NATIONAL CENTER FOR EARTHQUAKE
ENGINEERING RESEARCH
State University of New York at Buffalo

MUMOID USER'S GUIDE
A PROGRAM FOR
THE IDENTIFICATION OF MODAL PARAMETERS

by

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Technical Report NCEER-90-0026

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PREFACE

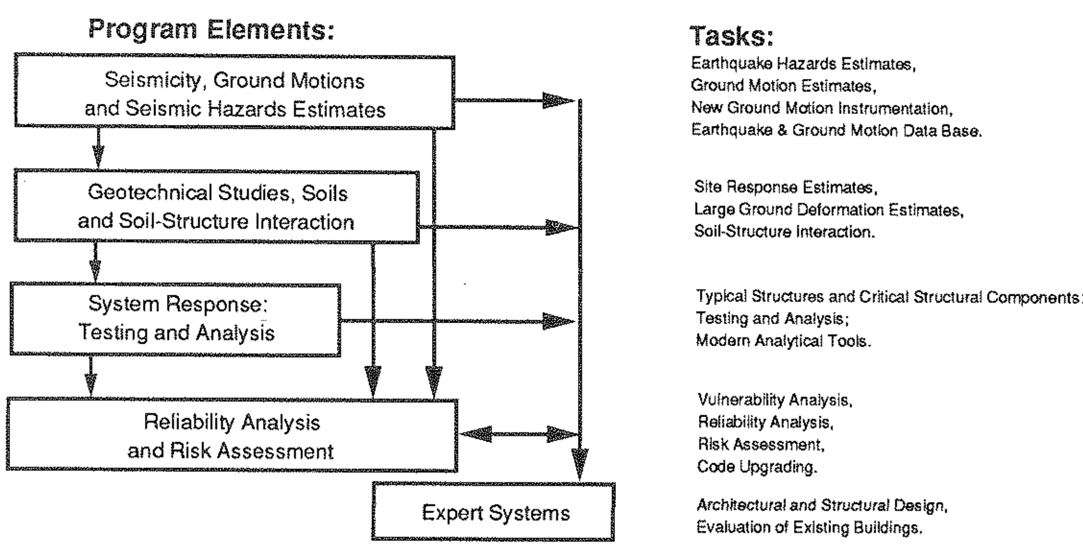
The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 1, Existing and New Structures, and more specifically to reliability analysis and risk assessment.

The long term goal of research in Existing and New Structures is to develop seismic hazard mitigation procedures through rational probabilistic risk assessment for damage or collapse of structures, mainly existing buildings, in regions of moderate to high seismicity. This work relies on improved definitions of seismicity and site response, experimental and analytical evaluations of systems response, and more accurate assessment of risk factors. This technology will be incorporated in expert systems tools and improved code formats for existing and new structures. Methods of retrofit will also be developed. When this work is completed, it should be possible to characterize and quantify societal impact of seismic risk in various geographical regions and large municipalities. Toward this goal, the program has been divided into five components, as shown in the figure below:



Reliability analysis and risk assessment research constitutes one of the important areas of Existing and New Structures. Current research addresses, among others, the following issues:

1. Code issues - Development of a probabilistic procedure to determine load and resistance factors. Load Resistance Factor Design (LRFD) includes the investigation of wind vs. seismic issues, and of estimating design seismic loads for areas of moderate to high seismicity.
2. Response modification factors - Evaluation of RMFs for buildings and bridges which combine the effect of shear and bending.
3. Seismic damage - Development of damage estimation procedures which include a global and local damage index, and damage control by design; and development of computer codes for identification of the degree of building damage and automated damage-based design procedures.
4. Seismic reliability analysis of building structures - Development of procedures to evaluate the seismic safety of buildings which includes limit states corresponding to serviceability and collapse.
5. Retrofit procedures and restoration strategies.
6. Risk assessment and societal impact.

Research projects concerned with reliability analysis and risk assessment are carried out to provide practical tools for engineers to assess seismic risk to structures for the ultimate purpose of mitigating societal impact.

The program MUMOID was developed for the purpose of computing global damage indices for seismically damaged structures on the basis of the vibrational parameters such as the Maximum Softening. As such, the computer program identifies the modal parameters of a linear structural system. Maximum likelihood method is used for the identification from the accelerograms recorded at the base and at some upper level of a structure. A time varying equivalent linear system is found for nonlinear systems, by dividing the recorded accelerograms in a series of time windows that may overlap. For each time window, structural softening is computed and the maximum among these is used as the measure of global structural damage.

ABSTRACT

A computer program for the identification of the modal parameters of a linear structural system is described. Maximum Likelihood Estimation is used for the identification of the modal parameters from the accelerograms recorded at the base and at some upper level of a structure.

A time varying equivalent linear system can be found for nonlinear systems, by dividing the recorded accelerograms in a series of time windows that may overlap or not.

The program MUMOID can be used for the evaluation of global damage indices based on the vibrational parameters such as the Maximum Softening.

ACKNOWLEDGEMENTS

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SECTION 1
INTRODUCTION

DiPasquale and Cakmak [2] proposed global damage indices based on the vibrational parameters of a structure to characterize the seismic damage. They developed a damage model based on the evolution of the natural period of a time-varying linear system equivalent to the actual nonlinear system for a series of non-overlapping time windows. A *maximum likelihood criteria* for the identification of the time-varying equivalent linear system from the acceleration records at the top and at the base of the structure was used.

Their global damage index, named Maximum Softening, is given by

$$\delta_M = 1 - \frac{T_0}{T_{max}} \tag{1.1}$$

where,

δ_M : Maximum Softening

T_0 : Initial natural period

T_{max} : Maximum natural period of an equivalent linear system

The Maximum Softening as a global damage index has been tested by using experimental results from reduced scale models and actual seismic records [2].

It has also been shown, from a Continuum Mechanics approach, that the Maximum Softening is related to the local stiffness and strength degradation through operations of averaging over the body volume.

This report documents the computer program MUMOID used for the identification of the time-varying equivalent linear system. MUMOID can be applied to the analysis of earthquake records of civil engineering structures, yielding a global damage index (Maximum Softening) and the probability of earthquake damage [2].

The following section contains the manual for MUMOID with general information about the program. The input and output variables, and the error messages are also described.

Section 3 presents the installation procedure. The way the program runs is illustrated with an example.

Finally, the fortran source is listed in an appendix.

SECTION 2

MUMOID USER'S GUIDE

2.1 Program Description

MUMOID is a program for the identification of the modal parameters of a linear structural system, from the accelerograms recorded at the base and at some upper level of the structure.

A time varying equivalent linear system can be found for nonlinear systems, by dividing the recorded accelerograms in a series of time windows that may overlap or not.

The procedure for Maximum Likelihood Estimation of the modal parameters was described by DiPasquale and Cakmak in Reference [1]. The structure is modeled as an n degree of freedom linear system with a measured earthquake ground motion. The sources of uncertainty are considered to be unmeasured exitation due to other effects, and the observation error. The modal parameters are found maximizing the likelihood function.

The program begins reading the input and output acceleration records. After that, it is decided how many time windows will be used, depending on the length of the records, the length of each time window and the number of windows which overlap.

For each time window, MUMOID computes the sum of the squares of the prediction errors for certain values of the modal parameters. The sum of the squares of the prediction errors is minimized by the IMSL subroutine called ZXMIN, which makes use of a modified Gauss-Newton algorithm.

If with the initial values of modal parameters convergence is not achieved, the process is repeated with the modal parameters that produced convergence in the previous time window. If convergence is still not achieved, the user can input interactively new trial modal parameters. The time window can also be changed.

If the trial values are to far from the solution, the program may stop due to overflow or division by zero errors. In that case, the analysis can be continued by modifying the input file.

2.2 Input

The input file for MUMOID must be named MUMO.PAR. This file must contain the following cards:

Card 1 (A80):

Provide a single card with the job title

Card 2 (A29):

Provide a single card with the file name for the input acceleration (GROUND). The file with the input acceleration is read using free format. The maximum number of sample points is 16000.

Card 3 (A29):

Provide a single card with the file name for the output acceleration (ROOF). The file with the output acceleration is read using free format. The maximum number of sample points is 16000.

Card 4 (9I5):

Columns 1 - 5: Number of modes in the model (NM).
The maximum number of modes is five. The most adequate number of modes in most cases is two.

Columns 6 - 10: Initial sample point of the time window (ISTART).

The lowest value of ISTART that should be used is four, because the previous sample points are used to evaluate the initial conditions.

Columns 11 - 15: Number of sample points in the time window (IDELTA).

IDELTA should be chosen so that the length of the time window is on the order of two or two and a half times the initial natural period. A smaller time window makes convergence difficult and may yield a negative estimate of the damping ratios. Larger time windows produce too much smoothing of the varying natural period.

Columns 16 - 20: Time shift between the two records expressed as the number of sample points (NLAG).

This input variable accounts for the fact that actual acceleration records may be not synchronized due to malfunctioning of the triggering devices or to digitalization errors.

Columns 21 - 25: Code for new analysis or continuation of a previous one (INEW).

0 : Continuation of a previous analysis. The results are appended to the existing file named "fper.res" (See Section 2.3).

1 : A new analysis is started. A new file named "fper.res" is created (See Section 2.3).

Columns 26 - 30: Code for subtraction of the mean (IMEAN).

0 : The modal parameters are identified from the given input and output acceleration.

