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INDUCED EARTHQUAKE MOTIONS IN CIVIL STRUCTURES BY PULSE METHODS

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ABSTRACT

The work reported herein constitutes Phase I of an NSF Small Business Innovative Research Project concerned with evaluating the feasibility and validity of simulating seismic motions on a sizable structure by using cold gas pulse generators that duplicate the effects of strong-motion earthquakes. To this end, the following tasks were accomplished: (1) a test structure resembling a three-story moment resisting building frame was designed and erected; (2) a finite-element model of the structure was developed and used to generate the system impulse and criteria response under the El Centro and San Fernando earthquakes; (3) previously-developed optimization techniques were then used to design suitable pulse trains for motion simulation; (4) two cold-gas pulse generators were mounted on the top floors of the test frame and after being connected to a suitable hydraulic system, energy storage devices, and a control microcomputer, were used to apply the optimum pulse trains. Analysis of the experimental measurements show that the demonstration tests were successful in validating the pulse simulation methodology as well as the capability of the gas pulse generators to reproduce, with sufficient accuracy, the microcomputer-commanded pulse trains. Additionally, this research was supplemented by design and construction of a solid propellant rocket which was test fired on the test structure. Patents for both the gas pulse system and the solid propellant rocket are being applied for.

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SECTION 1
INTRODUCTION

1.1 BACKGROUND

Recent analytical and experimental studies [1-4] indicate that a rudimentary series of rectangular or other simple pulses could be convolved with the impulse response functions of a structure to induce motions closely approximating those caused by nautral and man-made events. This result greatly simplifies the control of high energy devices as the problem is reduced to three functions of on, off, and amplitude control. It was further determined that the excitation could also be applied directly to structures at one location or at multiple locations of test convenience and in single or multiple axes. When the structural excitation is caused by base motions, pulse simulation with generators attached to the same structure can duplicate the natural or man-made event with the exception of the rigid body modes.

1.2 SCOPE OF WORK

The goal of this research project is to investigate the feasibility and validity of simulating motions of sizable structures by using cold gas pulse generators that duplicate strong motion earthquake effects. To this end, the following tasks were accomplished:

a. A test structure resembling a three-story building frame was designed and erected (Section 2).

b. A finite element model of the test structure was constructed and used to generate the system impulse response functions and criteria response under two well known earthquakes as well as under swept-sine excitation (Section 3).

c. Previously-developed parametric optimization techniques were then used to select suitable pulse trains for motion simulation (Section 4).

d. Two cold-gas pulse generators were mounted on the top floor of the test frame and attached to the hydraulic system, energy storage devices, and the control microcomputer (Section 5).

e. The pulse generators and the frame were then provided with suitable pressure, force and motion sensors together with the associated data acquisition hardware (Section 6).

f. The pulse generators were then used to furnish an impulsive excitation for force calibration purposes as well as to provide experimentally determined impulse response functions of the frame (Section 7).

g. With the pulsers configured as in part (d), they were used to apply the optimum pulse trains of part (c) (Section 8).

h. The measured frame response as well as the signals used to monitor the performance of the gas pulsers were recorded and later used to evaluate the test adequacy (Section 9).

i. A preliminary investigation of using solid fuel rockets to furnish needed pulse trains was conducted (Section 10).

SECTION 2
TEST STRUCTURE

2.1 DESIGN OF BUILDING FRAME

A building frame resembling a three-story steel frame structure [5] that has been extensively tested by means of the earthquake simulation facility at the University of California, Berkeley (UCB) was designed. This test structure consisted of two identical, single-bay, moment-resistant frames having the dimensions shown in Figure 2.1-1.

The test structure was designed to support a total weight of approximately 5000 lbs and to have a fundamental frequency of about 1.7 Hz. All columns were made of standard steel sections 5/8 in. x 6 in. flat bars of 1018 cold rolled steel and all beams were S 3 x 5.7.

2.2 MODAL CHARACTERISTICS OF BUILDING FRAME

A finite element analysis of the test frame shown in Figure 2.1-1 was conducted to determine its modal characteristics. The input data file used for this analysis is shown in Figure 2.2-1, the corresponding discretized mathematical model is given in Figure 2.2-2, and the first four mode shapes are illustrated in Figure 2.2-3.

2.3 STABILITY ANALYSIS OF BUILDING FRAME

In order to determine the stability boundaries of the test frame, a buckling analysis was performed to determine the critical static load W_{cr} that will cause the frame to buckle. The input file for the stability analysis is given in Figure 2.3-1.

Treating the concentrated masses in Figure 2.2-2 as concentrated weights totaling 13.308 units, results in the value of the eigenvalue λ_{cr} associated with the buckling analysis being equal to 7709 with a buckled shape indicated in Figure 2.3-2. Thus, the critical buckling weight W_{cr} in this case is 7709 x 13.308 = 102,560 lb. Using a knock-down factor of 10

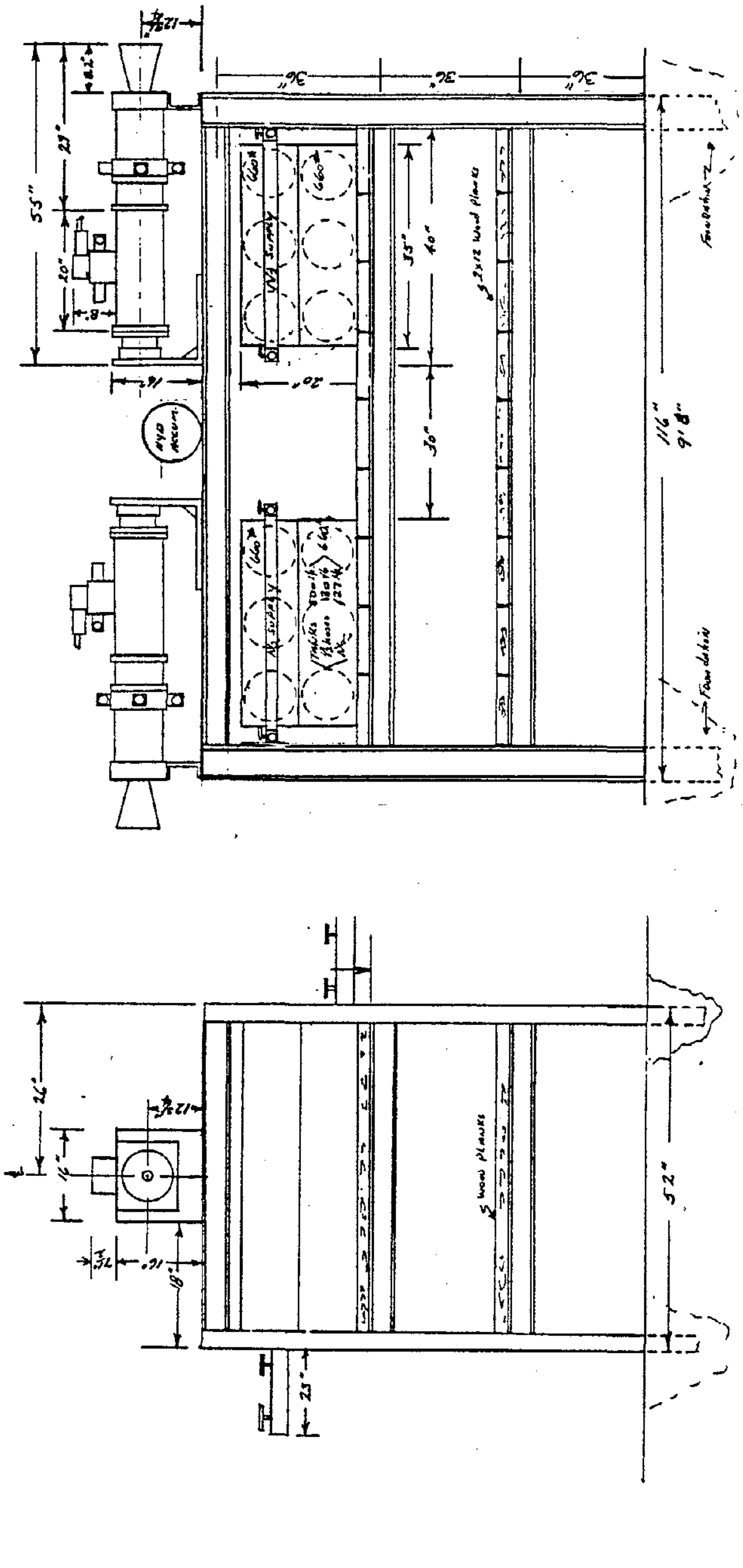

FIGURE 2.1-1. DIMENSIONS OF TEST FRAME

```
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10   58.    26.   72.0
11  -58.    26.   72.0
12  -58.   -26.   72.0
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14   58.    26.   108.0
15  -58.    26.   108.0
16  -58.   -26.   108.0
17   0.     0.    108.0
18   58.    0.    108.0
19  -58.    0.    108.0
20   0.     0.    116.0
21   58.    0.    123.0
22  -58.    0.    123.0
23   66.    0.    123.0
24  -66.    0.    123.0
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26   12.    26.   108.0
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30   12.    0.    108.0
31  -12.    0.    123.0
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+MASSES
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NM    6    6    1   0.215     0.215     0.215
NM    7    7    1   0.215     0.215     0.215
NM    8    8    1   0.215     0.215     0.215
NM    9    9    1   1.925     1.925     1.925
NM   10   10    1   1.925     1.925     1.925
NM   11   11    1   1.925     1.925     1.925
NM   12   12    1   1.925     1.925     1.925
NM   13   13    1   0.59      0.539     0.539
NM   14   14    1   0.539     0.539     0.539
NM   15   15    1   0.539     0.539     0.539
NM   16   16    1   0.539     0.539     0.539
NM   21   21    1   0.648     0.648     0.648
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2   5  9  2  1    0   1
3   9 13  2  1    0   1
4  13 27  4  2    0   1
5  16 12  3  1    0   1
6  12  8  3  1    0   1
7   8  4  3  1    0   1
8   8  5  4  2    0   1
9  12  9  4  2    0   1
10  2  6  1  1    0   1
11  6 10  1  1    0   1
12 10 14  1  1    0   1
13 14 26  3  2    0   1
14 15 11  4  1    0   1
15 11  7  4  1    0   1
16  7  3  4  1    0   1
17  7  6  2  2    0   1
18 11 10  2  2    0   1
19 13 18  1  2    0   1
20 18 14  1  2    0   1
21 15 19  4  2    0   1
22 19 16  4  2    0   1
23 30 18 13  3    0   1
24 29 19 13  3    0   1
25 17 20 18  3    0   1
26 32 21 18  3    0   1
27 21 23 18  3    0   1
28 22 31 18  3    0   1
29 22 24 18  3    0   1
30 18 21 17  3    0   1
31 19 22 17  3    0   1
32  5  6  1  2    0   1
33  9 10  1  2    0   1
34 11 12  4  2    0   1
35  7  8  4  2    0   1
36 27 28  4  2    0   1
37 28 16  4  2    0   1
38 25 26  3  2    0   1
39 15 25  3  2    0   1
40 29 17 13  3    0   1
41 30 17 13  3    0   1
42 30 32 18  3    0   1
43 29 31 18  3    0   1
44 25 29 31  2    0   1
45 29 28 31  2    0   1
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<B16.1;JOB TERMINATION CARD>+FINISH
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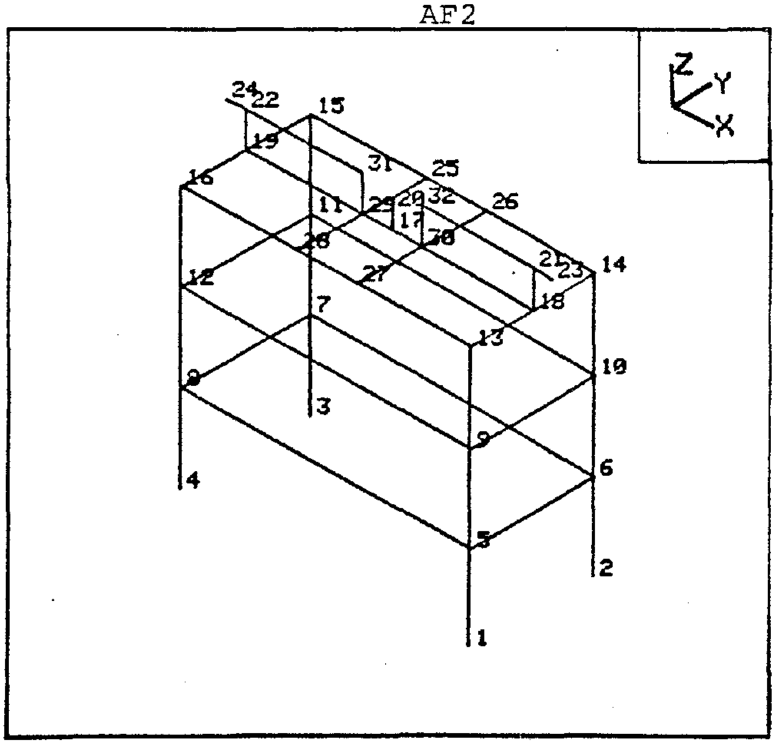
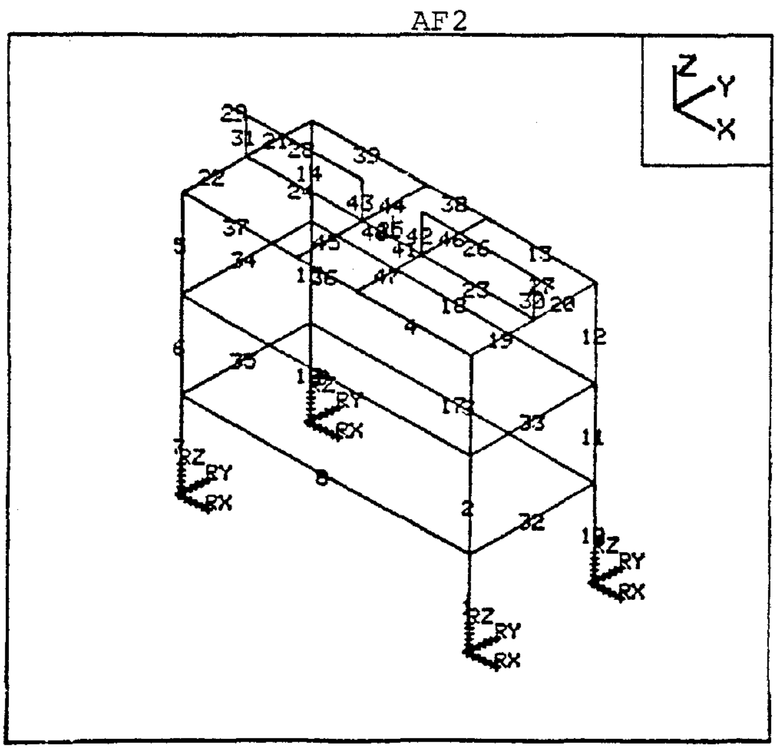
FIGURE 2.2-1. INPUT DATA FILE FOR FINITE ELEMENT ANALYSIS OF TEST FRAME



(a) Nodal Points



(b) Discrete Elements

FIGURE 2.2-2. FINITE ELEMENT MODEL OF TEST STRUCTURE

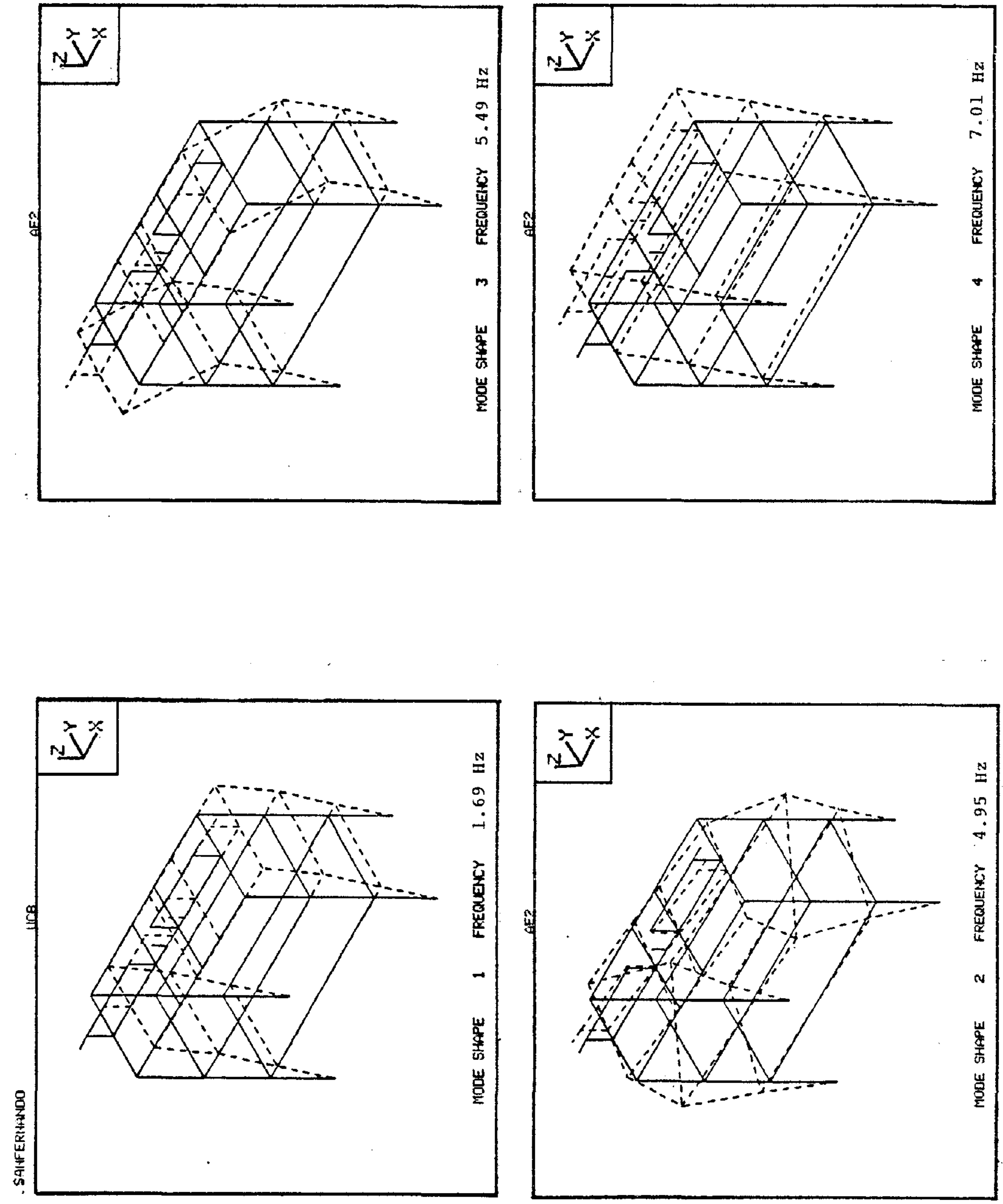


FIGURE 2.2-3. DOMINANT MODE SHAPES OF TEST FRAME

