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State University of New York at Buffalo

THE SYSTEM CHARACTERISTICS AND PERFORMANCE OF A SHAKING TABLE

by

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ABSTRACT

The system characteristics of the earthquake ground motion simulation facility at the State University of New York at Buffalo is described in this paper. The dynamic performance of the shaking table is assessed by comparing the results introduced by two separate input program signals, acceleration and displacement, of a known earthquake record. An off-line iterative compensation technique is used to improve the precision of the simulation of the desired signals. In addition, a modified frequency domain data processing procedure for an accelerogram is presented.

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SECTION 1
INTRODUCTION

During the past two decades, a number of servohydraulic shaking tables have been constructed (see references [1] and [2]). They have facilitated the study of the nonlinear inelastic physical properties of structures and have provided experimental validation of analytical approaches developed for the prediction of the inelastic dynamic responses of structures.

In most of the existing shaking tables, there usually exists a certain level of distortion in simulated ground motions both in time histories and in response spectra. It is recognized that the simulation with only one variable (displacement or acceleration) control system may result in the loss of accuracy within a certain frequency interval over a broad frequency range. The displacement controlled system will generally lose fidelity at the high frequency range while the acceleration controlled system cannot reach high accuracy at low frequency range for a signal having wide frequency content. Primarily with this in mind, the Buffalo shaking table is installed as a three-variable closed-loop control system. In addition, an off-line compensation technique (see reference [13]) was incorporated in the system to account for possible simulation distortions caused by inherent system characteristics.

Most available standard earthquake records in the U.S. have been manipulated by the Standard Data Processing Procedure developed by Trifunac and Lee (see reference [6]). The incompatibility among the acceleration, velocity, and displacement traces obtained by this procedure could be one of the causes in shaking table simulation distortion. The inconsistency is more obvious for the displacement controlled system if the reproduction of ground acceleration is the final purpose of simulation. More recent studies (see references [8] and [19]) have either presented new filter processing procedures or modified the Ormsby filter (see reference [16]) in using the Standard Data Processing Procedure. Blondet (see reference [8]) has made the Ormsby filter more flexible by using the Kaiser filter for the specific purpose of test data reduction. Sunder (see reference [19]) has proposed an elliptic infinite impulse response filter to achieve a faster transition between the stop and pass band. In this paper, the frequency domain data processing algorithm developed by Khemici and Shah (see reference [9]) and by Hodder (see reference [15]) is modified in formulating a procedure which can better preserve the correspondence among displacement, velocity and acceleration. This procedure is basically simple when compared with the time domain procedure. It also improves the so-called Gibb's phenomenon associated with the Ormsby filter. The validity of this modified procedure is examined experimentally by using the Buffalo shaking table.

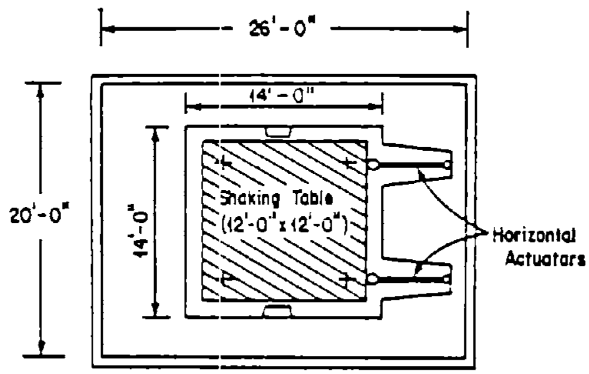
SECTION 2
SYSTEM CHARACTERISTICS

2.1 Shaking Table Configuration

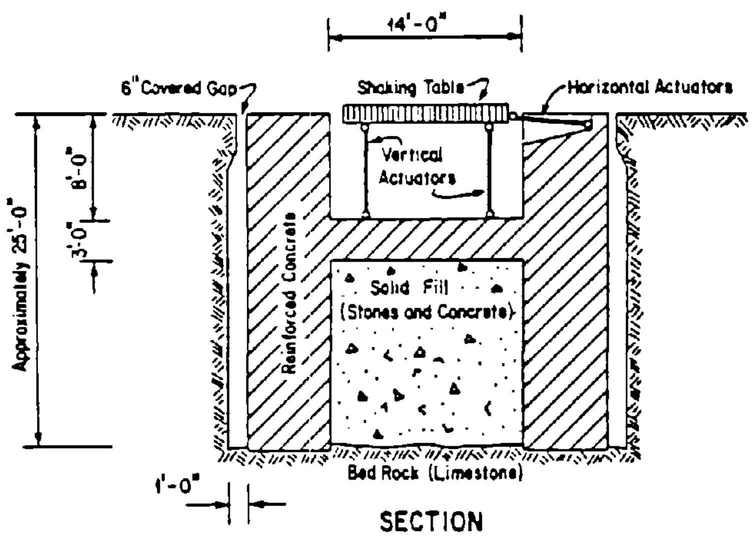
The shaking table weighs 16.5 kips and has a dimension of 12 ft. x 12 ft. x 1 1/4 ft. The table itself is a composite sandwich plate faced by ferrocement. The plate consists of a reinforced concrete grid and a welded, stress-released steel skeleton. The details of design and construction of the table have been reported by Reinhorn and Prawel (see reference [4]). The table has a maximum possible natural frequency approximately equal to 60 Hz corresponding to the free-free mode and the dish mode (see reference [4]). With this natural frequency, the table may be considered to behave as a rigid body in the usual operating frequency range, so that the effects of table-specimen interaction due to insufficient table rigidity is minimized.

The foundation block, weighing 1550 kips, is constructed by reinforced concrete infilled with a stone and concrete core. It is keyed to the bedrock but separated from the surrounding soil by a 1 ft. gap as shown in Figure 2-1. This foundation block has the dominant frequencies of 83 Hz, 95 Hz, and 57 Hz corresponding to the lateral, vertical, and rocking modes, respectively (see reference [3]).

The motions of the shaking table are governed by five controlled degrees of freedom. Restraint against the sixth (longitudinal) degree of freedom is provided by hydrostatic guide bearings consisting of a constant force bearing and a constant displacement bearing. These bearings apply a constant longitudinal preload at one side and a longitudinal position at the other side to passively restrain the longitudinal degree of freedom. Currently, only the lateral, vertical, and rolling



TOP VIEW



SECTION
IN THE FOUNDATION BLOCK

Total Weight of Foundation 700 Metric Tons (1,550,000 lbs.)

FIGURE 2-1 Schematic Views of the Shaking Table and Its Foundation degrees of freedom can be programmed. The system is expandable for complete six degree of freedom actuations.

2.2 Performance Limitation

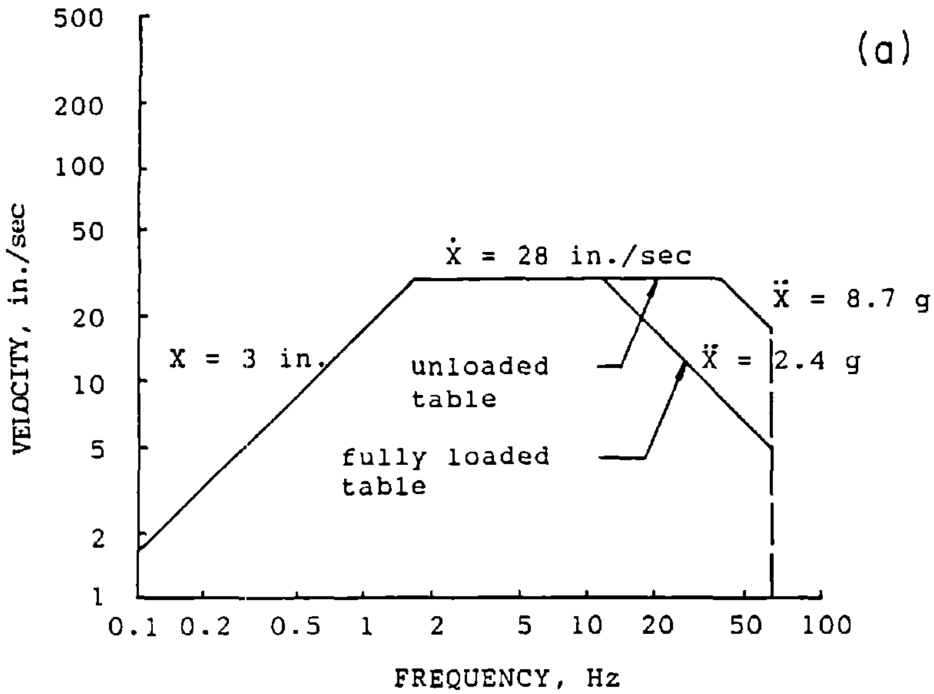
The shaking table is supported by four vertical actuators and connected to two horizontal actuators with swivel joints. The hydraulic power is supplied by two independent variable-volume pumps providing a total flow rate up to 280 gpm. The oil pressure provided by the hydraulic power supply and the hydraulic service manifold is 3000 psi during high pressure operation and is approximately 150 psi on low pressure operation.