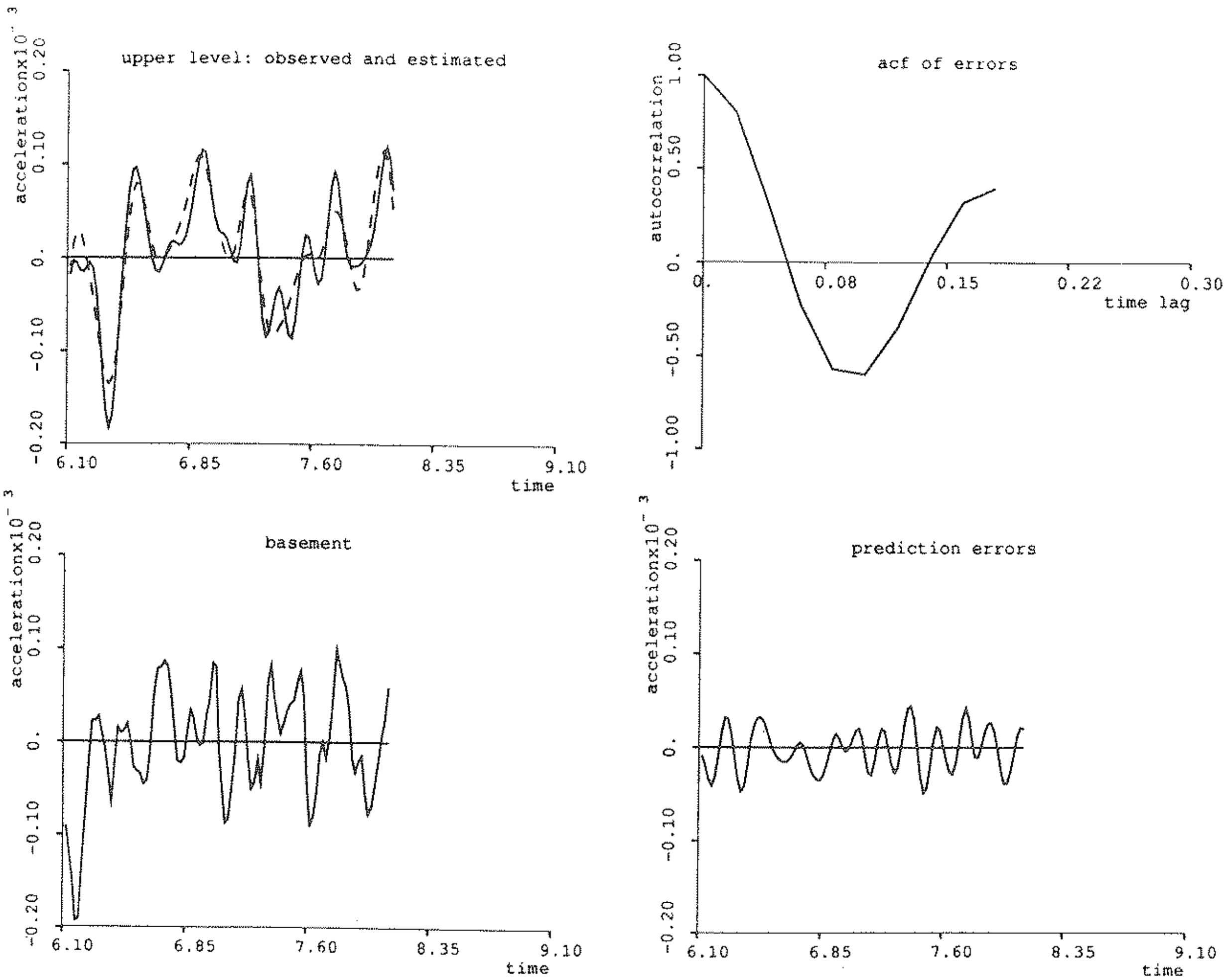

FIGURE 2-1 Graphic Output

1 : The mean of the given input and output acceleration is subtracted from the given input and output acceleration before the identification of the modal parameters takes place.

Columns 31 - 35: Number of overlapping windows (NOVERLAP).
When NOVERLAP is equal to one, each sample point is only in one window and there is no overlapping between windows, if NOVERLAP is equal to two each point is in two windows, etc.

Columns 36 - 40: Code for absolute or relative top level acceleration (NABS).

0 : The output acceleration at the top level is considered to be relative acceleration to the ground.

1 : The output acceleration at the top level is considered to be an absolute acceleration.

Columns 41 - 45: Code for graphics (IGRAPH)

0 : No graphic output is obtained

1 : A graphic output is obtained if the appropriate subroutine called EAGRA is available. Figure 2-1 shows an example of the graphic output.

Card 5 (F10):

Sampling interval in units of time for the input and output acceleration.

Cards 6 to 5+NM (3F10.0):

Initial values for the modal parameters of each mode:

Columns 1 - 10: Damping ratio (CSI(I))

Columns 11 - 20: Angular frequency (OM(I))

Columns 21 - 30: Participation factor (PART(I)).

It usually has a value between 1.2 and 1.5. A good trial value is 1.4. This value does not need to be input for the last mode, since all the participation factors add to one.

2.3 Output

The output of the program MUMOID consist of the following files:

"modes.res":

Contains a list of the estimated modal parameters for each time window. The covariance matrix, the variance of the error, the estimated natural period and its variance are also included.

"fper.res":

Contains a table with four columns for each time window. The first one is time at the time window's middle point, the second one is the length of the time window, the third one is the estimated natural period, and the fourth and last column is the standard deviation of the estimated natural period.

"damage":

This file is written after the estimation of the modal parameters for all the time windows in which the acceleration record is divided, is completed. When the computation stops before the end, the file "damage" may be obtained by using the program "DAMAGE" that computes the damage indices and the probability of damage. The input for the program "DAMAGE" consist of a file with the information contained in "fper.res". An interactive input of the initial, final and maximum natural period, plus their standard deviations, is also possible. The file "damage" includes the values of the following variables:

1. Maximum Softening, δ_M, given by Equation (1.1)

2. Maximum Softening Squared, δ_M^2, given by:

$$\delta_M^2 = 1 - \frac{T_0^2}{T_{max}^2} \tag{2.1}$$

where,

δ_M : Maximum Softening

T_0 : Initial natural period

T_{max} : Maximum natural period of an equivalent linear system

3. Final Softening, δ_F, given by:

$$\delta_F = 1 - \frac{T_0^2}{T_{final}^2} \tag{2.2}$$

where,

T_{final} : Final natural period

4. Plastic Softening, δ_P, given by:

$$\delta_P = 1 - \frac{T_{final}^2}{T_{max}^2} \tag{2.3}$$

5. Probability of Damage, P, according to Reference [DIPAS2] given by:

$$P = \int_{\frac{1-I}{\sigma_I}}^{\infty} \frac{1}{\sqrt{2\pi}} \, e^{-\frac{x^2}{2}} \, dx \tag{2.4}$$

where,

$\bar{I} = \bar{\alpha} + \bar{\beta}\bar{\delta}_M$

$\bar{\alpha} = -1.081$

$\bar{\beta} = \;\; 4.813$

$\bar{\delta}_M$ = Maximum Softening

$$\sigma_I = \sigma_\alpha^2 + \sigma_\beta^2\sigma_\delta^2 + \bar{\beta}^2\sigma_\delta^2 + \bar{\delta}_M^2\sigma_\beta^2$$
$$\sigma_\alpha = 0.260$$
$$\sigma_\beta = 0.446$$
$$\sigma_\delta = \bar{\delta}_M\left(\frac{\sigma_{T_0}}{T_0} + \frac{\sigma_{T_{max}}}{T_{max}}\right)$$

6. Initial natural period (TZERO INITIAL) and its standard deviation:

   It is the estimated natural period for the first time window. Its value can be interactively changed, if other sources of information about the initial natural period are available.

7. Maximum natural period (TZERO MAX) and its standard deviation:

   Maximum value of the natural period's estimations, used for the computation of the Maximum and Plastic Softening. See Equations (1.1) and (2.3).

8. Final natural period (TZERO FINAL):

   Is the estimated natural period for the last time window. Used for the computation of the Final Softening. See Equation (2.2).

2.4 Error Messages

The following error messages from the IMSL routines may appear on the screen:

```
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
```

This error implies that the initial Hessian used by the routine ZXMIN is not positive definite, even after adding a multiple of the identity to make all diagonal terms positive. When this occurs convergence can not be achieved and new trial values are necessary. First, the estimated modal parameters for the previous time window are used (if a previous time window exits). If those values do not produce convergence, the user has to provide new trial values. It will be seen later, that in some cases a "division by zero" error may occur after this error. In that case the program stops, and it is necessary to run it again after modifying the file MUMO.PAR in such a way that the computation continues on the problematic time window with different trial values.

```
*** TERMINAL ERROR            (IER = 130) FROM IMSL ROUTINE ZXMIN
```

This error implies that the the iteration was terminated due to rounding errors becoming dominant. The parameter estimates have been determined with less than three digits. The program does not stop, therefore, the user should judge the value of the results. The value of the standard deviation of the natural period gives an indication of the error involved.

If the trial values are to far from the solution, the program may stop due to overflow or division by zero errors. In that case, the analysis can be continued by modifying the input file MUMO.PAR so that INEW is equal to zero and ISTART has the value corresponding to the problematic time window. New trial values must be introduced.

SECTION 3
INSTALLATION AND EXECUTION

3.1 Installation

MUMOID is written in Fortran-77 language and has been successfully installed on VAX computer systems. All the calculations are performed in double precision. MUMOID calls several IMSL subroutines [4] that are not listed in the appendix because the IMSL library is proprietary.

The procedure to install MUMOID in a Micro-Vax II is listed below:

```
f77 -c -O  MUMOID.f
f77 -o MUMOID MUMOID.o -limsl
```

3.2 Example

In this section the way the program is executed is illustrated with an example. The modal parameters of a four story three bay building are identified from its nonlinear response. A computer model was used for the computation of the response in this case, but the procedure is equally applied in the case of a recorded response.