```
EFFS REFER TO JANUARY 1983 COSMOS MANUAL)
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(B2.2; MI)M1,(MDOFLG)6D,(NEGL)L,(MODEX)E,(IPSF1,...,6)0,0,0,0,0,1
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(B2 6; MI)M3,(IEIG=1;FIND FREQ & SHAPES)4
(B2 9; MI)M5,(NSTE)1,(DELT)1.0
(B2.16;NME)*PLOT
(B3.1;NODAL POINT DATA CARD;NME)*NODES
(B3.2;IC NODE1 NODE2 NG ICONST; CONSTRAINTS CARD)
C 1 4 1 NM
(B3.4;NODE COORDINATE CARDS)
(N    X     Y     Z    KN   IT)
1    58.  -26.   0.0
2    58.   26.   0.0
3   -58.   26.   0.0
4   -58.  -26.   0.0
5    58.  -26.  36.0
6    58.   26.  36.0
7   -58.   26.  36.0
8   -58.  -26.  36.0
9    58.  -26.  72.0
10   58.   26.  72.0
11  -58.   26.  72.0
12  -58.  -26.  72.0
13   58.  -26. 108.0
14   58.   26. 108.0
15  -58.   26. 108.0
16  -58.  -26. 108.0
17   0.    0.  108.0
18   58.   0.  108.0
19  -58.   0.  108.0
20   0.    0.  116.0
21   58.   0.  123.0
22  -58.   0.  123.0
23   66.   0.  123.0
24  -66.   0.  123.0
25  -12.  26.  108.0
26   12.  26.  108.0
27   12. -26.  108.0
28  -12. -26.0 108.0
29  -12.   0.  108.0
30   12.   0.  108.0
31  -12.   0.  123.0
32   12.   0.  123.0
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(B4 3; NTF)1,(NPTS)2,
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L      6    6    1    3       1      -0.215
L      7    7    1    3       1      -0.215
L      8    8    1    3       1      -0.215
L      9    9    1    3       1      -1.925
L      10   10   1    3       1      -1.925
L      11   11   1    3       1      -1.925
L      12   12   1    3       1      -1.925
L      13   13   1    3       1      -0.539
L      14   14   1    3       1      -0.539
L      15   15   1    3       1      -0.539
L      16   16   1    3       1      -0.539
L      21   21   1    3       1      -0.648
L      22   22   1    3       1      -0.648
L    23   23    1    3     1      -0.648
L    24   24    1    3     1      -0.684
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(B10.83; MATERIAL 1)1
(E1)3.0E7,(THEXP1)0.,(G1)1.0E7,(DEN1)0.0,(PRESS1)0.
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(AR,S,T)1.0,0.0,0.0,(IR,S,T)200.,100.,100.
(N II JJ KK MTYP IPS KG THS THT TCT INI INJ)
1   1  5  2  1  0  1
2   5  9  2  1  0  1
3   9 13  2  1  0  1
4  13 27  4  2  0  1
5  16 12  3  1  0  1
6  12  8  3  1  0  1
7   8  4  3  1  0  1
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11  6 10  1  1  0  1
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47 30 27 32  2  0  1
(B11.1;FREQ & MODE SHAPES;NME)*FREQUENCIES
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T)0.
(B16.1;JOB TERMINATION CARD)*FINISH
```


FIGURE 2.3-1. INPUT FILE FOR STABILITY ANALYSIS – APPLIED LOAD FACTOR w_t = 13.308 lbs

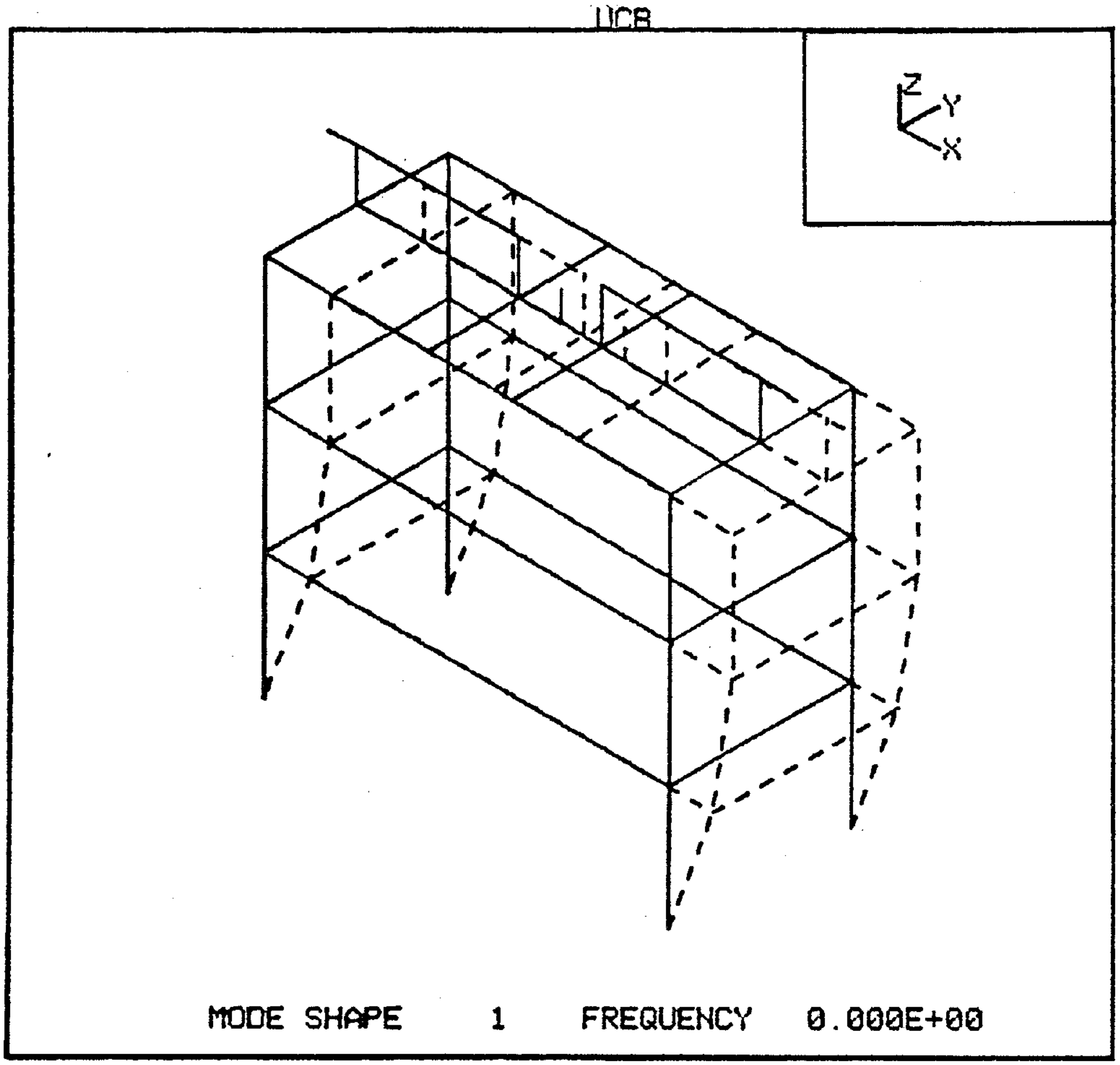

FIGURE 2.3-2. BUCKLING SHAPE OF TEST STRUCTURE – λ_{cr} = 7709, w_{cr} = 102,560 lbs

leads to a corresponding buckling load of 10,256 lb which is significantly higher than the operational values used during the test.

2.4 FOUNDATION DESIGN

Due to the high thrust levels anticipated during the test, special attention was devoted to the design of the base slab supporting the test stucture so as to ensure sufficient resistance to overturning. The plan and elevation views of the foundation are shown in Figure 2.4-1.

2.5 CONSTRUCTION PROCEDURE

The test structure was assembled at its final location from the individual components shown in Figure 2.1-1. Details of the construction procedure for the welded base plate as well as the welded structural joints are shown in Figures 2.5-1 and 2.5-2.

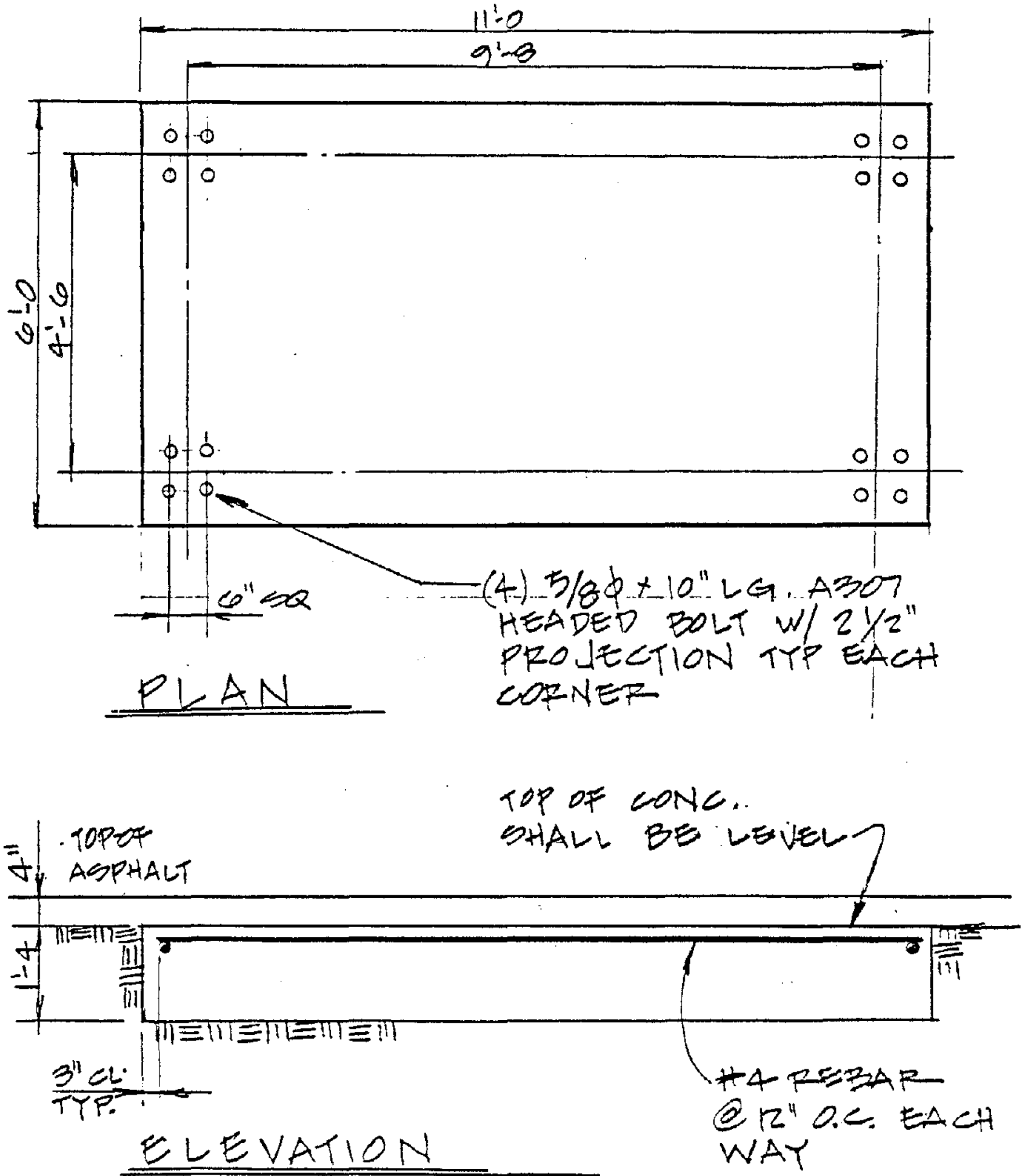

FIGURE 2.4-1. FOUNDATION DESIGN

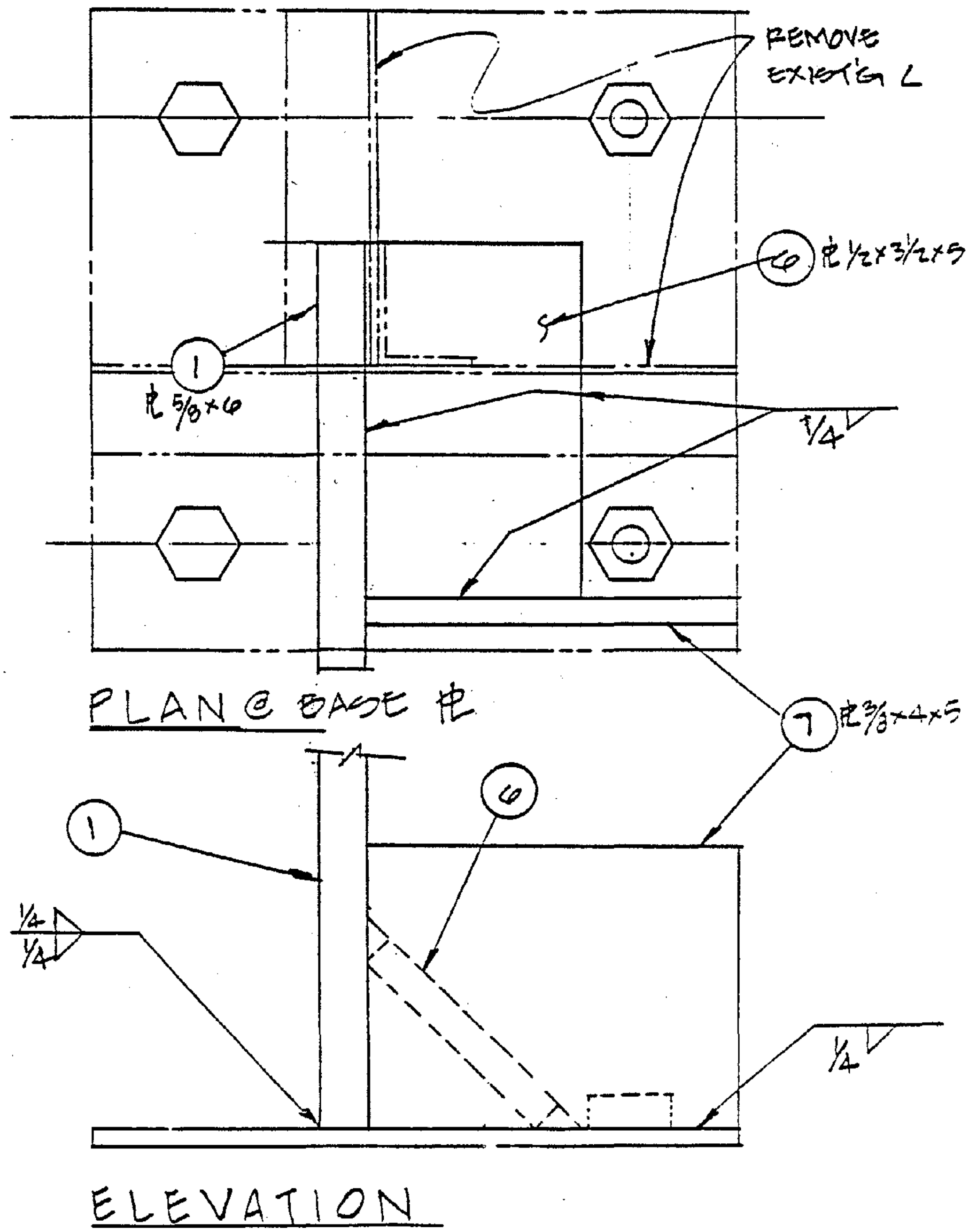

FIGURE 2.5-1. STRUCTURE BASE PLATE

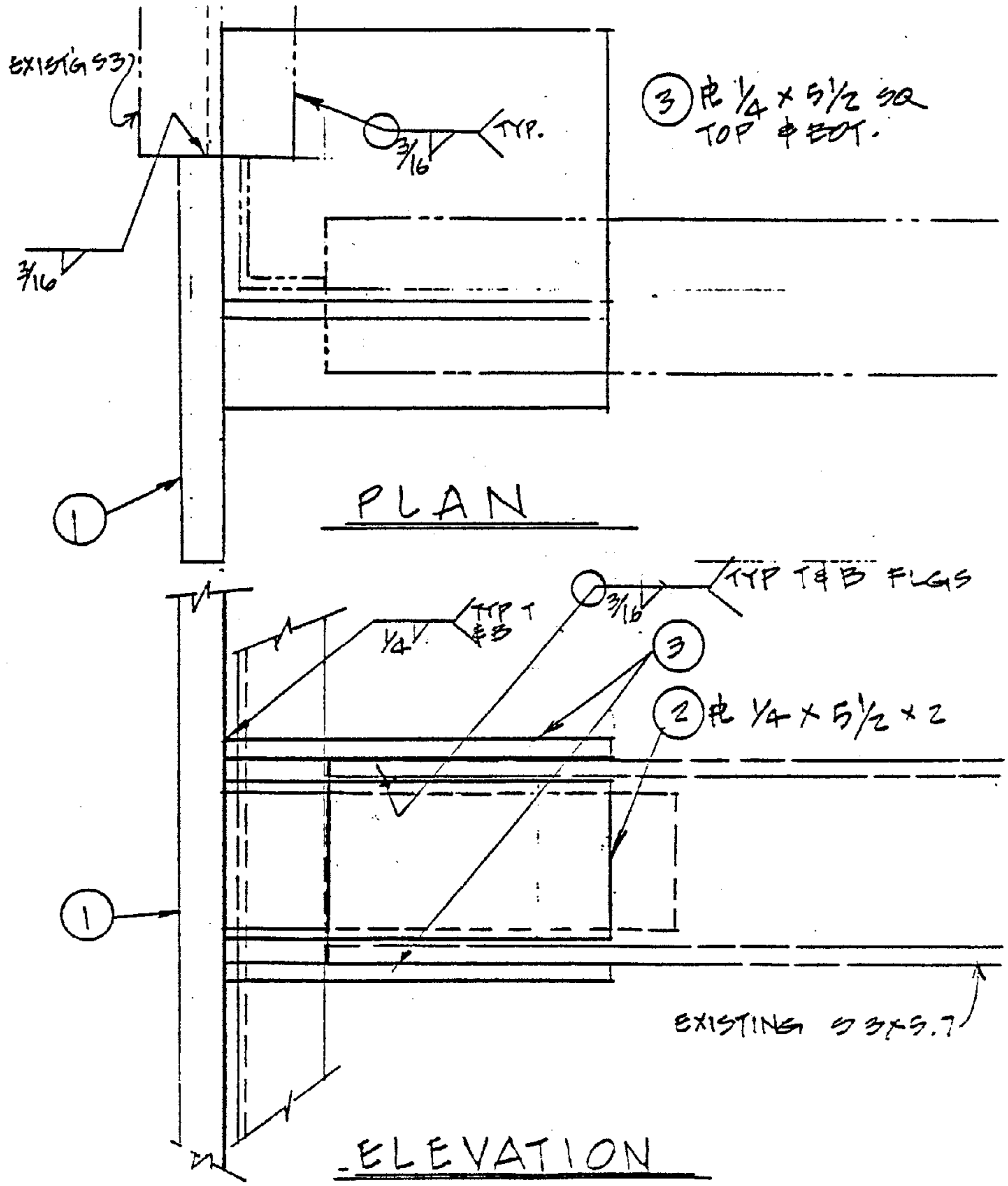

FIGURE 2.5-2. STRUCTURE JOINTS

SECTION 3

CRITERIA RESPONSE

3.1 GENERATION OF IMPULSE FUNCTIONS

The impulsive response of the test frame to a unit impulse applied to its top (free end) were analytically determined by applying a short duration force to the mathematical model shown in Figure 2.2-2. The resulting impulsive displacement, velocity, and acceleration responses, under the assumption that the test structure has a damping ratio $\zeta = 0.02$, are shown in Figures 3.1-1, 3.1-2, and 3.1-3 respectively.

3.2 GENERATION OF CRITERIA RESPONSE FOR EL CENTRO EARTHQUAKE

The acceleration time history corresponding to the 1940 El Centro earthquake was applied in the form of an inertia load to the finite element model shown in Figure 2.2-2. The El Centro earthquake record characteristics are summarized in Figure 3.2-1 and the corresponding criteria displacement response $x_1(t)$ of the top floor of the test structure is shown in Figure 3.2-2.

3.3 GENERATION OF CRITERIA RESPONSE FOR SAN FERNANDO EARTHQUAKE

The charateristics of the San Fernando earthquake record that was used are summarized in Figure 3.3-1 and the corresponding criteria response is shown in Figure 3.3-2.

3.4 GENERATION OF CRITERIA RESPONSE FOR SWEPT-SINE EXCITATION

The criteria response of the test structure under an example deterministic excitation consisting of a swept-sine excitation covering its fundamental frequency is shown in Figure 3.4-1.

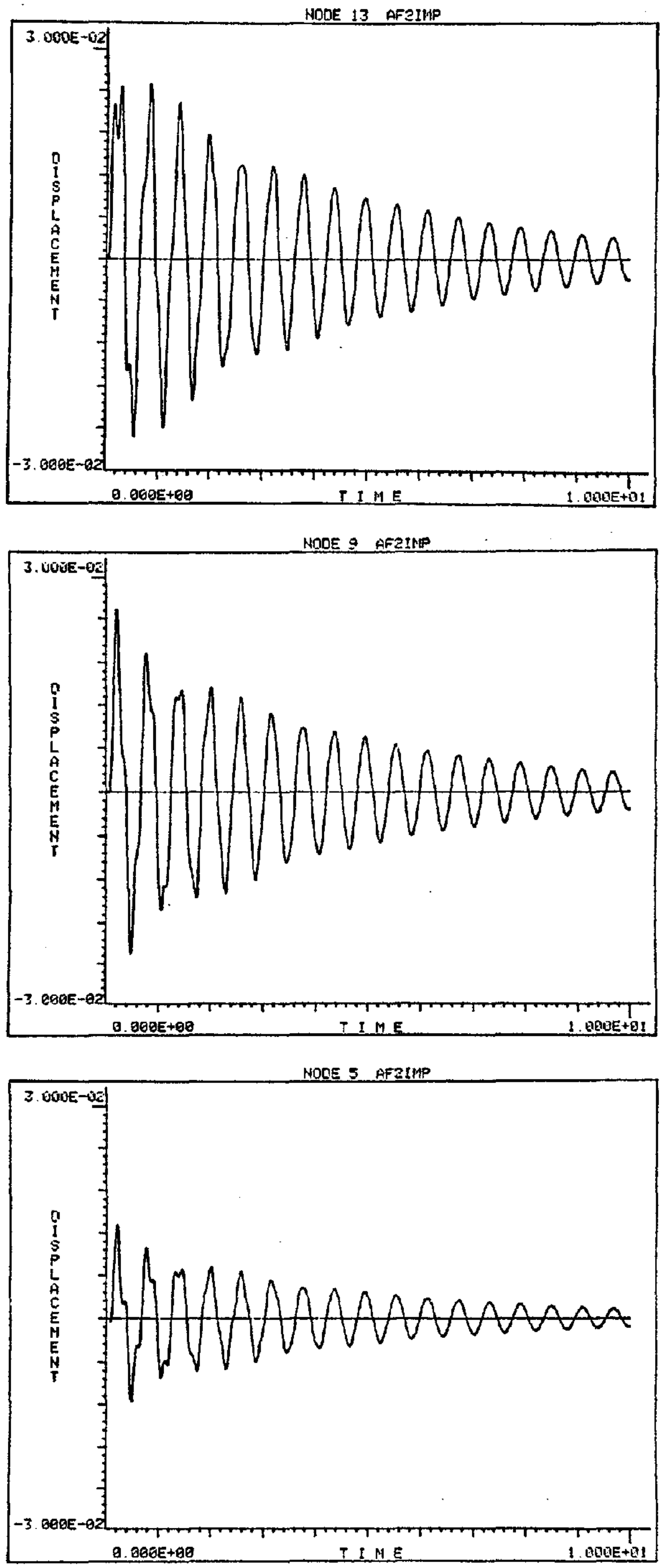

FIGURE 3.1-1. DISPLACEMENT RESPONSE DUE TO A UNIT IMPULSE AT NODE 13

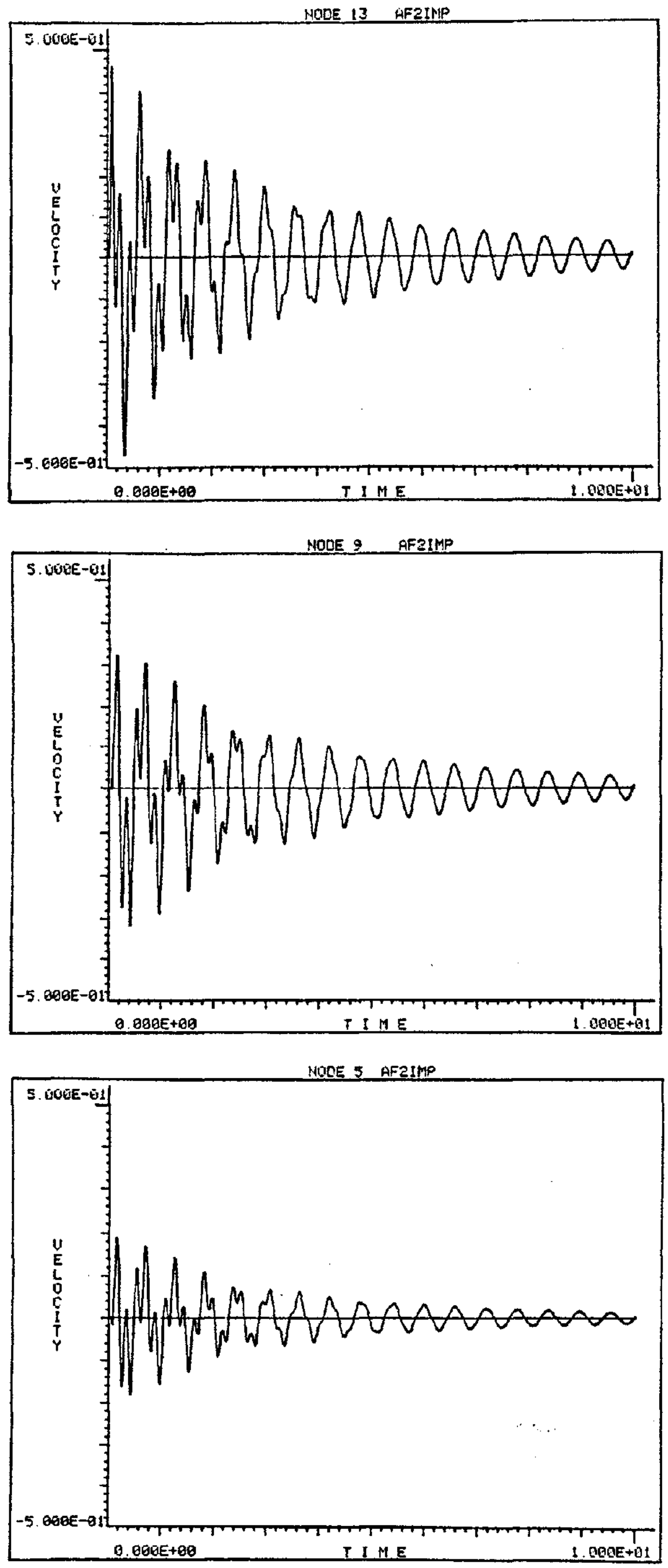

FIGURE 3.1-2. VELOCITY RESPONSE DUE TO A UNIT IMPULSE AT NODE 13

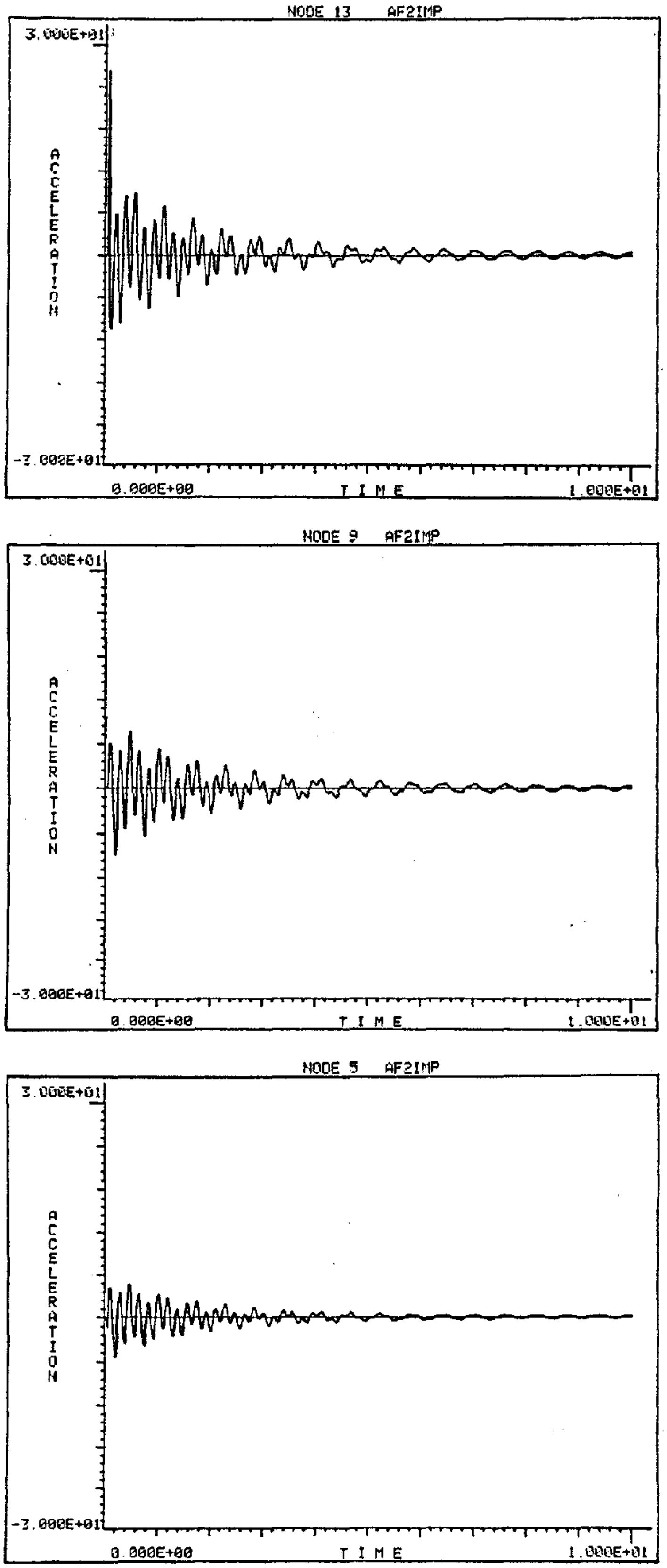

FIGURE 3.1-3. ACCELERATION RESPONSE DUE TO A UNIT IMPULSE AT NODE 13

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FILE   1  OF UNCORRECTED ACCELEROGRAM DATA OF VOL. I-A, EERL 70-20
IMPERIAL VALLEY EARTHQUAKE
MAY 18, 1940 - 2037 PST
IA001   40.001.0 S                                                      18
STATION NO. 117   32 47 43N,115 32 55W                                  38
EL CENTRO SITE IMPERIAL VALLEY IRRIGATION DISTRICT                      50
COMP S00E                                                               9
IMPERIAL VALLEY EARTHQUAKE   MAY 18, 1940 - 2037 PST                    52
EPICENTER  32 44 00N,115 27 00W                                         31
INSTR PERIOD = 0.0990 SEC  DAMPING = 0.552                              42
NO. OF POINTS = 985   DURATION = 53.73 SEC                              42
UNITS ARE SEC AND G/10.                                                 23
RMS ACCLN OF COMPLETE RECORD = 0.4876 G/10.                             43
ACCELEROGRAM IS BAND-PASS FILTERED BETWEEN   0.070  AND  25.000  CYC/SEC
  2687  INSTRUMENT AND BASELINE CORRECTED DATA
AT EQUALLY-SPACED INTERVALS OF   0.02   SEC.
PEAK ACCELERATION =   341.70508  CMS/SEC/SEC AT   2.1200 SEC
PEAK VELOCITY     =    33.44281  CMS/SEC     AT   2.1800 SEC
PEAK DISPLACEMENT =    10.87717  CMS         AT   8.5800 SEC
INITIAL VELOCITY  =    -4.58395  CMS/SEC        INITIAL DISP. =     2.17764  CMS
IMPERIAL VALLEY EARTHQUAKE   MAY 18, 1940 - 2037 PST

IIA001  40.001.0   EL CENTRO SITE IMPERIAL VALLEY IRRIGATION DISTRICT   COMP S00
E
    1    1    1    1   40    1    0    4  117   32   47   43 -115   32   55   32
   44    0 -115   27    0    5   18 1940 2037    0  180  985   26   50    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0  985  985 2687    2   10   10    1    0   52   81   10   10    2 1344
    5  538    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0
      .099      .552    53.730      .488      .100      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
      .000      .000      .000      .000      .000      .000      .000      .000
```

FIGURE 3.2-1. EL CENTRO EARTHQUAKE RECORD CHARACTERISTICS

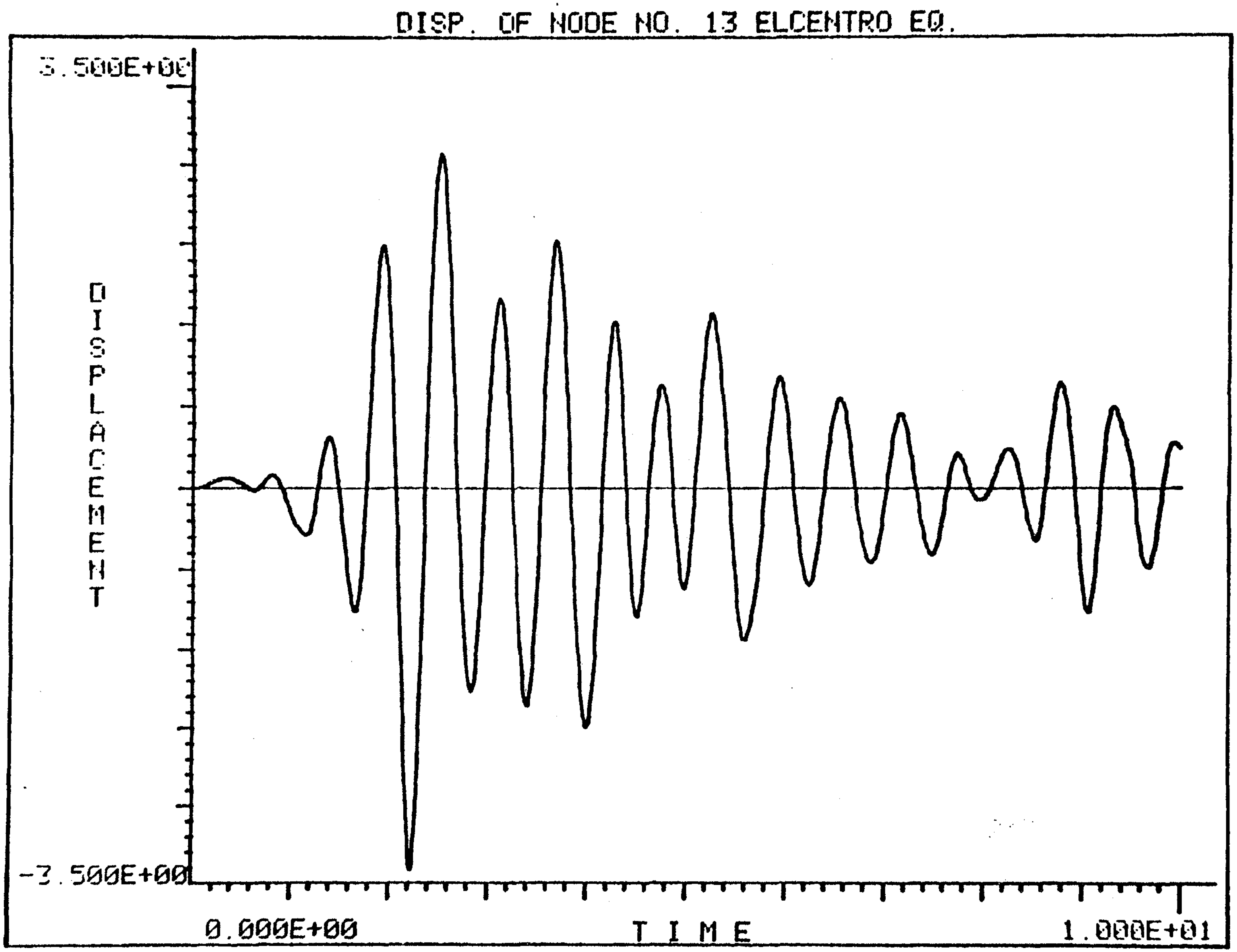


FIGURE 3.2-2. CRITERIA RESPONSE x_1 OF TEST STRUCTURE UNDER EL CENTRO EARTHQUAKE

```
$ TY ID.7
CORRECTED ACCELEROGRAM  IID056  71.007.0    COMP N21E   FILE ** DERIVED FROM:
FILE   1  OF UNCORRECTED ACCELEROGRAM DATA OF VOL$&I-D, EERL 71-21
SAN FERNANDO EARTHQUAKE
FEBRUARY 9, 1971 - 0600 PST
ID056   71.007.0 N                                                     18
STATION NO. 110   34 33 18N,118 39 24W                                 38
CASTAIC OLD RIDGE ROUTE, CAL.                                          29
COMP N21E                                                              9
SAN FERNANDO EARTHQUAKE   FEB 9, 1971 - 0600 PST                       48
EPICENTER  34 24 00N,118 23 42W                                        31
INSTR PERIOD = 0.0530 SEC  DAMPING = 0.592                             42
NO. OF POINTS = 3494  DURATION = 61.820 SEC                            43
UNITS ARE SEC AND G/10                                                 22
RMS ACCLN OF COMPLETE RECORD = 0.2761 G/10                             42
ACCELEROGRAM IS BAND-PASS FILTERED BETWEEN   0.070  AND  25.000  CYC/SEC
  3092  INSTRUMENT AND BASELINE CORRECTED DATA
AT EQUALLY-SPACED INTERVALS OF   0.02   SEC.
PEAK ACCELERATION =  -309.40479  CMS/SEC/SEC AT   2.6000 SEC
PEAK VELOCITY     =   -17.16028  CMS/SEC     AT   1.3400 SEC
PEAK DISPLACEMENT =     4.22678  CMS         AT   1.0400 SEC
INITIAL VELOCITY  =     2.82091  CMS/SEC        INITIAL DISP. =     0.13011  CMS
SAN FERNANDO EARTHQUAKE   FEB 9, 1971 - 0600 PST

IID056  71.007.0   CASTAIC OLD RIDGE ROUTE, CAL.   COMP N21E

    1    1    4   56   71    7    0    1  110   34   33   18  118   39   24   34
   24    0  118   23   42    2    9 1971  600    0   21 3494   23   29    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0 3494 3494 3092    2   10   10    1    0   48   60   10   10    2 1546
    5  619    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0    0
    0    0    0    0
     .053      .592     61.820      .2
^Y
```

FIGURE 3.3-1. SAN FERNANDO EARTHQUAKE RECORD CHARACTERISTICS

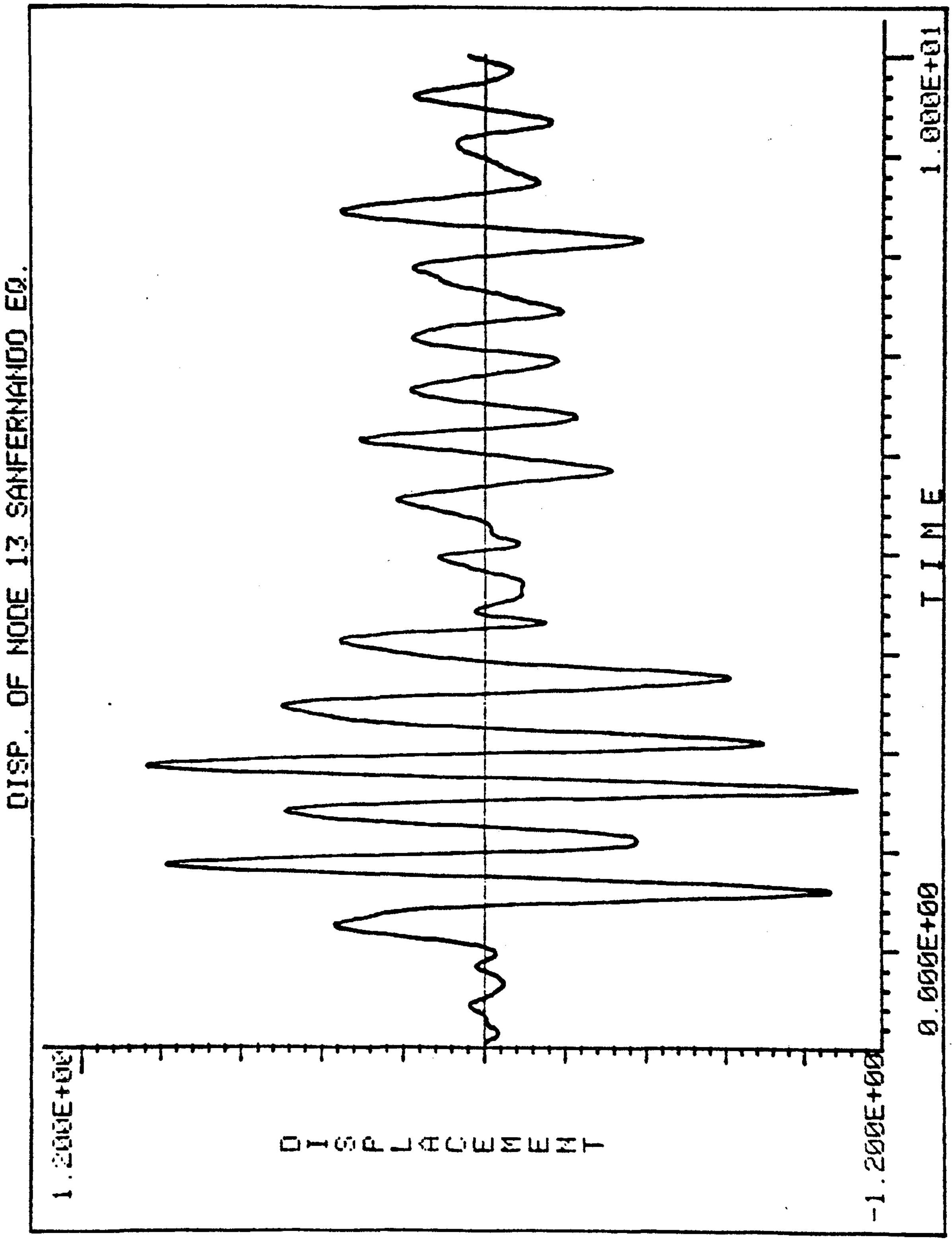


FIGURE 3.3-2. CRITERIA RESPONSE x_1 OF TEST STRUCTURE UNDER SAN FERNANDO EARTHQUAKE

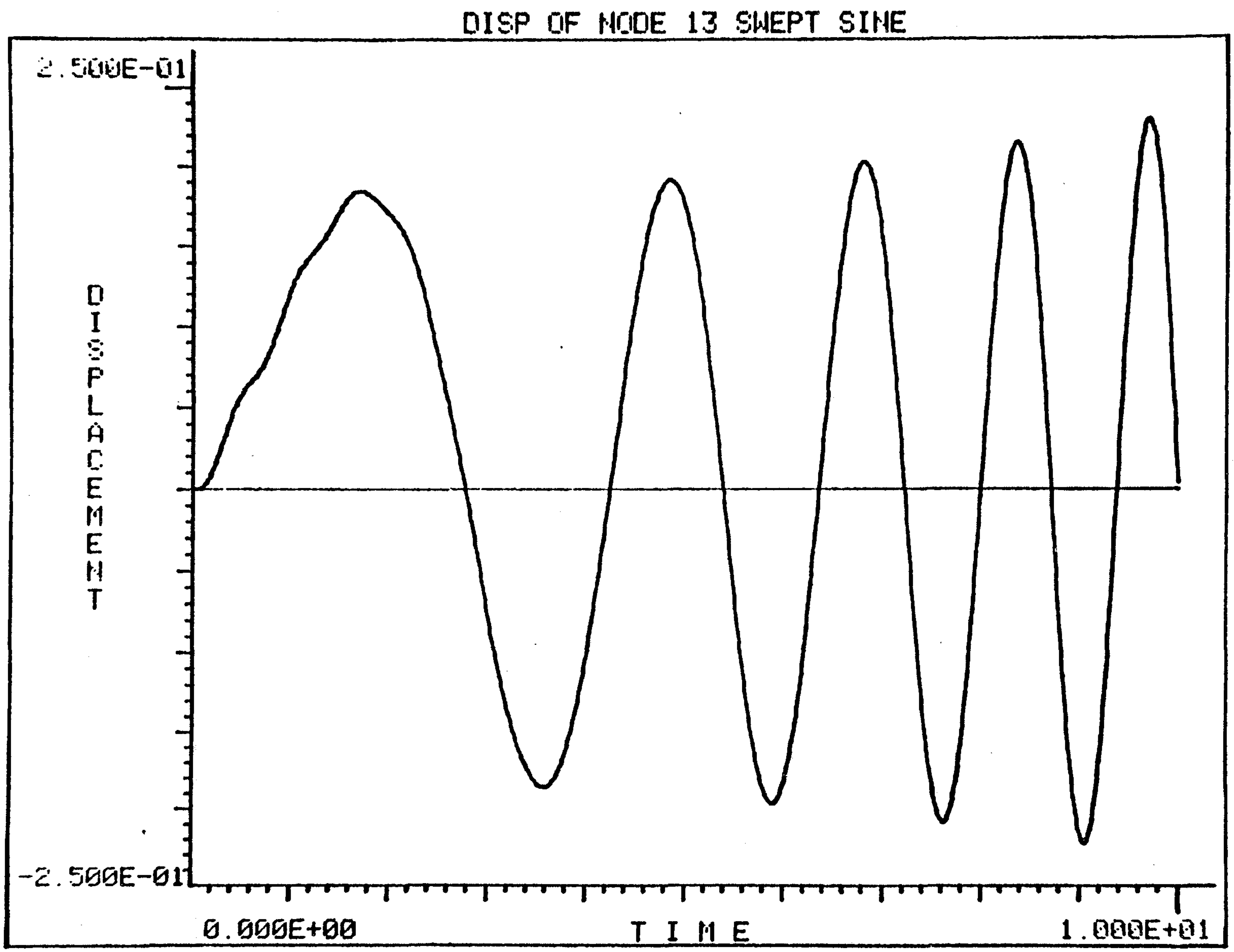


FIGURE 3.4-1. CRITERIA RESPONSE x_1 OF TEST STRUCTURE UNDER SWEPT-SINE EXCITATION

SECTION 4

OPTIMUM PULSE TRAINS

4.1 PULSE OPTIMIZATION TECHNIQUES

The mathematical approach depicted in Figure 4.1-1 was used to determine the optimum pulse trains for each of the criteria responses. Details concerning the computer algorithm used for pulse optimization are available in Reference [3].

4.2 GENERATION OF OPTIMUM PULSE TRAINS FOR EL CENTRO EARTHQUAKE

Following the procedure of Section 4.1, an optimum pulse train was determined to match the criteria response of the test structure under the El Centro earthquake. The optimum pulse train characteristics are summarized in Figure 4.2-1. The designations "APOLD," "DPOLD," and "TPOLD" correspond to the amplitude, duration, and initiation time, respectively, of each pulse.

Figure 4.2-2(a) compares the exact (criteria) and approximate (estimated) response. The corresponding optimum pulse train is shown in Figure 4.2-2(b). The same results in Figure 4.2-2 are plotted with more time resolution in Figures 4.2-3 to 4.2-5.

4.3 GENERATION OF OPTIMUM PULSE TRAIN FOR SAN FERNANDO EARTHQUAKE

The optimum pulse train characteristics for San Fernando earthquake are shown in Figure 4.3-1. A comparison of the exact and approximate response is given in Figure 4.3-2. Similar results with higher time resolution are shown in Figures 4.3-3 to 4.3-5.