The servovalves used for the facility are rated at 180 gpm for the lateral actuators and 90 gpm for the vertical actuators, respectively. The flow rate of servovalves and the dynamic piston area of actuators limit the maximum velocities to 57 in./sec. and 28 in./sec. in the lateral and vertical movements respectively.

The four vertical actuators, with a loading capacity of 36 kips each, and two lateral actuators with a loading capacity of 35 kips each, can drive the empty table with the accelerations up to 4.2 g in the lateral direction and 8.7 g in the vertical direction individually. With full load of 44 kips (rigid mass) placed on the table, the individual maximum accelerations are 1.2 g and 2.4 g in the lateral and vertical directions, respectively. The components of the maximum acceleration for coupled motion are less than those values given above. For any test that requires more than one programmed axis of control, the lateral capacity limitation should be taken as the dominant reference.

The maximum displacement of the table is ± 3 in. vertically and ± 6 in. horizontally. The table capacity limitations are

In the vertical direction



In the lateral direction

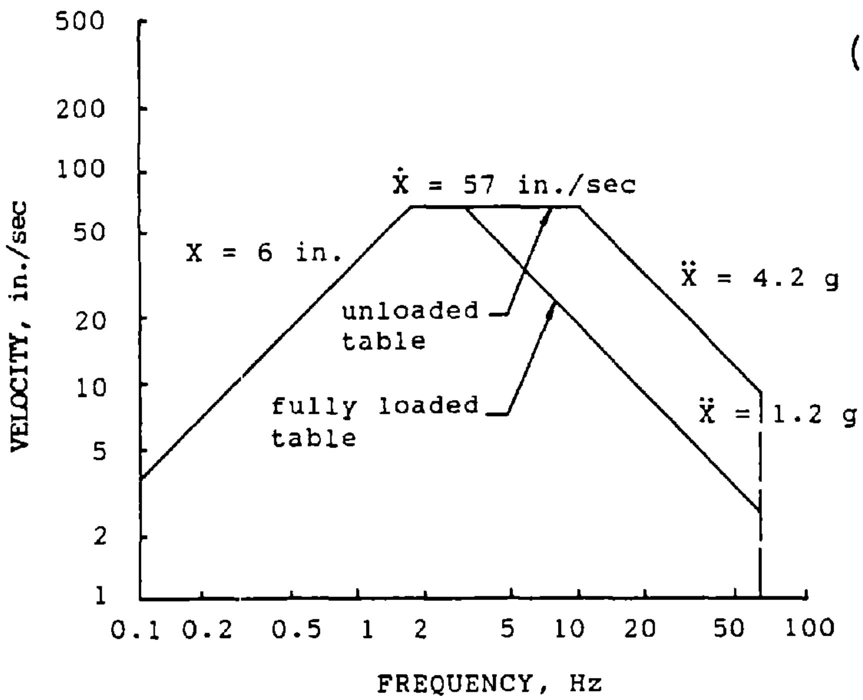


FIGURE 2-2 Shaking Table Capacity

summarized in Figure 2-2 (a) and (b). Additionally, the overturning moment is limited to 310 kip-ft.

2.3 Three Variable Control System

The feedback control of the shaking table is executed by a three variable control servo circuit (see reference [5]) which can simultaneously control the displacement, velocity, and acceleration. If the input program signal is defined in terms of acceleration (or displacement), the reference generator will produce velocity and displacement (or acceleration and velocity) command signals for the three variable control through a process of integration (or differentiation) and filtering. A velocity computer is installed in this control system to compute the velocity feedback from the measured acceleration and displacement signals. In addition, the system also provides force balance compensation, overturning moment compensation, eccentric loading compensation, cross coupling compensation and differential pressure stabilization.

2.4 Off-line Compensation Technique

An off-line compensation technique (see reference [13]) was implemented in this facility to improve the performance on the simulation fidelity such as the correction for the low frequency offset.

The principle of this compensation amounts to the determination of the transfer matrix, $H(f)$, of a mathematical model of the test system as expressed by Equation (1)

$$Y(f) = H(f)\, X(f) \tag{1}$$

where: $X(f)$ = Fourier transformed input
$Y(f)$ = Fourier transformed output

Normally, the transfer matrix is established by driving the shaking table with a banded white noise in the directions corresponding to the components of a given earthquake record. Once the system model is established, unacceptable motions may be improved by modifying the drive signals. This requires the establishment of the deviation $\Delta Y(f)$ between the desired and achieved ground motions

$$\Delta Y(f) = Y_d(f) - Y_a(f) \qquad (2)$$

where: $Y_d(f)$ = desired ground motion
$Y_a(f)$ = achieved ground motion

If the system is linear and is time invariant, an estimate of the required correction $\Delta X(f)$ to the drive signal may be obtained from

$$\Delta X(f) = H^{-1}(f)\, \Delta Y(f) \qquad (3)$$

The time history corresponding to $\Delta X(f)$ is then added to the old drive signal as the new input for the next iteration until the achieved motion is considered to be sufficiently accurate. To account for system nonlinearity and time variant, the use of a scale factor to the correction signal $\Delta X(f)$ may be desirable in order to prevent overcorrection of the drive signal and to reduce the number of iterations.

This iterative correction process applies well for the studies of elastic structural responses. For inelastic studies of large scale structures, this process is extremely tedious. The off-line compensation technique, therefore, is not to carry out the iterative process required, but to extrapolate the actual exciting level based on the information of a lower level test.

2.5 Data Acquisition System

The data acquisition system consists of a 64-channel MTS transducer conditioning system console of which 12 channels are reserved for system control, a 30-channel Measurements Group 2100 conditioner and amplifier system, four 16-channel A/D conversion subsystems, and a PDP-11 computer.

The analog-to-digital conversion subsystem has a data resolution of approximately 5 mV. It is approximately 0.05% of the maximum conditioner output of ± 10 Volts.

A special feature of the system is its ability to simultaneously sample the data by four A/D conversion subsystems for the total 64 data channels with negligible phase lag. The maximum conversion time for each digital output is about 13 usec so that the total required conversion time for the 64 channels is approximately 200 usec. This is almost 5 times faster than the allowable minimum data time interval of 0.001 sec. limited by the software.

SECTION 3
DYNAMIC PERFORMANCE

The basic information on the gains of the control console with respect to the five controlled degrees of freedom (lateral, vertical, roll, pitch, and yaw) corresponding to each control axis (displacement, velocity, and acceleration) will be discussed in the following paragraphs. The usual procedure for the "calibration" is to excite the shaking table with a random repeating signal produced by the function generator. The measured signals such as transfer functions, coherence functions, and phase angles are then observed from the readout selector, oscilloscope, and frequency analyzer. With this information, the gain factors, signal-to-noise ratios, and phase shifts can be quantitatively and/or qualitatively established so that the gains with respect to each degree of freedom for each control axis can be optimized. The acceleration gains are typically adjusted for the high frequency range where the velocity and displacement error signals are less dominant, and the velocity and displacement gains are adjusted at medium frequency range (9 Hz - 14 Hz) and low frequency range (0 Hz - 9 Hz), respectively.