The input ground motion is an artificially generated earthquake sampled at intervals of 0.02 seconds. The input acceleration time history is in a file called "s.088.acb". This file has a total of 1250 lines, corresponding to a duration of the earthquake of 25 seconds. The beginning and end of this file are as follows:

```
 -3.85519
 -3.69502
 -3.42330
```

3 BAYS 4 STORIES ARTIFICIAL QUAKE (M 8.8 , D 10 km)

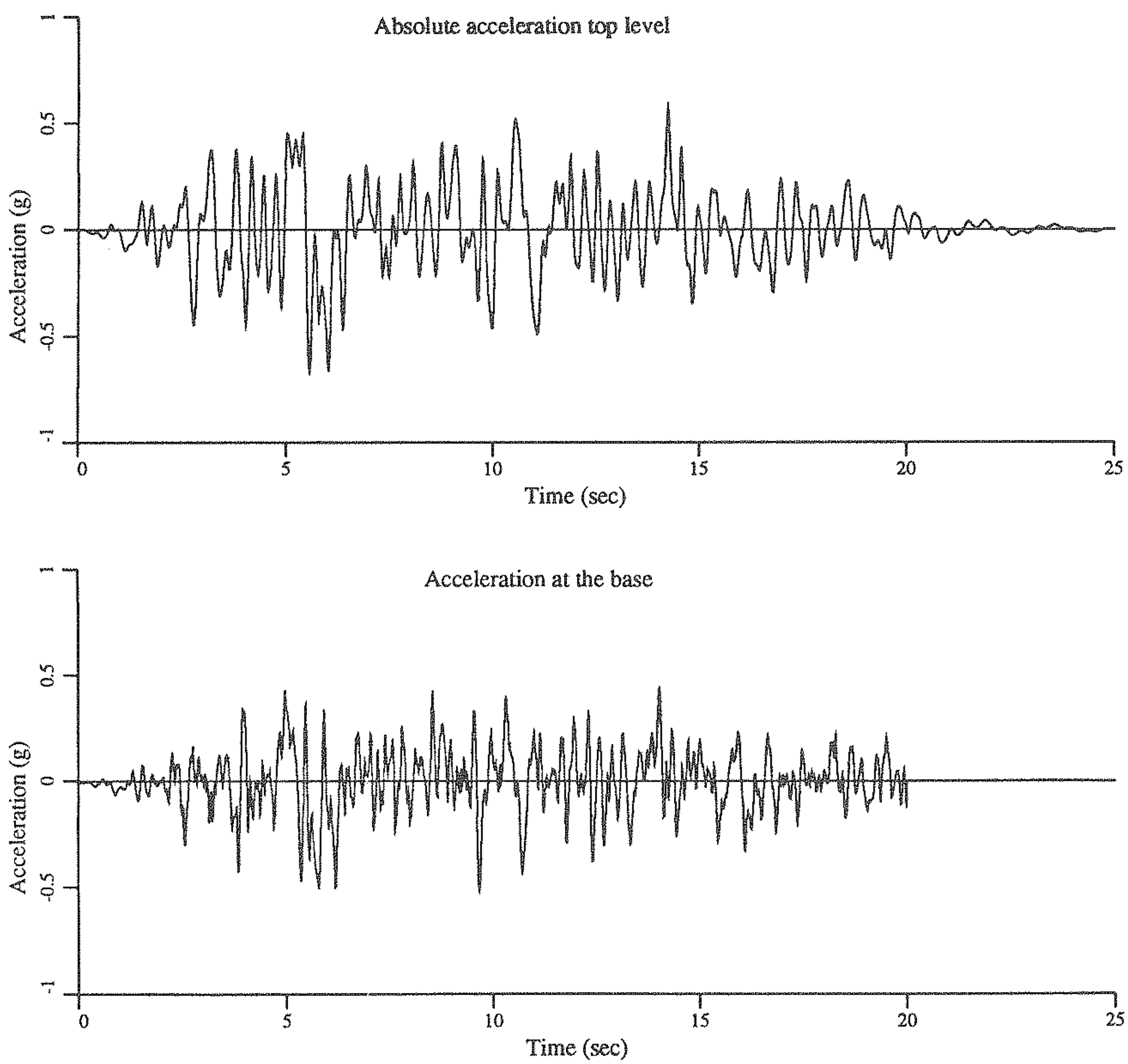

FIGURE 3-1 Input and Output Acceleration

```
-3.14241
-2.96653
. . . . . .
0.
0.
0.
```

The output acceleration in this case is the acceleration of the top level of the building, and is in a file called "s.088.act". The beginning and end of this file with a total of 1250 lines are as follows:

```
 3.83959
 3.63715
 3.31873
 3.08887
 3.14179
 3.93013
. . . . . .
0.192492
0.132576
0.209899
0.419071
0.737268
```

The input and output acceleration are shown in figure 3-1. The input file, called "MUMO.PAR" is as follows:

```
3 BAYS 4 STORIES   ARTIFICIAL QUAKE  (M 8.8 , D 10 km)
s.088.acb
s.088.act
    2    5  100    0    1    0    1    0    0
    0.020
    0.05    7.00    1.40
    0.05   22.00
```

The meaning of the entries in this input file was explained in Section 2.2. The most relevant aspects are described now. The modal parameters are identified for the first two modes. Two seconds nonoverlapping time windows are used, starting the identification procedure 0.1 seconds after the beginning of the records. No time shift is considered between the input and output acceleration, because the output acceleration was obtained by means of a computer program. The mean of the given input and output is not subtracted from them for the same reason. The sampling interval was 0.02 seconds. The starting trial values for the modal parameters were obtained from a structural evaluation of the computer model.

The program has to be run interactively, since new trial values for the modal parameters can be necessary.

The program runs typing the name of the executable "MUMOID". After that, the trial values of the modal parameters are displayed, first the damping ratios for all the modes, then the angular frequencies and finally the participation factors:

```
0.5000e-01   0.5000e-01   0.7000e+01   0.2200e+02   0.1400e+01
```

The identification procedure is applied to the various time windows in which the time history is divided. The starting and final sample points of each window are prompted as the calculation progresses:

```
 5   105
 105   205
 205   305
```

During the analysis of the third time window this message is obtained:

```
  *** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
 Double complex division by zero
 *** Execution terminated
```

The file "MUMO.PAR" is changed in this way:

```
 3 BAYS 4 STORIES   ARTIFICIAL QUAKE  (M 8.8 , D 10 km)
 s.088.acb
 s.088.act
     2  205  100    0    0    0    1    0    0
     0.020
     0.05     5.00     1.40
     0.05    22.00
```

The program is run again typing "MUMOID", but the new trial parameters do not produce convergence. The following message is obtained:

```
 0.5000e-01   0.5000e-01   0.5000e+01   0.2200e+02   0.1400e+01
205  305
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN

BOTH THE ORIGINAL AND THE LATEST VALUES FOR
THE PARAMETERS DO NOT WORK IN THE INTERVAL
TINITIAL=       4.10
TFINAL  =       6.10
DO YOU WANT TO CONTINUE? (Y/N)
Y
DO YOU WANT TO CHANGE THE WINDOW? (Y/N)
N
DO YOU WANT TO CHANGE THE STARTING GUESS? (Y/N)
Y
```

There is the choice of changing the window or providing directly new starting guesses. The use of a time window overlapped with the previous one may produce convergence with starting guesses similar to the estimated parameters in the previous window. This gives an indication of the changing in the modal parameters. In this case, after trial and error, the following values were provided:

```
WRITE THE NEW PARAMETERS MODE BY MODE
.4
4.9
1.45
```

```
.07

22.4
```

The computation continued till the end, with the following on-line messages:

```
 305  405
 405  505
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
 505  605
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
 605  705
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
*** TERMINAL ERROR          (IER = 130) FROM IMSL ROUTINE ZXMIN
 705  805
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
 805  905
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
 905  1005
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
 1005  1105
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
*** TERMINAL ERROR          (IER = 130) FROM IMSL ROUTINE ZXMIN
 1105  1205
*** TERMINAL ERROR          (IER = 129) FROM IMSL ROUTINE ZXMIN
```

After the last time window, before the computation of the probability of damage begins, there is the choice of giving a value for the initial natural period, otherwise the natural period estimated for the first time window is used:

```
TZERO INITIAL=  0.843740
DO YOU WANT TO CHANGE IT ? (Y/N)
N
```

The results are in the file "modes.res", of which the beginning and the end are shown:

```
 3 BAYS 4 STORIES   ARTIFICIAL QUAKE  (M 8.8 , D 10 km)


 INITIAL INSTANT              4.10
 FINAL INSTANT                6.10
 WINDOW WIDTH                 2.02


 NUMBER OF MODES              2
 NUMBER OF PARAMETERS         5
 TIME SHIFT                   0


MODE NO.   DAMPING FACTOR   ANGULAR FREQUENCY  PARTICIPATION FACTOR
     1          0.4219e+00          0.4871e+01          0.1448e+01
     2          0.6981e-01          0.2237e+02         -0.4476e+00


 VARIANCE OF THE ERROR        0.1341e+04


 COVARIANCE MATRIX (SIX ELEMENTS PER LINE)
```

0.5723e-02	0.2338e-03	-0.1724e-01	0.4958e-02	0.3137e-02
0.2338e-03	0.5390e-04	-0.1354e-02	-0.4301e-03	0.1195e-03
-0.1724e-01	-0.1354e-02	0.9590e-01	-0.7721e-02	-0.8268e-02
0.4958e-02	-0.4301e-03	-0.7721e-02	0.9789e-01	0.5673e-02
0.3137e-02	0.1195e-03	-0.8268e-02	0.5673e-02	0.3468e-02

FUNDAMENTAL PERIOD TZERO 1.29258

STANDARD DEVIATION OF TZERO 0.08202

. . . .

3 BAYS 4 STORIES ARTIFICIAL QUAKE (M 8.8 , D 10 km)

INITIAL INSTANT 22.10

FINAL INSTANT 24.10

WINDOW WIDTH 2.02

NUMBER OF MODES 2

NUMBER OF PARAMETERS 5

TIME SHIFT 0

MODE NO.	DAMPING FACTOR	ANGULAR FREQUENCY	PARTICIPATION FACTOR
1	0.9093e-01	0.3599e+01	0.1383e+01
2	0.3562e-01	0.1526e+02	-0.3830e+00

```
VARIANCE OF THE ERROR        0.3700e-01


COVARIANCE MATRIX (SIX ELEMENTS PER LINE)


   0.1688e-05   0.6245e-06   0.3799e-06   0.5859e-06   0.0000e+00

   0.6245e-06   0.7098e-06   0.2262e-05   0.4149e-05   0.0000e+00

   0.3799e-06   0.2262e-05   0.8914e-04   0.3444e-04   0.0000e+00

   0.5859e-06   0.4149e-05   0.3444e-04   0.4278e-03   0.0000e+00

   0.0000e+00   0.0000e+00   0.0000e+00   0.0000e+00   0.1960e-03


FUNDAMENTAL PERIOD TZERO        1.74568

STANDARD DEVIATION OF TZERO     0.00458
```

And in the file "fper.res":

```
3 BAYS 4 STORIES   ARTIFICIAL QUAKE  (M 8.8 , D 10 km)
   1.10000   2.00000   0.84374   0.00289
   3.10000   2.00000   0.84968   0.00364
   5.10000   2.00000   1.29258   0.08202
   7.10000   2.00000   1.16281   0.03392
   9.10000   2.00000   1.20824   0.02659
  11.10000   2.00000   1.32501   0.01805
  13.10000   2.00000  39.30780  11.09053
  15.10000   2.00000   1.46232   0.04094
  17.10000   2.00000   1.76910   0.12317
  19.10000   2.00000   2.01625   0.05336
```

```
   21.10000    2.00000    1.76128    0.08144
   23.10000    2.00000    1.74568    0.00458
```