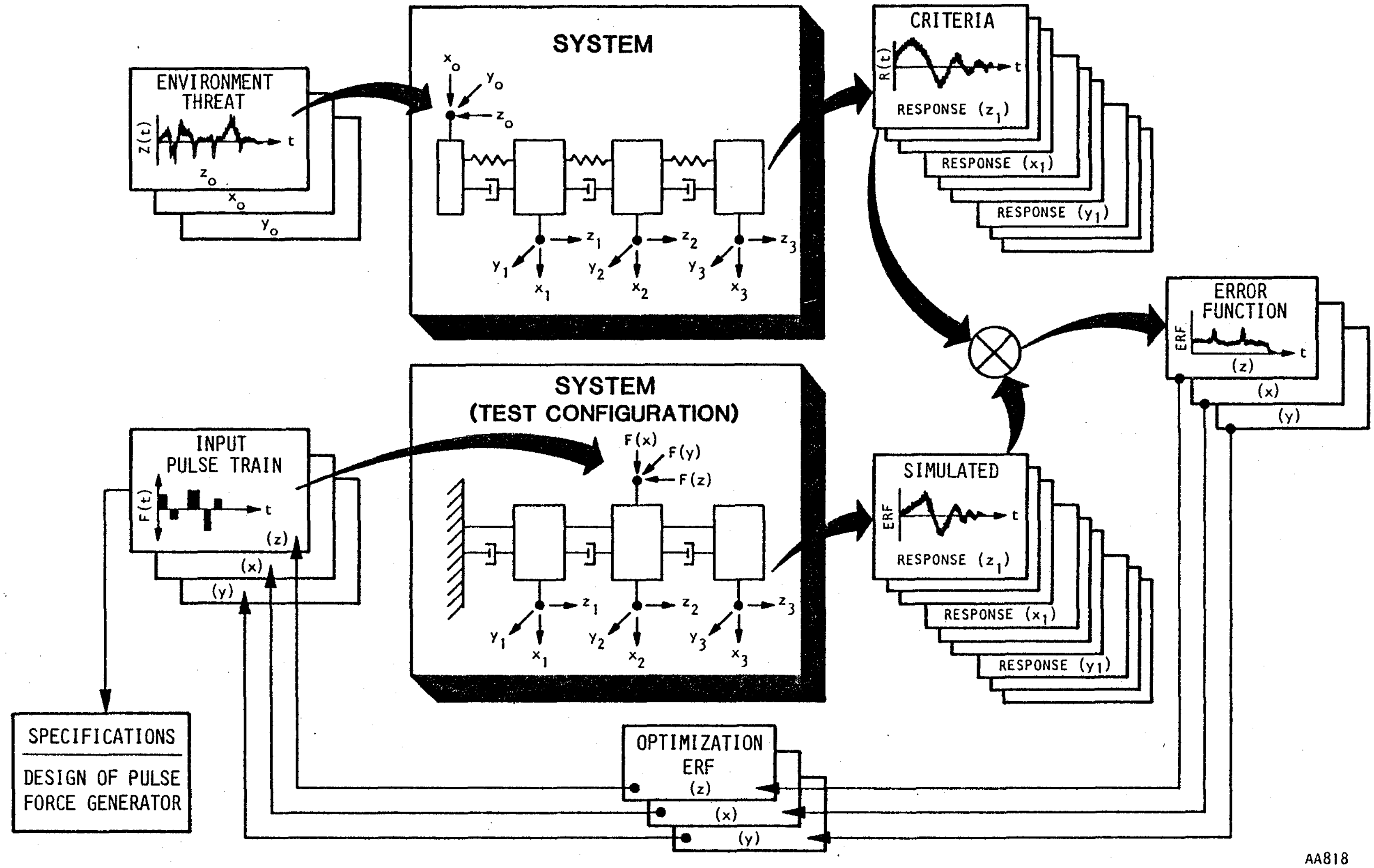
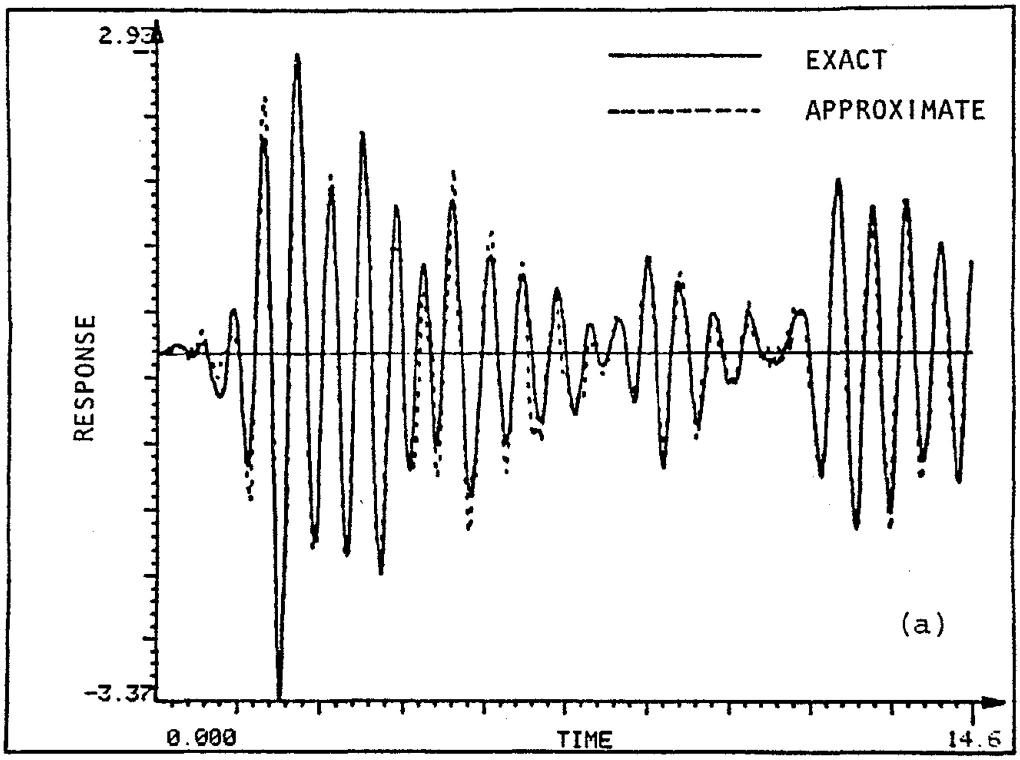


FIGURE 4.1-1. OPTIMUM RESPONSE SIMULATION OF MULTIDEGREE SYSTEMS BY PULSE EXCITATION

J	K	APOLD(J,K)	DPOLD(J,K)	TPOLD(J,K)
1	1	2.084E+02	4.442E-02	1.204E-01
1	2	5.762E+02	4.689E-02	5.001E-01
1	3	-9.041E+02	1.705E-01	1.400E+00
1	4	5.000E+03	3.000E-02	1.637E+00
1	5	-4.070E+03	3.003E-02	2.000E+00
1	6	7.371E+02	1.528E-01	2.531E+00
1	7	-4.421E+02	1.210E-01	3.024E+00
1	8	1.352E+03	3.715E-02	3.510E+00
1	9	-1.043E+03	9.481E-02	4.088E+00
1	10	-1.212E+03	1.020E-01	4.655E+00
1	11	2.663E+03	3.000E-02	5.000E+00
1	12	-3.192E+03	3.716E-02	5.545E+00
1	13	-1.196E+03	3.523E-02	6.233E+00
1	14	-1.773E+03	5.332E-02	6.745E+00
1	15	-1.892E+03	3.000E-02	7.376E+00
1	16	-1.239E+03	6.928E-02	7.616E+00
1	17	6.474E+02	6.250E-02	8.000E+00
1	18	1.021E+03	6.249E-02	8.506E+00
1	19	2.134E+02	9.296E-02	9.117E+00
1	20	-2.163E+02	8.215E-02	9.500E+00
1	21	-4.042E+02	6.736E-02	1.000E+01
1	22	1.125E+03	5.535E-02	1.059E+01
1	23	3.084E+03	3.000E-02	1.127E+01
1	24	-4.678E+03	3.000E-02	1.167E+01
1	25	3.434E+03	3.000E-02	1.200E+01
1	26	-1.338E+03	3.000E-02	1.250E+01
1	27	-2.969E+03	3.000E-02	1.300E+01
1	28	-4.874E+02	6.916E-02	1.362E+01
1	29	-5.678E+02	9.888E-02	1.419E+01

FIGURE 4.2-1. OPTIMUM PULSE TRAIN FOR EL CENTRO EARTHQUAKE



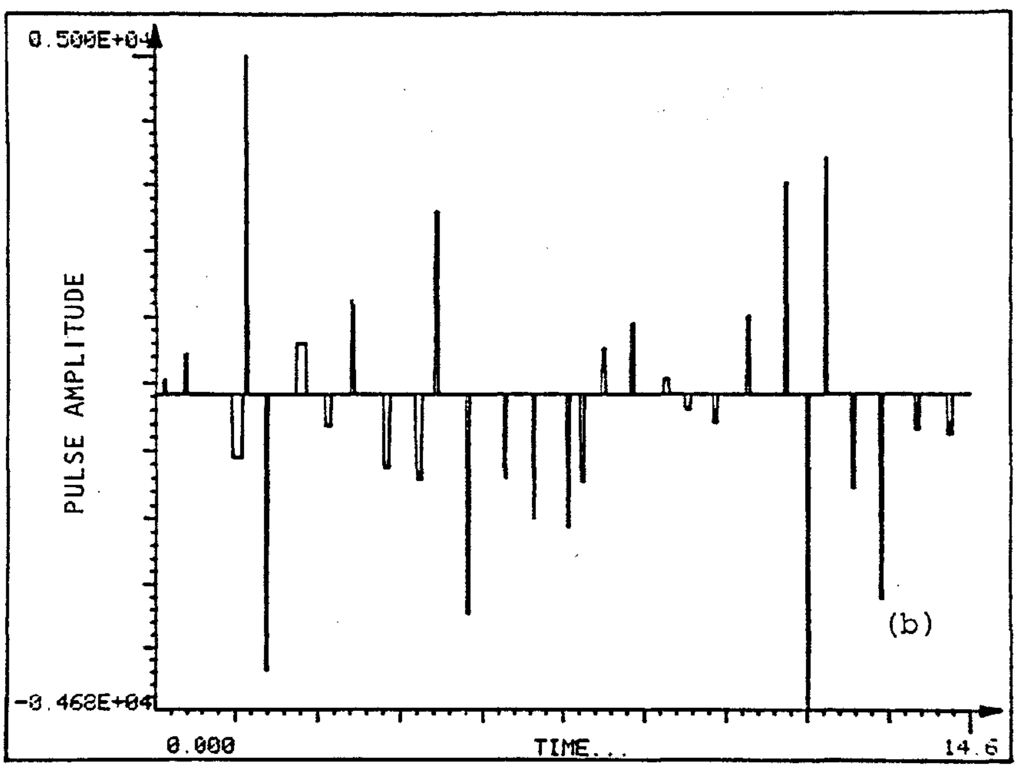
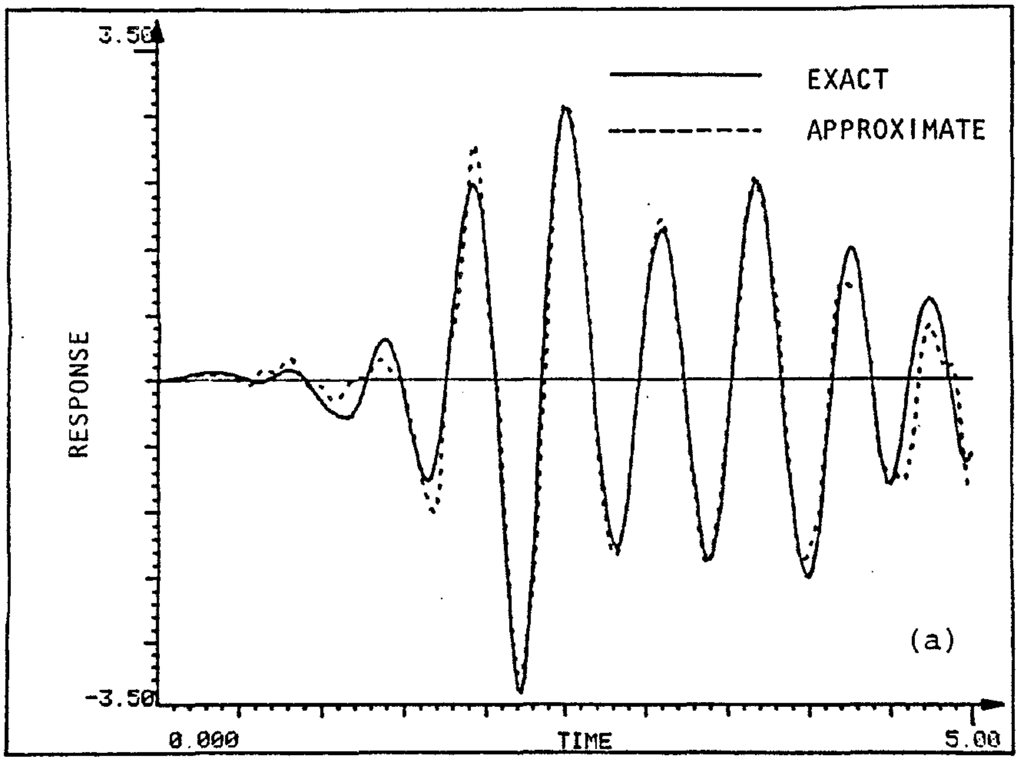


FIGURE 4.2-2. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER EL CENTRO EARTHQUAKE, t = 0 - 15s



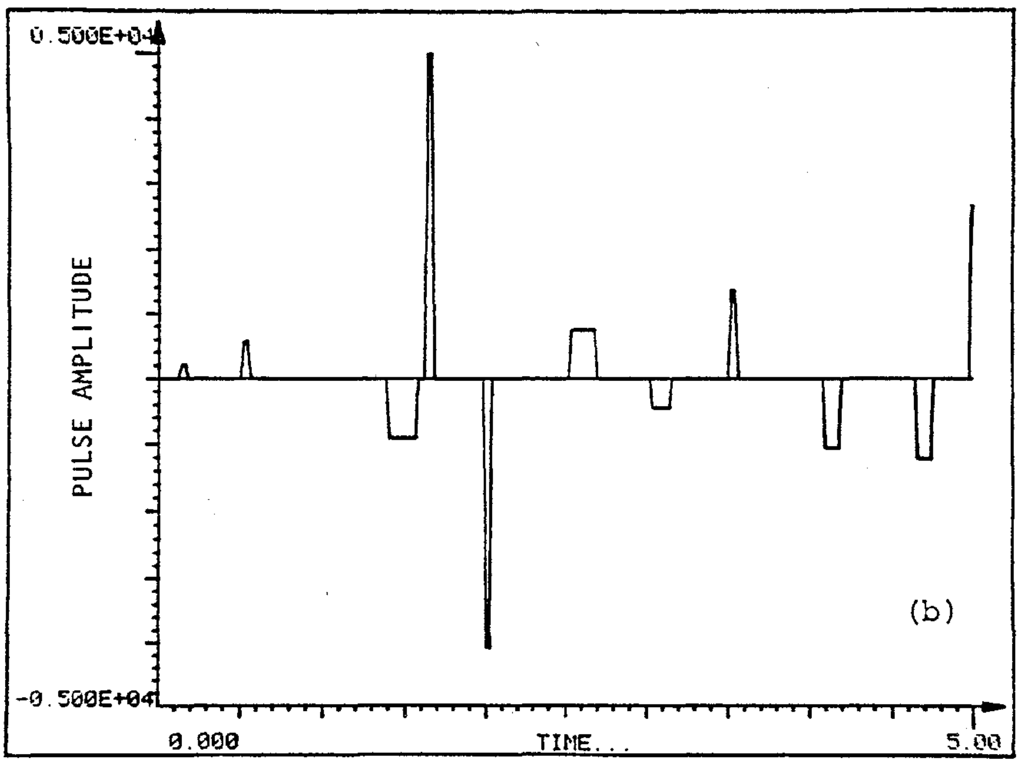


FIGURE 4.2-3. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER EL CENTRO EARTHQUAKE, t = 0 - 5s

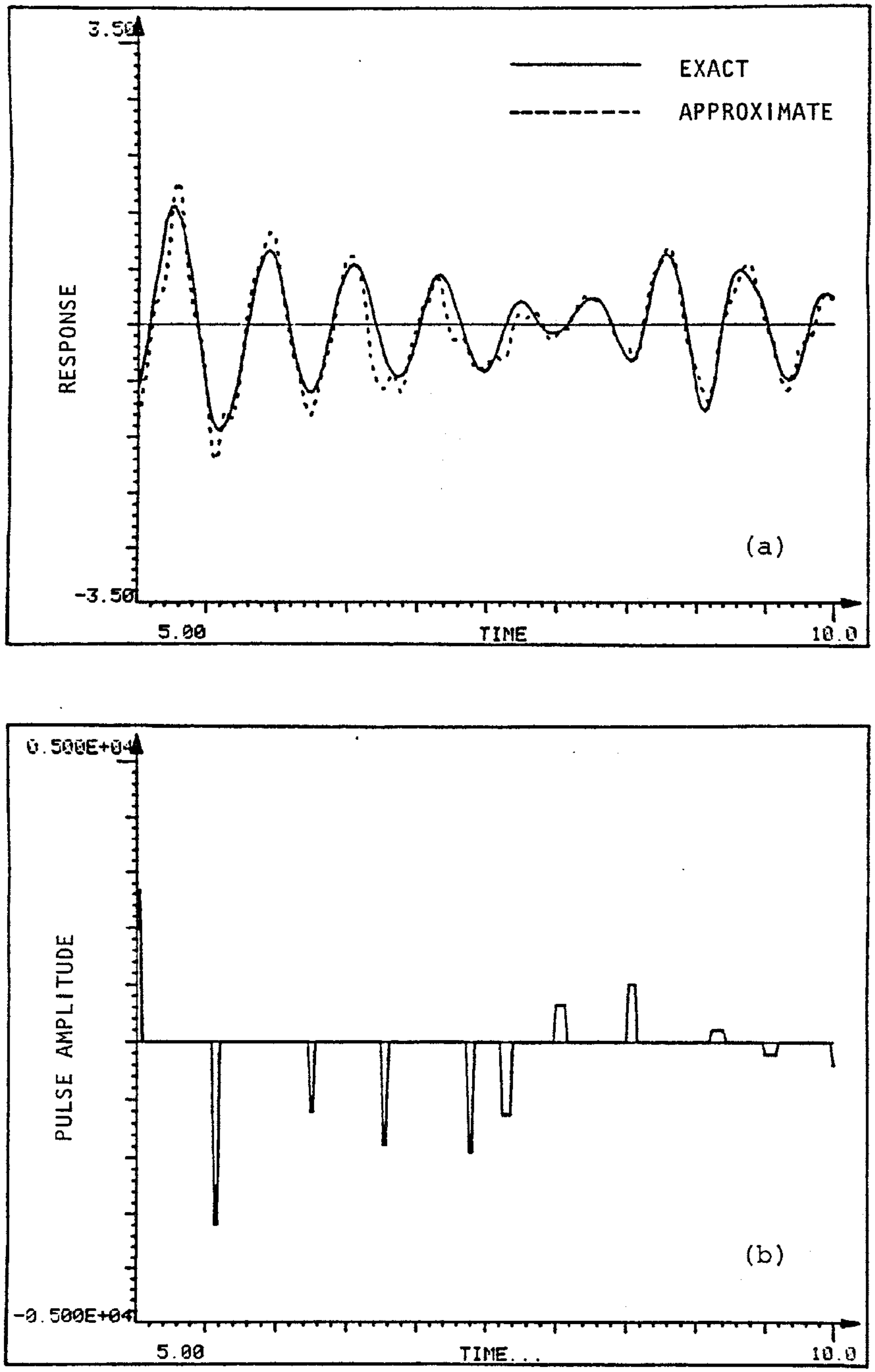


FIGURE 4.2-4. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER EL CENTRO EARTHQUAKE, t = 5 - 10s

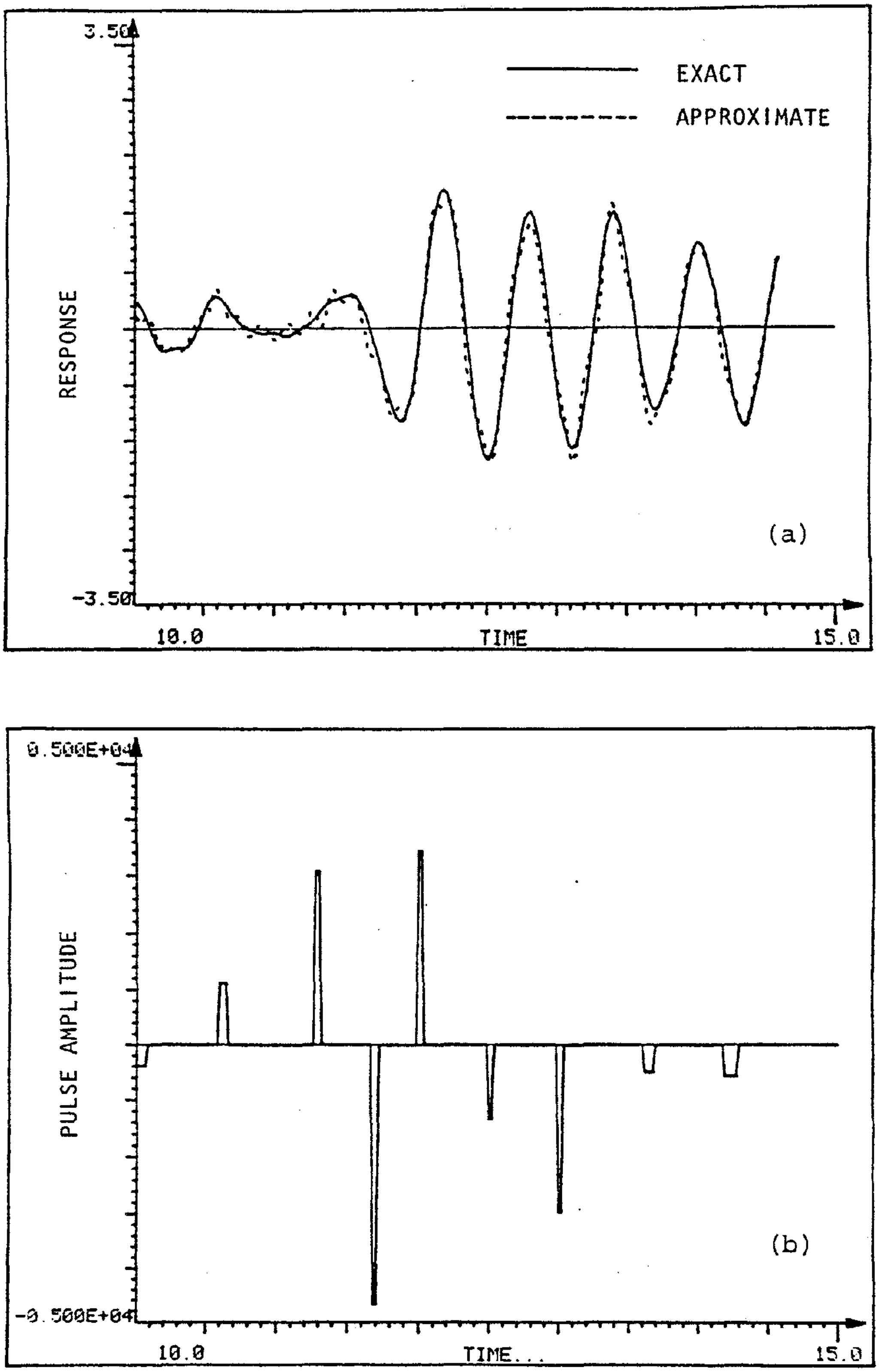
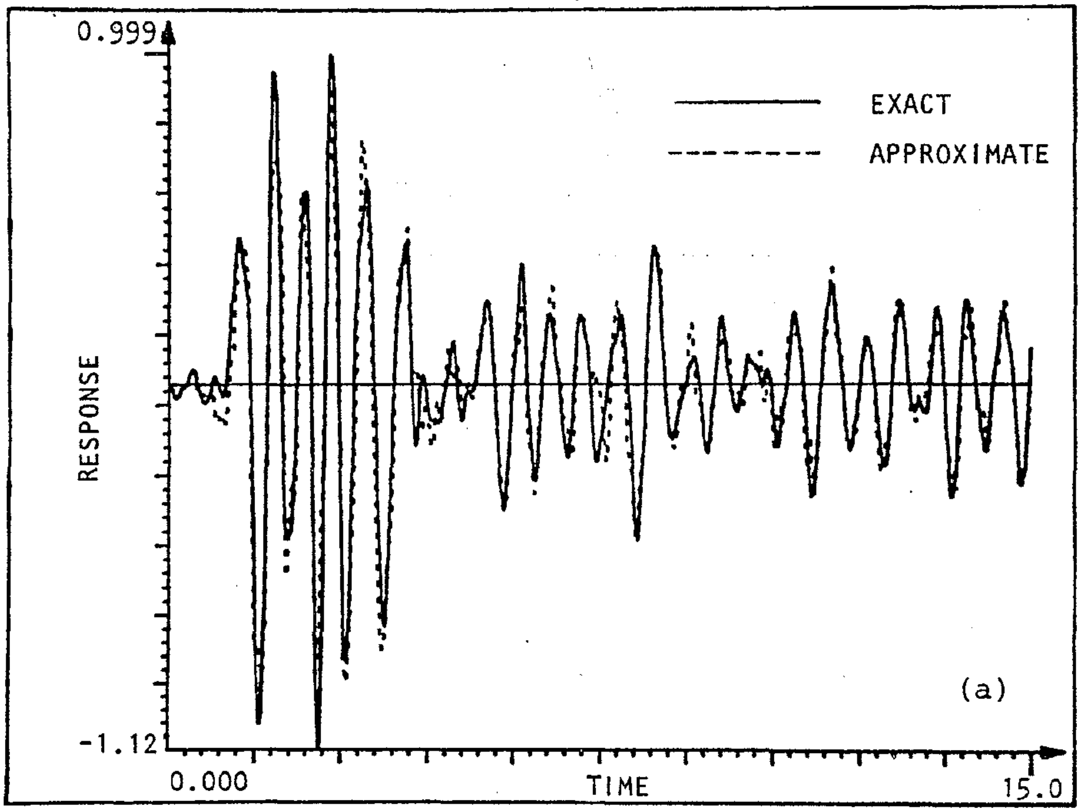


FIGURE 4.2-5. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER EL CENTRO EARTHQUAKE, t = 10 - 15s

J	K	APOLD(J,K)	DPOLD(J,K)	TPOLD(J,K)
1	1	-1.257E+01	4.888E-02	8.716E-03
1	2	-1.153E+02	4.125E-02	3.851E-01
1	3	-4.108E+02	4.203E-02	6.865E-01
1	4	1.335E+03	3.000E-02	1.052E+00
1	5	-1.075E+03	5.425E-02	1.358E+00
1	6	-5.821E+02	6.041E-02	1.750E+00
1	7	6.949E+02	7.554E-02	1.954E+00
1	8	-6.129E+02	1.080E-01	2.321E+00
1	9	6.490E+02	1.191E-01	2.480E+00
1	10	-7.794E+02	7.286E-02	2.713E+00
1	11	-7.828E+01	1.200E-01	3.160E+00
1	12	-3.266E+02	1.046E-01	3.550E+00
1	13	-7.234E+02	6.870E-02	3.723E+00
1	14	5.317E+02	7.521E-02	4.103E+00
1	15	-1.885E+02	1.118E-01	4.392E+00
1	16	-5.781E+01	1.111E-01	4.694E+00
1	17	3.305E+01	1.137E-01	4.988E+00
1	18	2.121E+02	1.142E-01	5.286E+00
1	19	-1.364E+02	1.068E-01	5.557E+00
1	20	-8.280E+01	1.043E-01	5.950E+00
1	21	-9.688E+02	3.000E-02	6.103E+00
1	22	5.867E+02	4.405E-02	6.300E+00
1	23	6.070E+02	4.219E-02	6.770E+00
1	24	-7.212E+02	3.021E-02	7.105E+00
1	25	9.877E+02	3.000E-02	7.241E+00
1	26	-2.090E+02	4.525E-02	7.523E+00
1	27	-1.455E+03	3.000E-02	7.979E+00
1	28	3.581E+02	3.709E-02	8.350E+00
1	29	4.764E+02	5.165E-02	8.567E+00
1	30	9.457E+01	4.843E-02	8.826E+00
1	31	-5.101E+02	4.552E-02	9.117E+00
1	32	5.442E+01	3.000E-02	9.429E+00
1	33	6.785E+02	3.000E-02	9.766E+00
1	34	2.676E+02	3.564E-02	1.015E+01
1	35	-6.254E+02	3.923E-02	1.036E+01
1	36	5.144E+02	3.000E-02	1.059E+01
1	37	-4.402E+02	3.049E-02	1.093E+01
1	38	7.322E+01	4.803E-02	1.110E+01
1	39	8.666E+02	3.000E-02	1.151E+01
1	40	-2.441E+02	5.151E-02	1.187E+01
1	41	-2.151E+02	8.623E-02	1.221E+01
1	42	6.519E+01	8.798E-02	1.251E+01
1	43	1.580E+02	8.778E-02	1.276E+01
1	44	1.702E+02	8.437E-02	1.308E+01
1	45	-2.147E+02	8.651E-02	1.337E+01
1	46	-1.411E+02	9.185E-02	1.369E+01
1	47	7.462E+01	8.985E-02	1.405E+01
1	48	1.532E+02	7.981E-02	1.431E+01

++++++++++++++++++++++++++++++

FIGURE 4.3-1. OPTIMUM PULSE TRAIN FOR SAN FERNANDO EARTHQUAKE



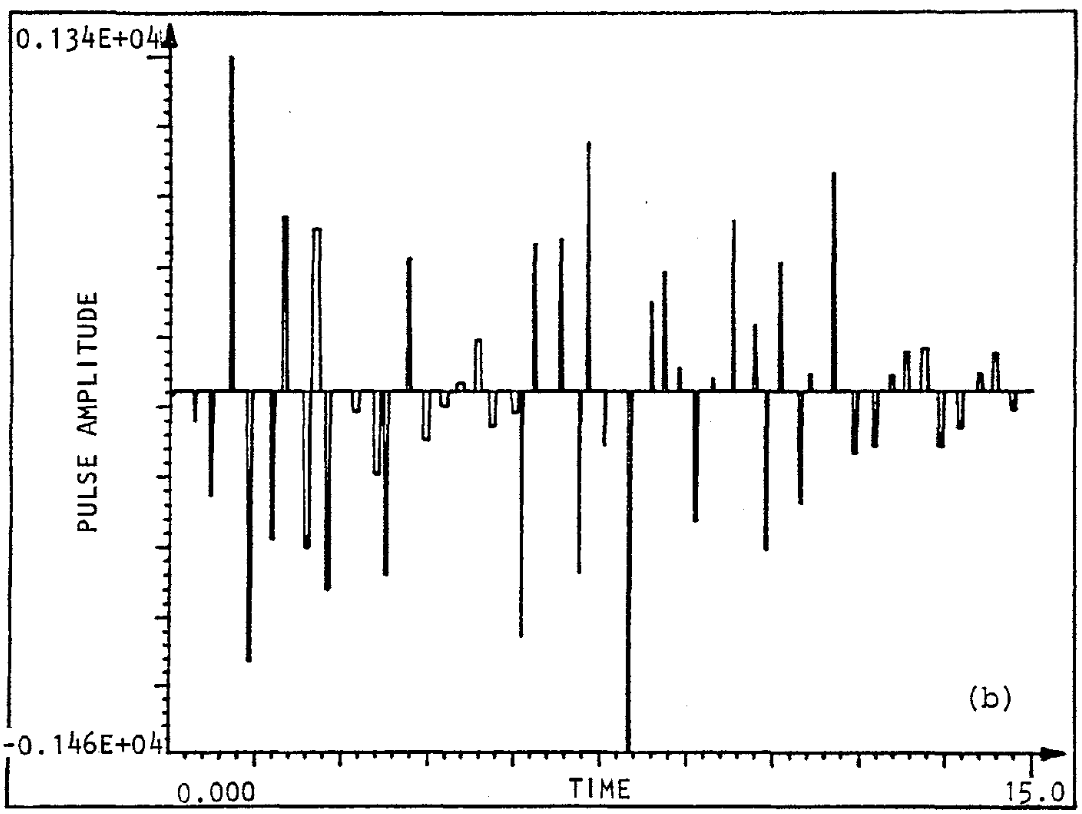


FIGURE 4.3-2. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER SAN FERNANDO EARTHQUAKE, t = 0 - 15s

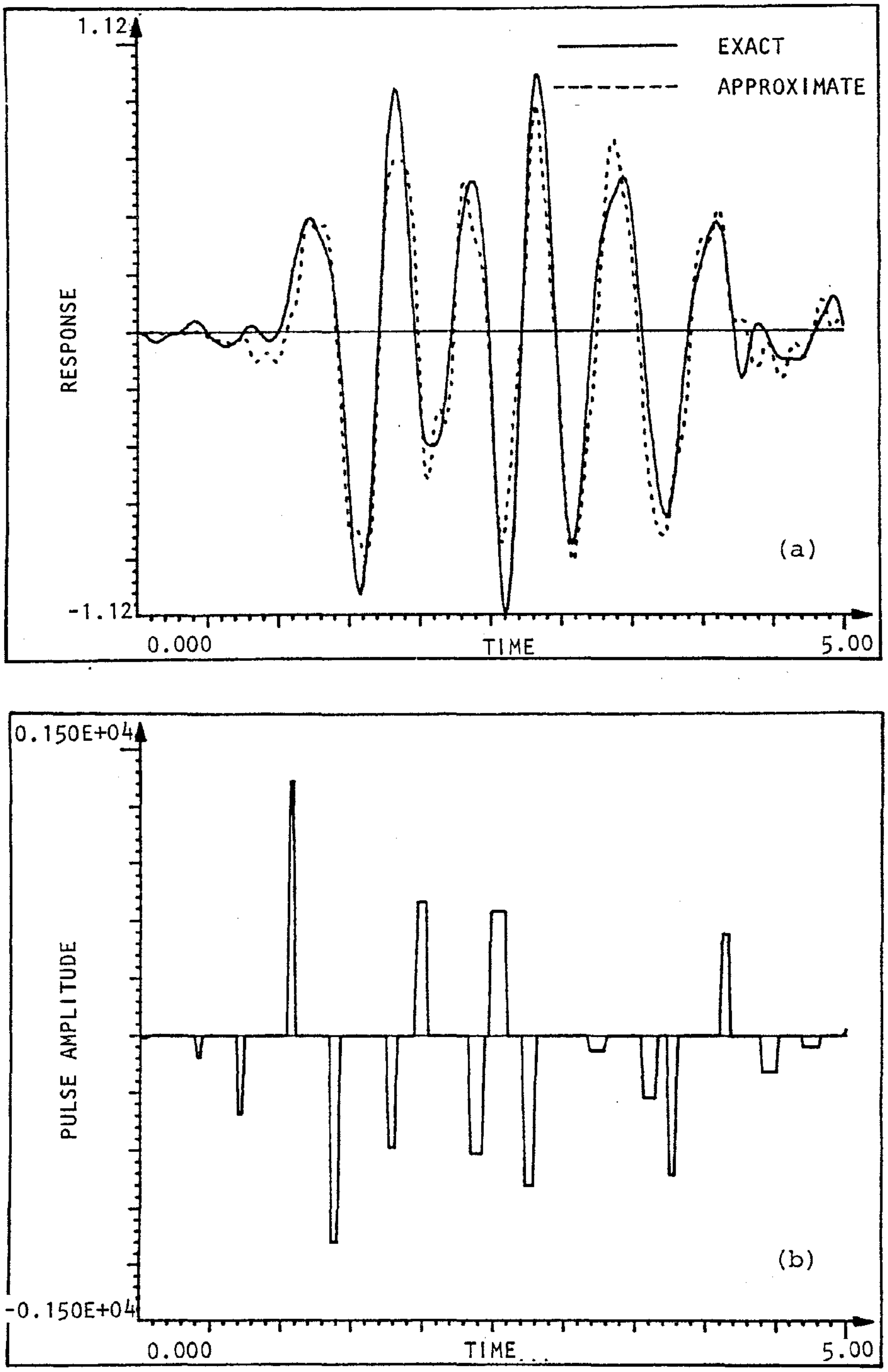


FIGURE 4.3-3. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER SAN FERNANDO EARTHQUAKE, t = 0 - 5s