3.1 Simulation for Real Earthquake Record Without System Model Compensation

To investigate the earthquake record simulation capacity of the shaking table carrying a 22 kip rigid mass, the corrected acceleration trace of the N-S component of the 1940 El Centro earthquake is used as the input program source. The standard record of Trifunac and Lee (see reference [6]), and the measured time histories are given in Figures 3-1 and 3-2. The measured acceleration seems to fit the standard record very well except in certain peak values. On the other hand, the measured displacement is quite different from the standard record. Two

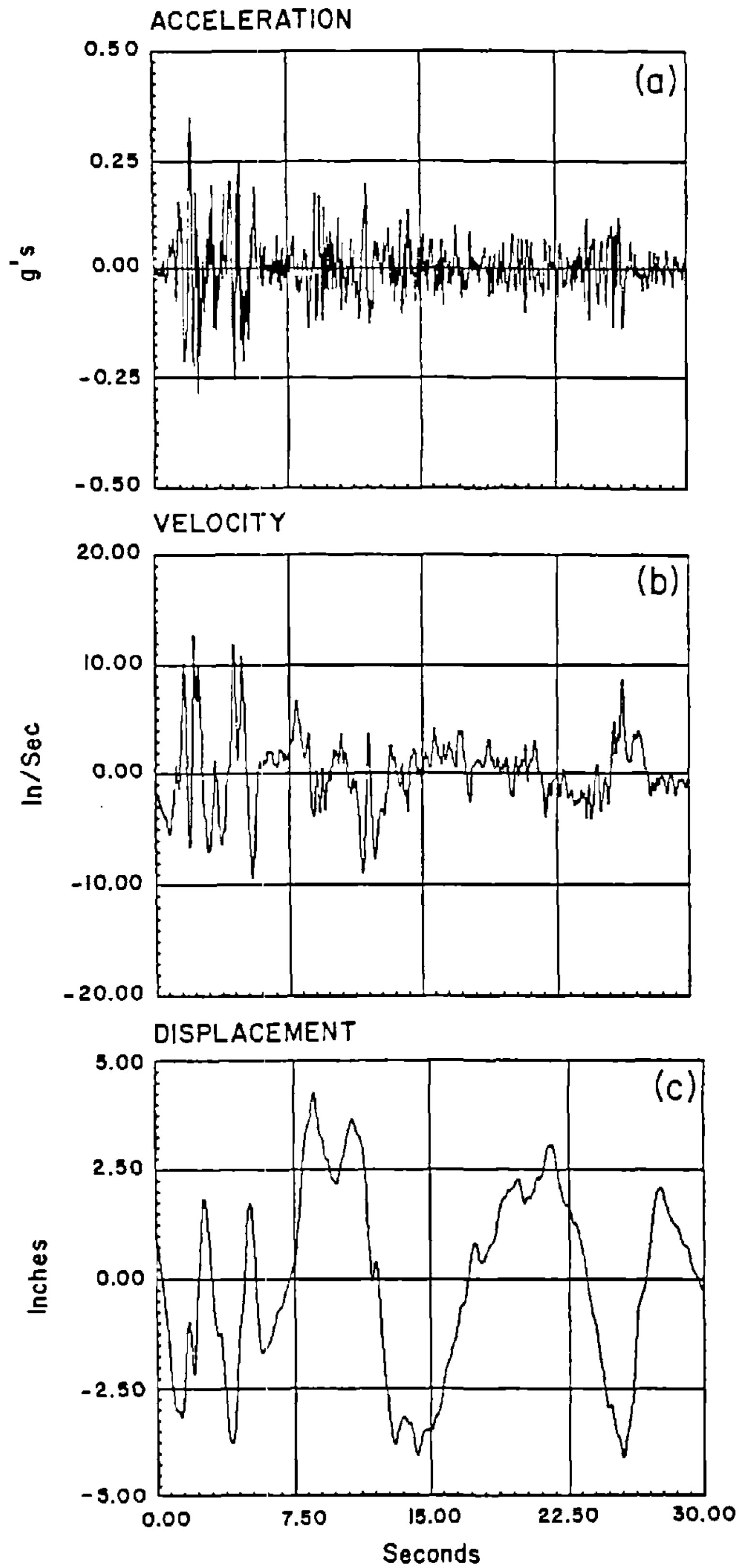


FIGURE 3-1 N-S Component of the 1940 El Centro Earthquake

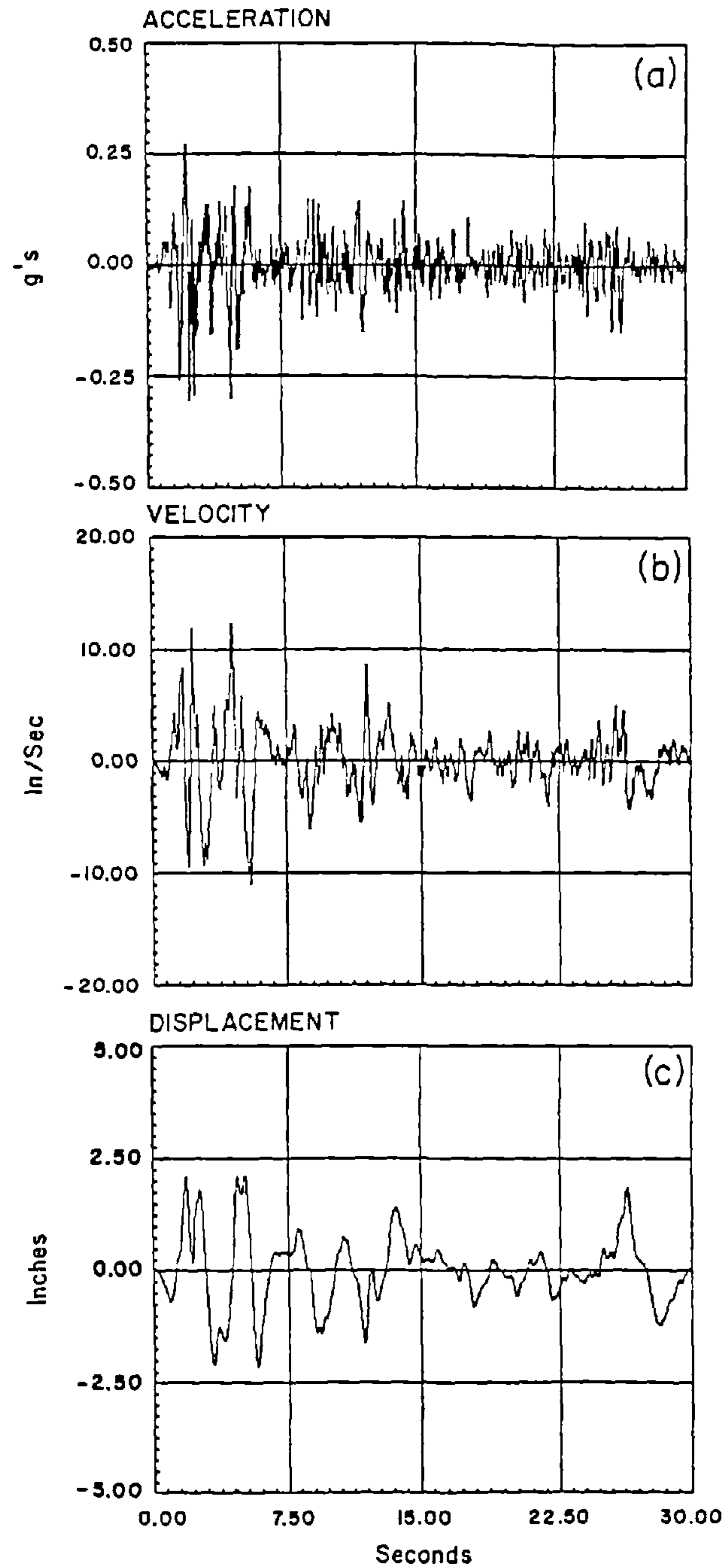


FIGURE 3-2 Measured El Centro Earthquake -- Uncompensated Test

possible reasons for this inconsistency are:

a. The correspondence among the corrected acceleration, velocity, and displacement of the standard record is not inherently preserved according to the Standard Data Processing Procedure (see references [6] and [7]).

b. Since the integrated displacement is very sensitive to the cutoff frequency of highpass filter (see references [8] and [9]), the low frequency noise may have a strong effect on the low frequency performance of the control system.