The meaning of this table was explained in a Section 2.3. It can be seen by looking at the file "fper.res", that the standard deviation of the natural period for the time window centered around the time equal to 13.1 seconds is too large. The analysis of the time window between 12.1 and 14.1 seconds is repeated using the following input file "MUMO.PAR":

```
3 BAYS 4 STORIES   ARTIFICIAL QUAKE  (M 8.8 , D 10 km)
s.088.acb
s.088.act
    2  605  100    0    0    0    1    0    0
  0.020
    0.20    4.80    1.45
    0.09   18.50
```

A new file "fper.res" is obtained, after eliminating the old line corresponding to the time window between 12.1 and 14.1 seconds:

```
3 BAYS 4 STORIES   ARTIFICIAL QUAKE  (M 8.8 , D 10 km)
    1.10000    2.00000    0.84374    0.00289
    3.10000    2.00000    0.84968    0.00364
    5.10000    2.00000    1.29258    0.08202
    7.10000    2.00000    1.16281    0.03392
    9.10000    2.00000    1.20824    0.02659
   11.10000    2.00000    1.32501    0.01805
   13.10000    2.00000    1.63382    0.06917
```

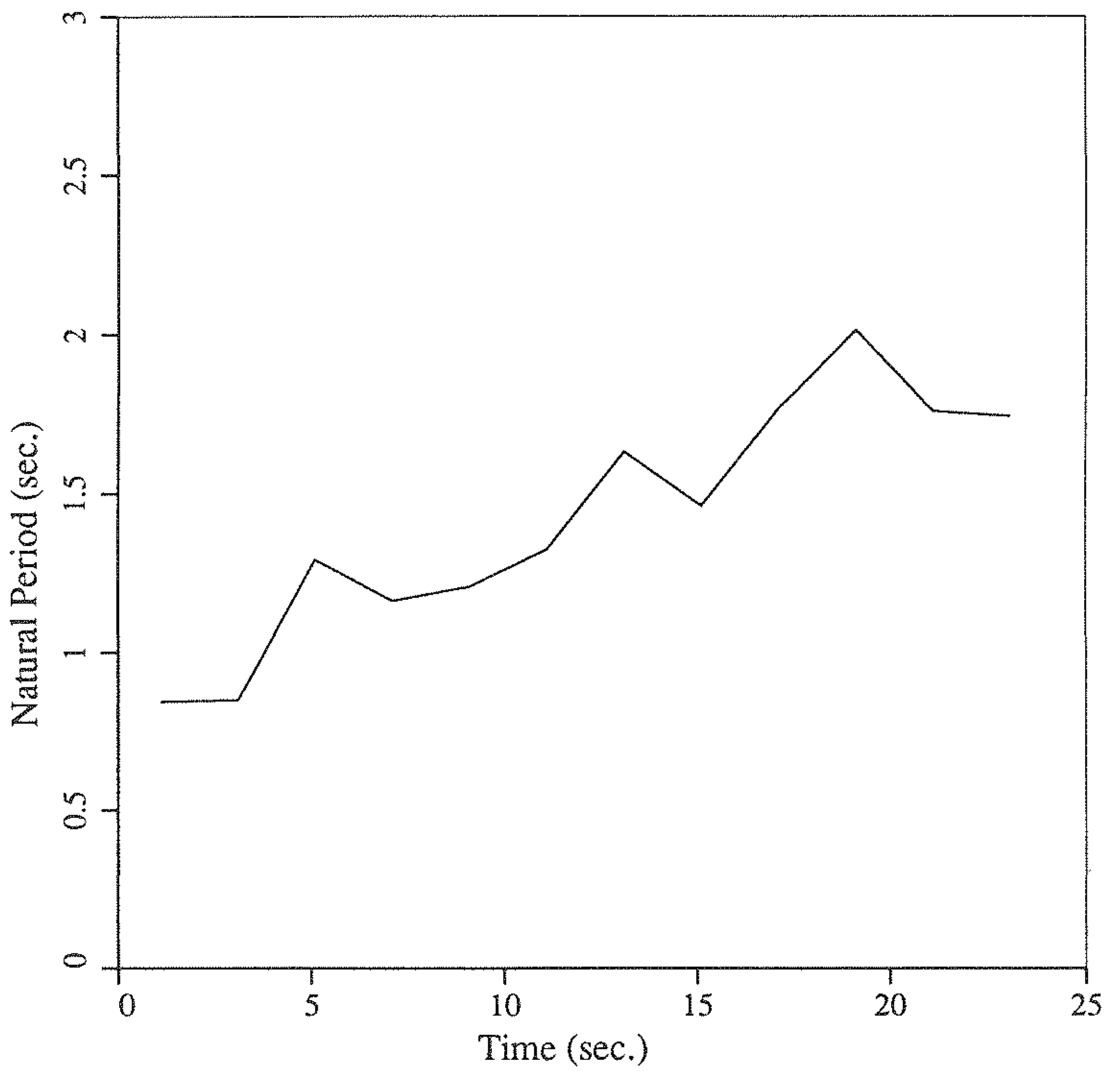

FIGURE 3-2 Natural Period of an Equivalent Linear System

15.10000	2.00000	1.46232	0.04094
17.10000	2.00000	1.76910	0.12317
19.10000	2.00000	2.01625	0.05336
21.10000	2.00000	1.76128	0.08144
23.10000	2.00000	1.74568	0.00458

Figure 3-2 shows the evolution of the natural period of an equivalent linear system obtained from the file "fper.res".

A file called "damage" with the damage indices and probability of damage, is obtained after the analysis of all the time windows. When there is an interruption in the calculation, as in the example presented herein, the damage indices have to be recomputed using the program "DAMAGE". A transcript of a session running the program "DAMAGE" with the file "fper.res" as the input file is now presented:

```
tremor:(example) 51 % DAMAGE


 COMPUTATION OF DAMAGE INDICES

     ARE THE DATA IN A FILE ? (Y/N)

Y

    WRITE  FILE NAME

fper.res

  TZERO INITIAL=  0.843740

  DO YOU WANT TO CHANGE IT ? (Y/N)

N
```

The file named "damage" that was obtained is:

3 BAYS 4 STORIES ARTIFICIAL QUAKE (M 8.8 , D 10 km)

TZERO INITIAL	0.84374
STANDARD DEVIATION	0.00289
TZERO MAX	2.01625
STANDARD DEVIATION	0.05336
TZERO FINAL	1.74568
MAXIMUM SOFTENING	0.58153
MAXIMUM SOFTENING(SQ)	0.82488
FINAL SOFTENING	0.76639
PLASTIC SOFTENING	0.25038
PROBABILITY OF DAMAGE	1.00000

SECTION 4

REFERENCES

[1] DiPasquale, E. and Cakmak, A.S., "Detection and Assessment of Seismic Structural Damage", NCEER-87-0015, National Center for Earthquake Engineering Research, State University of New York at Buffalo, 1988.

[2] DiPasquale, E. and Cakmak, A.S., "Identification of the Serviceability Limit State and Detection of Seismic Structural Damage", NCEER-88-0022, National Center for Earthquake Engineering Research, State University of New York at Buffalo, 1988.

[3] DiPasquale, E. and Cakmak, A.S., "On the Relation Between Local and Global Damage Indices", NCEER-89-0034, National Center for Earthquake Engineering Research, State University of New York at Buffalo, 1989.

[4] IMSL Library, "User's Manual, FORTRAN Subroutines for Mathematics and Statistics", Volume 1 to 4, IMSL, Inc, Houston, Texas, June 1982.

