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UPGRADE OF FIRST GENERATION UNIAXIAL SEISMIC SIMULATION SYSTEM WITH SECOND GENERATION REAL-TIME THREE-VARIABLE DIGITAL CONTROL SYSTEM

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SUMMARY

The uniaxial earthquake simulation system at the University of California in San Diego (UCSD) was commissioned in 1988 and incorporates shortcomings that were typical of first generation seismic systems, namely high frictional resistance and an analog displacement feedback control system. The objective of this paper is to examine the improvement to the UCSD uniaxial seismic system when upgraded with an advanced, second generation, digital controller incorporating an Adaptive Inverse Control (AIC) and On-Line Iteration (OLI) techniques. An experimental study was performed to compare the performance of the original displacement analog controller with the performance of the new digital control system. A 3-ton, single-story, steel frame model was mounted on the shake table and subjected to three different earthquake ground motions having widely different frequency contents. The time-histories and response spectra of the feedback and desired accelerograms are compared for the original controller and the new control system. It is shown that OLI algorithm is a very effective and stable technique for accurately reproducing earthquake ground motions in a seismic system with high frictional resistance. Since the frictional resistance is a repeatable mechanical phenomenon, the OLI algorithm is able to anticipate the friction disturbances after a number of iterations and correct the drive signal ahead of time to neutralize them.

INTRODUCTION

The closed loop electronic control of large-scale seismic simulators is a technically challenging application of control system theory. Seismic systems require high bandwidth response and system fidelity. However inherent realities of mechanical compliance, over-constraints of multi-degree of freedom systems, and specimen/system dynamics challenge control system design. Until recently, the speed of digital processors was inadequate to close all the control loops of a seismic simulation system. With the advance of computer speed, it is now possible to incorporate digital signal processing technology to seismic simulation systems. This has the advantage of retaining all the required control algorithms of the older, first generation, analog controllers, with the advantage of newer adaptive and iterative control procedures that are only available with digital technology. Recent seismic simulation systems incorporating this second-generation control technology incorporate also improved mechanical components such as very low-friction hydrostatic bearings [1]. It is unclear, however, how a second-generation digital control system would improve the performance of existing, high frictional, seismic simulation systems. In other words, can advanced digital control systems be used as software retrofit to older seismic simulation hardware?

In this paper, the performance of the existing uniaxial earthquake simulation system at the University of California in San Diego (UCSD) upgraded with a new digital control system is examined through a series of tests with different earthquake ground motions and different control algorithms. The time-histories and associated response spectra computed from the acceleration feedback signals measured on the shake table during

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the tests are used as the basis of comparison to assess the capability of the simulator to accurately reproduce earthquake ground motions. The performance of the system with the new digital controller is compared with the corresponding performance obtained with the original analog controller.

DESCRIPTION OF THE EARTHQUAKE SIMULATOR

Physical Characteristics

The uniaxial earthquake simulation system at the University of California in San Diego (UCSD) was commissioned in 1988. The shake table weighs 4.8 tons and is made of an all-welded steel construction. It has plan dimensions of 3.0 m x 4.9 m with a specimen payload capacity of 40 tons. A 350-kN fatigue-rated actuator drives the system. The bearing system consists of 8-125 mm Garlock DU cylinders sliding on two stationary shafts. The usable peak-to-peak stroke is 300 mm. The flow rate of the hydraulic system allows a peak sinusoidal velocity of 1 m/s. The actuator can induce peak accelerations of 9 g for the bare table and 1 g for the fully loaded table.

Frictional Characteristics

The Garlock bearings introduce significant frictional resistance to the system. Figure 1 presents the force-displacement characteristics of the bare table excited by a slow sinusoidal input having a peak velocity of 85 mm/s. The rectangular hysteretic behavior is typical of Coulomb-type friction. Sinusoidal tests were also conducted to evaluate the variation of the coefficient of friction with velocity. The coefficient of friction increased from 0.15 for low velocities to 0.25 for the maximum achievable velocity of 1 m/s.

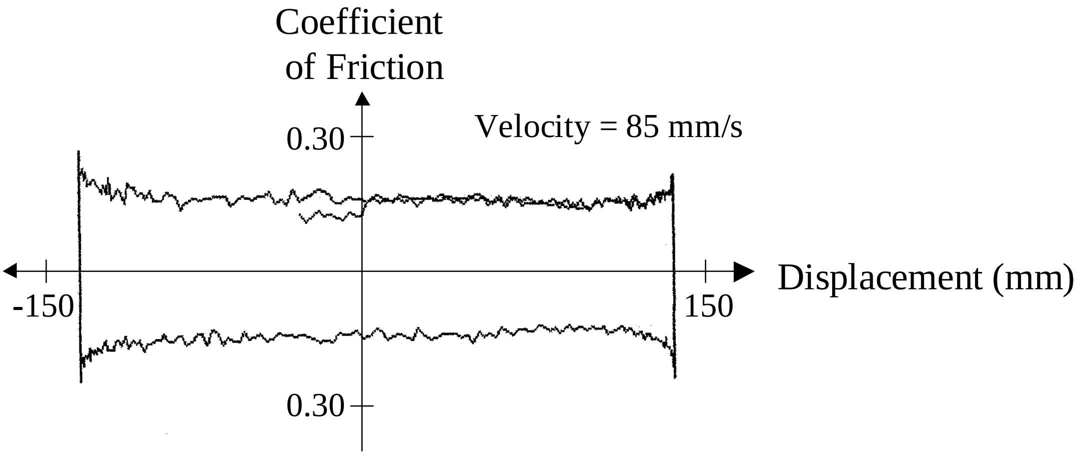

Figure 1 Frictional Characteristics of UCSD Uniaxial Seismic Simulation System.