With this discrepancy between the measured and the standard displacement records, it may be expected that a certain level of inconsistency in velocity will also exist. A low frequency level of distortion in velocity can be seen from Figures 3-1 and 3-2. This is because the lower frequency part of the velocity feedback is computed by the velocity computer by differentiating the displacement feedback and by sending the information through a lowpass filter.

A closer examination of the fidelity of record reproduction can be made from the calculated response spectra of the measured and standard acceleration records (see reference [10]). This is shown in Figure 3-3(a), where good performance of the system over the frequency range above 0.6 Hz is evident.

In the above consideration, the acceleration trace was chosen as the input program source. In order to compare the table performance with those of other shaking tables of the displacement control type, the standard displacement record with a time interval of 0.1 sec. is interpolated to have a time interval of 0.02 sec. This interpolation may be established by using a zeroth order Hermite interpolation (Lagrange interpolation) and a linear acceleration assumption (cubic variation of displacement). However, during an off-pressure simulation, a few unexpected acceleration peaks are detected. The largest peak is approximately equal to 0.66 g which is much larger than the peak value, 0.35 g, of the standard record. Besides, the general shape and amplitude of acceleration time history are quite different from those of the standard record. Similar observations have also been reported on other shaking tables (see references [11] and [12]). This offset is generally attributed to the incompatibility between the standard acceleration and displacement records.

3.2 Simulation for Real Earthquake Record With System Model Compensation

By applying the compensation technique described previously, the system model inverse $H^{-1}(f)$ and the correction signal $\Delta X(f)$ of the first iteration (corresponding to the previous simulation of N-S component of the 1940 El Centro earthquake) can be obtained. The results of the compensated test are shown in Figures 3-3(b) and 3-4 which show that the fidelity of simulation is successfully achieved except for the displacement record. However, this measured displacement only displays a slight low frequency base line shift when compared with the integrated displacement reported by Erdik and Kubin (see reference [14]). In reference [14], a few different cut-off frequencies are utilized for the highpass filter while correcting the accelerogram in the time domain.

3.3 A Modified Frequency Domain Data Processing Procedure

In general, the previously measured acceleration of compensated test agrees well with the standard record both in time history and in response spectra except for the discrepancy between the measured and standard displacement records. In order to ascertain the preservation among the acceleration, velocity and displacement traces, more efforts have been given to double integration of the measured acceleration. The integration is