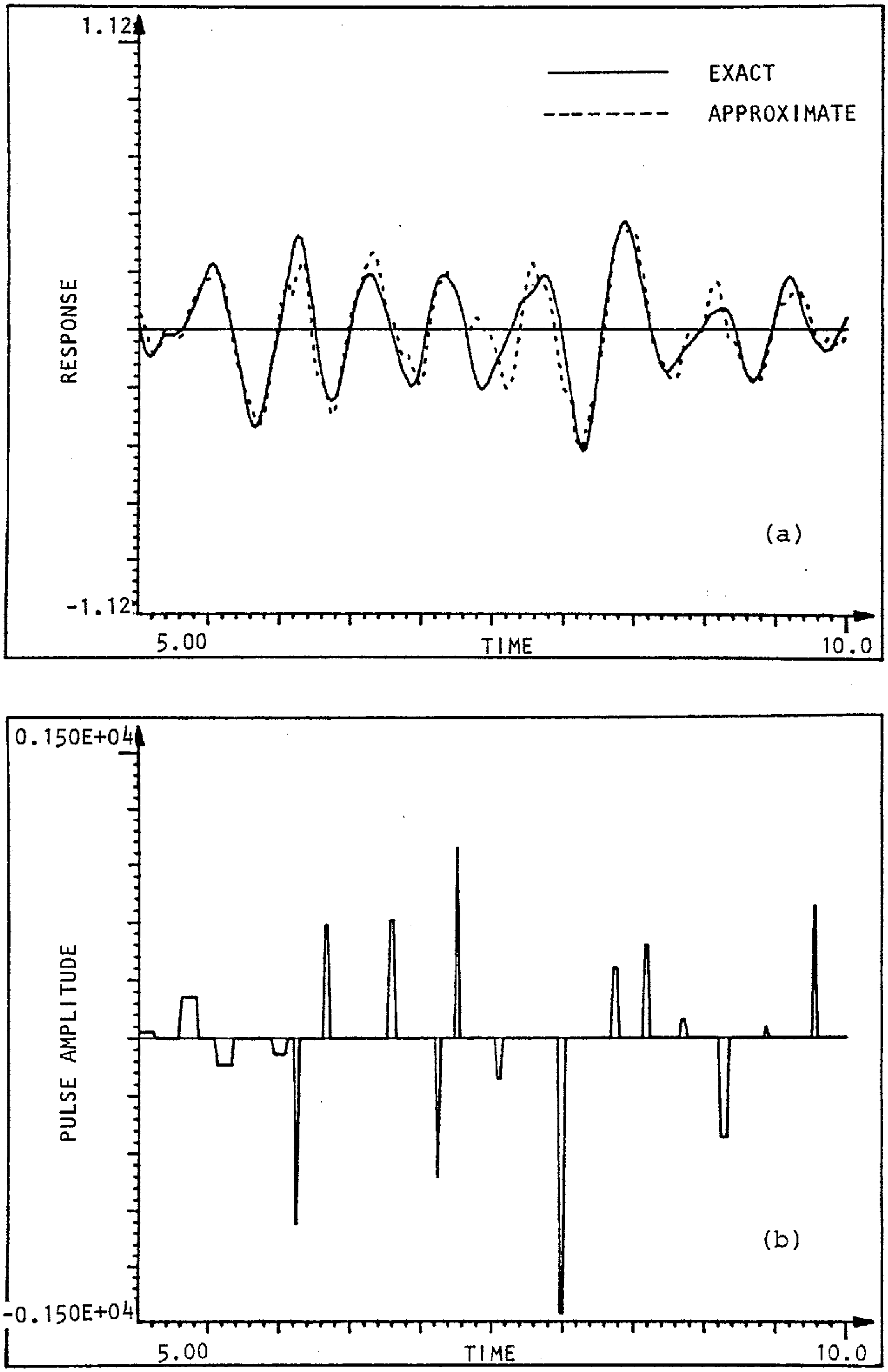
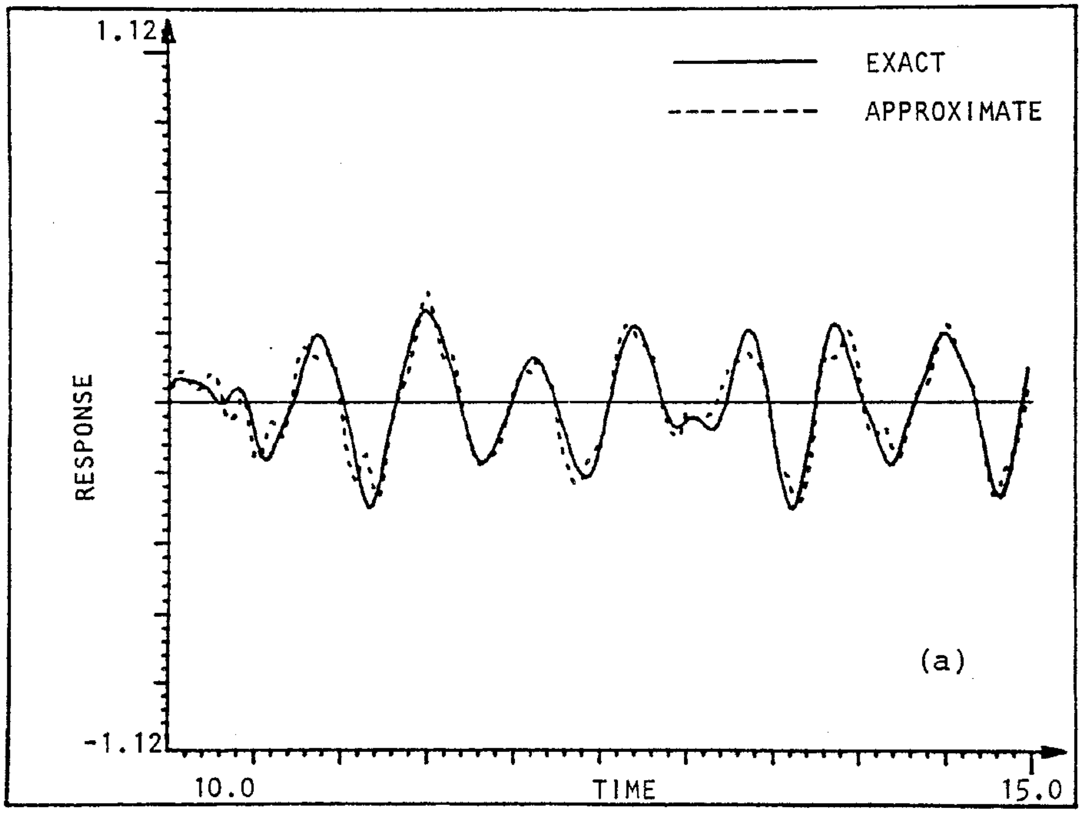


FIGURE 4.3-4. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER SAN FERNANDO EARTHQUAKE, t = 5 - 10s



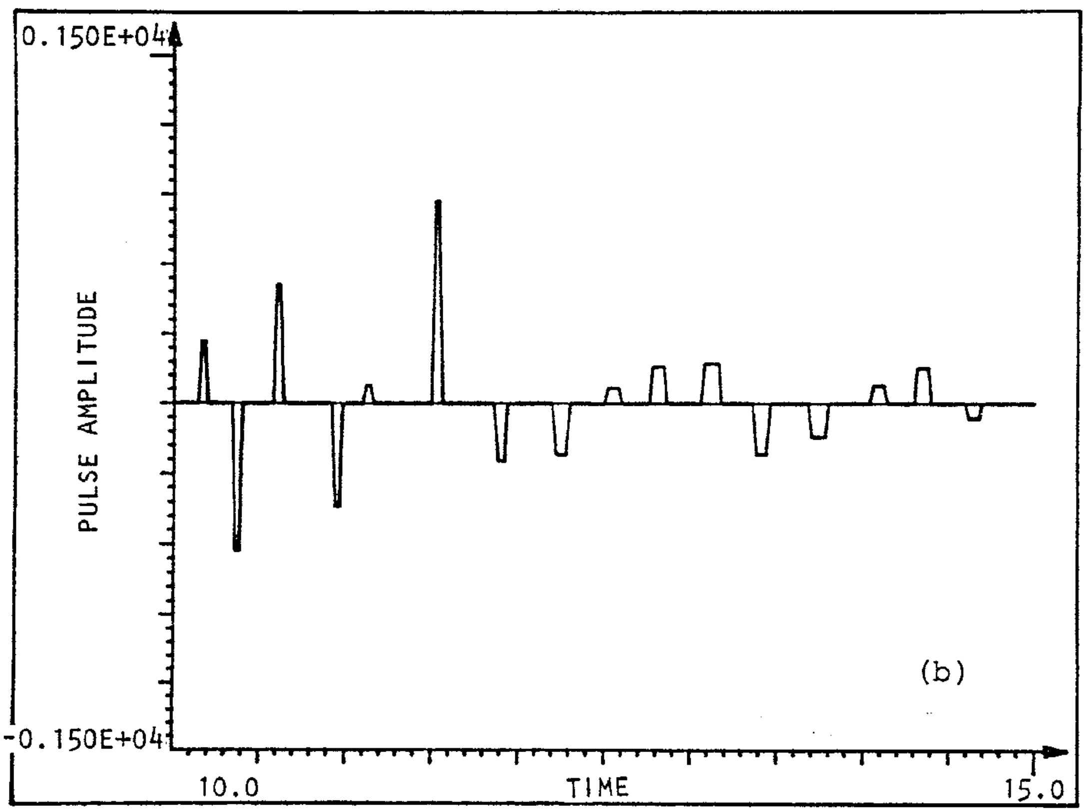


FIGURE 4.3-5. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER SAN FERNANDO EARTHQUAKE, t = 10 - 15s

4.4 GENERATION OF OPTIMUM PULSE TRAIN FOR SWEPT-SINE EXCITATION

The optimum pulse train characteristics for the swept-sine excitation are shown in Figure 4.4-1, and a comparison between the exact and approximate response is given in Figure 4.4-2.

J	K	APOLD(J,K)	DPOLD(J,K)	TPOLD(J,K)
1	1	-7.547E+01	3.000E-02	4.548E-05
1	2	2.882E+02	3.000E-02	5.500E-01
1	3	7.763E+02	3.015E-02	8.445E-01
1	4	1.196E+03	3.005E-02	1.148E+00
1	5	1.416E+03	3.007E-02	1.447E+00
1	6	1.471E+03	3.481E-02	1.733E+00
1	7	1.279E+03	3.577E-02	2.027E+00
1	8	8.401E+02	3.585E-02	2.317E+00
1	9	2.736E+02	3.000E-02	2.579E+00
1	10	-4.487E+02	4.109E-02	2.950E+00
1	11	-9.754E+02	4.314E-02	3.245E+00
1	12	-1.083E+03	4.007E-02	3.521E+00
1	13	-1.053E+03	3.842E-02	3.815E+00
1	14	-1.806E+02	4.022E-02	4.068E+00
1	15	6.559E+02	4.686E-02	4.450E+00
1	16	9.930E+02	4.420E-02	4.731E+00
1	17	9.640E+02	3.284E-02	5.010E+00
1	18	1.375E+02	3.000E-02	5.100E+00
1	19	2.996E+02	3.004E-02	5.405E+00
1	20	-2.565E+02	4.448E-02	5.764E+00
1	21	-6.691E+02	4.436E-02	6.070E+00
1	22	5.468E+02	5.172E-02	6.550E+00
1	23	1.163E+03	3.021E-02	6.819E+00
1	24	2.378E+02	3.000E-02	6.901E+00
1	25	-1.366E+03	3.089E-02	7.445E+00
1	26	-1.016E+03	3.746E-02	7.711E+00
1	27	4.709E+02	5.422E-02	8.050E+00
1	28	1.149E+03	4.408E-02	8.315E+00
1	29	4.117E+02	3.808E-02	8.552E+00
1	30	-7.334E+02	4.152E-02	8.930E+00
1	31	-4.918E+02	3.294E-02	9.170E+00
1	32	7.623E+02	4.040E-02	9.517E+00
1	33	4.094E+02	5.227E-02	9.736E+00
1	34	-5.194E+02	8.043E-02	1.011E+01
1	35	-2.808E+02	7.904E-02	1.038E+01

FIGURE 4.4-1. OPTIMUM PULSE TRAIN FOR SWEPT-SINE EXCITATION

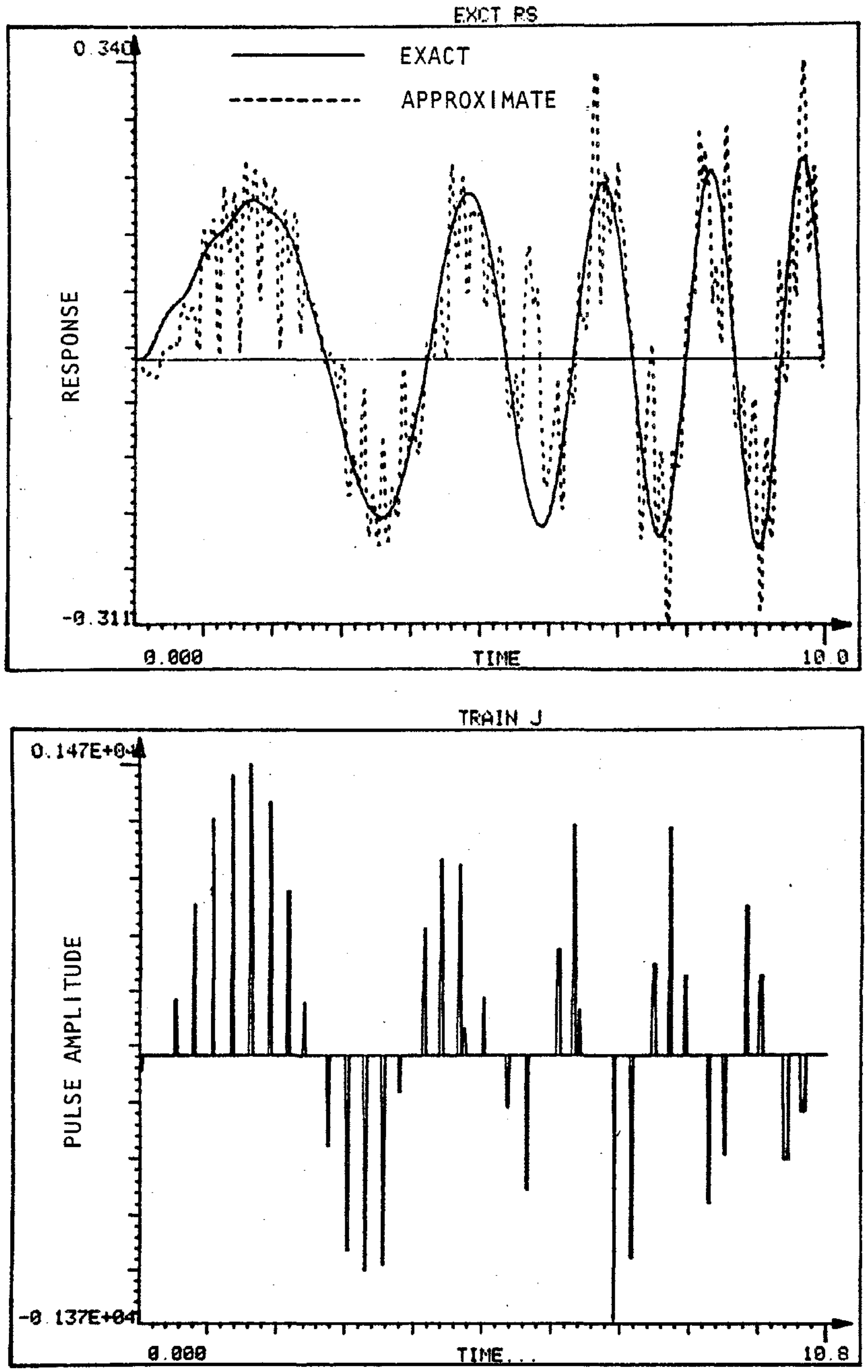


FIGURE 4.4-2. PULSE-SIMULATED MOTION OF THE TEST STRUCTURE UNDER SWEPT-SINE EXCITATION, t = 0 - 10s

SECTION 5

GAS PULSE GENERATOR

5.1 SYSTEM CHARACTERISTICS

Two gas pulse systems were used and are schematically illustrated in Figure 5.1-1. The pulsers were positioned so as to place each system in opposing directions during the test of the structure. This "opposed positioning" permits the sense of positive and negative force pulses. The operations of the two systems are controlled by a common microcomputer. Each gas pulse system is composed of the following subsystems:

- Pulse Rocket
- Hydraulic subsystem
- High pressure gas supply
- Control microcomputer

In addition, signal monitors and data recordings are provided. A photograph of the gas pulse generator is shown in Figure 5.1-2 and a sketch of the system including a slave valve and a pilot valve is given in Figure 5.1-3.

5.2 HYDRAULIC SUBSYSTEM

The function of the hydraulic subsystem, upon command from a microcomputer, is to position the metering plug in the gas rocket. This subsystem consists of a hydraulic actuator, hydraulic power supply, power control panel and signal controller.

The hydraulic actuator is shown schematically in Figures 5.1-1 and 5.1-3. This actuator has an output force of 6,600 lbf and a stroke of 2 in. Overall dimensions are 24 in. in length and 6.3 in. body diameter.

The hydraulic power supply is given in the schematic of Figure 5.2-1. The principal energy source is the 10 gal accumulator which is used to drive the actuators. The accumulator has sufficient capacity for most earthquake applications

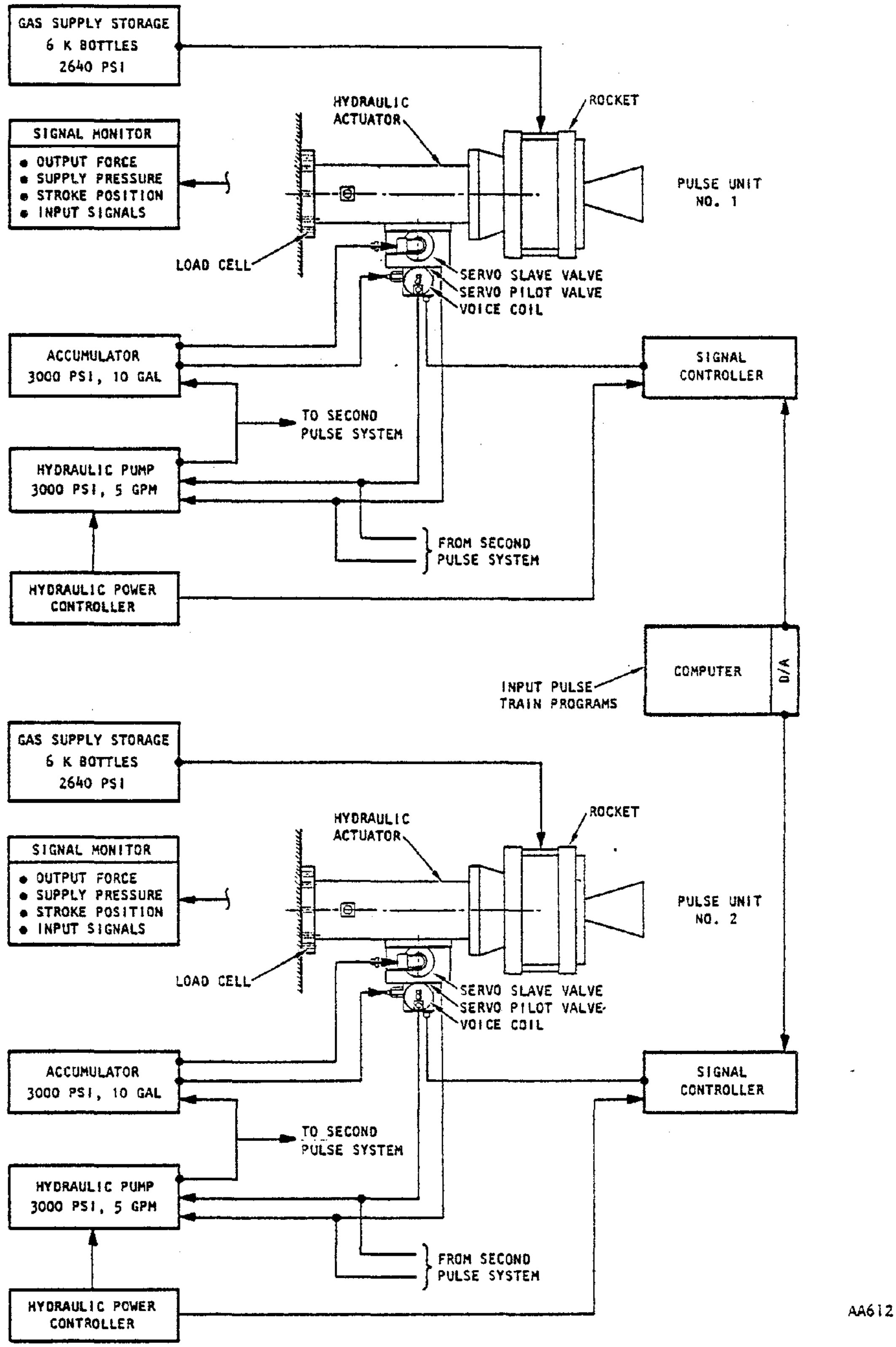


FIGURE 5.1-1. SCHEMATIC OF TWO GAS REACTION PULSE-GENERATING SYSTEMS CONTROLLED BY CENTRAL MICROCOMPUTER

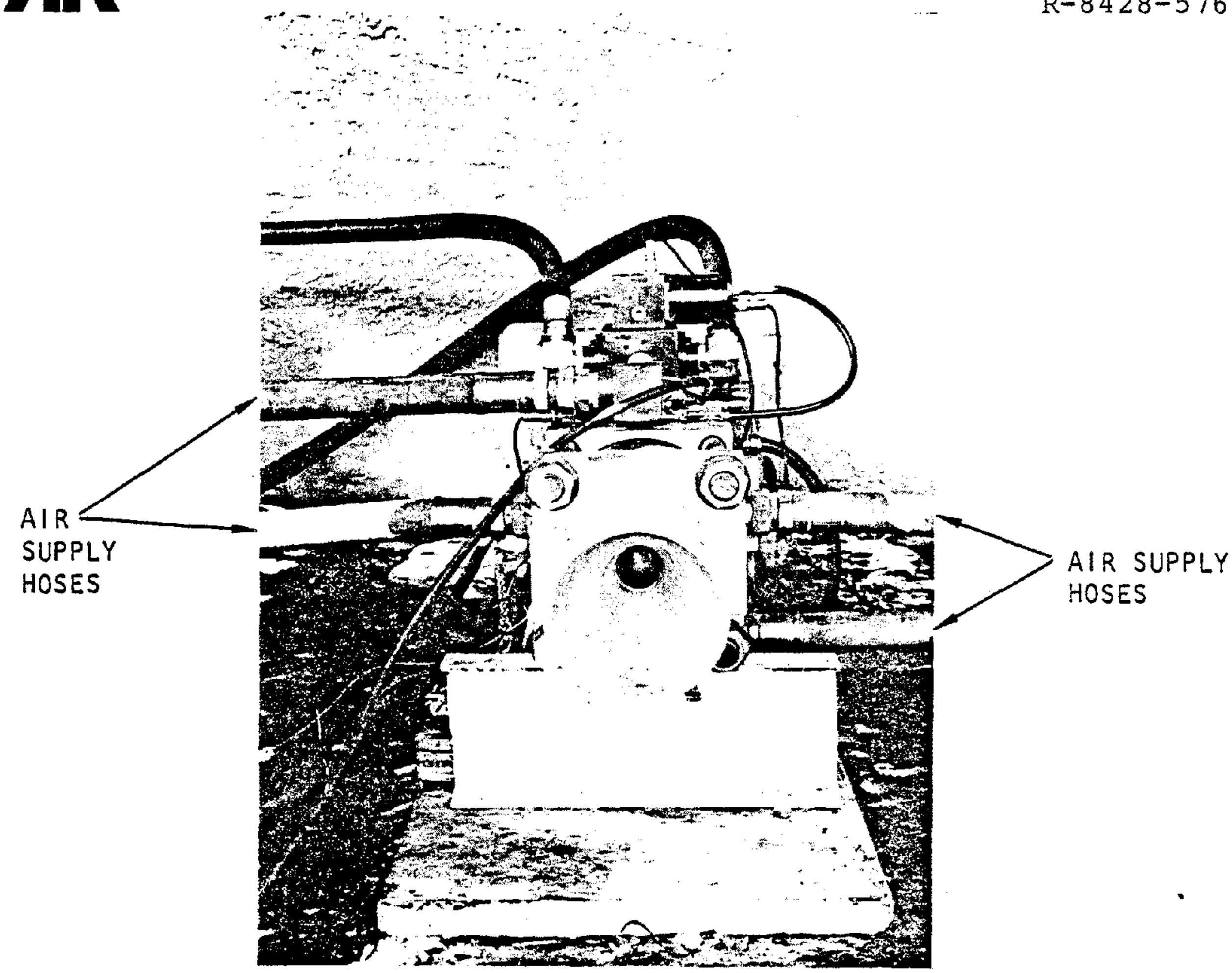


FIGURE 5.1-2. FRONT VIEW OF GAS PULSE GENERATOR

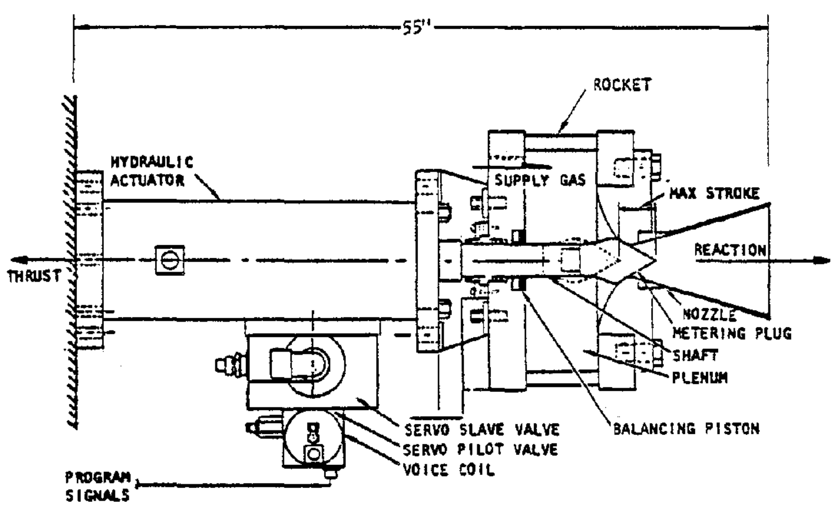


FIGURE 5.1-3. GAS REACTION FORCE PULSE GENERATOR EQUIPPED WITH A 90-GPM SLAVE VALVE AND A 5-GPM PILOT VALVE

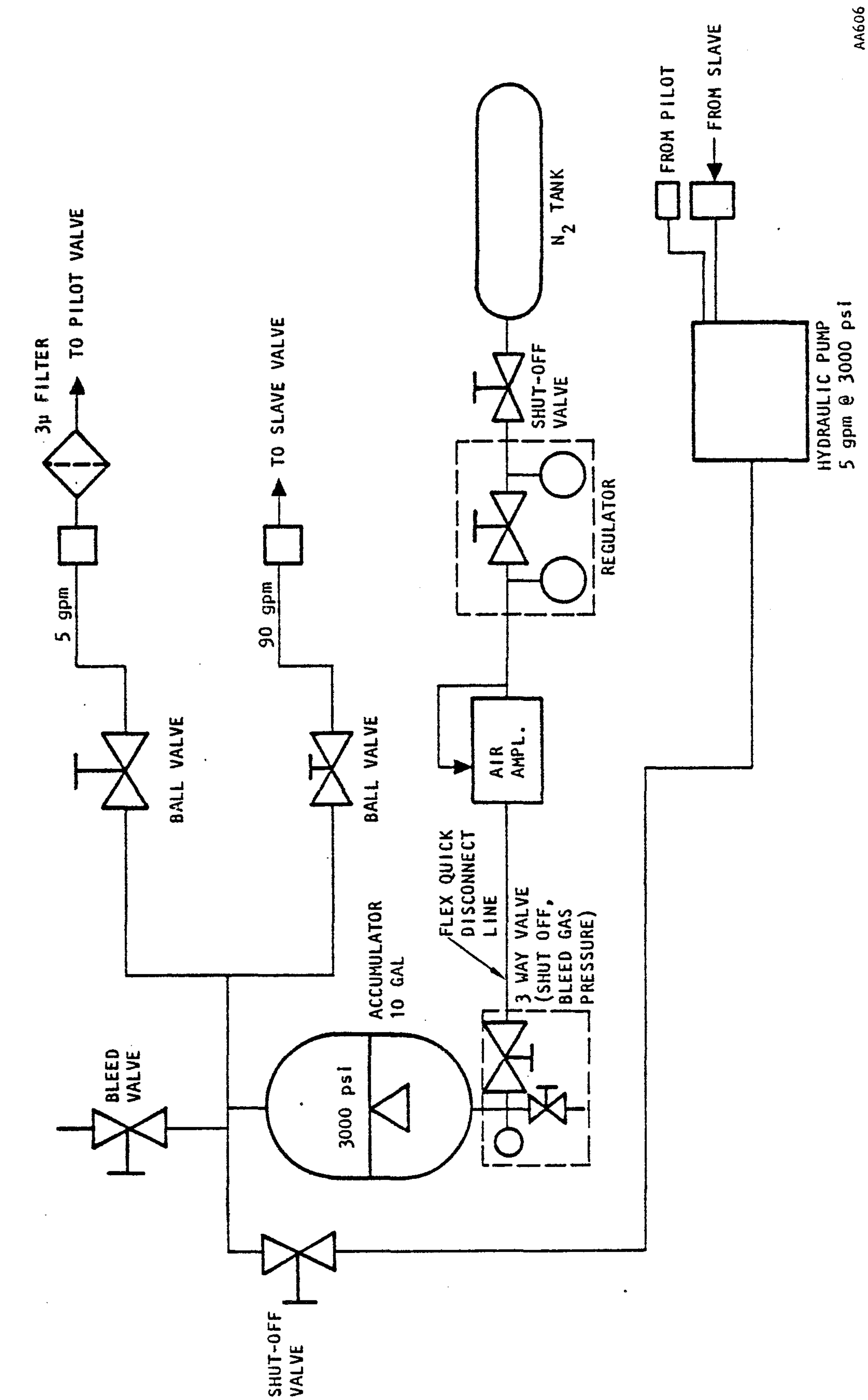


FIGURE 5.2-1. HYDRAULIC POWER SUPPLY AND CHARGING SYSTEM, PLUG NOZZLE ACTUATOR

and thereby eliminates the need for a high cost hydraulic pump. A small hydrualic pump (5 gpm) proved adequate to bring the subsystem up to operating pressure (3000 psi) and sustain the leakage flow in the actuator because actuator leakage occurs in both slave and pilot valves and in the hydrostatic bearings.

5.3 GAS STORAGE SUBSYSTEM

Gas supply storage for nitrogen gas consists of six standard industrial high pressure tanks, four 10 ft long 1-1/4 in. dia. flexible hoses and the plenum chamber for each gas pulse generator system. Three pressure tanks are mounted as a group with each tank equipped with a valve and a manifold. A typical unit is pictured in Figure 5.3-1.

5.4 CONTROL MICROCOMPUTER

The microcomputer controls the firing pulses for both pulse generating systems. This computer, a PDP 11V03L, manufactured by the Digital Equipment Corp., is pictured in Figure 5.4-1, and its main features are diagrammed in Figure 5.4-2. Operation of the pulse generator requires that the pulse generating algorithm be programmed in machine language (real time).

Four channels are available for output via a D/A converter, and these are used in channel pairs for valve position and time commands to each pulse generator (hydraulic servo controller). Sixteen system channels are available for input via A/D converter to receive input signals of dynamic response of structures.

Programming for earthquake testing is straightforward. A test program is initiated and the valve position (amplitude) and the on/off times are entered for each pulse unit from the keyboard. The desired pulse program is stored in memory and upon call-up will initiate the pulse firing sequence.