APPENDIX A

FORTRAN SOURCE LISTING OF THE PROGRAM MUMOID

```
C ---------------------------------------------------------------------
C
C       MUMOID IS A PROGRAM FOR THE IDENTIFICATION
C       OF STRUCTURAL PARAMETERS FROM EARTHQUAKE RECORDS
C       OF THE MOTION OF THE BASEMENT AND OF SOME UPPER LEVEL
C
C       WRITTEN BY: EDMONDO DI PASQUALE AND SANTIAGO RODRIGUEZ-GOMEZ
C                   DEPT. OF CIVIL ENGINEERING
C                   PRINCETON UNIVERSITY
C       MARCH 5, 1987
C
C       LAST MODIFICATION JULY 1990
C
C       THE PARAMETERS IDENTIFIED ARE
C       DAMPING FACTORS
C       NATURAL FREQUENCIES
C       PARTICIPATION FACTORS
C       FOR EACH OF THE NM MODES THE USER SEEKS (MAXIMUM FIVE)
C
C       THE PROCEDURE USED IS MAXIMUM LIKELIHOOD ESTIMATION
C       THE LIKELIHOOD FUNCTION IS WRITTEN IN TERMS OF THE MODAL
C       PARAMETERS
C
C       THE PROGRAM EXPECTS AN INPUT FILE 'MUMO.PAR'
C
C       THE PROGRAM GENERATES A DATABASE FOR TREMOR GRAPHICS
C       ROUTINES THROUGH THE SUBROUTINE EAGRA IN FILE eaq.graphcomm
C       AND A DATA OUTPUT IN THE FILES:
C                                       'modes.res'
C                                       'fper.res'
C                                       'damage'
C
C
C ---------------------------------------------------------------------
C
C             REQUIRES THE FOLLOWING ROUTINES FROM
C               THE IMSL LIBRARY (1980 VERSION):
C
C                ZXMIN, LEQT1F, LINV1P AND MDNOR
C
C----------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      CHARACTER*1 ACONT
      CHARACTER*80 COMMA
      CHARACTER*80 TITLE
      CHARACTER*29 GROUND,ROOF
      EXTERNAL FUNLINO
C
      COMMON/NMODES/NM
```

```
      COMMON/EAQUA/U(16000),Y(16000),E(16000)
      COMMON/CONLIK/ICON
      COMMON/WINDOW/ISTART,IFIN
      COMMON/SAMP/DT
      COMMON/ERR/IIER
C
      DIMENSION PAR(24),XGUESS(24),PAROLD(24),
     X          G(24),H(300),W(500)
C
      OPEN (24,FILE='MUMO.PAR',STATUS='OLD')
      READ(24,997) TITLE
      READ(24,999) GROUND
      READ(24,999) ROOF
      READ(24,1000) NM,ISTART,IDELTA,NLAG,INEW,IMEAN,NOVERLAP
     X              ,NABS,IGRAPH
      IF (NOVERLAP .LE. 0) NOVERLAP=1
      CALL MUMOSET (TITLE,GROUND,ROOF,IGRAPH)
C     READ(20,*) NT
      NT=16000
      READ(20,*,END=17,ERR=17)(U(I),I=1,NT)
C     READ(22,*)NT
 17   READ(22,*,END=19,ERR=19)(Y(I),I=1,NT)
 19   NM1=NM-1
      NT=I-1
      IF(NABS .EQ. 1) GOTO 18
      DO 29 II=1,NT
 29   Y(II)=Y(II)+U(II)
 18   N=3*NM-1
      NH=N*(N+1)/2
      READ(24,1020) DT
      IF (NM.EQ.1) GOTO 25
      DO 20 I=1,NM1
   20 READ(24,1020) XGUESS(I),XGUESS(NM+I),XGUESS(2*NM+I)
   25 READ(24,1020) XGUESS(NM),XGUESS(2*NM)
C
      NT=NT-IABS(NLAG)
      IF(NLAG.EQ.0) GOTO 60
      IF (NLAG.LT.0) GOTO 40
      DO 30 I=1,NT
   30 Y(I)=Y(I+NLAG)
      GOTO 60
   40 DO 50 I=1,NT
   50 U(I)=U(I-NLAG)
   60 CONTINUE
C
      WRITE(6,1010) (XGUESS(I),I=1,N)
C
      NWIND=(NT-ISTART)/IDELTA
      NWIND=NOVERLAP*(NWIND-1)+1
C
      DO 1 IWIND=1,NWIND
      IFIN=ISTART+IDELTA
      WRITE(6,*) ISTART,IFIN
C
      IF (IMEAN.EQ.1) CALL ZERMEA
C
   72 DO 71 I=1,N
      PAR(I)=XGUESS(I)
```

```
   71 CONTINUE
      NSIG=3
      MAXFN=1000
      IOPT=3
      CALL ZXMIN(FUNLINO,N,NSIG,MAXFN,IOPT,PAR,H,G,V,W,IER)
C
      IF (IER.NE.129) GOTO 80
      IF (IWIND.EQ.1) GOTO 80
      DO 74 I=1,N
      PAR(I)=PAROLD(I)
   74 CONTINUE
C
      CALL ZXMIN(FUNLINO,N,NSIG,MAXFN,IOPT,PAR,H,G,V,W,IER)
C
   80 CONTINUE
      IF (IER.EQ.129 .OR. IIER.EQ.1) THEN
      WRITE(6,2000) DT*ISTART, DT*IFIN
      READ(5,991) ACONT
      IF (ACONT.EQ.'N') STOP
      WRITE(6,2005)
      READ(5,991) ACONT
      IF(ACONT.EQ.'Y') THEN
      WRITE(6,2006)
      READ(5,*) TST,TFI
      ISTART=INT(TST/DT)
      IFIN=INT(TFI/DT)
      WRITE(6,2007) ISTART,IFIN
      ENDIF
      WRITE(6,2008)
      READ(5,991) ACONT
      IF(ACONT.EQ.'Y') THEN
      WRITE(6,2010)
      IF (NM.EQ.1) GOTO 82
      DO 81 I=1,NM1
   81 READ(5,*) XGUESS(I),XGUESS(NM+I),XGUESS(2*NM+I)
   82 READ(5,*) XGUESS(NM),XGUESS(2*NM)
      ENDIF
C
      GOTO 72
      ENDIF
C
      IF(IGRAPH .EQ. 0) GOTO 111
      CALL EAGRA(U(ISTART+1),Y(ISTART+1),E(ISTART+1),W(1),W(401),
     XW(411),DT,ISTART,IFIN,TITLE)
      COMMA='plots -input eaq.graphcomm > junk'
      ICO=SYSTEM(COMMA)
C
  111 CALL COVAL(PAR,V,N,NM,NLAG,NH,H,W(1),W(NH+1),DT,ISTART,IFIN,
     X           TITLE,INEW,W(NH+N+1))
C     ICO=SYSTEM('lpr modes.res')
C
      ISTART=ISTART+IDELTA/NOVERLAP
      DO 85 I=1,N
      PAROLD(I)=PAR(I)
   85 CONTINUE
    1 CONTINUE
      CALL DAMIND('fper.res')
      STOP
```

```
  991 FORMAT(A1)
  997 FORMAT(A80)
  998 FORMAT(A80)
  999 FORMAT(A19)
 1000 FORMAT(10I5)
 1010 FORMAT(5E13.4)
 1020 FORMAT(10F10.0)
 2000 FORMAT(/,'BOTH THE ORIGINAL AND THE LATEST VALUES FOR',/,
     X'THE PARAMETERS DO NOT WORK IN THE INTERVAL',/,
     X'TINITIAL=     ',F7.2,/,
     X'TFINAL  =     ',F7.2,/,
     X'DO YOU WANT TO CONTINUE? (Y/N)')
 2005 FORMAT('DO YOU WANT TO CHANGE THE WINDOW? (Y/N)')
 2006 FORMAT(/,'WRITE THE NEW WINDOW')
 2007 FORMAT(/,'NEW ISTART= ',I5,/'NEW IFIN= ',I5)
 2008 FORMAT('DO YOU WANT TO CHANGE THE STARTING GUESS? (Y/N)')
 2010 FORMAT(/,'WRITE THE NEW PARAMETERS MODE BY MODE')
      END
C
      SUBROUTINE CHANGE(ALFA,N,WK)
C ----------------------------------------------------------------------
C                REARRANGE THE COEFFICIENTS ALFA
C ----------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION ALFA(1),WK(1)
      DO 10 I=1,N
   10 WK(N-I+1)=ALFA(I)
      DO 20 I=1,N
   20 ALFA(I)=WK(I)
      RETURN
      END
      SUBROUTINE CLEAR(A,N)
C ----------------------------------------------------------------------
C    SET A DOUBLE PRECISION ARRAY TO ZERO
C ----------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(1)
      DO 10 I=1,N
   10 A(I)=0.D0
      RETURN
      END
C
      SUBROUTINE COFCAR(CSI,OM,ALFA,N,DT,AVAN,WK)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION CSI(1),OM(1),ALFA(1),AVAN(N,1)
C
      NM=N/2
      CALL CLEAR(AVAN,N*N)
C
      DO 50 I=1,NM
      AVAN(2*I-1,1)=1.D0
      SC=DSQRT(1.D0-CSI(I)*CSI(I))
      DO 40 J=2,N
      J1=J-1
      ESP=DEXP(-CSI(I)*OM(I)*DT*DFLOAT(J1))
      ANG=OM(I)*DT*DFLOAT(J1)*SC
      AVAN(2*I-1,J)=ESP*DCOS(ANG)
      AVAN(2*I  ,J)=ESP*DSIN(ANG)
```

```
   40 CONTINUE
      ESP=DEXP(-CSI(I)*OM(I)*DT*DFLOAT(N))
      ANG=OM(I)*DT*FLOAT(N)*SC
      ALFA(2*I-1)=-ESP*DCOS(ANG)
      ALFA(2*I  )=-ESP*DSIN(ANG)
   50 CONTINUE
      IDGT=8
      CALL LEQT1F(AVAN,1,N,N,ALFA,IDGT,WK,IER)
      RETURN
      END
      SUBROUTINE COMCLE(Z,N)
C -------------------------------------------------------------------
C      ZEROES AN ARRAY OF COMPLEX NUMBERS
C --------------------------------------------------------------------
      COMPLEX*16 Z(1)
      DO 10 I=1,N
   10 Z(I)=(0.D0,0.D0)
      RETURN
      END
C
C---------------------------------------------------------------------
C
      SUBROUTINE COMP(TITLE,TMAX,STMAX,TINI,STINI,TFIN)
      CHARACTER*80 TITLE
40    SMAX= 1.- TINI/TMAX
      SMAX2=1.- (TINI/TMAX)**2
      SFIN =1.- (TINI/TFIN)**2
      SPLAS=1.- (TFIN/TMAX)**2
      SDELTA= SMAX*(STINI/TINI + STMAX/TMAX)
      ALFA  = -1.081
      SALFA = .26
      BETA  =  4.813
      SBETA = .446
      SI = SALFA**2+(SBETA*SDELTA)**2+(BETA*SDELTA)**2+(SMAX*SBETA)**2
      XI = ALFA + BETA*SMAX
C     PDAM = 1. - ANORDF((1.-XI)/SI)
      CALL MDNOR((1.-XI)/SI,ANOR)
      PDAM = 1. - ANOR
      WRITE(55,200) TITLE
      WRITE(55,150) TINI,STINI,TMAX,STMAX,TFIN
      WRITE(55,100)SMAX,SMAX2,SFIN,SPLAS,PDAM
C     ICO=SYSTEM('lpr damage')
200   FORMAT (A80)
100   FORMAT (/,"MAXIMUM SOFTENING",4X,F14.5,
     X        /,"MAXIMUM SOFTENING(SQ)",F14.5,
     X        /,"FINAL SOFTENING",6X,F14.5,
     X        /,"PLASTIC SOFTENING",4X,F14.5,
     X        /,"PROBABILITY OF DAMAGE",F14.5)
150   FORMAT (/,/,"TZERO INITIAL",8X,F14.5,
     X           /,"STANDARD DEVIATION",3X,F14.5,
     X           /,"TZERO MAX",12X,F14.5,
     X           /,"STANDARD DEVIATION",3X,F14.5,
     X           /,"TZERO FINAL",10X,F14.5)
      RETURN
      END
      SUBROUTINE COVAL (PAR,V,N,NM,NLAG,NH,H,COV,Z,DT,ISTART,IFIN,TITLE,
     X                  INEW,W)
C -------------------------------------------------------------------