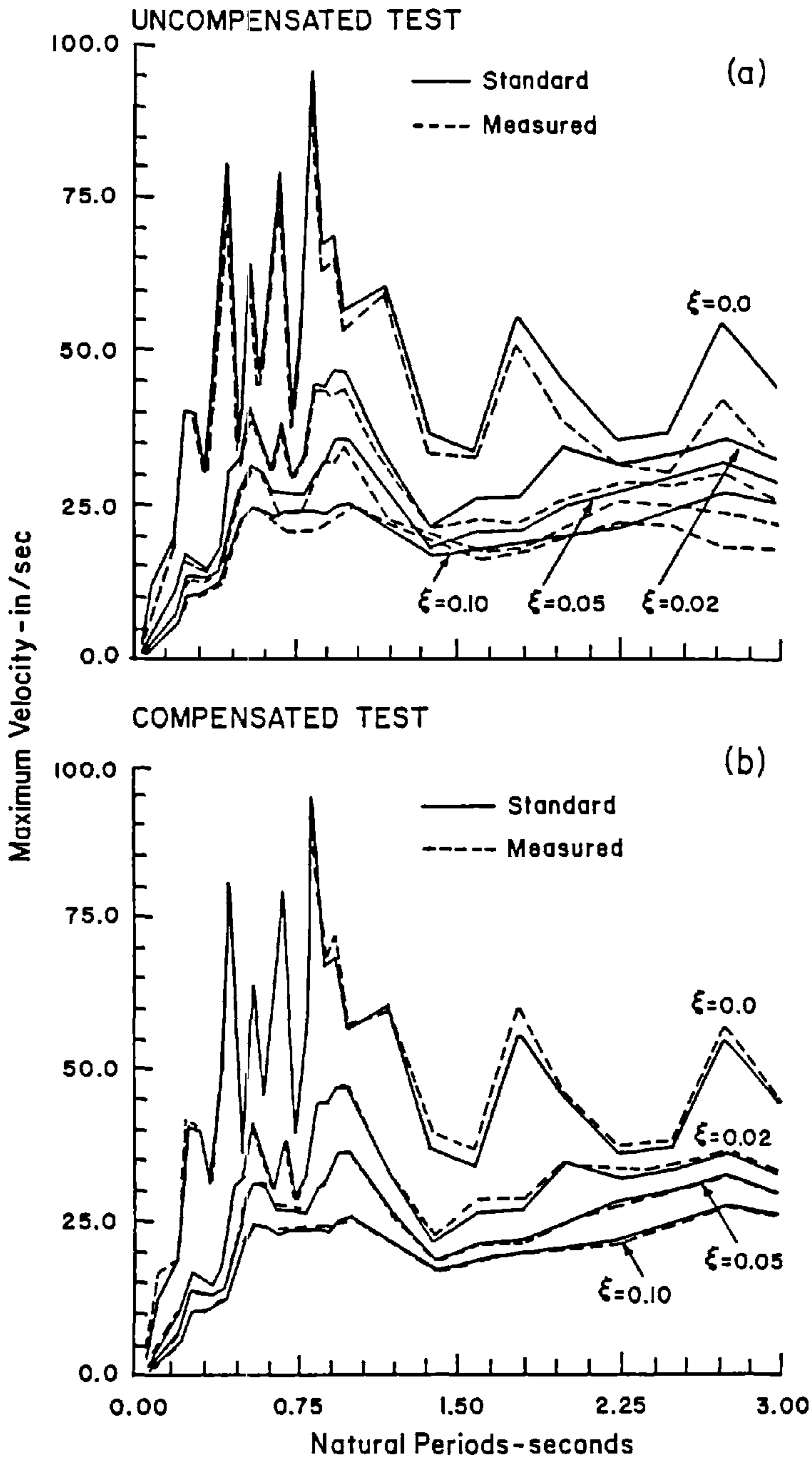


FIGURE 3-3 Response Spectra of Standard and Measured Time Histories

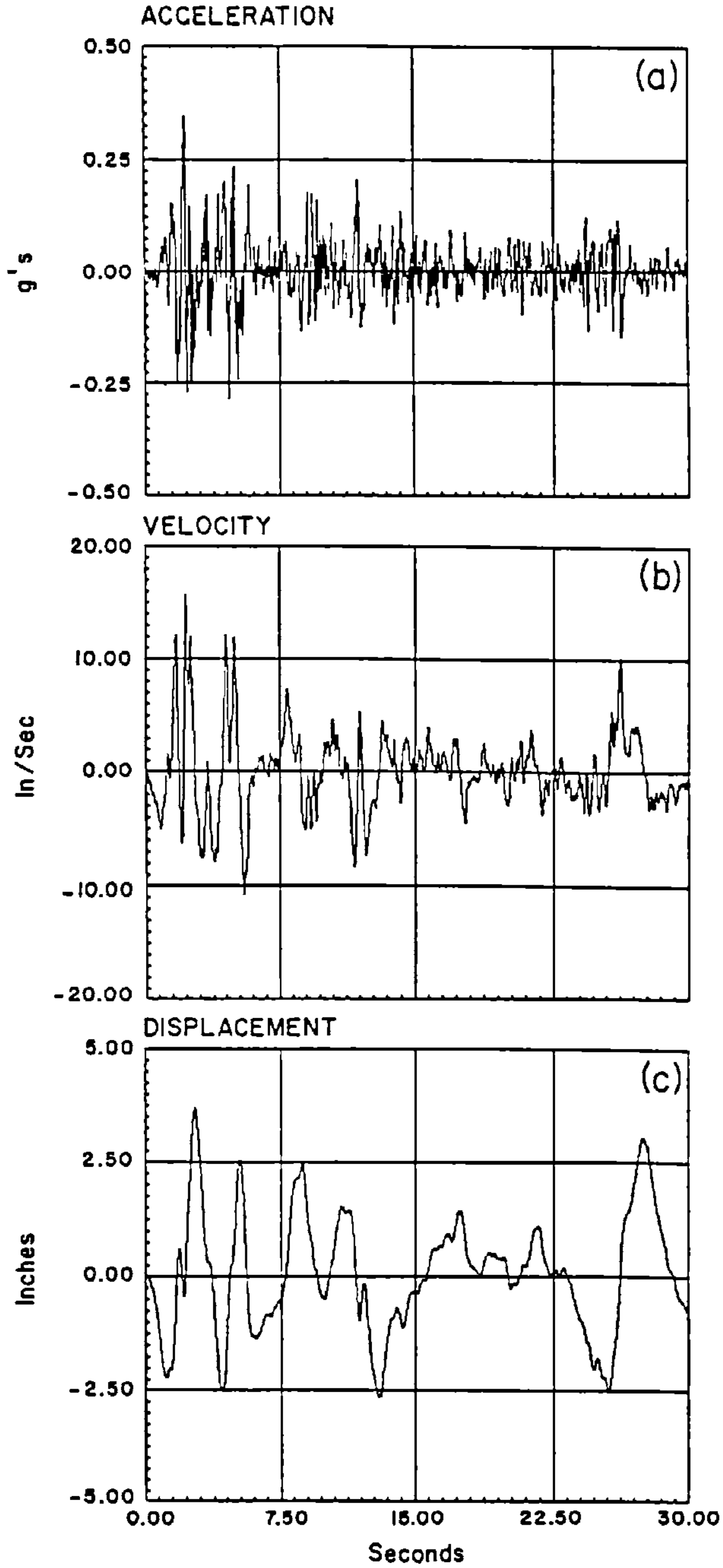


FIGURE 3-4 Measured El Centro Earthquake -- Compensated Test

executed in the frequency domain by Khemici and Shah (see reference [9]) and by Hodder (see reference [15]). Both have independently concluded that the algorithm is less time consuming than the Standard Data Processing (see reference [6]) which performs the base line correction of the time domain. Other advantages of this technique are that the Gibb's Phenomenon associated with the Ormsby Filter (see reference [16]) incorporated in the Standard Data Processing is improved. However, the approach of References [9] and [15] always results in complex time histories of ground velocity and, therefore, in complex time history of ground displacement. In the following, a modification to this approach is given.

As conceived by Khemici and Shah as by Hodder, the traces of earthquake ground motions corrected from the measured relative displacement of accelerograph, x_r, can be obtained in the frequency domain from references [9] and [15]

$$\ddot{x}_g(m) = \sum_{k=0}^{N-1} - \frac{H(k)}{DMF(k)} \left(\frac{1}{N} \sum_{n=0}^{N-1} x_r(n)\, e^{-i2\pi kn/N} \right) e^{i2\pi mk/N} \qquad (4)$$

$$\dot{x}_g(m) = \sum_{n=0}^{N-1} - \frac{H(k)}{DMF(k)(i\omega_k)} \left(\frac{1}{N} \sum_{n=0}^{N-1} x_r(n) e^{-i2\pi kn/N} \right) e^{i2\pi mk/N} \qquad (5)$$

$$x_g(m) = \sum_{k=0}^{N-1} - \frac{H(k)}{DMF(k)\ \omega_k^2} \left(\frac{1}{N} \sum_{n=0}^{N-1} x_r(n) e^{-i2\pi kn/N} \right) e^{i2\pi mk/N} \qquad (6)$$

$$m = 0,1,2 \ldots, N-1$$

$$X_r(k) = \frac{1}{N} \sum_{n=0}^{N-1} x_r(n)\, e^{-i2\pi kn/N} \qquad (7)$$

where: $\omega_k = 2\pi k/T$ = Circular frequency content of ground acceleration

$T = N\Delta t$ = Duration of ground motion

The transfer function of filter, H(k), defined in Reference [15] is given in Equation (8) which is mathematically identical to the one used in Reference [9].

$$H(k) = \begin{cases} 0, & 0 \leq \omega_k \leq \omega_h^t; \\ \sin^2 \dfrac{\pi}{2} \dfrac{\omega_k - \omega_h^t}{\omega_h^c - \omega_h^t}, & \omega_h^t \leq \omega_k \leq \omega_h^c; \\ 1, & \omega_h^c \leq \omega_k \leq \omega_l^c; \\ \sin^2 \dfrac{\pi}{2} \dfrac{\omega_l^t - \omega_k}{\omega_l^t - \omega_l^c}, & \omega_l^c \leq \omega_k \leq \omega_l^t; \\ 0, & \omega_l^t \leq \omega_k \leq \dfrac{\pi}{\Delta t}; \end{cases} \quad (8)$$

where H(k) is symmetric about $\omega_k = \pi/\Delta t$.

The Dynamic Magnification Factor or gain factor corresponding to the input ground acceleration and the output relative displacement measured by accelerometer is defined as

$$DMF(k) = \frac{1/\omega^2}{1 - (\omega_k/\omega)^2 + i2\xi(\omega_k/\omega)} \quad (9)$$

where: ω = Circular natural frequency
ξ = Damping ratio of the accelerometer

The acceleration term $\ddot{x}_g(m)$ in Equation (4) is a real time function, since both $X_r(k)$ of Equation (7) and the DMF(k) in Equation (8) are complex functions consisting of a real-even part and an imaginary-odd part (see reference [20]). The velocity trace obtained by Equation (5) is similarly a real time history. This is because the Fourier transform of $\ddot{x}_g(m)$, defined by Equation (10)

$$\ddot{X}_g(k) = - \frac{H(k)}{DMF(k)} X_r(k) \tag{10}$$

has the real-even and imaginary-odd property and $i\omega_k$ is an imaginary odd function which enables the Fourier transform of the velocity trace to result in the same type of complex function as Equation (10). However, during numerical integration in the frequency domain by using a digital computer, the characteristics of $i\omega_k$ (an imaginary odd function) can only appear in the interval of [-N/2 + 1, N/2] and not in the interval of [0, N-1]. The latter interval is, however, used in References [9] and [15].

The fact that the interval [-N/2 + 1, N/2] should be used can also be substantiated by recognizing the symmetrical property of the Fourier transform of a real time function that states

$$\begin{aligned} \ddot{X}_g^*(N - k) &= \ddot{X}_g^*(-k) \\ &= \ddot{X}_g(k) \\ &= - \frac{H(k)}{DMF(k)} \left(\frac{1}{N} \sum_{n=0}^{N-1} x_r(n) e^{-i2\pi kn/N} \right) \end{aligned} \tag{11}$$

where $\ddot{X}_g^*(N-k)$ and $\ddot{X}_g^*(-k)$ are the conjugates of $\ddot{X}_g(N-k)$ and $\ddot{X}_g(-k)$, respectively.

The integration for velocity function in the frequency domain can be written as

$$\begin{aligned} \dot{X}_g(k) &= \frac{\ddot{X}_g(k)}{i\omega_k} \\ &= \frac{\ddot{X}_g(k)}{i2\pi km/N} \end{aligned} \tag{12}$$

If the integration is performed over the interval of [-N/2 + 1, N/2], the symmetrical properties can be satisfied as:

$$\dot{X}_g(-k) = \frac{\ddot{X}_g(-k)}{-i2\pi km/N}$$

$$= \frac{\ddot{X}_g^*(k)}{-i2\pi km/N} \tag{13}$$

$$= \dot{X}_g^*(k)$$

Hence, the integrated velocity is a real-time function.

The displacement traces obtained by integrating the El Centro earthquake accelerogram measured by the Buffalo shaking table by using both the modified processing procedures and the procedure of references [9] and [15] are compared in Figure 3-5. The chosen cut-off and roll-off frequencies for the transition zones of filter are 0.10 Hz - 0.12 Hz and 20.0 Hz - 25.0 Hz. Figure 3-5 clearly shows the superiority of the modified algorithm.