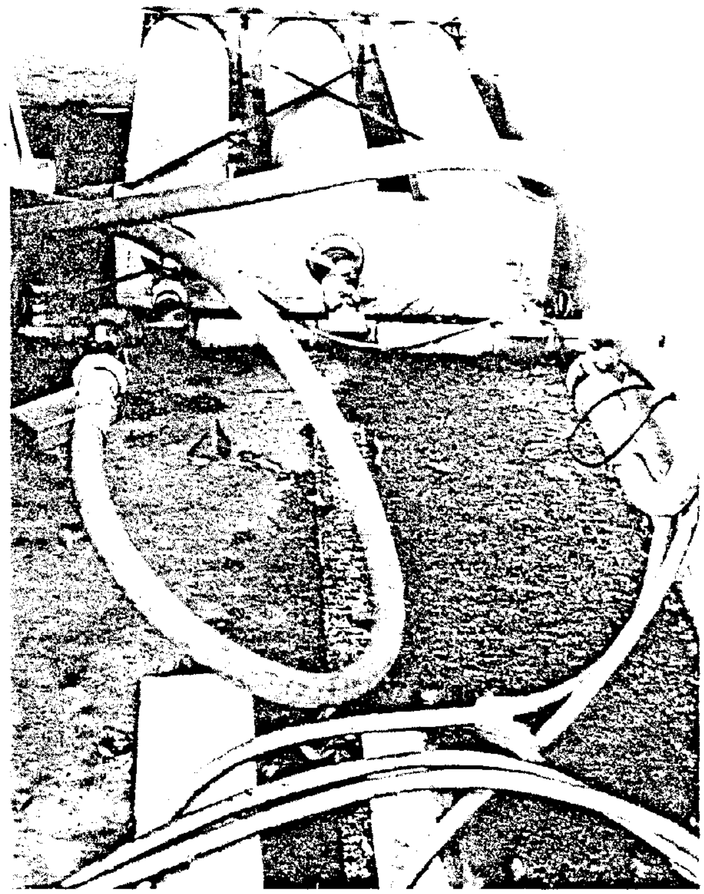


FIGURE 5.3-1. HIGH PRESSURE GAS STORAGE UNITS (ONE SET OF FOUR) USED TO SUPPLY PULSER

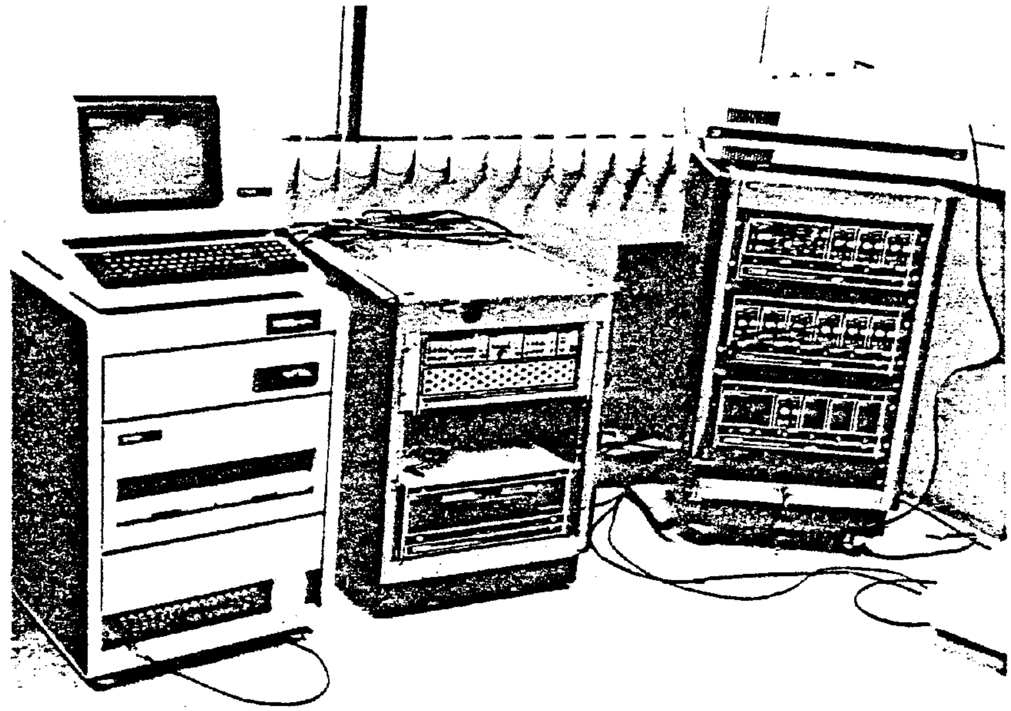
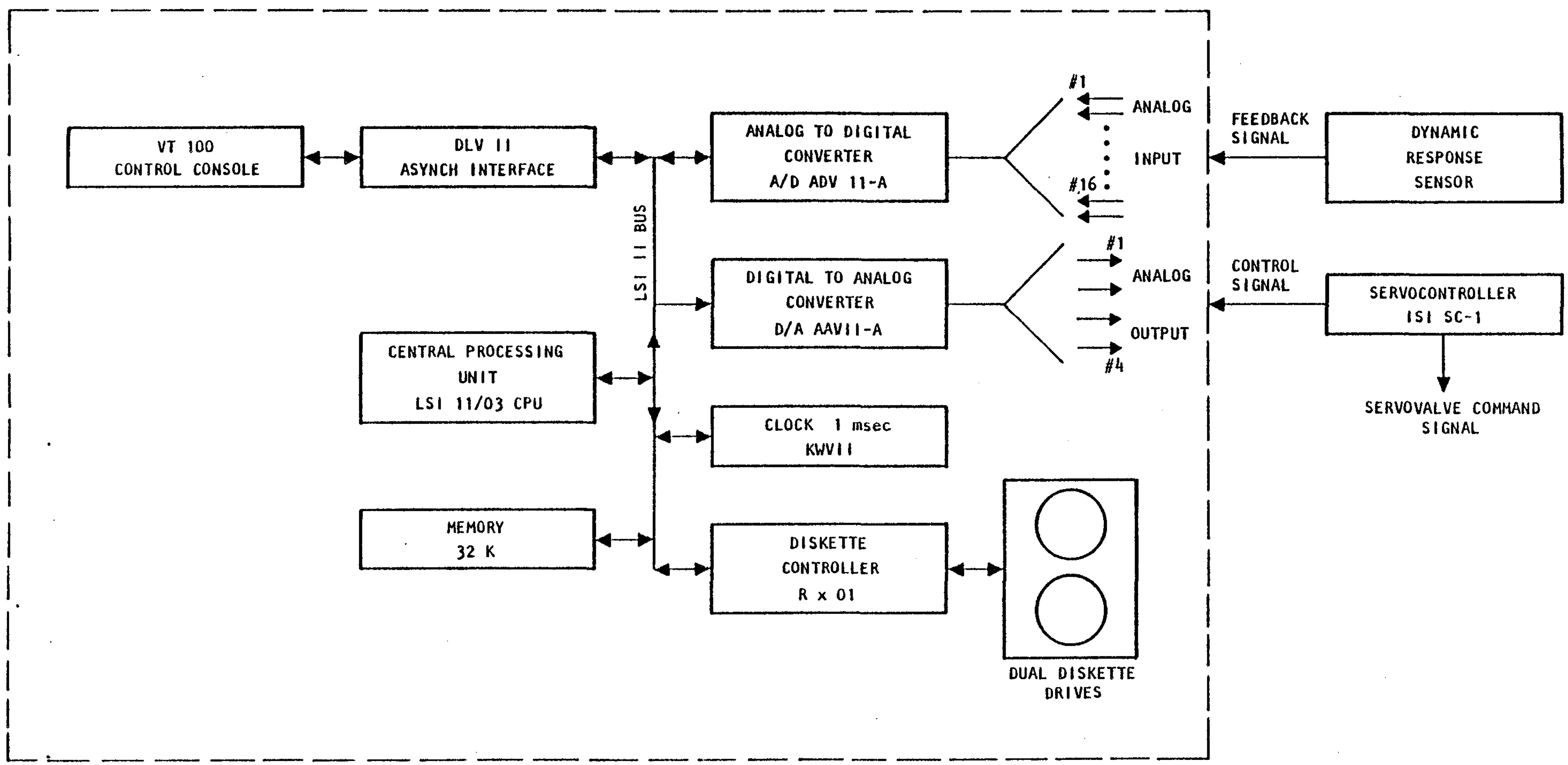


FIGURE 5.4-1. CONTROL MICROCOMPUTER (LEFT) AND DATA RECORDING AND PROCESSING SYSTEM (CENTER AND RIGHT)



AA607

FIGURE 5.4-2. MICROCOMPUTER SYSTEM USED TO CONTROL PULSE GENERATOR SYSTEM

SECTION 6

INSTRUMENTATION

6.1 SENSORS

Potentiometer-type displacement sensors were used to measure the dynamic response of the test structure. The location of the motion sensors is shown in Figure 9.3-1.

The following sensors are used to measure the performance of the pulse generators:

- Metering nozzle position - Hydraulic actuator LVDT
- Plenum chamber pressure - Pressure transducer Teledyne model 206AGX, 0-3000 psig
- Thrust - Load cell Interface model 1220AF, 0-25,000 lbf
- Command pulse train - Direct recording signals.

6.2 SIGNAL MONITORING AND DATA ACQUISITION

The method used in this report for recording test results is by signal capture via an A/D converter into circulating registers. Subsequent processiug on digital data acquisition/ processing equipment is performed within a few minutes after testing; the Zonic equipment used for this procedure is pictured in Figure 5.4-1. Data diaplays are in time histories and Fourier spectra. Eventually, data is transferred to a main-frame computer for time series analysis.

SECTION 7

THRUST CALCULATIONS

7.1 MACHINE OPERATIONS

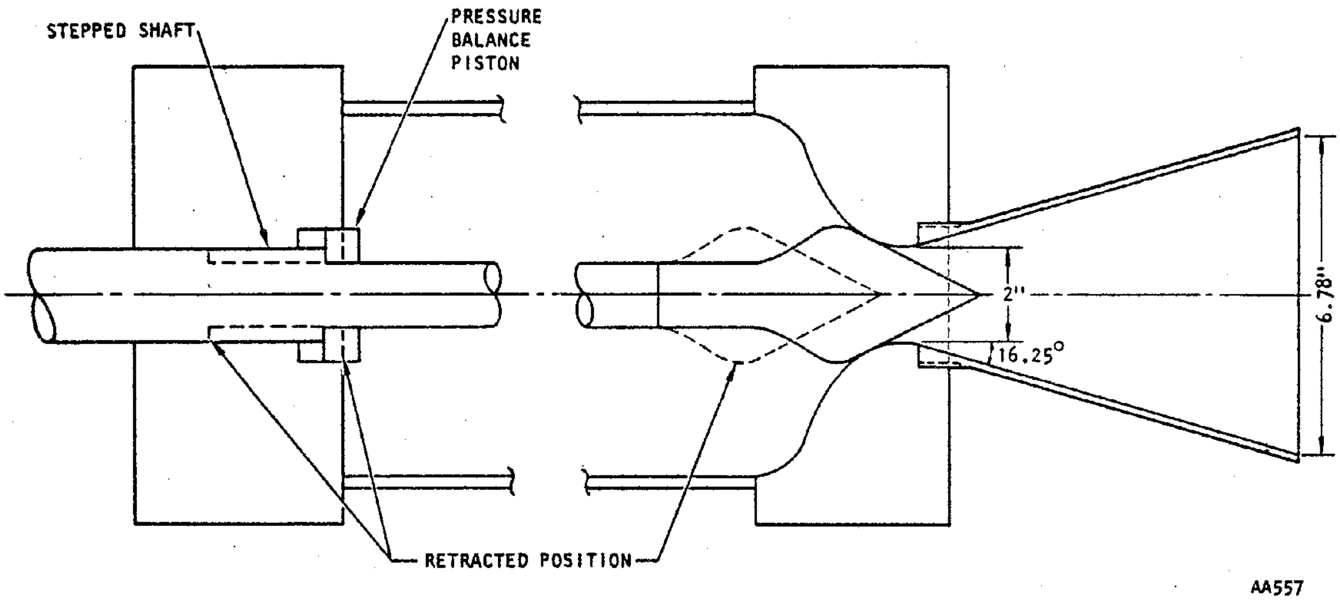
A major factor that influences the performance of the pulse generator is the value of the internal gas pressure. The setting of maximum pressure levels was determined by safety considerations and the availability of standard pipe fittings and hoses and commercially available high pessure nitrogen tanks. These considerations set the nominal operating gas pressure of the system at 2640 psig (standard commercial K size gas storage bottle 1.54 ft^3).

In order to improve the high frequency performance of the pulse generator, a pressure balancing piston was added to compensate for the pressure forces on the rear of the metering nozzle. Other key features of the metering nozzle unit are a throat diameter d_t of the De Laval nozzle at 2 in. and a hydraulic actuator with a 6,600 lb force capacity (see Fig. 7.1-1)

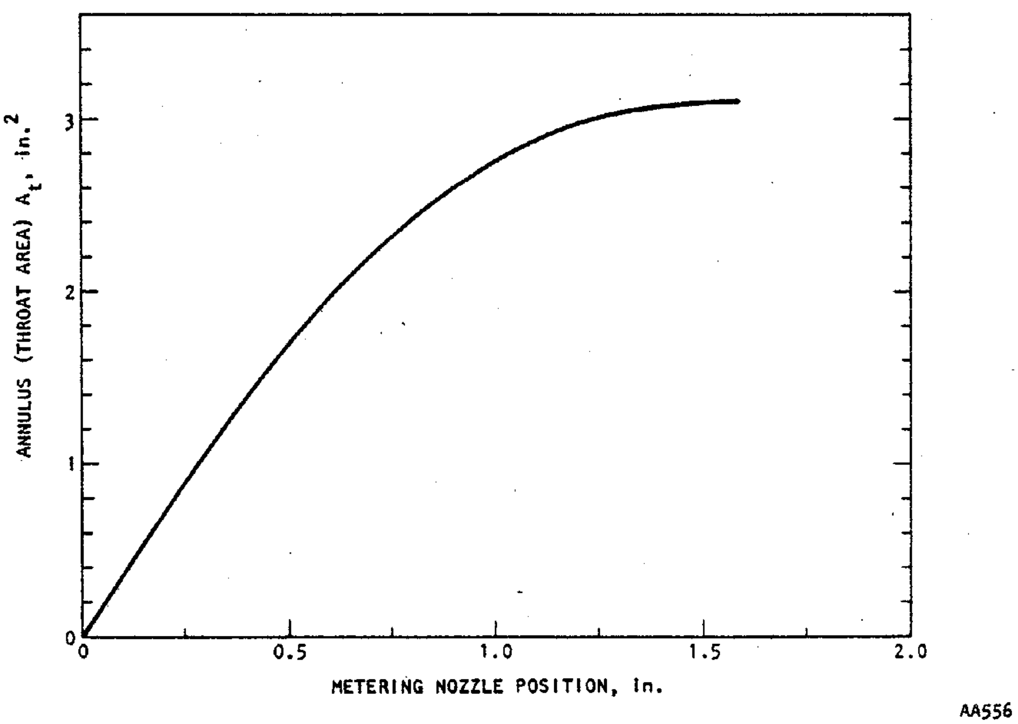
Thrust may be varied by commanding the position of the metering plug from the closed (no flow) position to the full open (maximum flow). On command from a signal programmed in the microcomputer, the metering plug retracts to a specified position, at which point the throat area is an annulus between the conic surface of the metering plug and the wall of the convergent section of the nozzle. Figure 7.1-1 shows the functional relation between the retracted position of the metering plug and the throat are, A_t.

7.2 THRUST CALCULATIONS

The gas storage capacity for each pulse generator consists of six gas bottles, four 10 ft long hoses, and the plenum chamber of the gas rocket. This storage capacity amounts to 10.2 ft^3, and 134 lb of nitrogen compressed at 2640 psig. After



(a) Metering nozzle and pressure balance piston configuration



(b) Calibration curve

FIGURE 7.1-1. THROAT AREA (ANNULUS) AS A FUNCTION OF METERING NOZZLE POSITION each pulse, the stored gas is reduced in pressure, and hence, less potential energy is available. Thus, to program a pulse train, a series of incremental solutions to the gas equations are required. For example, in a particular test, the initial chamber pressure of 2640 psig can reduce to 400 psig and internal energy would reduce thereby from 134 BTU/lb to 119 BTU/lb after the last pulse. At the beginning of each pulse, the state of the pressure, internal energy, temperature, and weight of gas (reservoir) must be known in order to program the next pulse for thrust, by the throat area and the calibrated nozzle coefficient. An example of these calculations is given in Table 7.2-1.

Thrust is given by

$$F = - \dot{m} V_{xe} + A_e (P_e - P_o)$$

where

F = Thrust, lbf

$\dot{m}$ = Mass rate of flow, lb-sec/ft

A_e = Exit area of nozzle, in.2

P_e = Exit pressure, psia

P_o = Ambient pressure, psia

For these calculations $P_e = P_o$ was assumed, with subsequent correction made using the calibrated nozzle coefficient C_{FX}.

For the jet velocity,

$$V_{xe} = \lambda V_e$$

TABLE 7.2-1. EXAMPLE OF INCREMENTAL CALCULATIONS NEEDED TO ESTABLISH VALVE POSITION FOR THRUST REQUIREMENTS

				Plenum Chamber			Storage Capacity			Weight Rate of Flow	Jet Velocity	Density
				Static		Transient						
Pulse No.	Req'd Force	Valve Position in.	Valve Position in^2	P_{start} (psig)	P_{end} (psig)	P_c (psig)	Start W (lb)	Stop W (lb)	Diff. ΔW (lb)	$\dot{w}$ lb/sec	V_{ex} ft/sec	ω lbs/ft^3
1	1,230	0.12	0.44	2,200	2,157	2,145	111.87	110.32	1.55	18.3	2,161	10.97
2	847	0.10	0.34	2,157	2,127	2,099	110.32	109.3	1.07	12.68	2,149	10.86
3	4,332	0.46	1.63	2,127	1,985	1,812	109.3	104.1	5.2	66.1	2,109	10.13
4	2,742	0.30	1.12	1,985	1,896	1,793	104.1	100.8	3.3	41.63	2,119	9.71
5	1,105	0.13	0.51	1,896	1,876	1,828	100.8	100.15	0.75	16.7	2,124	9.53
6	2,078	0.23	0.88	1,876	1,810	1,716	100.05	97.54	2.51	31.52	2,121	9.17
7	2,348	0.29	1.08	1,810	1,735	1,658	97.54	94.68	2.86	35.63	2,120	8.81
8	3,554	0.45	1.60	1,735	1,625	1,542	94.68	90.45	4.23	54.13	2,112	8.45
9	1,400	0.2	0.75	1,625	1,583	1,537	90.45	88.8	1.65	21.53	2,092	8.27
10	302	0.05	0.18	1,583	1,574	1,556	88.8	88.43	0.375	4.64	2,093	8.20

where

λ = Nozzle divergence factor = 0.98

V_e = Jet velocity, ft/sec

$$V_e = \left\{ \left(\frac{2\gamma}{\gamma - 1} \right) \left(\frac{P_c}{\rho_c} \right) \left[1 - \frac{P_o}{P_c}^{\frac{\gamma-1}{\gamma}} \right] \right\}^{1/2}$$

where

ρ_c = Gas density in chamber, $lb\text{-}sec^2/ft^4$

Other parameters as given before.

The mass flow through nozzle is

$$\dot{m} = \left[\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{2(\gamma - 1)}} \right] \frac{P_c A_t}{A_c}$$

where A_c is the acoustic velocity (ft/sec) in the chamber and is given by:

$$A_c = \sqrt{\gamma \frac{P_c}{\rho_c}} \quad \text{plus temperature correction}$$

Other parameters have been defined previously.

From the general flow equation and for the condition of no flow, the chamber pressure is given by:

$$\frac{P_c \nu_c}{J} + U_c = \text{constant}$$

where

ν_c = Specific volume, ft^3/lb

U_c = Internal energy, Btu/lb

J = Heat equivalent of work, 778 ft-lb/BTU

Flow occurs upon retraction of the metering plug, which results in a drop in chamber pressure (P_c). This quantity is required to predict thrust:

$$\frac{P_c \nu_c - 0.53 P_c \nu_t}{J} + (U_c - U_t) = \frac{V_t^2}{2gJ}$$

and

$$P_t = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} P_c = 0.53 P_c$$

$$V_t \approx \sqrt{\gamma \frac{0.53 P_c}{\rho_t}}$$

where

ν_c, ν_t = Specific volumes at chamber and throat, ft^3/lb

ρ_t = Density at throat, $lb\text{-}sec^2/ft^4$

P_t = Pressure at throat, psia

V_t = Velocity in throat, ft/sec

For practical applications, the nozzle coefficient C_{FX} must be calibrated for a range of chamber pressure, throat area, and thrust, using the relation

$$C_{FX} = \frac{F_i}{A_{t_i} P_{c_i}}$$

The preceeding thrust calculation equations have been converted to a computer algorithm and implemented on a digital computer. The listing of the FORTRAN code, together with a sample input and output file, are shown in Figures 7.2-1 through 7.2-4.

7.3 THRUST PREDICTION FOR EL CENTRO EARTHQUAKE

Since a single pulse generator can produce thrust forces in only one direction (opposite to the direction of mass ejection), the positive and negative pulses in the optimum pulse train of Section 4.2 were separated into two groups: (1) the positive pulses to be generated by the pulser on the North side of the test frame, and (2) the negative pulses to be generated by the pulser on the South side of that frame.

The thrust calculation results based on the algorithm discussed in Section 7.2 are shown in Figures 7.3-1 and 7.3-4.

7.4 THRUST PREDICTION FOR SAN FERNANDO EARTHQUAKE

The thrust calculations corresponding to the positive and negative pulses of the optimum pulse train for the San Fernando earthquake are shown in Figures 7.4-1 through 7.4-4.

```
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
C 201.FOR     SFM     8-14-84
C
      DOUBLE PRECISION  INS, OUT6
      DIMENSION  ALPHA(50),CFX(50),F(50),DT(50),P(50),W(50)
      DATA NU5,NU6 /5,6/
C-----------------------------------------------------------------------
      WRITE ( 10, 1 )
    1 FORMAT(1X,'TYPE NAME OF INPUT FILE: ', Z )
      READ ( 11, 2 ) INS
    2 FORMAT ( S8 )
C
C OPEN A NEW OUTPUT FILE
C
    3 OPEN NU5, INS, ATT='B'
    4 READ (NU5,11) B1,B2,B3,B4,B5
   11 FORMAT ( A1 )
    5 READ(NU5,12) OUT6
   12 FORMAT (10X, S8 )
    6 OPEN NU6,OUT6,ATT='P'
    7 WRITE (NU6,13) INS,OUT6
   13 FORMAT (5X,'THRUST ANALYSIS, INS=',S8,3X,'OUT6=',S8)
   20 READ(NU5,21) N
   21 FORMAT ( 10X,I10)
   30 READ(NU5,31) P0,GAMMA,G,VOLUME,PSTART,WSTART
   31 FORMAT ( 10X,E10.0)
   40 WRITE(NU6,41) P0,GAMMA,G,VOLUME,PSTART,WSTART
   41 FORMAT(5X,'P0     =',1PE10.3,5X,'GAMMA =',1PE10.3
     1       /5X,'G      =',1PE10.3,5X,'VOLUME=',1PE10.3
     2       /5X,'PSTART=',1PE10.3,5X,'WSTART=',1PE10.3)
C
C SKIP 5 LINES
C
   50 READ(NU5,11) B1, B2, B3, B4, B5
   60 WRITE(NU6,61)
   61 FORMAT (//8X,'N',6X,'F',8X,'DT',7X,'ALPHA',5X,'CFX'
     * ,8X,'P',9X,'W',7X,'FCHECK',4X,'PNEW',7X,'WNEW')
C
C DEFINE STARTING CONDITIONS
C
   70 P(1)  =  PSTART
      W(1)  =  WSTART
      DO 100 K = 1, N
   85 READ(NU5,86) F(K),DT(K),ALPHA(K),CFX(K)
   86 FORMAT(10X,4E10.0)
   90 CALL THRUST(P0,GAMMA,G,VOLUME,ALPHA(K),CFX(K),F(K),DT(K)
     1            ,P(K),W(K),P(K+1),W(K+1),NCHECK)
C
   95 WRITE(NU6,96) K,F(K),DT(K),ALPHA(K),CFX(K),P(K),W(K)
     *               ,FCHECK,P(K+1),W(K+1)
   96 FORMAT(I10,1P9E10.3)
  100 CONTINUE
  110 WRITE(NU6,111)
  111 FORMAT(//10X,'** NATURAL END OF THRUST ANALYSIS **',1X,50('+'))
  120 STOP
      END
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
```

FIGURE 7.2-1. LISTING OF THRUST MAIN PROGRAM

```
C------------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C------------------------------------------------------------------------
      SUBROUTINE THRUST(P0,GAMMA,G,VOLUME,ALPHA,CFX,FORCE,DELT
     *                 ,PSTART,WSTART,PFINAL,WFINAL,FCHECK)
C
      DATA KWRITE,NU6 /1,6/
C EQ1
    1 PC = ALPHA*PSTART
C EQ2
    2 AT = FORCE/(CFX*PC)
C EQ3
    3 RHO= WSTART/VOLUME
      RHOC= RHO*(PC/PSTART)**(1.0/GAMMA)
C EQ4
    4 AC = SQRT(GAMMA*PC*G/RHOC)
C EQ5
    5 PART1 = ((2.0*GAMMA)/(GAMMA-1.0))*(PC*G/RHOC)
      PART2 = 1.0 - (P0/PC)**((GAMMA-1.0)/GAMMA)
      VXE = 0.98*SQRT(PART1*PART2)
C EQ6
    6 TERM = GAMMA*(2.0/(GAMMA+1.0))**((GAMMA+1.0)/(2.0*(GAMMA-1.0)))
      WDOT = G*TERM*PC*AT/AC
C EQ7
    7 DELW = WDOT*DELT
C EQ8
    8 WFINAL = WSTART - DELW
C EQ9
    9 RHONEW = WFINAL/VOLUME
C EQ10
   10 PFINAL = PSTART*(WFINAL/WSTART)**GAMMA
C EQ11
   11 FCHECK = WDOT*VXE/G
C------------------------------------------------------------------------
  101 IF(KWRITE.NE.1)  GO TO 104
  102 WRITE(NU6,103)P0,GAMMA,G,VOLUME,ALPHA,CFX,FORCE
     1              ,DELT,PSTART,WSTART,PFINAL,WFINAL,FCHECK
     2              ,PC,AT,RHO,RHOC,AC,VXE,WDOT,DELW,RHONEW
C
  103 FORMAT (5X,'FROM END OF THRUST',5X,30('*')/
     1   3X,'P0     =',1PE10.3,3X,'GAMMA =',1PE10.3
     2  ,3X,'G      =',1PE10.3,3X,'VOLUME=',1PE10.3/
     3   3X,'ALPHA  =',1PE10.3,3X,'CFX   =',1PE10.3
     4  ,3X,'FORCE  =',1PE10.3,3X,'DELT  =',1PE10.3/
     5   3X,'PSTART=',1PE10.3,3X,'WSTART=',1PE10.3
     6  ,3X,'PFINAL=',1PE10.3,3X,'WFINAL=',1PE10.3/
     7   3X,'FCHECK=',1PE10.3,3X,'PC    =',1PE10.3
     8  ,3X,'AT     =',1PE10.3,3X,'RHO   =',1PE10.3/
     9   3X,'RHOC   =',1PE10.3,3X,'AC    =',1PE10.3
     1  ,3X,'VXE    =',1PE10.3,3X,'WDOT  =',1PE10.3/
     2   3X,'DELW   =',1PE10.3,3X,'RHONEW=',1PE10.3)
  104 CONTINUE
      RETURN
      END
```

FIGURE 7.2-2. LISTING OF THRUST SUBPROGRAM

```
 DATA FILE FOR THRUST CALCULATIONS
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890l2
C-----------------------------------------------------------------------
OUT6      =THRST.OT** NAME OF OUTPUT FILE (C*8)
N         =         3 TOTAL NUMBER OF PULSES (I10)
PO        = 14.7    E0 ATMOSPHERIC PRESSURE (PSI) (E10.0)
GAMMA     = 1.41    E0 GAS CONSTANT
G         = 386.4   E0 ACCEL. OF GRAVITY (IN/S**2)
VOLUME    = 17625.6E0 VOLUME (IN**3)
PSTART    = 1815.   E0 STARTING PRESSURE (PSI)
WSTART    = 91.7    E0 STARTING WEIGHT    (POUNDS)
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
         N1  FORCE(N)    DELT(N) ALPHA(N)    CFX(N)
          1 208.    E0 0.044   E0 0.99    E0 1.0     E0
          2 576.    E0 0.047   E0 0.98    E0 1.2     E0
          2 5000.   E0 0.030   E0 0.90    E0 1.5     E0
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
```

FIGURE 7.2-3. INPUT FILE FOR THRUST

```
THRUST ANALYSIS, IN5=THRUST.1   OUT6=THRST.OT
PO     = 1.470E 01     GAMMA = 1.410E 00
G      = 3.864E 02     VOLUME= 1.763E 04
PSTART= 1.815E 03      WSTART= 9.170E 01


     N        F          DT        ALPHA      CFX         P           W          FCHECK      PNEW       WNEW
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.900E-01     CFX   = 1.000E 00    FORCE = 2.080E 02     DELT   = 4.400E-02
PSTART= 1.815E 03     WSTART= 9.170E 01    PFINAL= 1.809E 03     WFINAL= 9.149E 01
FCHECK= 3.184E 02     PC    = 1.797E 03    AT     = 1.158E-01    RHO    = 5.203E-03
RHOC  = 5.166E-03     AC    = 1.377E 04    VXE    = 2.585E 04    WDOT   = 4.759E 00
DELW  = 2.094E-01     RHONEW= 5.191E-03
      1 2.080E 02 4.400E-02 9.900E-01 1.000E 00 1.815E 03 9.170E 01 0.000E-01 1.809E 03 9.149E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.800E-01     CFX   = 1.200E 00    FORCE = 5.760E 02     DELT   = 4.700E-02
PSTART= 1.809E 03     WSTART= 9.149E 01    PFINAL= 1.795E 03     WFINAL= 9.097E 01
FCHECK= 7.342E 02     PC    = 1.773E 03    AT     = 2.707E-01    RHO    = 5.191E-03
RHOC  = 5.117E-03     AC    = 1.374E 04    VXE    = 2.579E 04    WDOT   = 1.100E 01
DELW  = 5.171E-01     RHONEW= 5.161E-03
      2 5.760E 02 4.700E-02 9.800E-01 1.200E 00 1.809E 03 9.149E 01 0.000E-01 1.795E 03 9.097E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.000E-01     CFX   = 1.500E 00    FORCE = 5.000E 03     DELT   = 3.000E-02
PSTART= 1.795E 03     WSTART= 9.097E 01    PFINAL= 1.730E 03     WFINAL= 8.865E 01
FCHECK= 5.076E 03     PC    = 1.615E 03    AT     = 2.064E 00    RHO    = 5.161E-03
RHOC  = 4.790E-03     AC    = 1.355E 04    VXE    = 2.532E 04    WDOT   = 7.745E 01
DELW  = 2.323E 00     RHONEW= 5.030E-03
      3 5.000E 03 3.000E-02 9.000E-01 1.500E 00 1.795E 03 9.097E 01 0.000E-01 1.730E 03 8.865E 01

   ** NATURAL END OF THRUST ANALYSIS ** ++++++++++++++++++++++++++++++++++++++++++++++++++++
```

FIGURE 7.2-4. OUTPUT FILE FOR THRUST

```
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890123
C-----------------------------------------------------------------------
OUT6       =ELCN1.OT** NAME OF OUTPUT FILE (C*8)
N          =         12 TOTAL NUMBER OF PULSES (I10)
P0         = 14.7    E0 ATMOSPHERIC PRESSURE (PSI) (E10.0)
GAMMA      = 1.41    E0 GAS CONSTANT
G          = 386.4   E0 ACCEL. OF GRAVITY (IN/S**2)
VOLUME     = 17625.6E0 VOLUME (IN**3)
PSTART     = 1314.7 E0 STARTING PRESSURE (PSI)
WSTART     = 66.785 E0 STARTING WEIGHT   (POUNDS)
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890123
C-----------------------------------------------------------------------
        N1  FORCE(N)    DELT(N) ALPHA(N)    CFX(N)
         1 208.    E0 0.044   E0 0.99    E0 1.0     E0
         2 576.    E0 0.047   E0 0.98    E0 1.2     E0
         3 5000.   E0 0.030   E0 0.90    E0 1.5     E0
         4 737.    E0 0.153   E0 0.97    E0 1.25    E0
         5 1353.   E0 0.037   E0 0.95    E0 1.30    E0
         6 2663.   E0 0.030   E0 0.91    E0 1.4     E0
         7 648.    E0 0.063   E0 0.97    E0 1.25    E0
         8 1021.   E0 0.063   E0 0.96    E0 1.3     E0
         9 214.    E0 0.093   E0 0.99    E0 1.0     E0
        10 1125.   E0 0.055   E0 0.96    E0 1.3     E0
        11 3084.   E0 0.030   E0 0.90    E0 1.4     E0
        12 3434.   E0 0.030   E0 0.90    E0 1.45    E0
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890123
C-----------------------------------------------------------------------
```