```

```
C      PROCESS THE RESULTS OF THE MODAL IDENTIFICATION
C      AND GENERATES THE OUTPUT TO UNIT 56
C ------------------------------------------------------------------
      IMPLICIT REAL*8 (A-H,O-Z)
      CHARACTER*80 TITLE
      DIMENSION PAR(1),COV(1),Z(1),H(1),W(1)
      DIMENSION CSI(5),OM(5),PART(5)
      DATA PI /3.14159265/
C
C     REWIND 56
      NM1=NM-1
      NT=IFIN-ISTART+1
      TIN=DT*FLOAT(ISTART)
      TFIN=DT*FLOAT(IFIN)
      TWIND=DT*FLOAT(NT)
      DO 1 I=1,NM
    1 CSI(I)=PAR(I)
      DO 2 I=1,NM
    2 OM(I)=PAR(NM+I)
      PART(NM)=1.D0
      IF (NM.EQ.1) GOTO 5
      DO 3 I=1,NM1
    3 PART(I)=PAR(2*NM+I)
      DO 4 I=1,NM1
    4 PART(NM)=PART(NM)-PART(I)
    5 CONTINUE
      WRITE(56,990) TITLE
      WRITE(56,995) TIN,TFIN,TWIND
      WRITE(56,1000) NM
      WRITE(56,1001) N
      WRITE(56,1002) NLAG
      WRITE(56,1010)
      DO 10 I=1,NM
   10 WRITE(56,1020) I,CSI(I),OM(I),PART(I)
      V=V/FLOAT(NT)
      WRITE(56,1030) V
C      INVERT H IN COV
      IDGT=4
      CALL LINV1P (H,N,COV,IDGT,D1,D2,IER)
C      GENERATE THE CORRELATION MATRIX
      DO 50 I=1,NH
   50 COV(I)=2.D0*V*COV(I)
C      PRINT OUT THE COVARIANCE MATRIX
      WRITE(56,1040)
      DO 80 I=1,N
      I1=I-1
      IF (I.EQ.1) GOTO 65
      DO 60 J=1,I1
   60 Z(J)=COV(I*(I+1)/2+J-I)
   65 CONTINUE
      DO 70 J=I,N
   70 Z(J)=COV(I+J*(J-1)/2)
   80 WRITE(56,1050) (Z(J),J=1,N)
C      COMPUTE THE FUNDAMENTAL PERIOD AND ITS VARIANCE
      T0=2.D0*PI/OM(1)
      VT0=COV((NM+1)*(NM+2)/2)
      D1T0=-T0/OM(1)
      D2T0=-D1T0/OM(1)
```

```
      T0=T0+D2T0*VT0/2.D0
      VT0=D1T0*D1T0*VT0
      WRITE(56,1060) T0
      VT0=DSQRT(VT0)
      WRITE(56,1070) VT0
C
      CALL WRIFP(T0,VT0,INEW,TIN,TFIN,TITLE,W(1),W(101),W(201),W(301))
      RETURN
  991 FORMAT(A1)
  990 FORMAT(///,A80)
  995 FORMAT(/,'INITIAL INSTANT',10X,F8.2,/,'FINAL INSTANT',12X,F8.2,/,
     X'WINDOW WIDTH',13X,F8.2)
 1000 FORMAT(/,'NUMBER OF MODES',10X,I5)
 1001 FORMAT('NUMBER OF PARAMETERS',5X,I5)
 1002 FORMAT('TIME SHIFT',15X,I5)
 1010 FORMAT(/,'MODE NO.',1X,'  DAMPING FACTOR    ',1X,
     X'  ANGULAR FREQUENCY  ',1X,'PARTICIPATION FACTOR')
 1020 FORMAT(I6,3E19.4)
 1030 FORMAT(/,'VARIANCE OF THE ERROR',5X,E13.4)
 1040 FORMAT(/,'COVARIANCE MATRIX (SIX ELEMENTS PER LINE) ',/)
 1050 FORMAT(6E13.4)
 1060 FORMAT(/,'FUNDAMENTAL PERIOD TZERO',5X,F10.5)
 1070 FORMAT('STANDARD DEVIATION OF TZERO',F12.5)
      END
C
C-----------------------------------------------------------------------
C
      SUBROUTINE DAMIND
      CHARACTER*80 TITLE
      CHARACTER*1 AA
      DIMENSION TME(100),TW(100),T0(100),ST0(100)
      I=1
      REWIND 54
      READ(54,200) TITLE
 5    READ(54,210,END=20) TME(I),TW(I),T0(I),ST0(I)
      I=I+1
      GO TO 5
20    CONTINUE
      NPER=I-1
      TINI=T0(1)
      STINI=ST0(1)
      TFIN=T0(NPER)
      TMAX=T0(1)
      KMAX=1
      DO 30 J=2,NPER
      IF (T0(J) .LE. TMAX) GO TO 30
      TMAX=T0(J)
      KMAX=J
30    CONTINUE
      STMAX=ST0(KMAX)
50    PRINT* ,"TZERO INITIAL=",TINI
      PRINT* ,"DO YOU WANT TO CHANGE IT ? (Y/N)"
      READ (5,1010) AA
      IF (AA .EQ. "N")  GO TO 80
      IF (AA .NE. "Y") GO TO 50
      WRITE(6,*) 'WRITE TZERO INITIAL AND ITS STANDARD DEVIATION (F10)'
      READ (5,1050) TINI, STINI
80    CALL COMP(TITLE,TMAX,STMAX,TINI,STINI,TFIN)
```

```
200   FORMAT (A80)
210   FORMAT (4F10.4)
1010  FORMAT (A1)
1050  FORMAT (2F10.0)
      RETURN
      END
C
C
C
      SUBROUTINE DIFCOF(A,B,C,CSI,OM,DT,ALFA,BETA,N,OL,ON,WK)
C ------------------------------------------------------------------
C       COMPUTE THE COEFFICIENTS OF THE DIFFERENCE EQUATION
C       FROM THE DISCRETE-TIME SYSTEM (C,A,B)
C ------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(N,1),B(1),C(1),ALFA(1),BETA(1),OL(N,1),ON(N,1),
     X          CSI(1),OM(1),WK(1)
C       COMPUTE THE COEFFICIENTS OF THE CHARACTERISTIC POLYNOMIAL
      CALL COFCAR(CSI,OM,ALFA,N,DT,WK(1),WK(N*N+1))
C       COMPUTE THE TRANSFORMATION MATRIX T TO THE OBSERVABILITY C. F.
      CALL OBSITY(A,C,OL,N,WK)
C       COMPUTE THE INVERSE OF THE NEW OBSERVABILITY MATRIX
      CALL MCOS(ALFA,ON,N)
C       COMPUTE BNEW=ON**-1*OL*B
      CALL VECNEW(ON,OL,B,N,WK)
C     WRITE(6,1010)(ALFA(I),I=1,N)
C       REARRANGE THE BETA COEFFICIENTS
      DO 10 I=1,N
   10 BETA(I)=B(N-I+1)
C       REARRANGE THE COEFFICIENTS IN ALFA
      CALL CHANGE(ALFA,N,WK)
      RETURN
 1010 FORMAT(4E13.4)
      END
      SUBROUTINE DISAPP(CSI,OM,B,AEX,BDI,DT,WK,N)
C ------------------------------------------------------------------
C   COMPUTES THE DISCRETE APPROXIMATION TO A DYNAMIC LINEAR SYSTEM
C ------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION B(1),AEX(N,1),BDI(1),WK(1),CSI(1),OM(1)
      COMPLEX*16 WC(440)
C       COMPUTES THE STATE TRANSITION MATRIX AND ITS INTEGRAL
      NO1=1
      NO2=N*N+1
      NO3=2*N*N+1
      NO4=2*N*N+N+1
      CALL MATEXP(CSI,OM,B,AEX,WK(1),N,DT,WC(NO1),WC(NO2),WC(NO3),
     X            WC(NO4),WK(NO2))
C       COMPUTES THE DISCRETE INPUT VECTOR
      CALL MULMA(WK(1),B,BDI,N,N,1)
      RETURN
 1010 FORMAT(4E13.4)
      END
C
      SUBROUTINE EIGINV(ZI,W,N)
      COMPLEX*16 ZI(N,1),W(1),WCO
      NM=N/2
      CALL COMCLE(ZI,N*N)
```

```
      DO 50 I=1,NM
      WCO=(1.D0,0.D0)/(DCONJG(W(2*I-1))-W(2*I-1))
      ZI(2*I-1,I   )=DCONJG(W(2*I-1))*WCO
      ZI(2*I-1,NM+I)=-WCO
      ZI(2*I  ,I   )=-W(2*I-1)*WCO
      ZI(2*I  ,NM+I)=WCO
   50 CONTINUE
      RETURN
      END
      SUBROUTINE EIGMOD(CSI,OM,N,Z,W)
C      COMPUTE EIGENVALUES AND EIGENVECTORS FROM THE MODAL MODEL
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION CSI(1),OM(1)
      COMPLEX*16 Z(N,1),W(1)
      NM=N/2
      CALL COMCLE(W,N)
      CALL COMCLE(Z,N*N)
      DO 10 I=1,NM
      DRE=-CSI(I)*OM(I)
      DIM=OM(I)*DSQRT(1.D0-CSI(I)*CSI(I))
      W(2*I-1)=DCMPLX(DRE,DIM)
      W(2*I)  =DCMPLX(DRE,-DIM)
      Z(I,2*I-1)=(1.D0,0.D0)
      Z(I,2*I)  =(1.D0,0.D0)
      Z(NM+I,2*I-1)=W(2*I-1)
      Z(NM+I,2*I)  =W(2*I)
   10 CONTINUE
      RETURN
 1010 FORMAT(4E13.4)
      END
C
      SUBROUTINE FIGAT(AEX,AEXI,Z,ZI,W,DT,N)
      IMPLICIT REAL*8(A-H,O-Z)
      COMPLEX*16 Z(N,1),W(1),ZI(N,1)
      DIMENSION AEX(N,1),AEXI(N,1)
      DO 10 I=1,N
      DO 10 J=1,N
      AEX(I,J)=0.D0
      AEXI(I,J)=0.D0
      DO 10 K=1,N
      AEX(I,J)=AEX(I,J)+DREAL(CDEXP(W(K)*DCMPLX(DT,0.D0))*Z(I,K)*
     X         ZI(K,J))
   10 AEXI(I,J)=AEXI(I,J)+DREAL((CDEXP(W(K)*DCMPLX(DT,0.D0))-1.D0)*
     X          Z(I,K)*ZI(K,J)/W(K))
      RETURN
 1010 FORMAT(4E13.4)
      END
C
      SUBROUTINE FUNLINO (N,PAR,V)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/NMODES/NM
      COMMON/EAQUA/U(16000),Y(16000),E(16000)
      COMMON/CONLIK/ICON
      COMMON/WINDOW/ISTART,IFIN
      COMMON/SAMP/DT
C
      DIMENSION PAR(1),
     X          CSI(5),OM(5),PART(5),
```

```
     X          B(10),C(10),
     X          ADI(100),BDI(10),
     X          ALFA(10),BETA(10),
     X          U0(10),Y0(10),E0(10),
     X          WK(1000)
C
C        INITIALIZATION
C
      N2=2*NM
      NM1=NM-1
      DO 10 I=1,NM
   10 CSI(I)=PAR(I)
      DO 20 I=1,NM
   20 OM(I)=PAR(NM+I)
      PART(1)=1.D0
      IF(NM.EQ.1) GOTO 50
      DO 30 I=1,NM1
   30 PART(I)=PAR(2*NM+I)
      PART(NM)=1.D0
      DO 40 I=1,NM1
   40 PART(NM)=PART(NM)-PART(I)
   50 CONTINUE
C     WRITE(58,2000)
 2000 FORMAT(/)
C     WRITE(58,1010)(CSI(I),I=1,NM)
C     WRITE(58,1010)(OM(I),I=1,NM)
C     WRITE(58,1010)(PART(I),I=1,NM)
C     REWIND 58
C
C      GENERATE THE SYSTEM MATRIX
C
      CALL SYSVEC(B,C,CSI,OM,PART,2*NM)
C      COMPUTE THE DISCRETE APPROXIMATION
      CALL DISAPP(CSI,OM,B,ADI,BDI,DT,WK,2*NM)
C      COMPUTE THE COEFFICIENTS OF THE DIFFERENCE EQUATION
      N11=1
      N12=N2*N2+1
      N13=2*N2*N2+1
      CALL DIFCOF(ADI,BDI,C,CSI,OM,DT,ALFA,BETA,2*NM,WK(N11),WK(N12),
     X            WK(N13))
      N11=1
      N12=N11+N2*N2
      N13=N12+N2
      N14=N13+N2
      N15=N14+N2
      N16=N15+N2*N2
      CALL LOURD (Y,U,ISTART,IFIN,ALFA,BETA,N2,E0,Y0,U0,
     X            WK(N11),WK(N12),WK(N13),WK(N14),WK(N15),WK(N16))
C      COMPUTE THE LIKELIHOOD FUNCTION
      CALL LIKFUN(U,Y,E,ALFA,BETA,U0,Y0,E0,NM,ISTART,IFIN,V)
C     WRITE(58,1010) V
C
      RETURN
 1010 FORMAT(4E13.4)
      END
C
      SUBROUTINE LIKFUN(U,Y,E,ALFA,BETA,U0,Y0,E0,NM,ISTART,IFIN,V)