3.4 Simulation for Artificial Earthquake

In the studies of Rea and Penzien (see reference [17]) and Rea et al (see reference [18]), a different base line correction algorithm from the standard process is used to obtain a displacement which is different from the standard record but acceptable for their purposes. Results of their studies showed good replica to the N-S component of 1940 El Centro earthquake subjected to their specific manipulation. In order to make use of this idea and to investigate the performance of the record simulation ability of the Buffalo shaking table by using displacement trace as input program signal, an artificial earthquake is generated. The base line of the generated accelerogram is corrected by using a processing procedure in which the modified frequency domain algorithm is incorporated and the correspondence among the acceleration, velocity, and

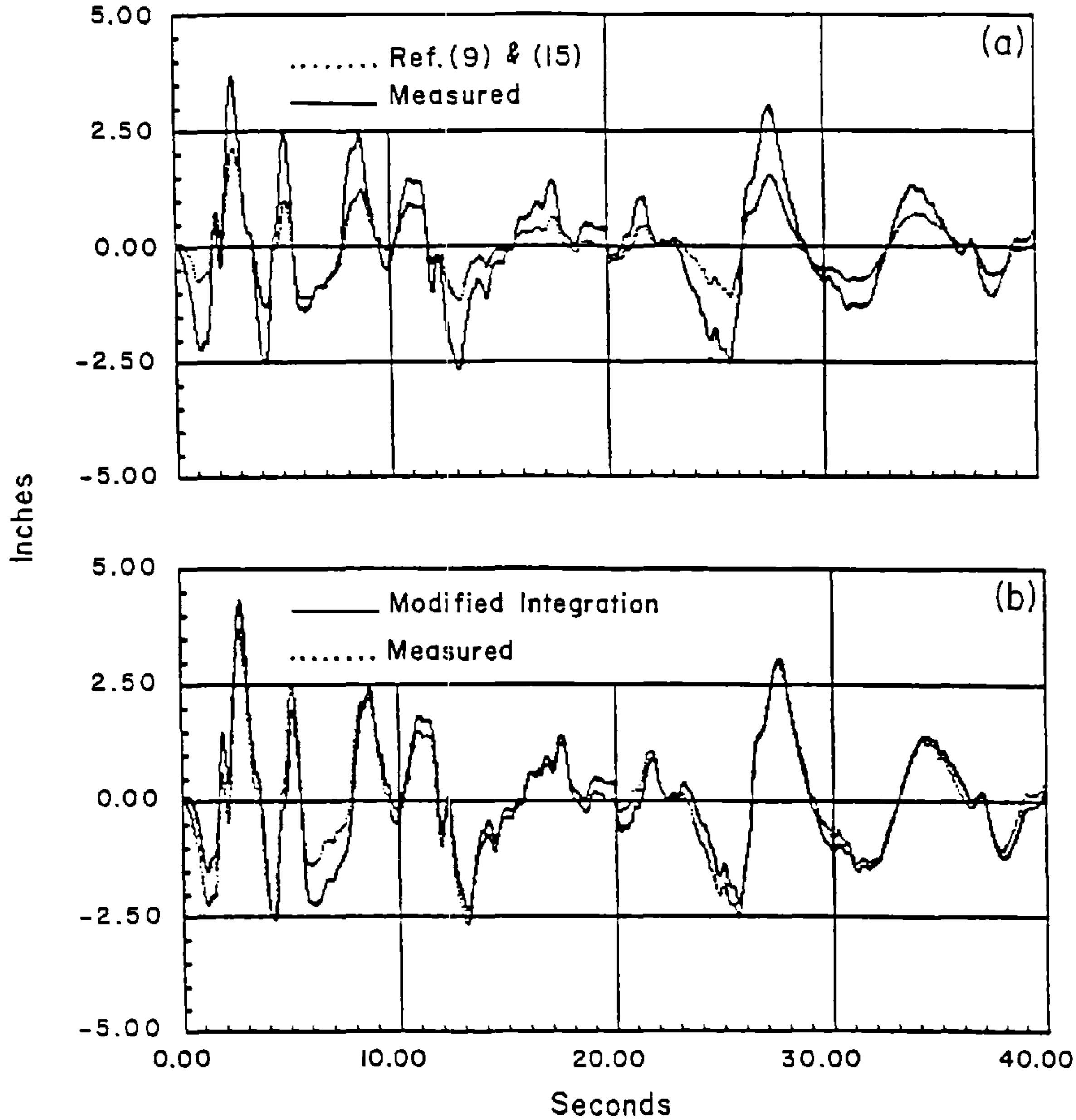


FIGURE 3-5 Measured Displacement and Integrated Displacements Using Refs. [9,15] and Modified Algorithm

displacement traces is preserved. The base line corrected acceleration trace (0.35 g peak) as well as the velocity and displacement time histories are shown in Figure 3-6. The cut-off and roll-off frequencies are (0.15 Hz - 0.20 Hz) and 23.0 Hz - 25.0 Hz) corresponding to highpass and lowpass filterings.

The simulation by using acceleration trace as program source is first executed. The results are illustrated in Figure 3-7 which shows that the achieved acceleration and velocity time histories are almost identical to the desired curves. The measured displacement does have visible but small differences from the desired curve. The simulation by using the displacement trace as the program source is next performed and the results are shown in Figure 3-8. In displacement, the fidelity is well achieved except for a slight phase shift. This phase shift is considered to be inherent in nature because it is discovered in the oscilloscope and the frequency analyzer during the adjustment of control gain setting. The achieved acceleration and velocity in Figure 3-8 have both achieved the desired accuracy. The response spectra given in Figure 3-9 (a) and (b) also show the excellent ability of the shaking table, in record simulation.