FIGURE 7.3-1. INPUT FILE FOR EL CENTRO (NORTH DIRECTION)

```
  THRUST ANALYSIS, INS=ELC.NI      OUTo=ELCN1.01
  PO     = 1.470E 01      GAMMA = 1.410E 00
  G      = 3.864E 02      VOLUME= 1.763E 04
  PSTART= 1.315E 03      WSTART= 6.679E 01


     N       F         DT        ALPHA      CFX         P           W         FCHECK     PNEW       WNEW
  FROM END OF THRUST      ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.000E 00   FORCE = 2.080E 02   DELT   = 4.400E-02
PSTART= 1.315E 03   WSTART= 6.679E 01   PFINAL= 1.309E 03   WFINAL= 6.658E 01
FCHECK= 3.132E 02   PC     = 1.302E 03   AT     = 1.598E-01   RHO    = 3.789E-03
RHOC   = 3.762E-03   AC     = 1.373E 04   VXE    = 2.536E 04   WDOT   = 4.772E 00
DELW   = 2.099E-01   RHONEW= 3.777E-03
      1 2.080E 02 4.400E-02 9.900E-01 1.000E 00 1.315E 03 6.679E 01 0.000E-01 1.309E 03 6.658E 01
  FROM END OF THRUST      ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.800E-01   CFX    = 1.200E 00   FORCE = 5.760E 02   DELT   = 4.700E-02
PSTART= 1.309E 03   WSTART= 6.658E 01   PFINAL= 1.295E 03   WFINAL= 6.606E 01
FCHECK= 7.222E 02   PC     = 1.283E 03   AT     = 3.742E-01   RHO    = 3.777E-03
RHOC   = 3.723E-03   AC     = 1.370E 04   VXE    = 2.529E 04   WDOT   = 1.103E 01
DELW   = 5.186E-01   RHONEW= 3.748E-03
      2 5.760E 02 4.700E-02 9.800E-01 1.200E 00 1.309E 03 6.658E 01 0.000E-01 1.295E 03 6.606E 01
  FROM END OF THRUST      ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.000E-01   CFX    = 1.500E 00   FORCE = 5.000E 03   DELT   = 3.000E-02
PSTART= 1.295E 03   WSTART= 6.606E 01   PFINAL= 1.231E 03   WFINAL= 6.373E 01
FCHECK= 4.988E 03   PC     = 1.165E 03   AT     = 2.861E 00   RHO    = 3.748E-03
RHOC   = 3.478E-03   AC     = 1.351E 04   VXE    = 2.480E 04   WDOT   = 7.771E 01
DELW   = 2.331E 00   RHONEW= 3.615E-03
      3 5.000E 03 3.000E-02 9.000E-01 1.500E 00 1.295E 03 6.606E 01 0.000E-01 1.231E 03 6.373E 01
  FROM END OF THRUST      ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.700E-01   CFX    = 1.250E 00   FORCE = 7.370E 02   DELT   = 1.530E-01
PSTART= 1.231E 03   WSTART= 6.373E 01   PFINAL= 1.174E 03   WFINAL= 6.163E 01
FCHECK= 8.836E 02   PC     = 1.194E 03   AT     = 4.939E-01   RHO    = 3.615E-03
RHOC   = 3.538E-03   AC     = 1.356E 04   VXE    = 2.493E 04   WDOT   = 1.370E 01
DELW   = 2.096E 00   RHONEW= 3.497E-03
      4 7.370E 02 1.530E-01 9.700E-01 1.250E 00 1.231E 03 6.373E 01 0.000E-01 1.174E 03 6.163E 01
  FROM END OF THRUST      ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.500E-01   CFX    = 1.300E 00   FORCE = 1.353E 03   DELT   = 3.700E-02
PSTART= 1.174E 03   WSTART= 6.163E 01   PFINAL= 1.150E 03   WFINAL= 6.073E 01
FCHECK= 1.554E 03   PC     = 1.115E 03   AT     = 9.333E-01   RHO    = 3.497E-03
RHOC   = 3.372E-03   AC     = 1.342E 04   VXE    = 2.459E 04   WDOT   = 2.442E 01
DELW   = 9.035E-01   RHONEW= 3.445E-03
      5 1.353E 03 3.700E-02 9.500E-01 1.300E 00 1.174E 03 6.163E 01 0.000E-01 1.150E 03 6.073E 01
  FROM END OF THRUST      ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.100E-01   CFX    = 1.400E 00   FORCE = 2.663E 03   DELT   = 3.000E-02
PSTART= 1.150E 03   WSTART= 6.073E 01   PFINAL= 1.114E 03   WFINAL= 5.937E 01
FCHECK= 2.829E 03   PC     = 1.046E 03   AT     = 1.818E 00   RHO    = 3.445E-03
RHOC   = 3.222E-03   AC     = 1.330E 04   VXE    = 2.427E 04   WDOT   = 4.504E 01
DELW   = 1.351E 00   RHONEW= 3.369E-03
      6 2.663E 03 3.000E-02 9.100E-01 1.400E 00 1.150E 03 6.073E 01 0.000E-01 1.114E 03 5.937E 01
  FROM END OF THRUST      ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.700E-01   CFX    = 1.250E 00   FORCE = 6.480E 02   DELT   = 6.300E-02
PSTART= 1.114E 03   WSTART= 5.937E 01   PFINAL= 1.093E 03   WFINAL= 5.861E 01
FCHECK= 7.724E 02   PC     = 1.080E 03   AT     = 4.798E-01   RHO    = 3.369E-03
RHOC   = 3.297E-03   AC     = 1.336E 04   VXE    = 2.443E 04   WDOT   = 1.222E 01
DELW   = 7.698E-01   RHONEW= 3.325E-03
```

FIGURE 7.3-2(a). OUTPUT FILE FOR EL CENTRO (NORTH)

```
      7 6.480E 02 6.300E-02 9.700E-01 1.250E 00 1.114E 03 5.937E 01 0.000E-01 1.093E 03 5.861E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.600E-01    CFX    = 1.300E 00    FORCE = 1.021E 03    DELT   = 6.300E-02
PSTART= 1.093E 03    WSTART= 5.861E 01    PFINAL= 1.063E 03    WFINAL= 5.743E 01
FCHECK= 1.168E 03    PC     = 1.050E 03    AT     = 7.482E-01    RHO    = 3.325E-03
RHOC   = 3.230E-03    AC     = 1.331E 04    VXE    = 2.428E 04    WOUT   = 1.859E 01
DELW   = 1.171E 00    RHONEW= 3.259E-03
      8 1.021E 03 6.300E-02 9.600E-01 1.300E 00 1.093E 03 5.861E 01 0.000E-01 1.063E 03 5.743E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.900E-01    CFX    = 1.000E 00    FORCE = 2.140E 02    DELT   = 9.300E-02
PSTART= 1.063E 03    WSTART= 5.743E 01    PFINAL= 1.051E 03    WFINAL= 5.696E 01
FCHECK= 3.184E 02    PC     = 1.052E 03    AT     = 2.034E-01    RHO    = 3.259E-03
RHOC   = 3.235E-03    AC     = 1.331E 04    VXE    = 2.430E 04    WOUT   = 5.063E 00
DELW   = 4.709E-01    RHONEW= 3.232E-03
      9 2.140E 02 9.300E-02 9.900E-01 1.000E 00 1.063E 03 5.743E 01 0.000E-01 1.051E 03 5.696E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.600E-01    CFX    = 1.300E 00    FORCE = 1.125E 03    DELT   = 5.500E-02
PSTART= 1.051E 03    WSTART= 5.696E 01    PFINAL= 1.021E 03    WFINAL= 5.583E 01
FCHECK= 1.284E 03    PC     = 1.009E 03    AT     = 8.581E-01    RHO    = 3.232E-03
RHOC   = 3.140E-03    AC     = 1.323E 04    VXE    = 2.409E 04    WOUT   = 2.060E 01
DELW   = 1.133E 00    RHONEW= 3.168E-03
     10 1.125E 03 5.500E-02 9.600E-01 1.300E 00 1.051E 03 5.696E 01 0.000E-01 1.021E 03 5.583E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.000E-01    CFX    = 1.400E 00    FORCE = 3.084E 03    DELT   = 3.000E-02
PSTART= 1.021E 03    WSTART= 5.583E 01    PFINAL= 9.803E 02    WFINAL= 5.424E 01
FCHECK= 3.250E 03    PC     = 9.191E 02    AT     = 2.397E 00    RHO    = 3.168E-03
RHOC   = 2.939E-03    AC     = 1.305E 04    VXE    = 2.363E 04    WOUT   = 5.316E 01
DELW   = 1.595E 00    RHONEW= 3.077E-03
     11 3.084E 03 3.000E-02 9.000E-01 1.400E 00 1.021E 03 5.583E 01 0.000E-01 9.803E 02 5.424E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.000E-01    CFX    = 1.450E 00    FORCE = 3.434E 03    DELT   = 3.000E-02
PSTART= 9.803E 02    WSTART= 5.424E 01    PFINAL= 9.367E 02    WFINAL= 5.251E 01
FCHECK= 3.486E 03    PC     = 8.823E 02    AT     = 2.684E 00    RHO    = 3.077E-03
RHOC   = 2.856E-03    AC     = 1.297E 04    VXE    = 2.343E 04    WOUT   = 5.749E 01
DELW   = 1.725E 00    RHONEW= 2.979E-03
     12 3.434E 03 3.000E-02 9.000E-01 1.450E 00 9.803E 02 5.424E 01 0.000E-01 9.367E 02 5.251E 01

      ** NATURAL END OF THRUST ANALYSIS ** +++++++++++++++++++++++++++++++++++++++++++++++++++++
```

FIGURE 7.3-2(b). OUTPUT FILE FOR EL CENTRO (NORTH)

```
 DATA FILE FOR THRUST CALCULATIONS
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
OUT6      =ELCS3.UT** NAME OF OUTPUT FILE (C*8)
N         =         17 TOTAL NUMBER OF PULSES (I10)
PO        = 14.7    E0 ATMOSPHERIC PRESSURE (PSI) (E10.0)
GAMMA     = 1.41    E0 GAS CONSTANT
G         = 386.4   E0 ACCEL. OF GRAVITY (IN/S**2)
VOLUME    = 17625.6E0 VOLUME (IN**3)
PSTART    = 1714.7 E0 STARTING PRESSURE (PSI)
WSTART    = 87.100 E0 STARTING WEIGHT   (POUNDS)
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
        NI  FORCE(N)    DELT(N) ALPHA(N)    CFX(N)
         1 904.     E0 0.171  E0 0.96    E0 1.3     E0
         2 4070.    E0 0.030  E0 0.90    E0 1.5     E0
         3 442.     E0 0.121  E0 0.98    E0 1.2     E0
         4 1043.    E0 0.095  E0 0.96    E0 1.3     E0
         5 1212.    E0 0.100  E0 0.96    E0 1.30    E0
         6 3192.    E0 0.037  E0 0.90    E0 1.45    E0
         7 1196.    E0 0.035  E0 0.96    E0 1.30    E0
         8 1773.    E0 0.053  E0 0.93    E0 1.3     E0
         9 1892.    E0 0.030  E0 0.92    E0 1.35    E0
        10 1239.    E0 0.069  E0 0.96    E0 1.35    E0
        11 216.     E0 0.082  E0 0.99    E0 1.15    E0
        12 404.     E0 0.067  E0 0.98    E0 1.20    E0
        13 4678.    E0 0.030  E0 0.90    E0 1.5     E0
        14 1338.    E0 0.030  E0 0.96    E0 1.3     E0
        15 2969.    E0 0.030  E0 0.90    E0 1.45    E0
        16 487.     E0 0.069  E0 0.98    E0 1.25    E0
        17 568.     E0 0.099  E0 0.98    E0 1.25    E0
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C234567890123456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
```

FIGURE 7.3-3. INPUT FILE FOR EL CENTRO (SOUTH DIRECTION)

```
THRUST ANALYSIS, IN5=ELC.S3      OUT6=ELCS3.OT
PO     = 1.470E 01      GAMMA = 1.410E 00
G      = 3.864E 02      VOLUME= 1.763E 04
PSTART= 1.715E 03      WSTART= 8.710E 01

      N        F          DT         ALPHA      CFX          P            W         FCHECK     PNEW        WNEW
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.600E-01    CFX   = 1.300E 00    FORCE  = 9.040E 02    DELT  = 1.710E-01
PSTART= 1.715E 03    WSTART= 8.710E 01    PFINAL= 1.639E 03    WFINAL= 8.436E 01
FCHECK= 1.060E 03    PC    = 1.646E 03    AT     = 4.224E-01    RHO   = 4.942E-03
RHOC   = 4.801E-03    AC    = 1.367E 04    VXE    = 2.556E 04    WDOT  = 1.602E 01
DELW   = 2.740E 00    RHONEW= 4.786E-03
      1 9.040E 02 1.710E-01 9.600E-01 1.300E 00 1.715E 03 8.710E 01 0.000E-01 1.639E 03 8.436E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.000E-01    CFX   = 1.500E 00    FORCE  = 4.070E 03    DELT  = 3.000E-02
PSTART= 1.639E 03    WSTART= 8.436E 01    PFINAL= 1.587E 03    WFINAL= 8.245E 01
FCHECK= 4.113E 03    PC    = 1.475E 03    AT     = 1.839E 00    RHO   = 4.786E-03
RHOC   = 4.442E-03    AC    = 1.345E 04    VXE    = 2.502E 04    WDOT  = 6.353E 01
DELW   = 1.906E 00    RHONEW= 4.678E-03
      2 4.070E 03 3.000E-02 9.000E-01 1.500E 00 1.639E 03 8.436E 01 0.000E-01 1.587E 03 8.245E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.200E 00    FORCE  = 4.420E 02    DELT  = 1.210E-01
PSTART= 1.587E 03    WSTART= 8.245E 01    PFINAL= 1.559E 03    WFINAL= 8.142E 01
FCHECK= 5.598E 02    PC    = 1.555E 03    AT     = 2.360E-01    RHO   = 4.678E-03
RHOC   = 4.612E-03    AC    = 1.356E 04    VXE    = 2.528E 04    WDOT  = 8.557E 00
DELW   = 1.035E 00    RHONEW= 4.619E-03
      3 4.420E 02 1.210E-01 9.800E-01 1.200E 00 1.587E 03 8.245E 01 0.000E-01 1.559E 03 8.142E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.600E-01    CFX   = 1.300E 00    FORCE  = 1.043E 03    DELT  = 9.500E-02
PSTART= 1.559E 03    WSTART= 8.142E 01    PFINAL= 1.511E 03    WFINAL= 7.964E 01
FCHECK= 1.217E 03    PC    = 1.497E 03    AT     = 5.360E-01    RHO   = 4.619E-03
RHOC   = 4.488E-03    AC    = 1.348E 04    VXE    = 2.509E 04    WDOT  = 1.874E 01
DELW   = 1.781E 00    RHONEW= 4.518E-03
      4 1.043E 03 9.500E-02 9.600E-01 1.300E 00 1.559E 03 8.142E 01 0.000E-01 1.511E 03 7.964E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.600E-01    CFX   = 1.300E 00    FORCE  = 1.212E 03    DELT  = 1.000E-01
PSTART= 1.511E 03    WSTART= 7.964E 01    PFINAL= 1.453E 03    WFINAL= 7.745E 01
FCHECK= 1.412E 03    PC    = 1.451E 03    AT     = 6.426E-01    RHO   = 4.518E-03
RHOC   = 4.389E-03    AC    = 1.342E 04    VXE    = 2.493E 04    WDOT  = 2.188E 01
DELW   = 2.188E 00    RHONEW= 4.394E-03
      5 1.212E 03 1.000E-01 9.600E-01 1.300E 00 1.511E 03 7.964E 01 0.000E-01 1.453E 03 7.745E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.000E-01    CFX   = 1.450E 00    FORCE  = 3.192E 03    DELT  = 3.700E-02
PSTART= 1.453E 03    WSTART= 7.745E 01    PFINAL= 1.402E 03    WFINAL= 7.551E 01
FCHECK= 3.316E 03    PC    = 1.308E 03    AT     = 1.683E 00    RHO   = 4.394E-03
RHOC   = 4.078E-03    AC    = 1.322E 04    VXE    = 2.443E 04    WDOT  = 5.245E 01
DELW   = 1.941E 00    RHONEW= 4.284E-03
      6 3.192E 03 3.700E-02 9.000E-01 1.450E 00 1.453E 03 7.745E 01 0.000E-01 1.402E 03 7.551E 01
  FROM END OF THRUST        ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.600E-01    CFX   = 1.300E 00    FORCE  = 1.196E 03    DELT  = 3.500E-02
PSTART= 1.402E 03    WSTART= 7.551E 01    PFINAL= 1.382E 03    WFINAL= 7.475E 01
FCHECK= 1.388E 03    PC    = 1.346E 03    AT     = 6.836E-01    RHO   = 4.284E-03
RHOC   = 4.162E-03    AC    = 1.327E 04    VXE    = 2.457E 04    WDOT  = 2.183E 01
DELW   = 7.640E-01    RHONEW= 4.241E-03
```

FIGURE 7.3-4(a). OUTPUT FILE FOR EL CENTRO (SOUTH)

```
      7 1.196E 03 3.500E-02 9.600E-01 1.300E 00 1.402E 03 7.551E 01 0.000E-01 1.382E 03 7.475E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.300E-01   CFX   = 1.300E 00   FORCE = 1.773E 03   DELT  = 5.300E-02
PSTART= 1.382E 03   WSTART= 7.475E 01   PFINAL= 1.337E 03   WFINAL= 7.302E 01
FCHECK= 2.052E 03   PC    = 1.265E 03   AT    = 1.061E 00   RHO   = 4.241E-03
RHOC  = 4.028E-03   AC    = 1.319E 04   VXE   = 2.434E 04   WDOT  = 3.256E 01
DELW  = 1.727E 00   RHONEW= 4.143E-03
      8 1.773E 03 5.300E-02 9.300E-01 1.300E 00 1.382E 03 7.475E 01 0.000E-01 1.337E 03 7.302E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.200E-01   CFX   = 1.350E 00   FORCE = 1.892E 03   DELT  = 3.000E-02
PSTART= 1.337E 03   WSTART= 7.302E 01   PFINAL= 1.311E 03   WFINAL= 7.201E 01
FCHECK= 2.104E 03   PC    = 1.230E 03   AT    = 1.139E 00   RHO   = 4.143E-03
RHOC  = 3.905E-03   AC    = 1.310E 04   VXE   = 2.413E 04   WDOT  = 3.369E 01
DELW  = 1.011E 00   RHONEW= 4.085E-03
      9 1.892E 03 3.000E-02 9.200E-01 1.350E 00 1.337E 03 7.302E 01 0.000E-01 1.311E 03 7.201E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.600E-01   CFX   = 1.350E 00   FORCE = 1.239E 03   DELT  = 6.900E-02
PSTART= 1.311E 03   WSTART= 7.201E 01   PFINAL= 1.272E 03   WFINAL= 7.049E 01
FCHECK= 1.379E 03   PC    = 1.259E 03   AT    = 7.291E-01   RHO   = 4.085E-03
RHOC  = 3.969E-03   AC    = 1.315E 04   VXE   = 2.424E 04   WDOT  = 2.199E 01
DELW  = 1.517E 00   RHONEW= 3.999E-03
     10 1.239E 03 6.900E-02 9.600E-01 1.350E 00 1.311E 03 7.201E 01 0.000E-01 1.272E 03 7.049E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX   = 1.150E 00   FORCE = 2.160E 02   DELT  = 8.200E-02
PSTART= 1.272E 03   WSTART= 7.049E 01   PFINAL= 1.263E 03   WFINAL= 7.012E 01
FCHECK= 2.823E 02   PC    = 1.260E 03   AT    = 1.491E-01   RHO   = 3.999E-03
RHOC  = 3.971E-03   AC    = 1.315E 04   VXE   = 2.424E 04   WDOT  = 4.500E 00
DELW  = 3.690E-01   RHONEW= 3.978E-03
     11 2.160E 02 8.200E-02 9.900E-01 1.150E 00 1.272E 03 7.049E 01 0.000E-01 1.263E 03 7.012E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.800E-01   CFX   = 1.200E 00   FORCE = 4.040E 02   DELT  = 6.700E-02
PSTART= 1.263E 03   WSTART= 7.012E 01   PFINAL= 1.249E 03   WFINAL= 6.958E 01
FCHECK= 5.055E 02   PC    = 1.238E 03   AT    = 2.720E-01   RHO   = 3.978E-03
RHOC  = 3.922E-03   AC    = 1.311E 04   VXE   = 2.416E 04   WDOT  = 8.086E 00
DELW  = 5.418E-01   RHONEW= 3.948E-03
     12 4.040E 02 6.700E-02 9.800E-01 1.200E 00 1.263E 03 7.012E 01 0.000E-01 1.249E 03 6.958E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.000E-01   CFX   = 1.500E 00   FORCE = 4.678E 03   DELT  = 3.000E-02
PSTART= 1.249E 03   WSTART= 6.958E 01   PFINAL= 1.192E 03   WFINAL= 6.730E 01
FCHECK= 4.658E 03   PC    = 1.124E 03   AT    = 2.774E 00   RHO   = 3.948E-03
RHOC  = 3.663E-03   AC    = 1.293E 04   VXE   = 2.369E 04   WDOT  = 7.596E 01
DELW  = 2.279E 00   RHONEW= 3.818E-03
     13 4.678E 03 3.000E-02 9.000E-01 1.500E 00 1.249E 03 6.958E 01 0.000E-01 1.192E 03 6.730E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.600E-01   CFX   = 1.300E 00   FORCE = 1.338E 03   DELT  = 3.000E-02
PSTART= 1.192E 03   WSTART= 6.730E 01   PFINAL= 1.173E 03   WFINAL= 6.655E 01
FCHECK= 1.539E 03   PC    = 1.144E 03   AT    = 8.994E-01   RHO   = 3.818E-03
RHOC  = 3.709E-03   AC    = 1.296E 04   VXE   = 2.378E 04   WDOT  = 2.500E 01
DELW  = 7.501E-01   RHONEW= 3.776E-03
     14 1.338E 03 3.000E-02 9.600E-01 1.300E 00 1.192E 03 6.730E 01 0.000E-01 1.173E 03 6.655E 01
  FROM END OF THRUST       ********************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.000E-01   CFX   = 1.450E 00   FORCE = 2.969E 03   DELT  = 3.000E-02
PSTART= 1.173E 03   WSTART= 6.655E 01   PFINAL= 1.136E 03   WFINAL= 6.504E 01
FCHECK= 3.047E 03   PC    = 1.056E 03   AT    = 1.939E 00   RHO   = 3.776E-03
RHOC  = 3.504E-03   AC    = 1.281E 04   VXE   = 2.339E 04   WDOT  = 5.033E 01
```

FIGURE 7.3-4(b). OUTPUT FILE FOR EL CENTRO (SOUTH)

```
DELW   = 1.510E 00    RHONEW= 3.690E-03
      15 2.969E 03 3.000E-02 9.000E-01 1.450E 00 1.173E 03 6.655E 01 0.000E-01 1.136E 03 6.504E 01
  FROM END OF THRUST         ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.250E 00    FORCE  = 4.870E 02    DELT   = 6.900E-02
PSTART= 1.136E 03    WSTART= 6.504E 01    PFINAL= 1.120E 03    WFINAL= 6.439E 01
FCHECK= 5.815E 02    PC    = 1.113E 03    AT     = 3.500E-01    RHO    = 3.690E-03
RHOC   = 3.638E-03    AC    = 1.291E 04    VXE    = 2.365E 04    WDOT   = 9.503E 00
DELW   = 6.557E-01    RHONEW= 3.653E-03
      16 4.870E 02 6.900E-02 9.800E-01 1.250E 00 1.136E 03 6.504E 01 0.000E-01 1.120E 03 6.439E 01
  FROM END OF THRUST         ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.250E 00    FORCE  = 5.680E 02    DELT   = 9.900E-02
PSTART= 1.120E 03    WSTART= 6.439E 01    PFINAL= 1.093E 03    WFINAL= 6.329E 01
FCHECK= 6.777E 02    PC    = 1.097E 03    AT     = 4.141E-01    RHO    = 3.653E-03
RHOC   = 3.601E-03    AC    = 1.269E 04    VXE    = 2.358E 04    WDOT   = 1.111E 01
DELW   = 1.100E 00    RHONEW= 3.591E-03
      17 5.680E 02 9.900E-02 9.800E-01 1.250E 00 1.120E 03 6.439E 01 0.000E-01 1.093E 03 6.329E 01

         ** NATURAL END OF THRUST ANALYSIS ** ++++++++++++++++++++++++++++++++++++++++++++++++++++
```

FIGURE 7.3-4(c). OUTPUT FILE FOR EL CENTRO (SOUTH)

```
 DATA FILE FOR THRUST CALCULATIONS
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
OUT6      =SFCN1.OT** NAME OF OUTPUT FILE (C*8)
N         =        23 TOTAL NUMBER OF PULSES (I10)
P0        = 14.7    E0 ATMOSPHERIC PRESSURE (PSI) (E10.0)
GAMMA     = 1.41    E0 GAS CONSTANT
G         = 386.4   E0 ACCEL. OF GRAVITY (IN/S**2)
VOLUME    = 17625.6E0 VOLUME (IN**3)
PSTART    = 1314.7 E0 STARTING PRESSURE (PSI)
WSTART    = 66.785 E0 STARTING WEIGHT    (POUNDS)
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
         NI  FORCE(N)    DELT(N) ALPHA(N)    CFX(N)
          1 1335.    E0 0.030    E0 0.95     E0 1.32     E0
          2 695.     E0 0.076    E0 0.97     E0 1.26     E0
          3 650.     E0 0.119    E0 0.97     E0 1.25     E0
          4 532.     E0 0.075    E0 0.98     E0 1.23     E0
          5 125.     E0 0.030    E0 0.99     E0 1.12     E0
          6 403.     E0 0.060    E0 0.98     E0 1.20     E0
          7 587.     E0 0.044    E0 0.97     E0 1.24     E0
          8 607.     E0 0.042    E0 0.97     E0 1.25     E0
          9 988.     E0 0.030    E0 0.97     E0 1.26     E0
         10 358.     E0 0.037    E0 0.96     E0 1.20     E0
         11 477.     E0 0.052    E0 0.98     E0 1.22     E0
         12 155.     E0 0.030    E0 0.98     E0 1.10     E0
         13 162.     E0 0.010    E0 0.99     E0 1.10     E0
         14 679.     E0 0.030    E0 0.99     E0 1.26     E0
         15 268.     E0 0.036    E0 0.97     E0 1.18     E0
         16 514.     E0 0.030    E0 0.99     E0 1.24     E0
         17 178.     E0 0.030    E0 0.98     E0 1.18     E0
         18 867.     E0 0.030    E0 0.99     E0 1.28     E0
         19 191.     E0 0.030    E0 0.96     E0 1.10     E0
         20 158.     E0 0.088    E0 0.99     E0 1.10     E0
         21 170.     E0 0.084    E0 0.99     E0 1.10     E0
         22 225.     E0 0.030    E0 0.99     E0 1.16     E0
         23 153.     E0 0.080    E0 0.99     E0 1.10     E0
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
```

FIGURE 7.4-1. INPUT FILE FOR SAN FERNANDO (NORTH DIRECTION)

```
THRUST ANALYSIS, INS=SFC.N1      OUT6=SFCN1.OT
PO     = 1.470E 01      GAMMA = 1.410E 00
G      = 3.864E 02      VOLUME= 1.763E 04
PSTART= 1.315E 03      WSTART= 6.679E 01


    N       F          DT         ALPHA      CFX         P           W        FCHECK     PNEW       WNEW
  FROM END OF THRUST       ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.500E-01   CFX    = 1.320E 00   FORCE = 1.335E 03   DELT   = 3.000E-02
PSTART= 1.315E 03   WSTART= 6.679E 01   PFINAL= 1.295E 03   WFINAL= 6.608E 01
FCHECK= 1.519E 03   PC     = 1.249E 03   AT     = 8.098E-01   RHO    = 3.789E-03
RHOC   = 3.654E-03   AC     = 1.305E 04   VXE    = 2.515E 04   WDOT   = 2.334E 01
DELW   = 7.002E-01   RHONEW= 3.749E-03
      1 1.335E 03 3.000E-02 9.500E-01 1.320E 00 1.315E 03 6.679E 01 0.000E-01 1.295E 03 6.608E 01
  FROM END OF THRUST       ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.700E-01   CFX    = 1.260E 00   FORCE = 6.950E 02   DELT   = 7.600E-02
PSTART= 1.295E 03   WSTART= 6.608E 01   PFINAL= 1.269E 03   WFINAL= 6.512E 01
FCHECK= 8.290E 02   PC     = 1.256E 03   AT     = 4.390E-01   RHO    = 3.749E-03
RHOC   = 3.669E-03   AC     = 1.366E 04   VXE    = 2.518E 04   WDOT   = 1.272E 01
DELW   = 9.666E-01   RHONEW= 3.695E-03
      2 6.950E 02 7.600E-02 9.700E-01 1.260E 00 1.295E 03 6.608E 01 0.000E-01 1.269E 03 6.512E 01
  FROM END OF THRUST       ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.700E-01   CFX    = 1.250E 00   FORCE = 6.500E 02   DELT   = 1.190E-01
PSTART= 1.269E 03   WSTART= 6.512E 01   PFINAL= 1.230E 03   WFINAL= 6.369E 01
FCHECK= 7.806E 02   PC     = 1.231E 03   AT     = 4.226E-01   RHO    = 3.695E-03
RHOC   = 3.616E-03   AC     = 1.362E 04   VXE    = 2.508E 04   WDOT   = 1.203E 01
DELW   = 1.431E 00   RHONEW= 3.613E-03
      3 6.500E 02 1.190E-01 9.700E-01 1.250E 00 1.269E 03 6.512E 01 0.000E-01 1.230E 03 6.369E 01
  FROM END OF THRUST       ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.800E-01   CFX    = 1.230E 00   FORCE = 5.320E 02   DELT   = 7.500E-02
PSTART= 1.230E 03   WSTART= 6.369E 01   PFINAL= 1.209E 03   WFINAL= 6.293E 01
FCHECK= 6.485E 02   PC     = 1.205E 03   AT     = 3.590E-01   RHO    = 3.613E-03
RHOC   = 3.562E-03   AC     = 1.358E 04   VXE    = 2.497E 04   WDOT   = 1.003E 01
DELW   = 7.525E-01   RHONEW= 3.571E-03
      4 5.320E 02 7.500E-02 9.800E-01 1.230E 00 1.230E 03 6.369E 01 0.000E-01 1.209E 03 6.293E 01
  FROM END OF THRUST       ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.120E 00   FORCE = 1.250E 02   DELT   = 3.000E-02
PSTART= 1.209E 03   WSTART= 6.293E 01   PFINAL= 1.207E 03   WFINAL= 6.286E 01
FCHECK= 1.673E 02   PC     = 1.197E 03   AT     = 9.324E-02   RHO    = 3.571E-03
RHOC   = 3.545E-03   AC     = 1.356E 04   VXE    = 2.494E 04   WDOT   = 2.592E 00
DELW   = 7.775E-02   RHONEW= 3.566E-03
      5 1.250E 02 3.000E-02 9.900E-01 1.120E 00 1.209E 03 6.293E 01 0.000E-01 1.207E 03 6.286E 01
  FROM END OF THRUST       ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.800E-01   CFX    = 1.200E 00   FORCE = 4.030E 02   DELT   = 6.000E-02
PSTART= 1.207E 03   WSTART= 6.286E 01   PFINAL= 1.194E 03   WFINAL= 6.239E 01
FCHECK= 5.030E 02   PC     = 1.163E 03   AT     = 2.839E-01   RHO    = 3.566E-03
RHOC   = 3.515E-03   AC     = 1.354E 04   VXE    = 2.488E 04   WDOT   = 7.812E 00
DELW   = 4.687E-01   RHONEW= 3.540E-03
      6 4.030E 02 6.000E-02 9.800E-01 1.200E 00 1.207E 03 6.286E 01 0.000E-01 1.194E 03 6.239E 01
  FROM END OF THRUST       ********************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.700E-01   CFX    = 1.240E 00   FORCE = 5.670E 02   DELT   = 4.400E-02
PSTART= 1.194E 03   WSTART= 6.239E 01   PFINAL= 1.181E 03   WFINAL= 6.190E 01
FCHECK= 7.082E 02   PC     = 1.156E 03   AT     = 4.086E-01   RHO    = 3.540E-03
RHOC   = 3.464E-03   AC     = 1.350E 04   VXE    = 2.478E 04   WDOT   = 1.104E 01
DELW   = 4.860E-01   RHONEW= 3.512E-03
```

FIGURE 7.4-2(a). OUTPUT FILE FOR SAN FERNANDO (NORTH)

```
       7 5.870E 02 4.400E-02 9.700E-01 1.240E 00 1.194E 03 6.239E 01 0.000E-01 1.181E 03 6.190E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.700E-01   CFX   = 1.250E 00   FORCE  = 6.070E 02   DELT  = 4.200E-02
PSTART= 1.181E 03    WSTART= 6.190E 01   PFINAL= 1.168E 03    WFINAL= 6.143E 01
FCHECK= 7.260E 02    PC    = 1.146E 03   AT     = 4.238E-01   RHO   = 3.512E-03
RHUC   = 3.437E-03   AC    = 1.348E 04   VXE    = 2.472E 04   WDOT  = 1.135E 01
DELW   = 4.766E-01   RHONEW= 3.485E-03
       8 6.070E 02 4.200E-02 9.700E-01 1.250E 00 1.181E 03 6.190E 01 0.000E-01 1.168E 03 6.143E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.700E-01   CFX   = 1.280E 00   FORCE  = 9.880E 02   DELT  = 3.000E-02
PSTART= 1.168E 03    WSTART= 6.143E 01   PFINAL= 1.154E 03    WFINAL= 6.088E 01
FCHECK= 1.153E 03    PC    = 1.133E 03   AT     = 6.810E-01   RHO   = 3.485E-03
RHUC   = 3.411E-03   AC    = 1.346E 04   VXE    = 2.467E 04   WDOT  = 1.807E 01
DELW   = 5.420E-01   RHONEW= 3.454E-03
       9 9.880E 02 3.000E-02 9.700E-01 1.280E 00 1.168E 03 6.143E 01 0.000E-01 1.154E 03 6.088E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.600E-01   CFX   = 1.200E 00   FORCE  = 3.580E 02   DELT  = 3.700E-02
PSTART= 1.154E 03    WSTART= 6.088E 01   PFINAL= 1.147E 03    WFINAL= 6.062E 01
FCHECK= 4.452E 02    PC    = 1.108E 03   AT     = 2.693E-01   RHO   = 3.454E-03
RHOC   = 3.356E-03   AC    = 1.341E 04   VXE    = 2.455E 04   WDOT  = 7.006E 00
DELW   = 2.592E-01   RHONEW= 3.440E-03
      10 3.580E 02 3.700E-02 9.600E-01 1.200E 00 1.154E 03 6.088E 01 0.000E-01 1.147E 03 6.062E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.800E-01   CFX   = 1.220E 00   FORCE  = 4.770E 02   DELT  = 5.200E-02
PSTART= 1.147E 03    WSTART= 6.062E 01   PFINAL= 1.134E 03    WFINAL= 6.015E 01
FCHECK= 5.839E 02    PC    = 1.124E 03   AT     = 3.478E-01   RHO   = 3.440E-03
RHUC   = 3.391E-03   AC    = 1.344E 04   VXE    = 2.463E 04   WDOT  = 9.162E 00
DELW   = 4.764E-01   RHUNEW= 3.413E-03
      11 4.770E 02 5.200E-02 9.800E-01 1.220E 00 1.147E 03 6.062E 01 0.000E-01 1.134E 03 6.015E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.800E-01   CFX   = 1.100E 00   FORCE  = 1.550E 02   DELT  = 3.000E-02
PSTART= 1.134E 03    WSTART= 6.015E 01   PFINAL= 1.132E 03    WFINAL= 6.005E 01
FCHECK= 2.103E 02    PC    = 1.112E 03   AT     = 1.266E-01   RHO   = 3.413E-03
RHUC   = 3.364E-03   AC    = 1.342E 04   VXE    = 2.457E 04   WDOT  = 3.307E 00
DELW   = 9.922E-02   RHONEW= 3.407E-03
      12 1.550E 02 3.000E-02 9.800E-01 1.100E 00 1.134E 03 6.015E 01 0.000E-01 1.132E 03 6.005E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.900E-01   CFX   = 1.100E 00   FORCE  = 1.620E 02   DELT  = 1.000E-02
PSTART= 1.132E 03    WSTART= 6.005E 01   PFINAL= 1.131E 03    WFINAL= 6.001E 01
FCHECK= 2.199E 02    PC    = 1.120E 03   AT     = 1.315E-01   RHO   = 3.407E-03
RHUC   = 3.383E-03   AC    = 1.343E 04   VXE    = 2.461E 04   WDOT  = 3.453E 00
DELW   = 3.453E-02   RHUNEW= 3.405E-03
      13 1.620E 02 1.000E-02 9.900E-01 1.100E 00 1.132E 03 6.005E 01 0.000E-01 1.131E 03 6.001E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.900E-01   CFX   = 1.260E 00   FORCE  = 6.790E 02   DELT  = 3.000E-02
PSTART= 1.131E 03    WSTART= 6.001E 01   PFINAL= 1.121E 03    WFINAL= 5.963E 01
FCHECK= 8.046E 02    PC    = 1.119E 03   AT     = 4.814E-01   RHO   = 3.405E-03
RHUC   = 3.381E-03   AC    = 1.343E 04   VXE    = 2.460E 04   WDOT  = 1.264E 01
DELW   = 3.791E-01   RHUNEW= 3.383E-03
      14 6.790E 02 3.000E-02 9.900E-01 1.260E 00 1.131E 03 6.001E 01 0.000E-01 1.121E 03 5.963E 01
   FROM END OF THRUST         *******************************
PO     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.700E-01   CFX   = 1.160E 00   FORCE  = 2.680E 02   DELT  = 3.600E-02
PSTART= 1.121E 03    WSTART= 5.963E 01   PFINAL= 1.116E 03    WFINAL= 5.944E 01
FCHECK= 3.385E 02    PC    = 1.067E 03   AT     = 2.089E-01   RHO   = 3.383E-03
RHUC   = 3.311E-03   AC    = 1.337E 04   VXE    = 2.446E 04   WDOT  = 5.348E 00
```