C -----------------------------------------------------------------
```

```
C    COMPUTE THE LIKELIHOOD FCT FOR A GIVEN SET OF PARAMETER
C    ALFA,BETA
C ---------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/ERR/IIER
      DIMENSION U(1),Y(1),E(1),ALFA(1),BETA(1),U0(1),Y0(1),E0(1)
C
      IIER=0
      N=2*NM
      N1=N-1
 2000 FORMAT(2E23.13)
      DO 5 J=1,N
      U0(J)=U(ISTART-J)
      Y0(J)=Y(ISTART-J)
    5 CONTINUE
C
      V=0.D0
C
      DO 30 I=ISTART,IFIN
      E(I)=Y(I)
      DO 10 J=1,N
   10 E(I)=E(I)-ALFA(J)*E0(J)+ALFA(J)*Y0(J)-BETA(J)*U0(J)
C     IF (DABS(E(I)) .LT. 1.D4) THEN
      V=V+E(I)*E(I)
C     ELSE
C     IIER = 1
C     V = 1.D0
C     END IF
      DO 20 J=1,N1
      NJ1=N-J+1
      NJ=N-J
      U0(NJ1)=U0(NJ)
      Y0(NJ1)=Y0(NJ)
   20 E0(NJ1)=E0(NJ)
      U0(1)=U(I)
      Y0(1)=Y(I)
   30 E0(1)=E(I)
C
      V=V/2.D0
      RETURN
 1010 FORMAT(4E13.3)
      END
C
      SUBROUTINE LOURD(Y,U,ISTART,IFIN,ALFA,BETA,N,E0,Y0,U0,
     X                 A,B,ET0,EN,EN0,WK)
C ---------------------------------------------------------------------
C   COMPUTE THE LEAST SQUARE ESTIMATES OF THE INITIAL PREDICTION ERRORS
C ---------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION Y(1),U(1),ALFA(1),BETA(1),E0(1),Y0(1),U0(1),
     X          A(N,1),B(1),ET0(1),EN(1),EN0(N,1),WK(1)
C       INITIALIZATION
      CALL CLEAR(EN,N)
      CALL CLEAR(EN0,N*N)
      CALL CLEAR(ET0,N)
      CALL CLEAR(A,N*N)
      CALL CLEAR(B,N)
      N1=N-1
```

```
      DO 5 I=1,N
    5 ENO(I,I)=1.DO
      DO 7 I=1,N
      UO(I)=U(ISTART-I)
    7 YO(I)=Y(ISTART-I)
C       LOOPVERO
      DO 100 I=ISTART,IFIN
C       COMPUTE ET
      ET=Y(I)
      DO 10 J=1,N
   10 ET=ET-ALFA(J)*ETO(J)+ALFA(J)*YO(J)-BETA(J)*UO(J)
C     WRITE(6,*) I,ET
C       COMPUTE EN
      DO 20 L=1,N
      EN(L)=0.DO
      DO 20 J=1,N
   20 EN(L)=EN(L)-ALFA(J)*ENO(L,J)
C     WRITE(6,1010)(EN(M),M=1,N)
C       COMPUTE A(K,L) AND B(K)
      DO 40 K=1,N
      B(K)=B(K)+ET*EN(K)
      DO 40 L=1,N
   40 A(K,L)=A(K,L)+EN(K)*EN(L)
C       RESET MEMORIES
      DO 50 J=1,N1
      NJ=N-J
      NJ1=N-J+1
      YO(NJ1)=YO(NJ)
      UO(NJ1)=UO(NJ)
      ETO(NJ1)=ETO(NJ)
      DO 50 K=1,N
   50 ENO(K,NJ1)=ENO(K,NJ)
      YO(1)=Y(I)
      UO(1)=U(I)
      ETO(1)=ET
      DO 100 K=1,N
  100 ENO(K,1)=EN(K)
      IDGT=4
      CALL LEQT1F (A,1,N,N,B,IDGT,WK,IER)
      DO 110 I=1,N
  110 EO(I)=-B(I)
      RETURN
 1010 FORMAT(4E13.4)
      END
C
      SUBROUTINE MATEXP(CSI,OM,B,AEX,AEXI,N,DT,Z,ZI,W,WA,WK)
C ---------------------------------------------------------------------
C      COMPUTES THE EXPONENTIAL OF A AND ITS INT FROM 0 TO DT
C ---------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION AEX(N,1),AEXI(N,1),CSI(1),OM(1),B(1),WK(1)
      COMPLEX*16 Z(N,1),ZI(N,1),W(1),WA(1)
C    COMPUTE THE EIGENVALUES AND THE EIGENVECTOR OF A
      CALL EIGMOD(CSI,OM,N,Z,W)
C    COMPUTE THE INVERSE OF THE MATRIX OF EIGENVECTORS
      CALL EIGINV(ZI,W,N)
C     CALL COMCHE(ZI,N,N,6)
C    COMPUTE AEX=PHI**-1 * DIAG(EXP(LAMBDA)) * PHI
```

```
      CALL FIGAT(AEX,AEXI,Z,ZI,W,DT,N)
      RETURN
 1010 FORMAT(4E13.4)
      END
C
      SUBROUTINE MCOS(A,AM,N)
C -------------------------------------------------------------------
C  COMPUTES THE INVERSE OF THE OBSERVABILITY MATRIX
C  FOR THE OBSERVER CANONICAL FORM
C -------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(1),AM(N,1)
      DATA UNO/1.DO/
      CALL CLEAR(AM,N*N)
      N1=N-1
      DO 10 K=1,N1
      DO 10 L=1,K
      AM(K-L+1,L)=A(K+1)
   10 CONTINUE
      DO 20 I=1,N
      AM(N-I+1,I)=UNO
   20 CONTINUE
      RETURN
      END
C
      SUBROUTINE MULMA (A,B,C,L,M,N)
C   COMPUTES C=A*B
C   L=NO OF ROWS IN A
C   N=NO OF COLUMNS IN B
C   M=COMMON DIMENSION
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(L,1),B(M,1),C(L,1)
      DO 10 I=1,L
      DO 10 J=1,N
      C(I,J)=0.DO
      DO 10 K=1,M
   10 C(I,J)=C(I,J)+A(I,K)*B(K,J)
      RETURN
      END
C
      SUBROUTINE MUMOSET(TITLE,GROUND,ROOF,IGRAPH)
      CHARACTER*80 TITLE
      CHARACTER*29 GROUND,ROOF
      OPEN(20,FILE=GROUND)
      OPEN(22,FILE=ROOF)
C     OPEN(58,FILE='diag.check')
      OPEN(56,FILE='modes.res')
      OPEN(55,FILE='damage')
      OPEN(54,FILE='fper.res')
      IF (IGRAPH .EQ. 1) OPEN(62,FILE='eaq.graphcomm')
      RETURN
      END
C
      SUBROUTINE OBSITY(A,C,O,N,OT)
C -----------------------------------------------------------------
C     COMPUTE THE OBSERVABILITY MATRIX O FOR (C,A)
C -----------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
```

```
      DIMENSION A(N,1),C(1),O(N,1),OT(N,1)
      DO 10 I=1,N
   10 OT(I,1)=C(I)
      DO 20 I=2,N
      CALL MULMA(OT(1,I-1),A,OT(1,I),1,N,N)
   20 CONTINUE
      CALL TRASP(OT,O,N,N)
      RETURN
      END
C
      SUBROUTINE SYSVEC(B,C,CSI,OM,PART,N2)
C ------------------------------------------------------------------
C       GENERATES THE
C    INPUT VECTOR B
C    OBSERVATION VECTOR C
C       FROM THE PHYSICAL PARAMETERS
C    CSI,OM.PART
C ------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION B(1),C(1),CSI(1),OM(1),PART(1)
      DATA UNO/1.DO/,DUE/2.DO/
      NM=N2/2
      CALL CLEAR(B,N2)
      CALL CLEAR(C,N2)
      DO 20 I=1,NM
   20 B(NM+I)=-PART(I)
      DO 30 I=1,NM
      C(I)=-OM(I)*OM(I)
   30 C(NM+I)=-DUE*CSI(I)*OM(I)
      RETURN
 1010 FORMAT(4E13.4)
      END
      SUBROUTINE TRASP(A,AT,N,M)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(N,1),AT(M,1)
      DO 10 I=1,N
      DO 10 J=1,M
   10 AT(J,I)=A(I,J)
      RETURN
      END
C
      SUBROUTINE VECNEW(ON,OL,B,N,WK)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION OL(N,1),ON(N,1),B(1),WK(1)
C
      CALL MULMA(OL,B,WK,N,N,1)
      CALL MULMA(ON,WK,B,N,N,1)
      RETURN
      END
C
      SUBROUTINE WRIFP(TO,VTO,INEW,TIN,TFIN,TITLE,TME,TW,FPER,VARF)
      CHARACTER*80 TITLE
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION TME(1),FPER(1),VARF(1),TW(1)
      TAV=(TIN+TFIN)/2.
      TWIND=TFIN-TIN
      IF (INEW.EQ.1) GOTO 250
      REWIND 54
```

```
      READ(54,999) TITLE
      I=1
   90 READ(54,1080,END=100) TME(I),TW(I),FPER(I),VARF(I)
      I=I+1
      GOTO 90
  100 CONTINUE
      NFPER=I
C
      I=1
      IF(TAV.LE.TME(I)) GOTO 150
  120 I=I+1
      IF (TAV.GE.TME(I-1).AND.TAV.LE.TME(I)) GOTO 150
      IF (I.GE.NFPER) GOTO 200
      GOTO 120
C
  150 CONTINUE
      NF1=NFPER-I
      DO 155 J=1,NF1
      TME(NFPER-J+1) =TME(NFPER-J)
      TW(NFPER-J+1)  =TW(NFPER-J)
      FPER(NFPER-J+1)=FPER(NFPER-J)
      VARF(NFPER-J+1)=VARF(NFPER-J)
  155 CONTINUE
      TME(I)=TAV
      TW(I)=TWIND
      FPER(I)=T0
      VARF(I)=VT0
      REWIND 54
      WRITE(54,999) TITLE
      DO 160 I=1,NFPER
      WRITE(54,1080) TME(I),TW(I),FPER(I),VARF(I)
C     WRITE(6,1080) TME(I),TW(I),FPER(I),VARF(I)
  160 CONTINUE
      RETURN
  200 CONTINUE
C     WRITE(6,1080) TAV,TWIND,T0,VT0
      WRITE(54,1080) TAV,TWIND,T0,VT0
      RETURN
  250 CONTINUE
      REWIND 54
      WRITE(54,999) TITLE
      INEW=0
C     WRITE(6,1080) TAV,TWIND,T0,VT0
      WRITE(54,1080) TAV,TWIND,T0,VT0
      RETURN
  999 FORMAT(A80)
 1080 FORMAT(4F10.5)
      END
C
      SUBROUTINE ZERMEA
C -----------------------------------------------------------------------
C ELIMINATE THE MEAN
C -----------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON/EAQUA/U(16000),Y(16000),E(16000)
      COMMON/WINDOW/ISTART,IFIN
C
      AMU=0.D0
```

```
      AMY=0.D0
      DO 10 I=ISTART,IFIN
      AMU=AMU+U(I)
      AMY=AMY+Y(I)
   10 CONTINUE
      NT1=IFIN-ISTART+1
      AMU=AMU/FLOAT(NT1)
      AMY=AMY/FLOAT(NT1)
      DO 20 I=ISTART,IFIN
      U(I)=U(I)-AMU
      Y(I)=Y(I)-AMY
   20 CONTINUE
      RETURN
      END
C
C     DESACTIVATE THE REMAINING CARDS IF THE SUBROUTINE EAGRA
C                     IS AVAILABLE
C
      SUBROUTINE EAGRA (U,Y,E,R,AX,AY,DT,ISTART,IFIN,TITLE)
C ---------------------------------------------------------------------
C      GENERATE THE DATABASE FOR THE PLOTTING FUNCTIONS
C      OUTPUT IN eaq.graphcomm
C ---------------------------------------------------------------------
      IMPLICIT REAL*8(A-H,O-Z)
      CHARACTER*80 TITLE
C
      WRITE(*,*) 'SUBROUTINE EAGRA NOT AVAILABLE'
      WRITE(*,*) 'GRAPHICS NOT POSSIBLE'
      STOP
      RETURN
      END
C
```