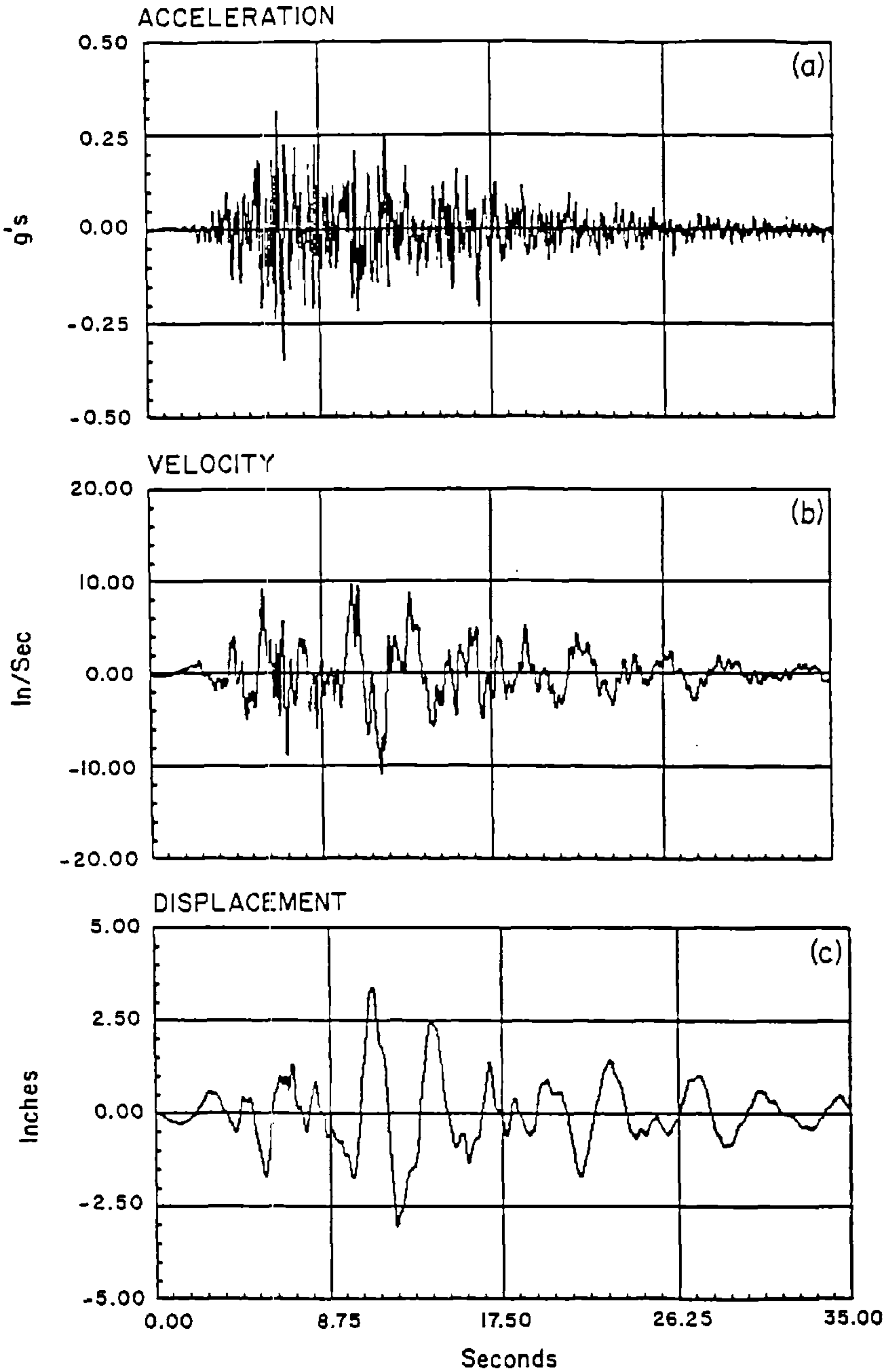


FIGURE 3-6 Artificial Earthquake Time Histories

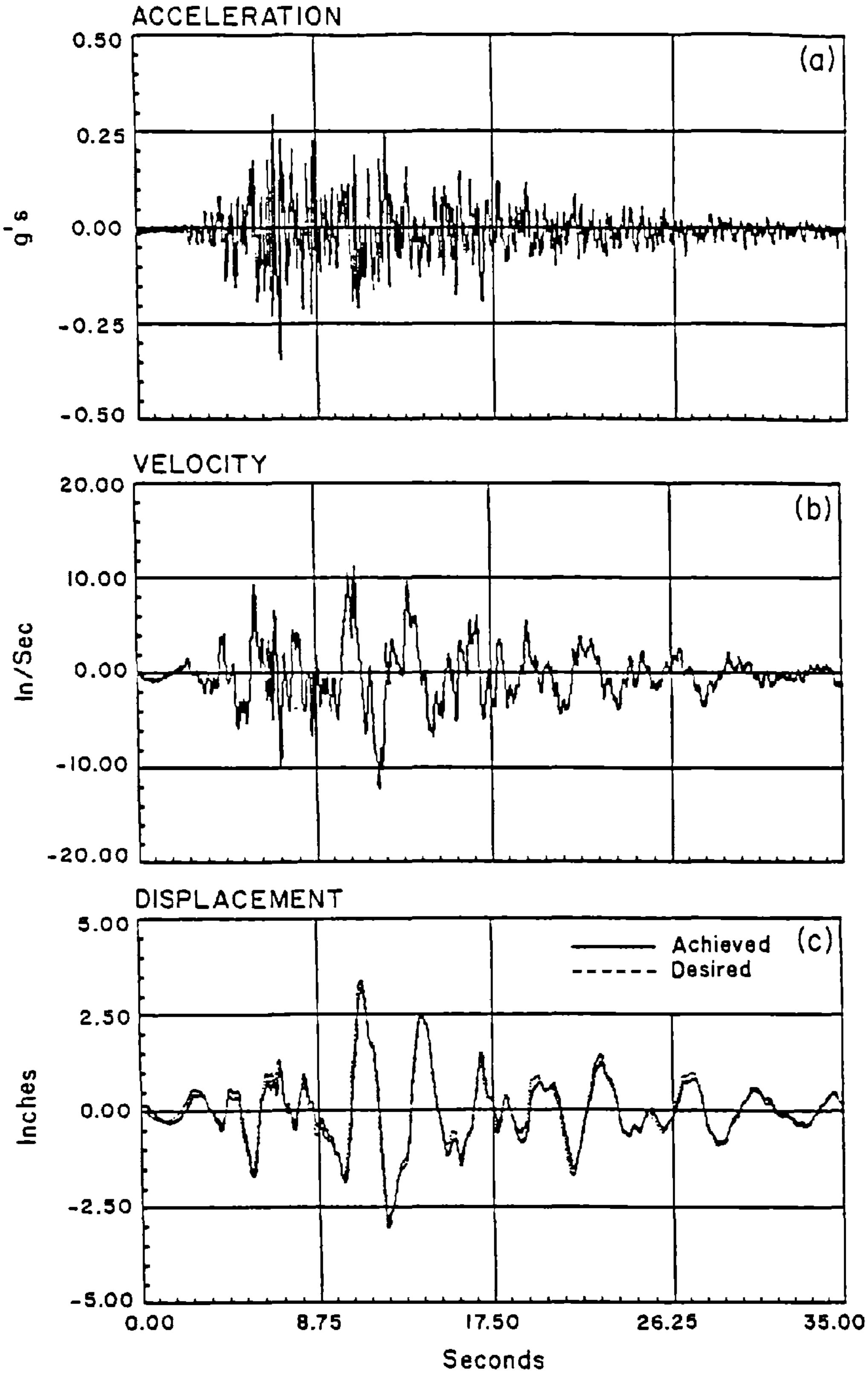


FIGURE 3-7 Measured Table Motion, Using Acceleration as Program Source

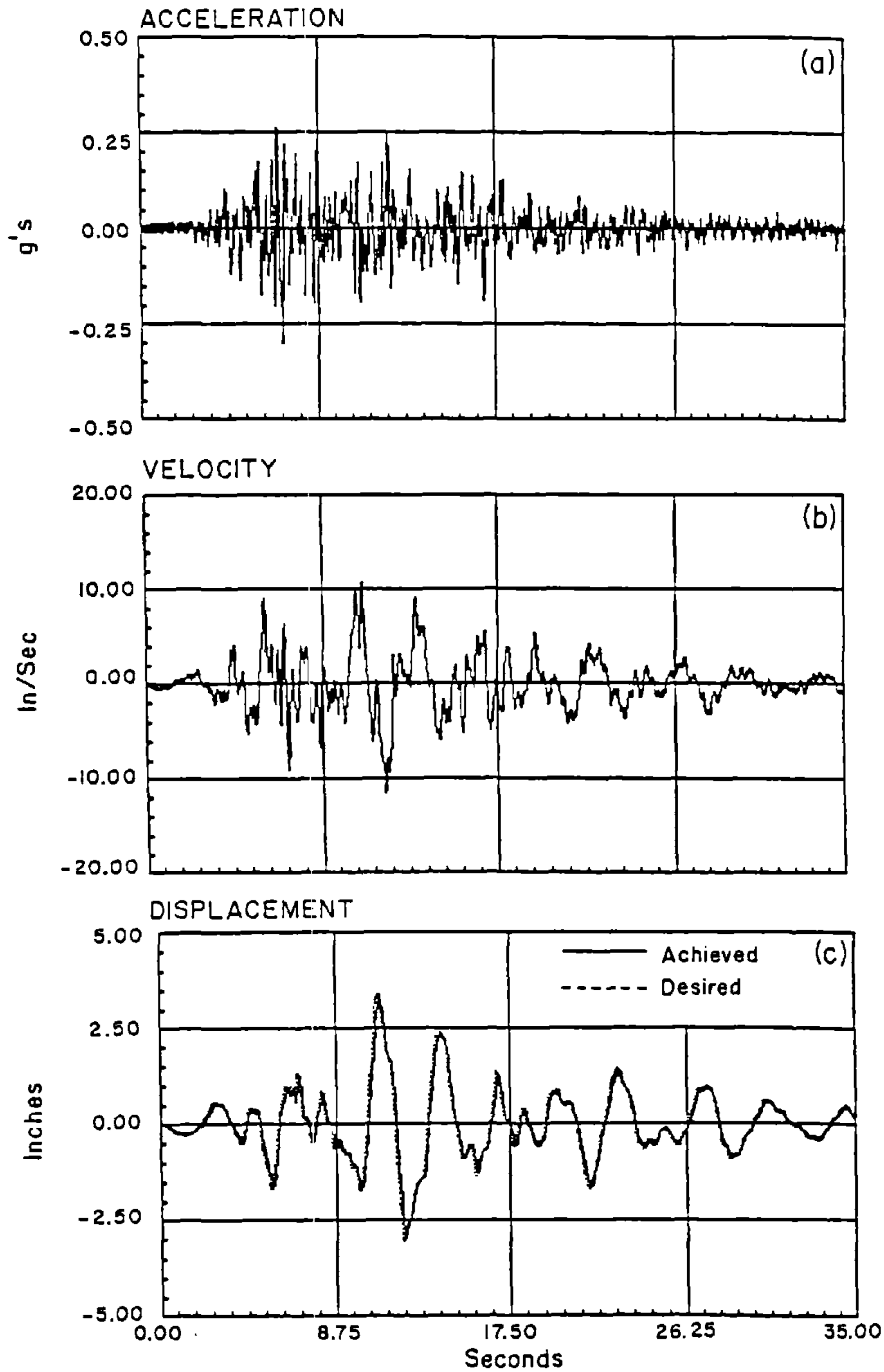


FIGURE 3-8 Measured Table Motion, Using Displacement as Program Source

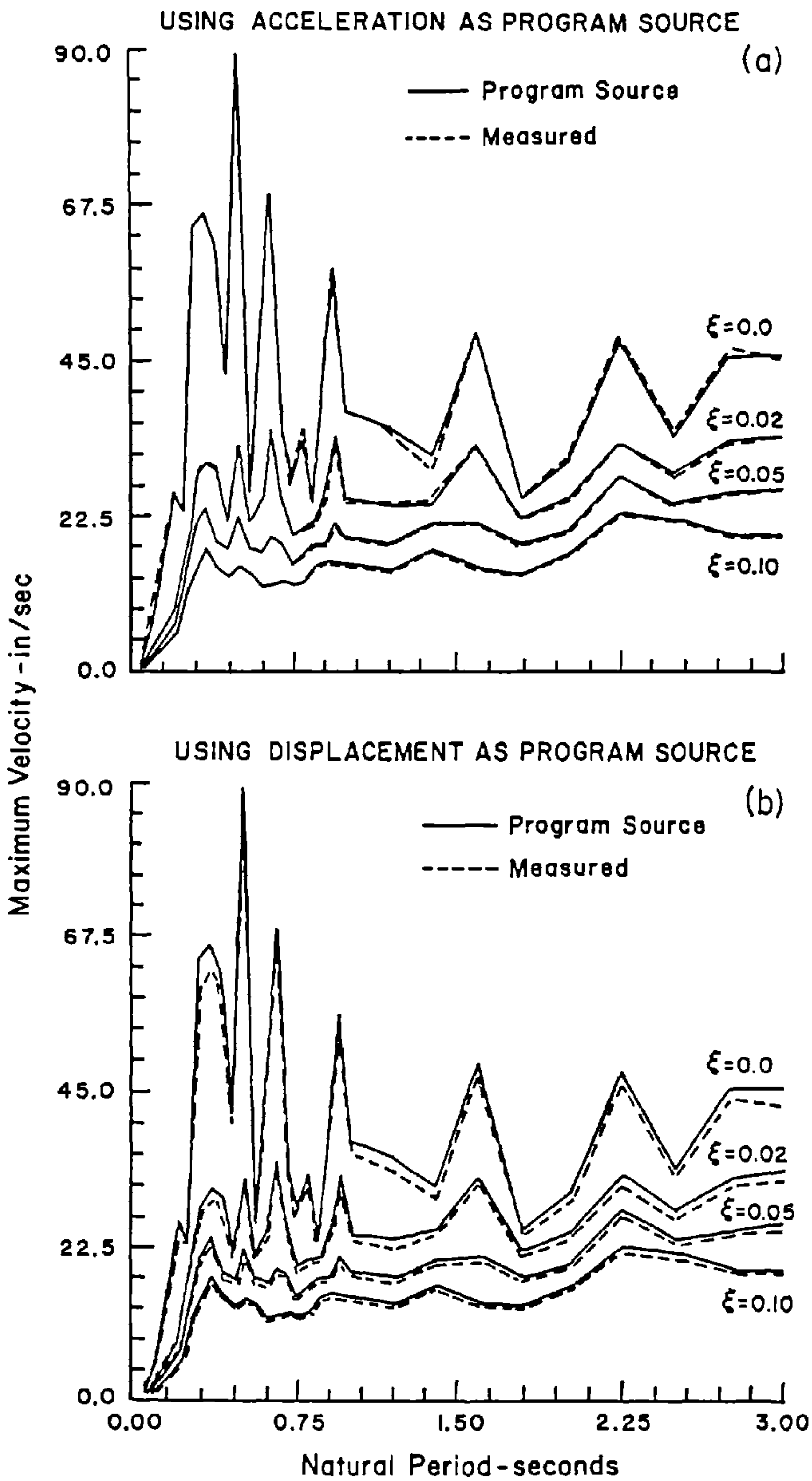


FIGURE 3-9 Response Spectra of Input and Output Time Histories

SECTION 4
SUMMARY

1. The simulation ability of the Buffalo shaking table which has a three variable control system is examined. The system can have both acceleration and displacement as input program source. Good fidelity of simulation of the shaking table is established.

2. The only possible phase lag in each 4-channel sample and hold card of the data acquisition system is negligibly small. In using this shaking table, there is no need to be concerned with the channel arrangement in inelastic structural tests where hysterisis curves are required. Consequently, the dissipated energy as estimated by the area of the hysterisis curves should be reasonably reliable.

3. The off-line compensation technique implemented in the Buffalo facility to enhance the simulation ability is for using the acceleration trace as the input program source. Because this technique is only an extrapolation of the desired exciting level based on a lower level test, it should not be automatically assumed to yield superior results than using the displacement input, in all cases.

4. In using the compensation technique, the system model is not uniquely determined because it depends on specific test specimen and gain setting. Any significant change on test specimen or gain setting may require the derivation of a new system model. Furthermore, there is no well established process for choosing the optimal peak value of the time history of white noise, especially for a very small level of excitations. The establishment of general guidelines to obtain the optimal system model for all specimens and excitation levels requires further study.