FIGURE 7.4-2(b). OUTPUT FILE FOR SAN FERNANDO (NORTH)

```
DELW   = 1.925E-01    RHONEW= 3.372E-03
      15 2.680E 02 3.600E-02 9.700E-01 1.180E 00 1.121E 03 5.963E 01 0.000E-01 1.116E 03 5.944E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.240E 00    FORCE  = 5.140E 02    DELT  = 3.000E-02
PSTART= 1.116E 03    WSTART= 5.944E 01    PFINAL= 1.108E 03    WFINAL= 5.915E 01
FCHECK= 6.184E 02    PC    = 1.104E 03    AT     = 3.753E-01    RHO   = 3.372E-03
RHOC   = 3.349E-03    AC    = 1.341E 04    VXE    = 2.454E 04    WDOT  = 9.739E 00
DELW   = 2.922E-01    RHONEW= 3.356E-03
      16 5.140E 02 3.000E-02 9.900E-01 1.240E 00 1.116E 03 5.944E 01 0.000E-01 1.108E 03 5.915E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.180E 00    FORCE  = 1.780E 02    DELT  = 3.000E-02
PSTART= 1.108E 03    WSTART= 5.915E 01    PFINAL= 1.105E 03    WFINAL= 5.904E 01
FCHECK= 2.248E 02    PC    = 1.066E 03    AT     = 1.389E-01    RHO   = 3.356E-03
RHOC   = 3.308E-03    AC    = 1.337E 04    VXE    = 2.445E 04    WDOT  = 3.553E 00
DELW   = 1.066E-01    RHONEW= 3.350E-03
      17 1.780E 02 3.000E-02 9.800E-01 1.180E 00 1.108E 03 5.915E 01 0.000E-01 1.105E 03 5.904E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.280E 00    FORCE  = 8.670E 02    DELT  = 3.000E-02
PSTART= 1.105E 03    WSTART= 5.904E 01    PFINAL= 1.092E 03    WFINAL= 5.857E 01
FCHECK= 1.010E 03    PC    = 1.094E 03    AT     = 6.191E-01    RHO   = 3.350E-03
RHOC   = 3.326E-03    AC    = 1.339E 04    VXE    = 2.449E 04    WDOT  = 1.594E 01
DELW   = 4.781E-01    RHONEW= 3.323E-03
      18 8.670E 02 3.000E-02 9.900E-01 1.280E 00 1.105E 03 5.904E 01 0.000E-01 1.092E 03 5.857E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.600E-01    CFX   = 1.100E 00    FORCE  = 1.910E 02    DELT  = 3.000E-02
PSTART= 1.092E 03    WSTART= 5.857E 01    PFINAL= 1.089E 03    WFINAL= 5.844E 01
FCHECK= 2.583E 02    PC    = 1.049E 03    AT     = 1.656E-01    RHO   = 3.323E-03
RHOC   = 3.228E-03    AC    = 1.330E 04    VXE    = 2.428E 04    WDOT  = 4.110E 00
DELW   = 1.233E-01    RHONEW= 3.316E-03
      19 1.910E 02 3.000E-02 9.600E-01 1.100E 00 1.092E 03 5.857E 01 0.000E-01 1.089E 03 5.844E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.100E 00    FORCE  = 1.560E 02    DELT  = 8.800E-02
PSTART= 1.089E 03    WSTART= 5.844E 01    PFINAL= 1.081E 03    WFINAL= 5.814E 01
FCHECK= 2.140E 02    PC    = 1.078E 03    AT     = 1.332E-01    RHO   = 3.316E-03
RHOC   = 3.292E-03    AC    = 1.336E 04    VXE    = 2.442E 04    WDOT  = 3.386E 00
DELW   = 2.980E-01    RHONEW= 3.299E-03
      20 1.580E 02 8.800E-02 9.900E-01 1.100E 00 1.089E 03 5.844E 01 0.000E-01 1.081E 03 5.814E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.100E 00    FORCE  = 1.700E 02    DELT  = 8.400E-02
PSTART= 1.081E 03    WSTART= 5.814E 01    PFINAL= 1.073E 03    WFINAL= 5.784E 01
FCHECK= 2.302E 02    PC    = 1.071E 03    AT     = 1.444E-01    RHO   = 3.299E-03
RHOC   = 3.275E-03    AC    = 1.334E 04    VXE    = 2.438E 04    WDOT  = 3.647E 00
DELW   = 3.064E-01    RHONEW= 3.281E-03
      21 1.700E 02 8.400E-02 9.900E-01 1.100E 00 1.081E 03 5.814E 01 0.000E-01 1.073E 03 5.784E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.160E 00    FORCE  = 2.250E 02    DELT  = 3.000E-02
PSTART= 1.073E 03    WSTART= 5.784E 01    PFINAL= 1.070E 03    WFINAL= 5.770E 01
FCHECK= 2.887E 02    PC    = 1.063E 03    AT     = 1.825E-01    RHO   = 3.281E-03
RHOC   = 3.258E-03    AC    = 1.333E 04    VXE    = 2.435E 04    WDOT  = 4.583E 00
DELW   = 1.375E-01    RHONEW= 3.274E-03
      22 2.250E 02 3.000E-02 9.900E-01 1.160E 00 1.073E 03 5.784E 01 0.000E-01 1.070E 03 5.770E 01
  FROM END OF THRUST       *******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.100E 00    FORCE  = 1.530E 02    DELT  = 8.000E-02
PSTART= 1.070E 03    WSTART= 5.770E 01    PFINAL= 1.063E 03    WFINAL= 5.744E 01
FCHECK= 2.070E 02    PC    = 1.059E 03    AT     = 1.313E-01    RHO   = 3.274E-03
```

FIGURE 7.4-2(c). OUTPUT FILE FOR SAN FERNANDO (NORTH)

```
RHOC  = 3.250E-03   AC     = 1.332E 04   VXE   = 2.433E 04   WOUT  = 3.288E 00
DELW  = 2.630E-01   RHONEW= 3.259E-03
     23 1.530E 02 8.000E-02 9.900E-01 1.100E 00 1.070E 03 5.770E 01 0.000E-01 1.063E 03 5.744E 01

     ** NATURAL END OF THRUST ANALYSIS ** ++++++++++++++++++++++++++++++++++++++++++++++++++++
```

FIGURE 7.4-2(d). OUTPUT FILE FOR SAN FERNANDO (NORTH)

```
  DATA FILE FOR THRUST CALCULATIONS
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
OUT6      =SFCS1.UT** NAME OF OUTPUT FILE (C*8)
N         =        26 TOTAL NUMBER OF PULSES (I10)
PO        = 14.7    E0 ATMOSPHERIC PRESSURE (PSI) (E10.0)
GAMMA     = 1.41    E0 GAS CONSTANT
G         = 386.4   E0 ACCEL. OF GRAVITY (IN/S**2)
VOLUME    = 17625.6E0 VOLUME (IN**3)
PSTART    = 1314.7 E0 STARTING PRESSURE (PSI)
WSTART    = 66.785 E0 STARTING WEIGHT    (POUNDS)
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
         N1  FORCE(N)   DELI(N) ALPHA(N)   CFX(N)
          1 65.      E0 0.010  E0 1.00   E0 1.00   E0
          2 115.     E0 0.041  E0 1.00   E0 1.20   E0
          3 411.     E0 0.042  E0 0.99   E0 1.20   E0
          4 1075.    E0 0.054  E0 0.96   E0 1.30   E0
          5 582.     E0 0.060  E0 0.98   E0 1.23   E0
          6 613.     E0 0.108  E0 0.98   E0 1.24   E0
          7 780.     E0 0.073  E0 0.97   E0 1.26   E0
          8 312.     E0 0.030  E0 0.99   E0 1.20   E0
          9 327.     E0 0.105  E0 0.99   E0 1.20   E0
         10 723.     E0 0.069  E0 0.98   E0 1.26   E0
         11 189.     E0 0.111  E0 0.99   E0 1.10   E0
         12 215.     E0 0.030  E0 0.99   E0 1.15   E0
         13 136.     E0 0.107  E0 0.99   E0 1.10   E0
         14 288.     E0 0.030  E0 0.99   E0 1.15   E0
         15 969.     E0 0.030  E0 0.96   E0 1.28   E0
         16 721.     E0 0.030  E0 0.98   E0 1.26   E0
         17 209.     E0 0.045  E0 0.99   E0 1.16   E0
         18 1456.    E0 0.030  E0 0.95   E0 1.34   E0
         19 510.     E0 0.046  E0 0.98   E0 1.24   E0
         20 626.     E0 0.039  E0 0.98   E0 1.24   E0
         21 440.     E0 0.031  E0 0.98   E0 1.22   E0
         22 244.     E0 0.052  E0 0.99   E0 1.18   E0
         23 215.     E0 0.086  E0 0.99   E0 1.16   E0
         24 215.     E0 0.087  E0 0.99   E0 1.16   E0
         25 141.     E0 0.092  E0 0.99   E0 1.10   E0
         26 172.     E0 0.030  E0 0.99   E0 1.10   E0
C-----------------------------------------------------------------------
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C-----------------------------------------------------------------------
```

FIGURE 7.4-3. INPUT FILE FOR SAN FERNANDO (SOUTH DIRECTION)

```
THRUST ANALYSIS, INS=SFC.S1      OUTO=SFCS1.OT
PO     = 1.470E 01       GAMMA = 1.410E 00
G      = 3.864E 02       VOLUME= 1.763E 04
PSTART= 1.315E 03        WSTART= 6.679E 01

      N        F           DT          ALPHA       CFX           P            W         FCHECK      PNEW        WNEW
  FROM END OF THRUST      ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 1.000E 00     CFX   = 1.000E 00    FORCE = 6.500E 01     DELT  = 1.000E-02
PSTART= 1.315E 03     WSTART= 6.679E 01    PFINAL= 1.314E 03     WFINAL= 6.677E 01
FCHECK= 9.793E 01     PC    = 1.315E 03    AT     = 4.944E-02    RHO   = 3.789E-03
RHOC  = 3.789E-03     AC    = 1.375E 04    VXE    = 2.541E 04    WDOT  = 1.489E 00
DELW  = 1.489E-02     RHONEW= 3.788E-03
      1 6.500E 01 1.000E-02 1.000E 00 1.000E 00 1.315E 03 6.679E 01 0.000E-01 1.314E 03 6.677E 01
  FROM END OF THRUST      ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 1.000E 00     CFX   = 1.200E 00    FORCE = 1.150E 02     DELT  = 4.100E-02
PSTART= 1.314E 03     WSTART= 6.677E 01    PFINAL= 1.312E 03     WFINAL= 6.668E 01
FCHECK= 1.444E 02     PC    = 1.314E 03    AT     = 7.292E-02    RHO   = 3.788E-03
RHOC  = 3.788E-03     AC    = 1.375E 04    VXE    = 2.541E 04    WDOT  = 2.195E 00
DELW  = 9.001E-02     RHONEW= 3.783E-03
      2 1.150E 02 4.100E-02 1.000E 00 1.200E 00 1.314E 03 6.677E 01 0.000E-01 1.312E 03 6.668E 01
  FROM END OF THRUST      ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.900E-01     CFX   = 1.200E 00    FORCE = 4.110E 02     DELT  = 4.200E-02
PSTART= 1.312E 03     WSTART= 6.668E 01    PFINAL= 1.303E 03     WFINAL= 6.635E 01
FCHECK= 5.157E 02     PC    = 1.299E 03    AT     = 2.637E-01    RHO   = 3.783E-03
RHOC  = 3.756E-03     AC    = 1.372E 04    VXE    = 2.535E 04    WDOT  = 7.859E 00
DELW  = 3.301E-01     RHONEW= 3.764E-03
      3 4.110E 02 4.200E-02 9.900E-01 1.200E 00 1.312E 03 6.668E 01 0.000E-01 1.303E 03 6.635E 01
  FROM END OF THRUST      ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.600E-01     CFX   = 1.300E 00    FORCE = 1.075E 03     DELT  = 5.400E-02
PSTART= 1.303E 03     WSTART= 6.635E 01    PFINAL= 1.274E 03     WFINAL= 6.532E 01
FCHECK= 1.242E 03     PC    = 1.251E 03    AT     = 6.613E-01    RHO   = 3.764E-03
RHOC  = 3.657E-03     AC    = 1.365E 04    VXE    = 2.516E 04    WDOT  = 1.908E 01
DELW  = 1.030E 00     RHONEW= 3.706E-03
      4 1.075E 03 5.400E-02 9.600E-01 1.300E 00 1.303E 03 6.635E 01 0.000E-01 1.274E 03 6.532E 01
  FROM END OF THRUST      ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.800E-01     CFX   = 1.230E 00    FORCE = 5.820E 02     DELT  = 6.000E-02
PSTART= 1.274E 03     WSTART= 6.532E 01    PFINAL= 1.256E 03     WFINAL= 6.466E 01
FCHECK= 7.109E 02     PC    = 1.249E 03    AT     = 3.789E-01    RHO   = 3.706E-03
RHOC  = 3.653E-03     AC    = 1.365E 04    VXE    = 2.515E 04    WDOT  = 1.092E 01
DELW  = 6.552E-01     RHONEW= 3.669E-03
      5 5.820E 02 6.000E-02 9.800E-01 1.230E 00 1.274E 03 6.532E 01 0.000E-01 1.256E 03 6.466E 01
  FROM END OF THRUST      ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.800E-01     CFX   = 1.240E 00    FORCE = 6.130E 02     DELT  = 1.080E-01
PSTART= 1.256E 03     WSTART= 6.466E 01    PFINAL= 1.223E 03     WFINAL= 6.343E 01
FCHECK= 7.421E 02     PC    = 1.231E 03    AT     = 4.016E-01    RHO   = 3.669E-03
RHOC  = 3.617E-03     AC    = 1.362E 04    VXE    = 2.508E 04    WDOT  = 1.143E 01
DELW  = 1.235E 00     RHONEW= 3.599E-03
      6 6.130E 02 1.080E-01 9.800E-01 1.240E 00 1.256E 03 6.466E 01 0.000E-01 1.223E 03 6.343E 01
  FROM END OF THRUST      ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00    G      = 3.864E 02    VOLUME= 1.763E 04
ALPHA = 9.700E-01     CFX   = 1.260E 00    FORCE = 7.800E 02     DELT  = 7.300E-02
PSTART= 1.223E 03     WSTART= 6.343E 01    PFINAL= 1.194E 03     WFINAL= 6.238E 01
FCHECK= 9.274E 02     PC    = 1.186E 03    AT     = 5.220E-01    RHO   = 3.599E-03
RHOC  = 3.522E-03     AC    = 1.354E 04    VXE    = 2.489E 04    WDOT  = 1.439E 01
DELW  = 1.051E 00     RHONEW= 3.539E-03
```

FIGURE 7.4-4(a). OUTPUT FILE FOR SAN FERNANDO (SOUTH)

```
ALPHA = 9.700E-01   CFX    = 1.260E 00   FORCE = 7.800E 02   DELT   = 7.300E-02
PSTART= 1.223E 03   WSTART= 6.343E 01   PFINAL= 1.194E 03   WFINAL= 6.238E 01
FCHECK= 9.274E 02   PC     = 1.186E 03   AT     = 5.220E-01   RHO    = 3.599E-03
RHOC  = 3.522E-03   AC     = 1.354E 04   VXE    = 2.489E 04   WDOT   = 1.439E 01
DELW  = 1.051E 00   RHONEW= 3.559E-03


      7 7.800E 02 7.300E-02 9.700E-01 1.260E 00 1.223E 03 6.343E 01 0.000E-01 1.194E 03 6.238E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.200E 00   FORCE = 3.120E 02   DELT   = 3.000E-02
PSTART= 1.194E 03   WSTART= 6.238E 01   PFINAL= 1.189E 03   WFINAL= 6.220E 01
FCHECK= 3.894E 02   PC     = 1.102E 03   AT     = 2.199E-01   RHO    = 3.539E-03
RHOC  = 3.514E-03   AC     = 1.354E 04   VXE    = 2.488E 04   WDOT   = 6.048E 00
DELW  = 1.815E-01   RHONEW= 3.529E-03
      8 3.120E 02 3.000E-02 9.900E-01 1.200E 00 1.194E 03 6.238E 01 0.000E-01 1.189E 03 6.220E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.200E 00   FORCE = 3.270E 02   DELT   = 1.050E-01
PSTART= 1.189E 03   WSTART= 6.220E 01   PFINAL= 1.171E 03   WFINAL= 6.153E 01
FCHECK= 4.080E 02   PC     = 1.177E 03   AT     = 2.315E-01   RHO    = 3.529E-03
RHOC  = 3.504E-03   AC     = 1.353E 04   VXE    = 2.486E 04   WDOT   = 6.343E 00
DELW  = 6.660E-01   RHONEW= 3.491E-03
      9 3.270E 02 1.050E-01 9.900E-01 1.200E 00 1.189E 03 6.220E 01 0.000E-01 1.171E 03 6.153E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.800E-01   CFX    = 1.260E 00   FORCE = 7.230E 02   DELT   = 6.900E-02
PSTART= 1.171E 03   WSTART= 6.153E 01   PFINAL= 1.147E 03   WFINAL= 6.061E 01
FCHECK= 8.580E 02   PC     = 1.148E 03   AT     = 4.999E-01   RHO    = 3.491E-03
RHOC  = 3.441E-03   AC     = 1.348E 04   VXE    = 2.473E 04   WDOT   = 1.341E 01
DELW  = 9.250E-01   RHONEW= 3.439E-03
     10 7.230E 02 6.900E-02 9.800E-01 1.260E 00 1.171E 03 6.153E 01 0.000E-01 1.147E 03 6.061E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.100E 00   FORCE = 1.890E 02   DELT   = 1.110E-01
PSTART= 1.147E 03   WSTART= 6.061E 01   PFINAL= 1.135E 03   WFINAL= 6.016E 01
FCHECK= 2.567E 02   PC     = 1.135E 03   AT     = 1.514E-01   RHO    = 3.439E-03
RHOC  = 3.414E-03   AC     = 1.346E 04   VXE    = 2.467E 04   WDOT   = 4.021E 00
DELW  = 4.463E-01   RHONEW= 3.413E-03
     11 1.890E 02 1.110E-01 9.900E-01 1.100E 00 1.147E 03 6.061E 01 0.000E-01 1.135E 03 6.016E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.150E 00   FORCE = 2.150E 02   DELT   = 3.000E-02
PSTART= 1.135E 03   WSTART= 6.016E 01   PFINAL= 1.131E 03   WFINAL= 6.003E 01
FCHECK= 2.792E 02   PC     = 1.123E 03   AT     = 1.664E-01   RHO    = 3.413E-03
RHOC  = 3.389E-03   AC     = 1.344E 04   VXE    = 2.462E 04   WDOT   = 4.382E 00
DELW  = 1.314E-01   RHONEW= 3.406E-03
     12 2.150E 02 3.000E-02 9.900E-01 1.150E 00 1.135E 03 6.016E 01 0.000E-01 1.131E 03 6.003E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.100E 00   FORCE = 1.360E 02   DELT   = 1.070E-01
PSTART= 1.131E 03   WSTART= 6.003E 01   PFINAL= 1.123E 03   WFINAL= 5.972E 01
FCHECK= 1.846E 02   PC     = 1.120E 03   AT     = 1.104E-01   RHO    = 3.406E-03
RHOC  = 3.382E-03   AC     = 1.343E 04   VXE    = 2.461E 04   WDOT   = 2.899E 00
DELW  = 3.102E-01   RHONEW= 3.388E-03
     13 1.360E 02 1.070E-01 9.900E-01 1.100E 00 1.131E 03 6.003E 01 0.000E-01 1.123E 03 5.972E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.150E 00   FORCE = 2.880E 02   DELT   = 3.000E-02
PSTART= 1.123E 03   WSTART= 5.972E 01   PFINAL= 1.118E 03   WFINAL= 5.954E 01
FCHECK= 3.738E 02   PC     = 1.112E 03   AT     = 2.253E-01   RHO    = 3.388E-03
RHOC  = 3.364E-03   AC     = 1.342E 04   VXE    = 2.457E 04   WDOT   = 5.878E 00
DELW  = 1.763E-01   RHONEW= 3.378E-03
     14 2.880E 02 3.000E-02 9.900E-01 1.150E 00 1.123E 03 5.972E 01 0.000E-01 1.118E 03 5.954E 01
  FROM END OF THRUST      ********************************
P0    = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.600E-01   CFX    = 1.280E 00   FORCE = 9.690E 02   DELT   = 3.000E-02
PSTART= 1.118E 03   WSTART= 5.954E 01   PFINAL= 1.104E 03   WFINAL= 5.901E 01
FCHECK= 1.128E 03   PC     = 1.074E 03   AT     = 7.052E-01   RHO    = 3.378E-03
RHOC  = 3.282E-03   AC     = 1.335E 04   VXE    = 2.440E 04   WDOT   = 1.788E 01
```

FIGURE 7.4-4(b). OUTPUT FILE FOR SAN FERNANDO (SOUTH)

```
DELW   = 5.358E-01    RHONEW= 3.348E-03
     15 9.690E 02 3.000E-02 9.600E-01 1.280E 00 1.118E 03 5.954E 01 0.000E-01 1.104E 03 5.901E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.280E 00   FORCE  = 7.210E 02   DELT   = 3.000E-02
PSTART= 1.104E 03     WSTART= 5.901E 01   PFINAL= 1.093E 03    WFINAL= 5.860E 01
FCHECK= 8.527E 02     PC    = 1.062E 03   AT     = 5.289E-01   RHO    = 3.348E-03
RHOC   = 3.300E-03    AC    = 1.337E 04   VXE    = 2.444E 04   WDOT   = 1.348E 01
DELW   = 4.045E-01    RHONEW= 3.325E-03
     16 7.210E 02 3.000E-02 9.800E-01 1.280E 00 1.104E 03 5.901E 01 0.000E-01 1.093E 03 5.860E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.160E 00   FORCE  = 2.090E 02   DELT   = 4.500E-02
PSTART= 1.093E 03     WSTART= 5.860E 01   PFINAL= 1.088E 03    WFINAL= 5.841E 01
FCHECK= 2.685E 02     PC    = 1.062E 03   AT     = 1.664E-01   RHO    = 3.325E-03
RHOC   = 3.301E-03    AC    = 1.337E 04   VXE    = 2.444E 04   WDOT   = 4.245E 00
DELW   = 1.910E-01    RHONEW= 3.314E-03
     17 2.090E 02 4.500E-02 9.900E-01 1.160E 00 1.093E 03 5.860E 01 0.000E-01 1.088E 03 5.841E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.500E-01    CFX   = 1.340E 00   FORCE  = 1.456E 03   DELT   = 3.000E-02
PSTART= 1.088E 03     WSTART= 5.841E 01   PFINAL= 1.068E 03    WFINAL= 5.764E 01
FCHECK= 1.615E 03     PC    = 1.034E 03   AT     = 1.051E 00   RHO    = 3.314E-03
RHOC   = 3.196E-03    AC    = 1.328E 04   VXE    = 2.421E 04   WDOT   = 2.577E 01
DELW   = 7.732E-01    RHONEW= 3.270E-03
     18 1.456E 03 3.000E-02 9.500E-01 1.340E 00 1.088E 03 5.841E 01 0.000E-01 1.068E 03 5.764E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.240E 00   FORCE  = 5.100E 02   DELT   = 4.600E-02
PSTART= 1.068E 03     WSTART= 5.764E 01   PFINAL= 1.056E 03    WFINAL= 5.719E 01
FCHECK= 6.117E 02     PC    = 1.047E 03   AT     = 3.929E-01   RHO    = 3.270E-03
RHOC   = 3.224E-03    AC    = 1.330E 04   VXE    = 2.427E 04   WDOT   = 9.739E 00
DELW   = 4.480E-01    RHONEW= 3.245E-03
     19 5.100E 02 4.600E-02 9.800E-01 1.240E 00 1.068E 03 5.764E 01 0.000E-01 1.056E 03 5.719E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.240E 00   FORCE  = 6.260E 02   DELT   = 3.900E-02
PSTART= 1.056E 03     WSTART= 5.719E 01   PFINAL= 1.044E 03    WFINAL= 5.672E 01
FCHECK= 7.503E 02     PC    = 1.035E 03   AT     = 4.876E-01   RHO    = 3.245E-03
RHOC   = 3.199E-03    AC    = 1.328E 04   VXE    = 2.422E 04   WDOT   = 1.197E 01
DELW   = 4.669E-01    RHONEW= 3.218E-03
     20 6.260E 02 3.900E-02 9.800E-01 1.240E 00 1.056E 03 5.719E 01 0.000E-01 1.044E 03 5.672E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.800E-01    CFX   = 1.220E 00   FORCE  = 4.400E 02   DELT   = 3.100E-02
PSTART= 1.044E 03     WSTART= 5.672E 01   PFINAL= 1.037E 03    WFINAL= 5.646E 01
FCHECK= 5.357E 02     PC    = 1.023E 03   AT     = 3.524E-01   RHO    = 3.218E-03
RHOC   = 3.172E-03    AC    = 1.326E 04   VXE    = 2.416E 04   WDOT   = 8.568E 00
DELW   = 2.656E-01    RHONEW= 3.203E-03
     21 4.400E 02 3.100E-02 9.800E-01 1.220E 00 1.044E 03 5.672E 01 0.000E-01 1.037E 03 5.646E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.180E 00   FORCE  = 2.440E 02   DELT   = 5.200E-02
PSTART= 1.037E 03     WSTART= 5.646E 01   PFINAL= 1.031E 03    WFINAL= 5.620E 01
FCHECK= 3.072E 02     PC    = 1.027E 03   AT     = 2.013E-01   RHO    = 3.203E-03
RHOC   = 3.180E-03    AC    = 1.326E 04   VXE    = 2.418E 04   WDOT   = 4.910E 00
DELW   = 2.553E-01    RHONEW= 3.189E-03
     22 2.440E 02 5.200E-02 9.900E-01 1.180E 00 1.037E 03 5.646E 01 0.000E-01 1.031E 03 5.620E 01
  FROM END OF THRUST          ******************************
PO     = 1.470E 01    GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA  = 9.900E-01    CFX   = 1.160E 00   FORCE  = 2.150E 02   DELT   = 8.600E-02
PSTART= 1.031E 03     WSTART= 5.620E 01   PFINAL= 1.021E 03    WFINAL= 5.582E 01
FCHECK= 2.752E 02     PC    = 1.020E 03   AT     = 1.616E-01   RHO    = 3.189E-03
```