APPENDIX B
FORTRAN SOURCE LISTING OF THE PROGRAM DAMAGE

```
C
C-----------------------------------------------------------------------
C
C     PROGRAM TO COMPUTE DAMAGE INDICES AND PROBABILITY OF
C     DAMAGE USING THE OUTPUT OF MUMOID  IN A FILE
C     OR VALUES FROM THE KEYBOARD
C
C-----------------------------------------------------------------------
C
C     WRITEN BY SANTIAGO RODRIGUEZ-GOMEZ
C               DEPARTMENT OF CIVIL ENGINEERING
C               PRINCETON UNIVERSITY
C               OCTOBER 1989
C
C-----------------------------------------------------------------------
C     NEEDS THE IMSL LIBRARY (1980 VERSION)
C-----------------------------------------------------------------------
C
      PROGRAM  DAMAGE
      CHARACTER*1 AA
      CHARACTER*78 FILENAME,TITLE
      OPEN (55,FILE="damage")
      PRINT*,"COMPUTATION OF DAMAGE INDICES"
   5  PRINT*,"   ARE THE DATA IN A FILE ? (Y/N)"
      READ (5,1010) AA
      IF (AA .EQ. "Y") GO TO 10
      IF (AA .NE. "N") GO TO 5
      PRINT* ,"WRITE TITLE"
      READ (5,*) TITLE
      PRINT*,"WRITE TZERO INICIAL AND ITS STANDAR DEVIATION"
      READ (5,*) TINI,STINI
      PRINT*,"WRITE TZERO MAXIMUN AND ITS STANDAR DEVIATION"
      READ (5,*) TMAX,STMAX
      PRINT*,"WRITE TZERO FINAL "
      READ (5,*) TFIN
      CALL COMP(TITLE,TMAX,STMAX,TINI,STINI,TFIN)
      STOP
 10   PRINT*," WRITE  FILE NAME"
      READ (5,1000) FILENAME
      CALL DAMIND(FILENAME)
1000  FORMAT (A78)
1010  FORMAT (A1 )
      STOP
      END
C
C-----------------------------------------------------------------------
C
      SUBROUTINE DAMIND(FILENAME)
      CHARACTER*78 TITLE ,FILENAME
      CHARACTER*1 AA
      DIMENSION T(1000,2)
```

```
      OPEN (54,FILE=FILENAME)
      I=1
      READ(54,200) TITLE
 5    READ(54,*,END=20)A,B,T(I,1),T(I,2)
      I=I+1
      GO TO 5
20    TINI=T(1,1)
      STINI=T(1,2)
      TFIN=T(I-1,1)
      TMAX=0
      STMAX=0
      DO 30 J=1,I-1
      IF (T(J,1) .LE. TMAX) GO TO 30
      TMAX=T(J,1)
      STMAX=T(J,2)
30    CONTINUE
50    PRINT* ,"TZERO INITIAL=",TINI
      PRINT* ,"DO YOU WANT TO CHANGE IT ? (Y/N)"
      READ (5,1010) AA
      IF (AA .EQ. "N")  GO TO 80
      IF (AA .NE. "Y") GO TO 50
      PRINT*,"WRITE TZERO INICIAL AND ITS STANDAR DEVIATION"
      READ (5,*) TINI,STINI
80    CALL COMP(TITLE,TMAX,STMAX,TINI,STINI,TFIN)
200   FORMAT (A78)
210   FORMAT (4F10.4)
1010  FORMAT (A1)
      RETURN
      END
C
C----------------------------------------------------------------------
C
      SUBROUTINE COMP(TITLE,TMAX,STMAX,TINI,STINI,TFIN)
      CHARACTER*78 TITLE
40    SMAX= 1.- TINI/TMAX
      SMAX2=1.- (TINI/TMAX)**2
      SFIN =1.- (TINI/TFIN)**2
      SPLAS=1.- (TFIN/TMAX)**2
      SDELTA= SMAX*(STINI/TINI + STMAX/TMAX)
      ALFA  = -1.081
      SALFA = .26
      BETA  =  4.813
      SBETA = .446
      SI = SALFA**2+(SBETA*SDELTA)**2+(BETA*SDELTA)**2+(SMAX*SBETA)**2
      XI = ALFA + BETA*SMAX
C     PDAM = 1. - ANORDF((1.-XI)/SI)
      CALL MDNOR((1.-XI)/SI,ANOR)
      PDAM = 1. - ANOR
      WRITE(55,200) TITLE
      WRITE(55,150) TINI,STINI,TMAX,STMAX,TFIN
      WRITE(55,100)SMAX,SMAX2,SFIN,SPLAS,PDAM
C     ICO=SYSTEM('LPR damage')
200   FORMAT (A78)
100   FORMAT (/,"MAXIMUM SOFTENING",4X,F14.5,
     X        /,"MAXIMUM SOFTENING(SQ)",F14.5,
     X        /,"FINAL SOFTENING",6X,F14.5,
     X        /,"PLASTIC SOFTENING",4X,F14.5,
     X        /,"PROBABILITY OF DAMAGE",F14.5)
```

```
150   FORMAT (/,/,"TZERO INITIAL",8X,F14.5,
     X           /,"STANDARD DEVIATION",3X,F14.5,
     X           /,"TZERO MAX",12X,F14.5,
     X           /,"STANDARD DEVIATION",3X,F14.5,
     X           /,"TZERO FINAL",10X,F14.5)
      RETURN
      END
```

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LIST OF TECHNICAL REPORTS

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NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341/AS).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259/AS). This report is available only through NTIS (see address given above).

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