5. The modified frequency domain data processing procedure is experimentally verified for its validity in preserving close correspondences of acceleration, velocity and displacement traces.

Desired acceleration may be achieved for the shaking table which has a displacement control system. The procedure may also be used for the data reduction of shaking table experiments. In addition, it may be applied to the base line correction of the uncorrected seismic data similar to the Standard Data Processing Procedure, with some level of improvement.

SECTION 5

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APPENDIX A
NOTATION

DMF(k)	= Dynamic magnification factor.
H(f)	= Transer matrix or function of system model.
$H^{-1}(f)$	= Expanded inverse of system model.
H(k)	= Transfer function of filter.
T	= Duration of ground motion.
Δt	= Time interval.
$\ddot{x}_g$, $\dot{x}_g$, x_g	= Base line corrected ground acceleration, velocity and displacement.
x_r	= Measured relative displacement of accelerograph.
X(f)	= Fourier transformed input.
$\ddot{X}_g$, $\dot{X}_g$, X_g	= Fourier transformed ground acceleration, velocity and displacement.
$\ddot{X}_g^*$, $\dot{X}_g^*$	= Conjugates of $\ddot{X}_g$ and $\dot{X}_g$.
$\Delta X(f)$	= Fourier transform of correction signal to input ground motion.
Y(f)	= Fourier transformed output.
$\Delta Y(f)$	= Fourier transform of the deviation between desired and achieved ground motion.
ξ	= Damping ratio of accelerometer or structure.
ω	= Natural frequency of accelerometer.
ω_h^t, ω_h^c	= Round-off termiation and cutoff frequencies of high pass filter.
ω_l^t, ω_l^c	= Round-off termination and cutoff frequencies of low pass filter.