FIGURE 7.4-4(c). OUTPUT FILE FOR SAN FERNANDO (SOUTH)

```
  FROM END OF THRUST       ******************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.160E 00   FORCE = 2.150E 02   DELT   = 8.600E-02
PSTART= 1.031E 03   WSTART= 5.620E 01   PFINAL= 1.021E 03   WFINAL= 5.582E 01
FCHECK= 2.752E 02   PC     = 1.020E 03   AT     = 1.816E-01   RHO    = 3.189E-03


RHOC   = 3.166E-03   AC     = 1.325E 04   VXE    = 2.414E 04   WDOT   = 4.405E 00
DELW   = 3.786E-01   RHONEW= 3.167E-03
      23 2.150E 02 8.600E-02 9.900E-01 1.160E 00 1.031E 03 5.620E 01 0.000E-01 1.021E 03 5.582E 01
  FROM END OF THRUST       ******************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.160E 00   FORCE = 2.150E 02   DELT   = 8.700E-02
PSTART= 1.021E 03   WSTART= 5.582E 01   PFINAL= 1.011E 03   WFINAL= 5.544E 01
FCHECK= 2.751E 02   PC     = 1.011E 03   AT     = 1.834E-01   RHO    = 3.167E-03
RHOC   = 3.145E-03   AC     = 1.323E 04   VXE    = 2.410E 04   WDOT   = 4.411E 00
DELW   = 3.838E-01   RHONEW= 3.145E-03
      24 2.150E 02 8.700E-02 9.900E-01 1.160E 00 1.021E 03 5.582E 01 0.000E-01 1.011E 03 5.544E 01
  FROM END OF THRUST       ******************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.100E 00   FORCE = 1.410E 02   DELT   = 9.200E-02
PSTART= 1.011E 03   WSTART= 5.544E 01   PFINAL= 1.004E 03   WFINAL= 5.516E 01
FCHECK= 1.901E 02   PC     = 1.001E 03   AT     = 1.281E-01   RHO    = 3.145E-03
RHOC   = 3.123E-03   AC     = 1.321E 04   VXE    = 2.405E 04   WDOT   = 3.055E 00
DELW   = 2.811E-01   RHONEW= 3.129E-03
      25 1.410E 02 9.200E-02 9.900E-01 1.100E 00 1.011E 03 5.544E 01 0.000E-01 1.004E 03 5.516E 01
  FROM END OF THRUST       ******************************
P0     = 1.470E 01   GAMMA = 1.410E 00   G      = 3.864E 02   VOLUME= 1.763E 04
ALPHA = 9.900E-01   CFX    = 1.100E 00   FORCE = 1.720E 02   DELT   = 3.000E-02
PSTART= 1.004E 03   WSTART= 5.516E 01   PFINAL= 1.001E 03   WFINAL= 5.505E 01
FCHECK= 2.318E 02   PC     = 9.939E 02   AT     = 1.573E-01   RHO    = 3.129E-03
RHOC   = 3.107E-03   AC     = 1.320E 04   VXE    = 2.401E 04   WDOT   = 3.730E 00
DELW   = 1.119E-01   RHONEW= 3.123E-03
      26 1.720E 02 3.000E-02 9.900E-01 1.100E 00 1.004E 03 5.516E 01 0.000E-01 1.001E 03 5.505E 01

        ** NATURAL END OF THRUST ANALYSIS ** ++++++++++++++++++++++++++++++++++++++++++++++++++++
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FIGURE 7.4-4(d). OUTPUT FILE FOR SAN FERNANDO (SOUTH)

SECTION 8

MOTION SIMULATION TESTS

8.1 OBJECTIVES

The objectives of the motion simulation tests were: (1) to specify a pulse train and compare it to the test pulse train achieved, and (2) compare the criterion motions with the measured simulated motions.

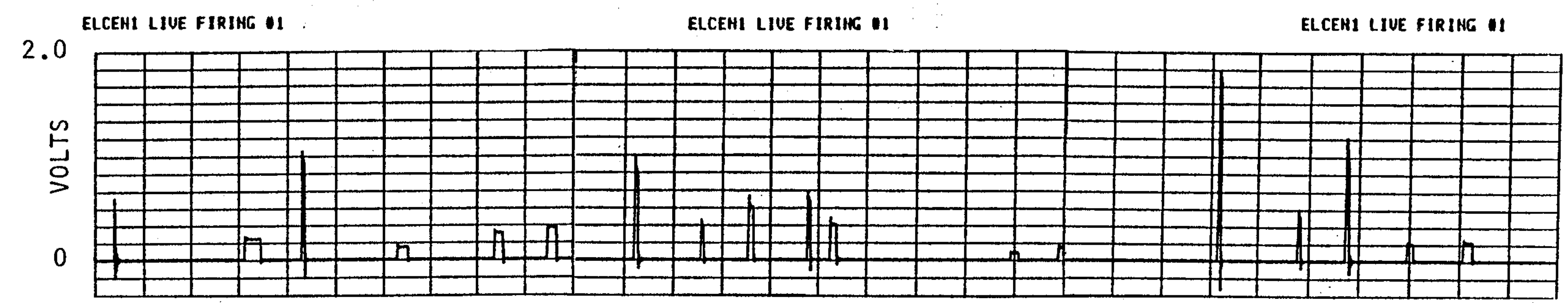
Originally, a more complete set of demonstration tests were planned; however, the design, fabrication, and construction of the test frame and teething problems with the electromechanical and hydraulic components of the gas pulsers were of such magnitude as to curtail the extent of the calibration/demonstration tests.

8.2 EL CENTRO EARTHQUAKE DEMONSTRATION

The optimum pulse train for El Centro earthquake discussed in Section 3.2 and Section 7.3 was applied to the demonstration structure. The measured excitation and response for this case are shown in Figures 8.2-1 through 8.2-2.

8.3 SAN FERNANDO EARTHQUAKE DEMONSTRATION

The optimum pulse train for San Fernando earthquake discussed in Section 3.3 and Section 7.4 was also applied to the demonstration structure. Measurements of the test excitation and the corresponding response are shown in Figures 8.3-1 and 8.3-2.



(a) Pulse Train Command Signals (South Pulse Unit)

(b) Metering Nozzle Position - Rocket Throat Area (South Pulse Unit)

FIGURE 8.2-1. ROCKET SYSTEM PERFORMANCE (SOUTH UNIT) FOR EL CENTRO 1940 EARTHQUAKE SIMULATION

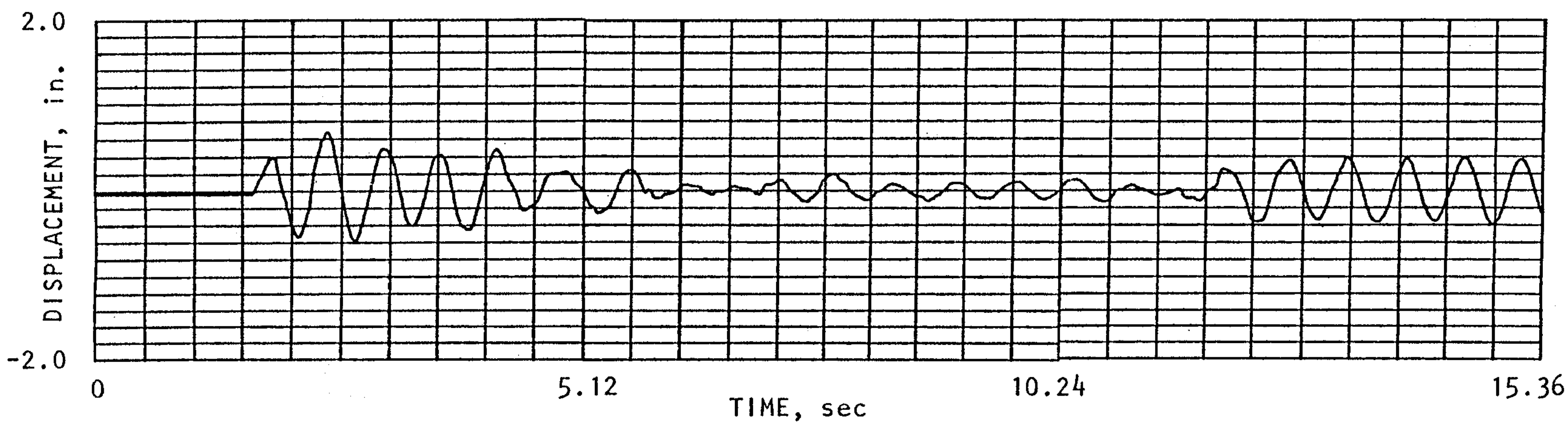
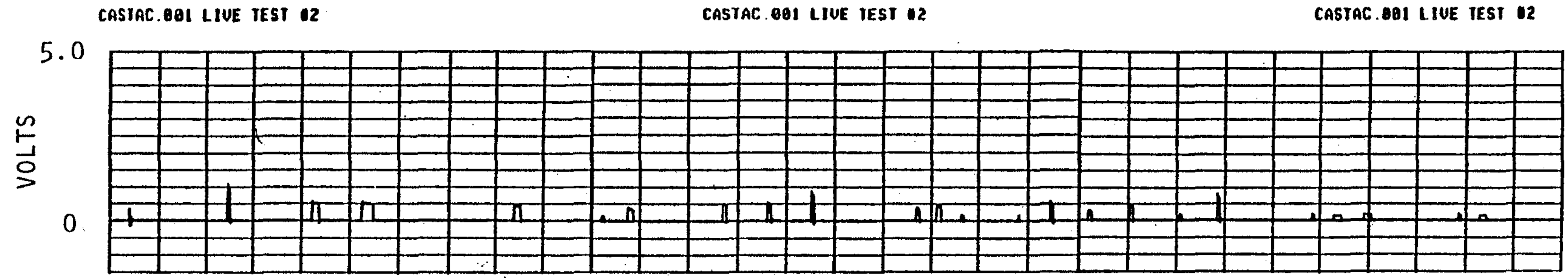


FIGURE 8.2-2. DISPLACEMENT-TIME HISTORY AT 3rd FLOOR OF TEST STRUCTURE FOR EL CENTRO 1940 EARTHQUAKE RESPONSE SIMULATION



(a) Pulse Train Command Signals (North Pulse Unit)

(b) Metering Nozzle Position – Rocket Throat Area (North Pulse Unit)

FIGURE 8.3-1. ROCKET SYSTEM PERFORMANCE (SOUTH UNIT) FOR SAN FERNANDO 1971 EARTHQUAKE SIMULATION

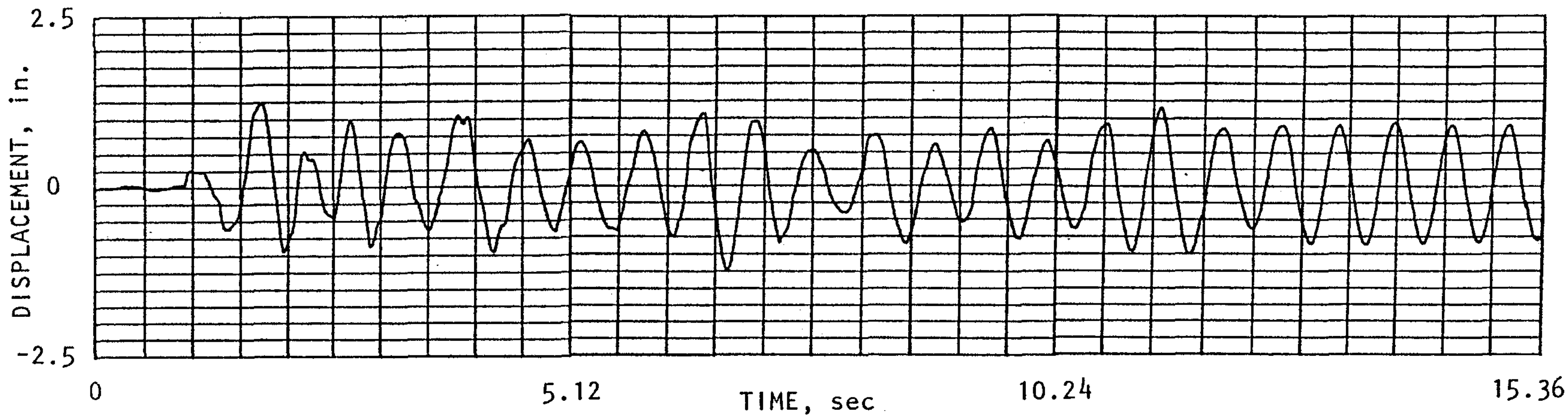


FIGURE 8.3-2. DISPLACEMENT-TIME HISTORY AT 3rd FLOOR OF TEST STRUCTURE FOR SAN FERNANDO 1971 – CASTAIC – RESPONSE SIMULATION

SECTION 9

SOLID PROPELLANT ROCKET

9.1 OBJECTIVE

In order to explore alternative energy sources for generating high-level pulse trains needed for use on massive structures, an exploratory study was conducted to evaluate the feasibility of using solid-propellant rockets.

9.2 ROCKET CHARACTERISTICS

A sketch of the basic design of a solid-propellant rocket that was built for structural dynamic testing purposes is illustrated in Figure 9.2-1 and a photograph is shown in Figures 9.2-2.

9.3 DEMONSTRATION TEST

The rocket under discussion was attached to the test structure as shown in Figure 9.3-1. Upon ignition (see Fig. 9.3-2), impulsive force generated by the rocket caused the demonstration structure to undergo the response shown in Figure 9.3-3. At this initial stage and the office area where the test stand was located, a prudent low yield propellant was used.

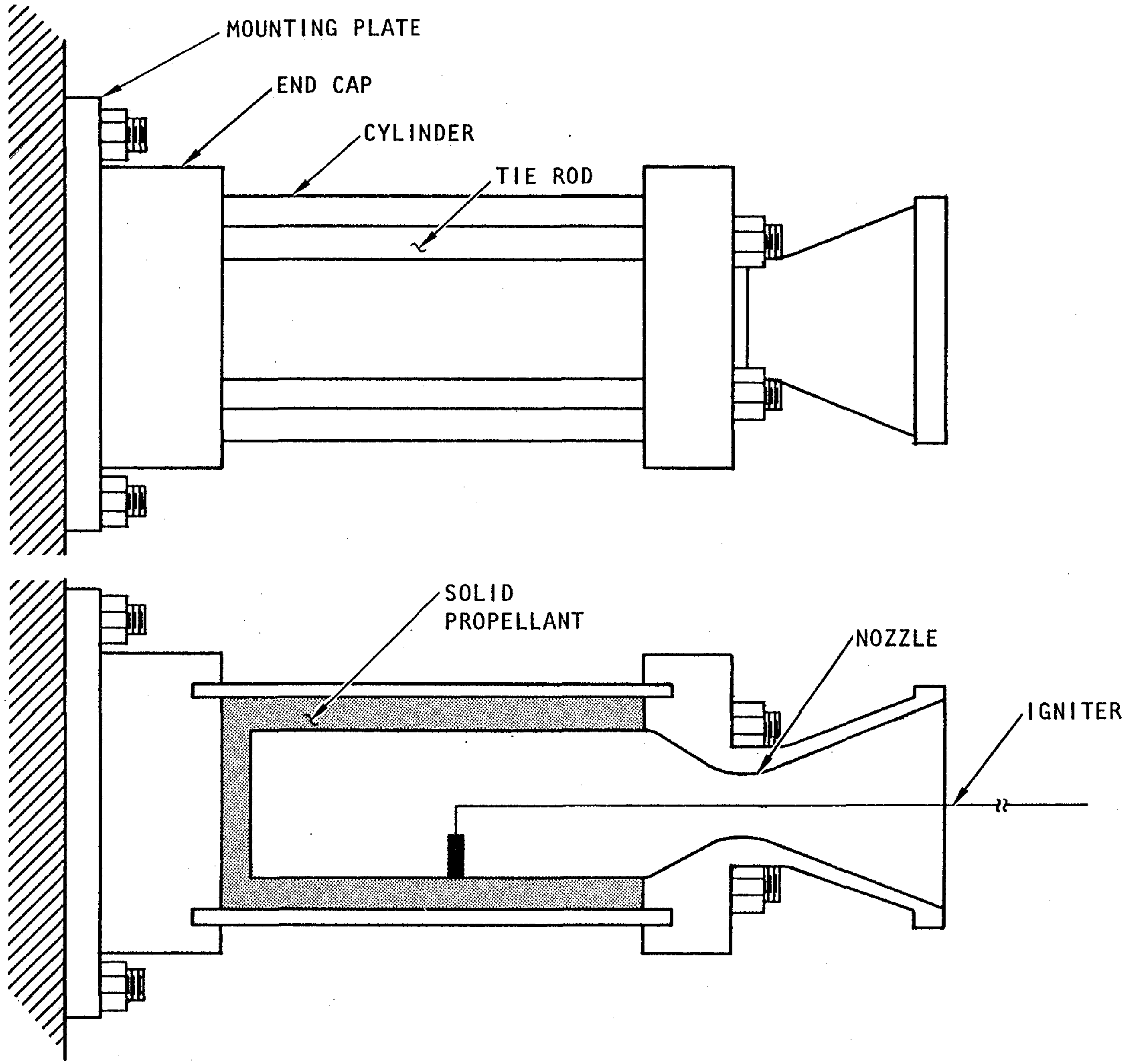


FIGURE 9.2-1. SOLID PROPELLANT ROCKET FOR USE ON MASSIVE STRUCTURES REQUIRING HIGH FORCE

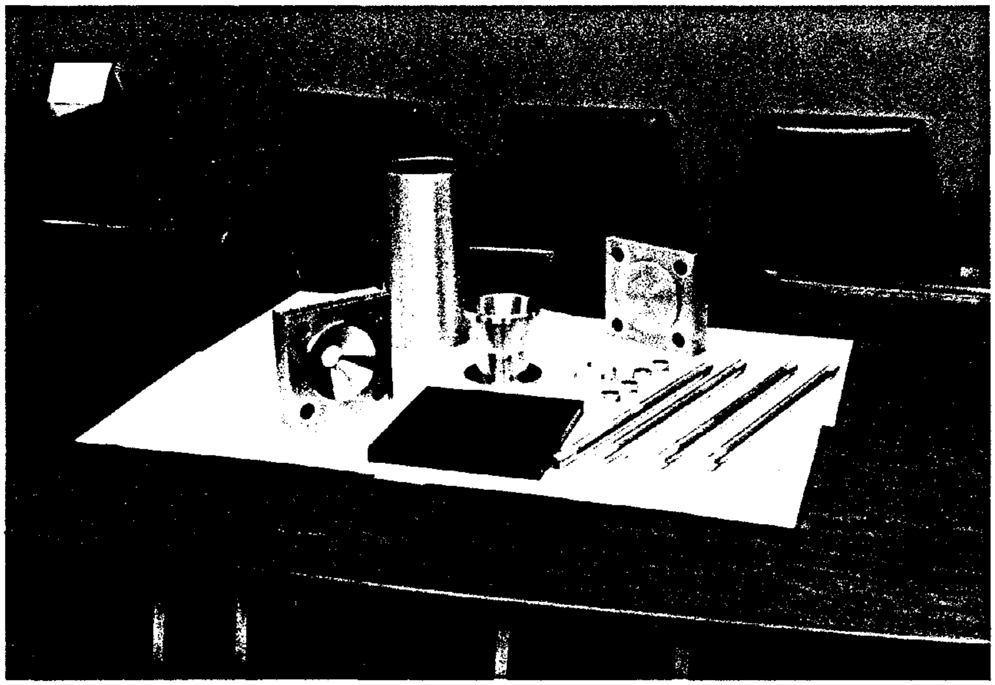


FIGURE 9.2-2. PHOTOGRAPH OF ROCKET COMPONENTS

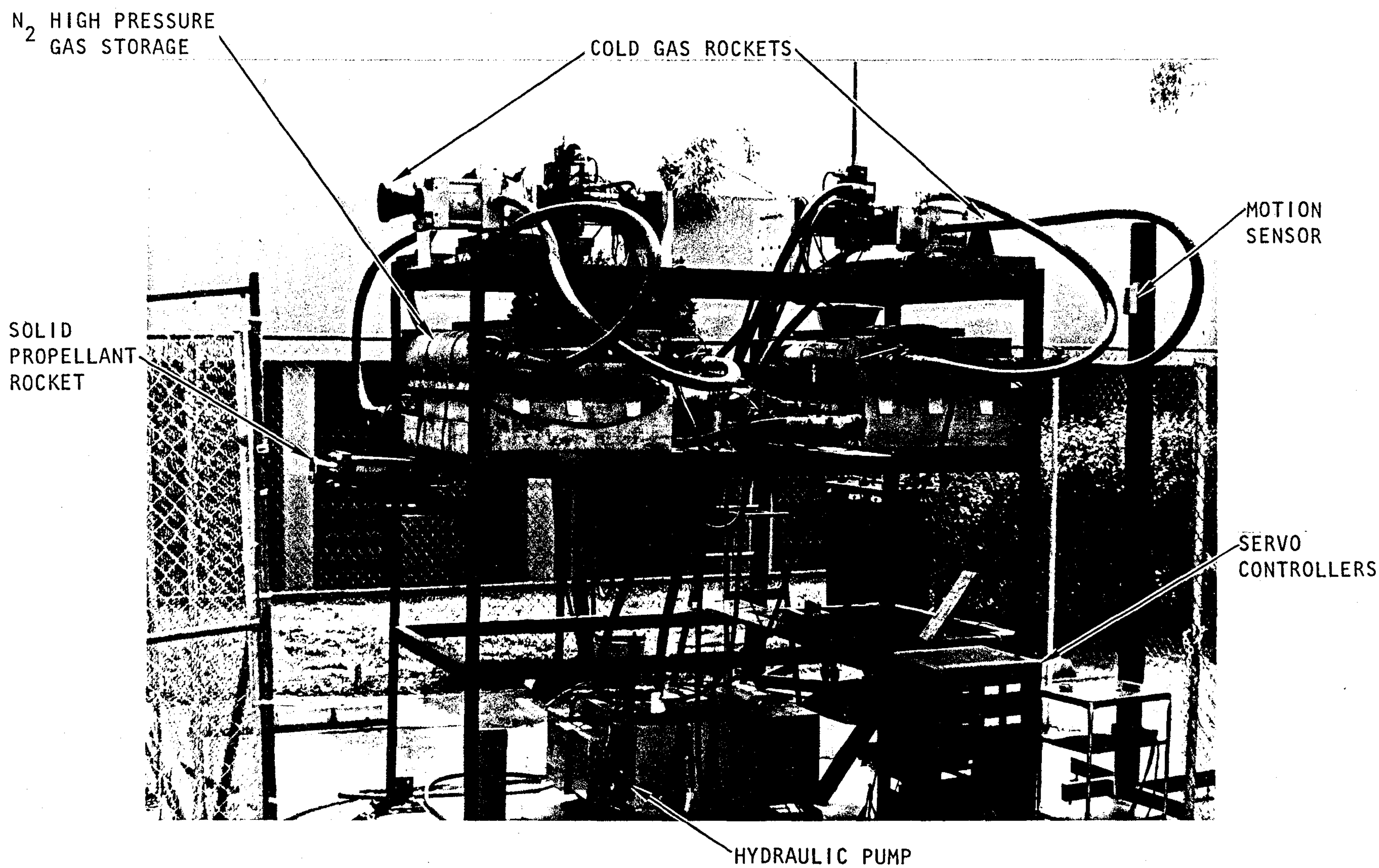


FIGURE 9.3-1. OVERALL VIEW OF STRUCTURE AND PULSE ROCKETS

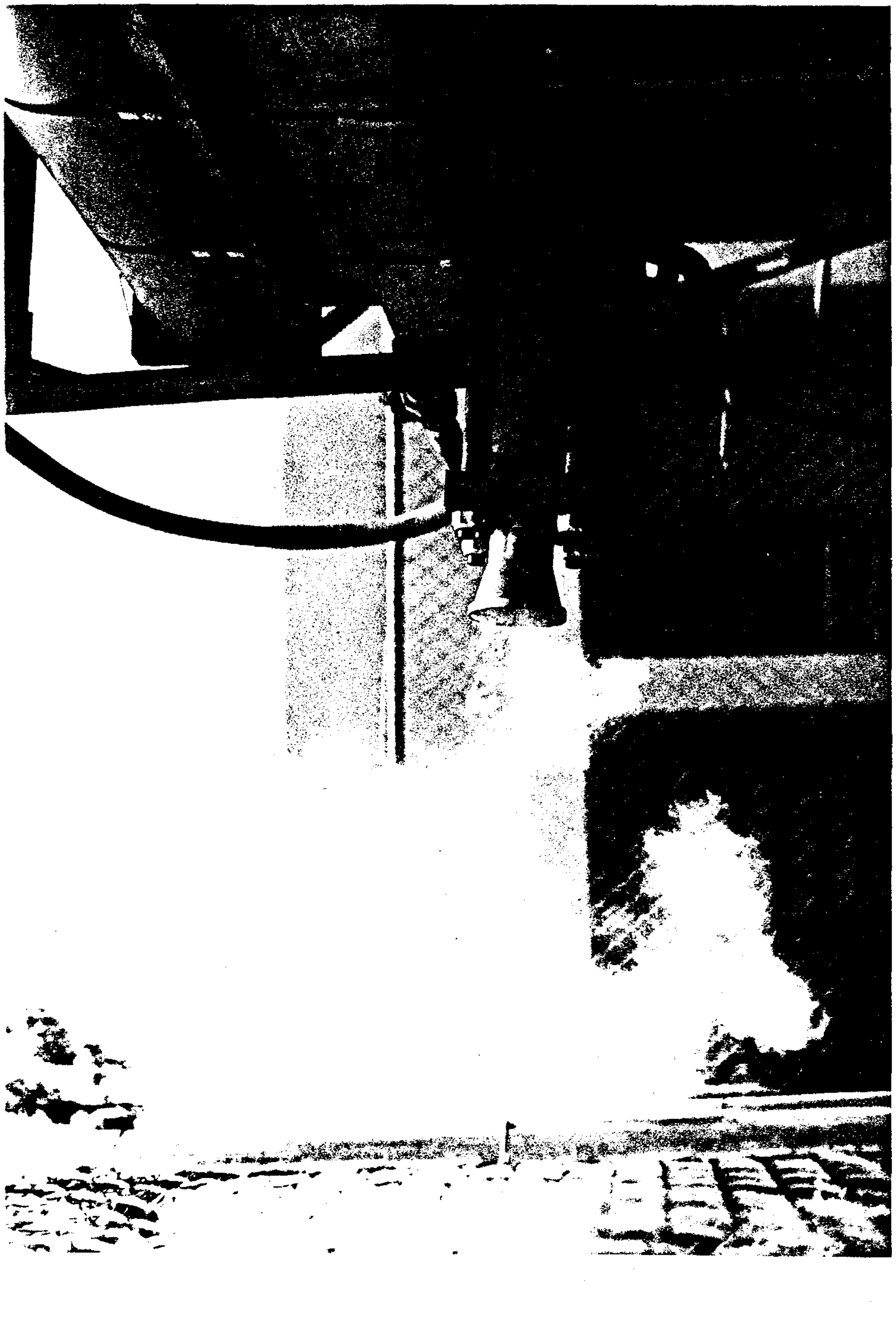


FIGURE 9.3-2. TEST FIRING OF SOLID PROPELLANT ROCKET (LOW YIELD FUEL)

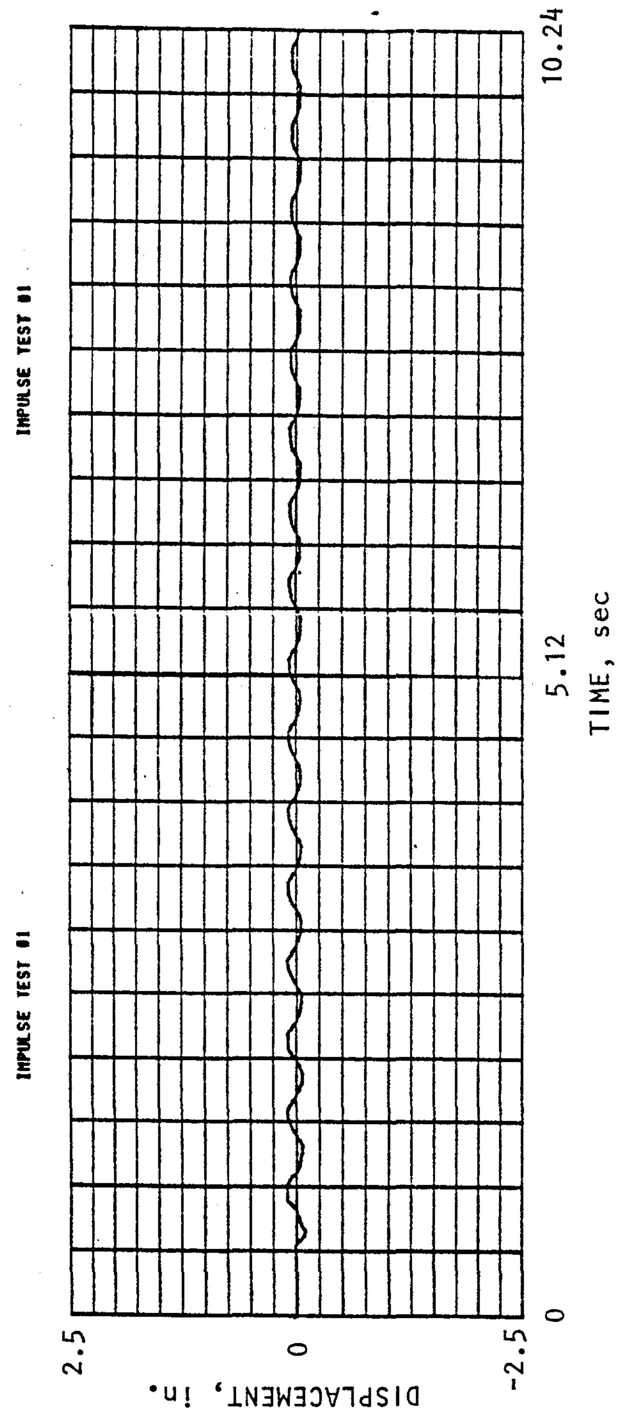


FIGURE 9.3-3. IMPULSE RESPONSE OF TEST STRUCTURE DUE TO SOLID-PROPELLANT ROCKET THRUST (LOW YIELD), ROCKET LOCATED ON THE SECOND FLOOR

SECTION 10

SYSTEM PERFORMANCE

Examination of the pulse train in Figure 8.2-1 and 8.3-1 show quite accurate timing of the test pulse train with respect to the command signal. The displacement of the metering nozzle also tracks the command signal voltage. Force output from the south pulse unit for the San Fernando earthquake, 1972 (Castaic) is displayed in Figure 10-1 together with its associated command signal. Short bars on the force signal plot indicate the specified force amplitude required. In general, these bars are located at midheight of the force pulses. The oscillation on the force trace between pulses is a consequence of the inertial reaction of the pulse units on the load cell due to motion of the test structure.

Preliminary tests showed for the pulse durations, that the thrust force was generally triangular in shape and that about half the impulse was actually delivered. This effect resulted in about a 50 percent reduction in the displacement response of the test structure in the test for El Centro (Fig. 8.2-1). For the Castaic test shown in Figure 10-1, the amplitude gain for the nozzle displacement was doubled for the entire programed pulse train to approximate the impulse required. This change really required individual pulse adjustment as the metering nozzle displacement is not a linear function of the thrust area (see Fig. 7.1-1).

The gas pulsers require two machine dependent empirical coefficients for thrust calculations for each pulse. These coefficients are the nozzle coefficient (C_{FX}) and the static to transient chamber pressure ratio (α). The nozzle coefficient varies from 1.5 down to less than unity and is dependent upon pulse duration, friction loss (particularly for smaller thrusts), and expansion in the nozzle. For maximum thrust, the system was designed for complete expansion at the exit plane of the nozzle at 10,000 lbf thrust. These smaller thrust openings

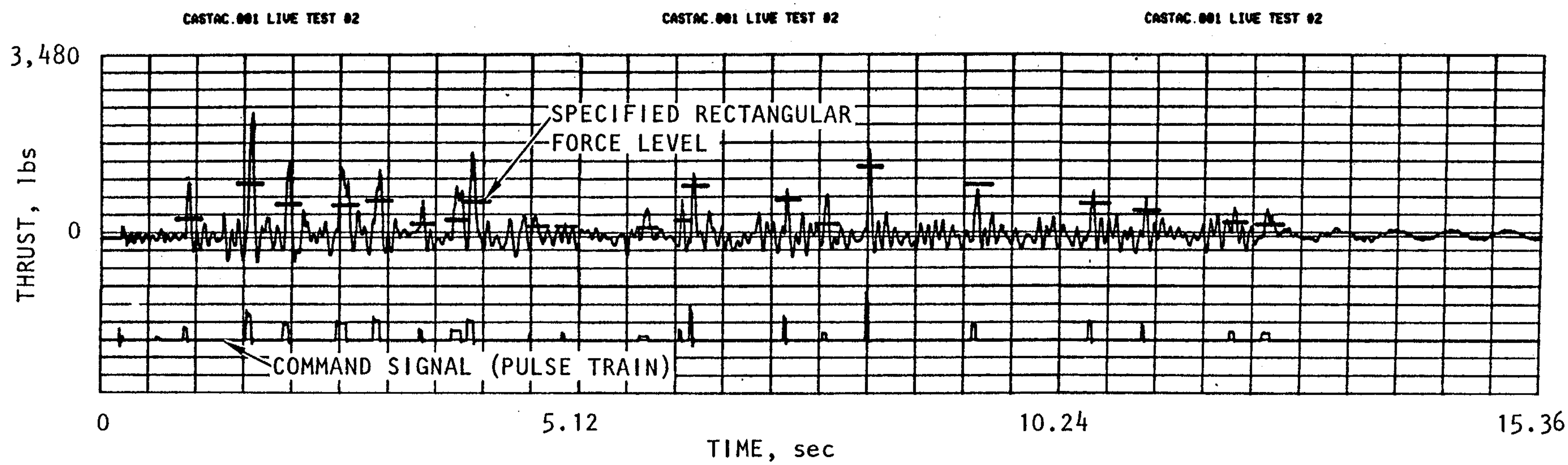


FIGURE 10.1. THRUST-TIME HISTORY OF PULSE GENERATOR — SAN FERNANDO (CASTAIC) EARTHQUAKE 1971 (SOUTH UNIT). BARS INDICATE RECTANGULAR FORCE PULSE LEVELS SPECIFIED, OSCILLATIONS BETWEEN PULSES RECORD INERTIAL REACTIONS OF TEST STRUCTURE ON LOAD CELLS

by the metering cone generate higher friction losses, over expansion and internal secondary expansion shocks. The last coefficient, α, relates the static chamber pressure to the transient chamber pressure during thrust. This relationship can be developed from the chamber pressure-time history shown in Figure 10-2.

The above two empirical coefficients do not present a serious problem nor does the thrust wave form (triangular vs rectangular). A detailed series of calibration tests will provide this information and permit quite accurate a priori thrust predictions.

Overall, the performance of the pulse units was quite good bearing in mind that thrusts ranged from 1500 lbf to 115 lbf for Castaic and from 5000 lbs to 200 lbf for El Centro.

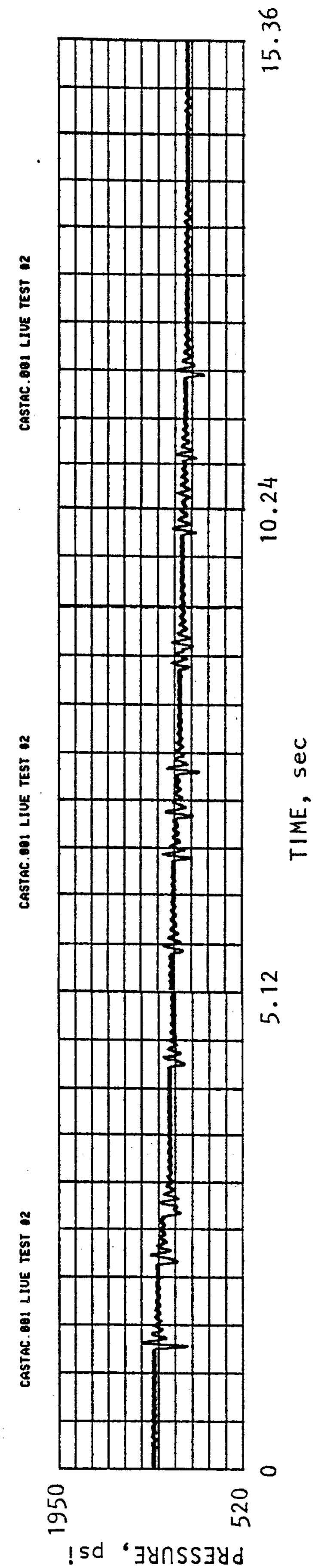


FIGURE 10.2. CHAMBER PRESSURE IN SOUTH ROCKET – SAN FERNANDO (CASTAIC) EARTHQUAKE TEST

SECTION 11

SUMMARY AND CONCLUSIONS

Phase I research was successfully accomplished in demonstrating the feasibility and validity of simulating motion on a sizeable structure by using cold gas pulse generators that duplicate strong motion earthquakes. This research was further supplemented by the development and construction of a solid propellant rocket which was test fired on the same test structure.

A test structure resembling a three story moment resisting frame was designed and erected upon a concrete foundation. Two cold gas pulse units were placed on the third floor in opposed directions and twelve high pressure nitrogen storage tanks were located on the second floor. Weight of the structure and equipment was 5,000 lbs.

A finite element model of the structure was developed and used to generate the system impulses and criteria responses under El Centro 1940 and San Fernando (Castaic) 1971 earthquakes. Previously developed optimization techniques were then used to design suitable pulse trains for motion simulation of the structure. Analysis of the experimental measurements showed that the demonstration tests were successful in validating the pulse simulation methodology as well as the capability of the gas pulse generators to reproduce with sufficient accuracy the microcomputer pulse trains.

A unique solid propellant rocket was designed, constructed, and test fired on the same test structure. A low yield propellant was used due to the considerations of the local office building community. This rocket departs from conventional rocket design in performance characteristics of high chamber pressures, rapid burn rates and short pulse durations suited to earthquake motion stimulation of structures.

Results of tests for both El Centro and San Fernando Valley earthquake disclosed the need for detailed calibration of the pulse units for more precise nozzle coefficients and chamber pressure static/transient ratios for the pulse time durations, thrust levels and thrust wave forms. Refined calibration will permit very accurate pulse simulation of structures.

Patents for both the cold gas system and for the solid propellant rocket are being applied for, with particular emphasis in earthquake applications. Overall, this research in Phase I is considered to be successful and presages that Phase II will deliver to the earthquake community a means of practical earthquake testing of massive civil structures up to damage and collapse levels.

SECTION 12
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2. Masri, S.F.; Bekey, G.A.; Safford, F.B. "Optimum Response Simulation of Multidegree Systems by Pulse Excitation," *Jnl. Dyn. Systems, Measurement and Control, ASME*, 97:1, Mar 1975.

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5. Clough, R.W. and Tang, D.T. *Earthquake Simulator Study of a Steel Frame Structure, Experimental Results*, Vol. 1, EERC 75-6. Berkeley, CA: Univ. of Calif. Earthquake Engineering Center, 1975.