	*40
	64	1047	1538
	128	723	2222
	256	681	2349

Small problems, such as (A), are communication bound and no improvement in performance occurs with more than 4 to 8 nodes. Medium size problems, such as (B) can effectively use up to 64 nodes with modest improvement for additional nodes; again communication cost limits performance to just under a Gigaflop. Large problems, such as (C), can effectively use 128 nodes with modest improvement for 256 nodes; communication dominates for large numbers of nodes but performance of 2.2 to 2.3 Gigaflops is acheived.

Summary

A general purpose solver for large, sparse, banded systems of equations has been developed and tested on the CM5E. This tool can be applied to any problem arising in finite element analysis such as structures, machinery, acoustic-structure interaction among many others. For a very large problem a factorization and solution takes 10 to 12 minutes; solutions for additional right hand sides will take on the order of one minute each.



PARALLEL LINEAR SOLVERS
FOR
REAL AND COMPLEX MATRICES
METHODS:
(A) GAUSS ELIMINATION
(B) CHOLESKY DECOMPOSITION
DISTRIBUTES MATRIX DATA EQUALLY TO MPP NODES OR CLUSTER NODES
(NOTE: MATRIX ASSEMBLY OF FEM CODES WILL BE MODIFIED FOR THIS DISTRIBUTION)
FACTORIZATION
UPDATES LOCAL DATA IN THE NODE MEMORY
EITHER BLOCK BROADCAST OR
RING COMMUNICATION TO OTHER NODES
USES MESSSAGE PASSING
ROUTINES OF CMMD.
BLOCK RECEIVE OF DATA FROM OTHER NODES
AND
UPDATING OF NODAL DATA USING RECEIVED DATA
CMAML ROUTINE MAY BE
USED FOR FASTER COMM.
BLOCK SEND AND RECEIVE WILL
BE REPLACED WITH ASYNC COMM
FORWARD ELIMINATION :
(1) NODAL VARIABLE UPDATING
(2) MESSAGE SENDING AND UPDATING
BACKWARD SUBSTITUTION :
(1) NODE VARIABLE SOLUTION
(2) MESSAGE SENDING AND UPDATING

Figure 1

Figure 2

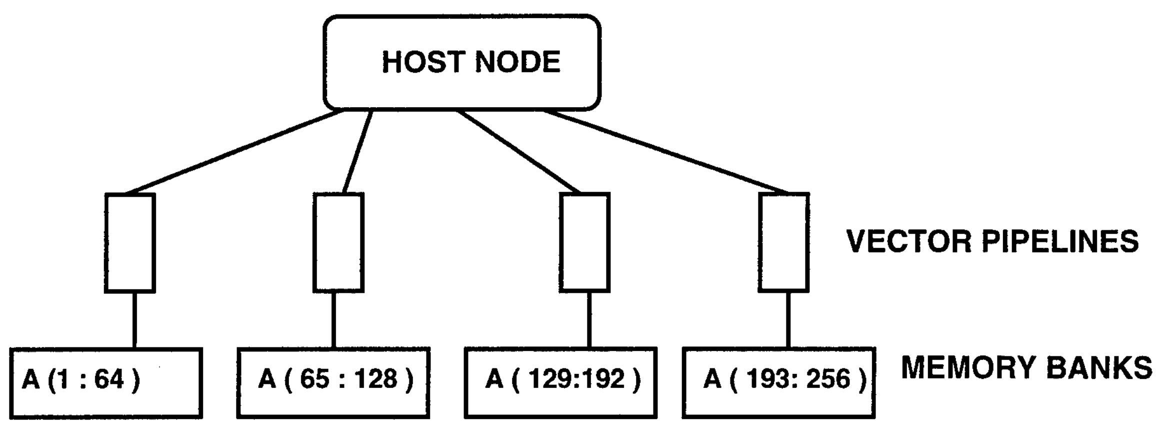
<u>CMFORTRAN LIMITATIONS</u>

- DISTRIBUTES DATA AMONG FOUR VECTOR PIPELINES AT COMPILE TIME.

- LOOP OPERATION ON SEGMENTS OF THE DECLARED VECTOR TAKE FIXED TIME

- FLOP RATES AS LOW AS 0.5 MFLOPS FOR LONG VECTORS.

EX: PARALLEL ARRAY A (256)



- OPERATIONS ON FIRST 16 ELEMENTS USE ALL VECTOR PIELINES AND USE SAME ELAPSED TIME AS OPERATING ON ALL 256 ELEMENTS.

Figure 3

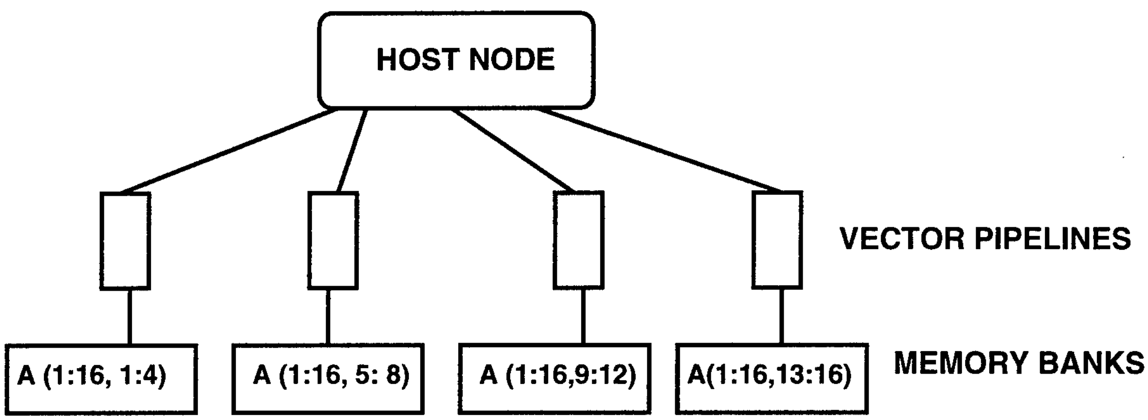
MATRIX DATA MODIFICATION FOR VECTOR EFFICIENCY UNDER CMFORTRAN

- ARRAY A (256) IS REDEFINED AS TWO DIMESIONAL VECTOR WITH AXIS 2 AS PARALLEL DIMENSION.

CHANGES - ARRAY A (256) ---- ARRAY A (16, 16)

- FLOP RATES AS HIGH AS 40.0 MFLOPS FOR LONG VECTORS.

EX: PARALLEL ARRAY A (16, 16)



- OPERATION ON FIRST 16 ELEMENTS ON SECOND DIMENSION USES ALL FOUR VECTOR PIPELINES.