Original Control System

The original control system of the UCSD uniaxial shake table is representative of the technology of first generation earthquake simulation systems. It includes a single, analog, displacement feedback loop with no direct control on acceleration or velocity signals. It has been shown that the reproduction fidelity of this type of control system is not adequate for a wide frequency bandwidth. Also, the system is unable to compensate for the possible interaction between the tested specimens and the table as well as for the distortion caused by the high frictional resistance of the bearing system. These shortcomings of the original UCSD system cause significant distortions, particularly at frequencies above 2.0 Hz, between the target acceleration drive signal and the acceleration feedback signal from the shake table.

New Control System

The controller used to upgrade the UCSD earthquake simulation system offers several different techniques to reproduce earthquake ground motions. Two of these techniques are briefly described below.

The first control algorithm is a frequency response compensation technique known as Adaptive Inverse Control (AIC). AIC calculates the tracking error between the desired profile and the actual response, and applies a compensation filter that reduces that tracking error. Through successive iterations, the tracking error is further reduced.

The second control algorithm is an On-Line Iteration (OLI) technique which operates when the control system causes significant tracking errors that AIC cannot cope with alone. Basic AIC relies on the compensation filter. This filter is linear, so it can only compensate a system that is mainly linear. With OLI the drive signal is played directly into the system, not through the compensation filter. Simultaneously, the desired signal is played out and compared to the system response to compute a response error. The response is run through the compensation filter, which represents the inverse transfer function of the system, thereby creating a drive correction signal. That signal is summed with the drive signal to create a new drive file. Playing this through again can reduce the response error.

TEST PROGRAM

Scope

The scope of the test program included three different earthquake accelerograms using two different control schemes. The tests were performed with the bare table and also with a structural model mounted on the shake table. The model was designed to provide a well-defined mechanical resonance.

Earthquake Ground Motions

The first accelerogram considered in the tests is the well-known S00E component of the ground motion recorded at El Centro, California, during the 1940 Imperial Valley earthquake. The second accelerogram was recorded at Chicoutimi North during the 1988 Saguenay Earthquake in Quebec, Canada. Finally, the third accelerogram is the SCT record of the 1985 Mexico City Earthquake.

The energy of the El Centro record is distributed over a period range below 1 s, which is typical of ground motions recorded on rock or on stiff soils in Western North America. The energy of the Saguenay earthquake is concentrated at low periods (high frequencies), which is typical of ground motions measured and anticipated in Eastern North America. Finally, the Mexico City record is typical of ground motions recorded on soft soils, with a substantial amount of energy at periods above 1 second.

Each record was scaled in amplitude not to exceed the physical limitations of the seismic simulation system and also to insure that the dynamic response of the test structure remains in the elastic range of the material. The El Centro record was scaled to 32% of its full amplitude. The corresponding scaling values for the Saguenay and Mexico records were 50% and 188%, respectively.

Test Structure

The single-story braced steel moment resisting frame shown in Fig. 2 was used in the study. The members of the frame were selected to achieve a fundamental frequency in the 5 Hz frequency range. A 25-kN concrete block was anchored to a steel plate that acted as horizontal roof diaphragm. Results of preliminary system identification tests indicated a fundamental frequency of 5.1 Hz (0.19 s period) for the test frame along with a first mode equivalent viscous damping ratio of 2% critical.

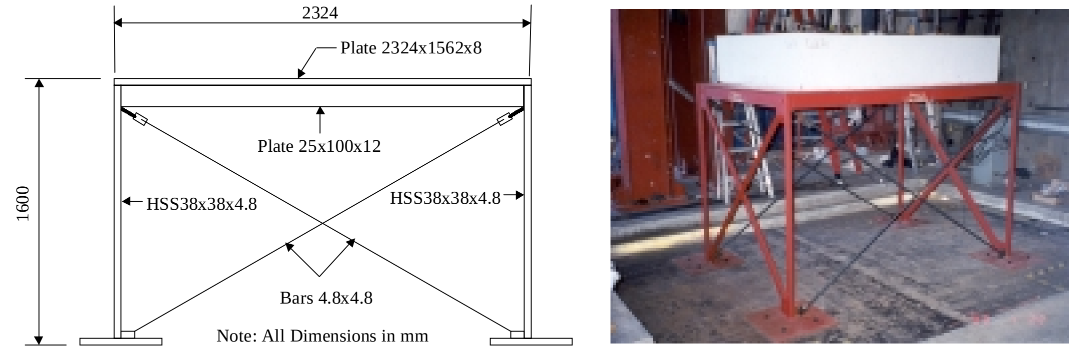

Figure 2 Single-Story Test Frame on Shake Table.

Control Algorithms

Results of preliminary tests indicated that the main source of distortion in the system is the high frictional resistance of the bearings. Since Coulomb friction is a nonlinear phenomenon, the AIC algorithm by itself could not generate a linear filter to adequately compensate for frictional interference. Therefore, AIC was used always in combination with OLI when adaptive inverse compensation algorithms were examined. The two control schemes that were investigated are 1) the original analog control system, and 2) the OLI algorithm with the AIC scheme.

Initial Tuning

The new digital control system includes a basic form of compensation, know as Three-Variable Control (TVC). The TVC concept provides simultaneous control of displacement, velocity, and acceleration variables. It combines the command and feedback signals of these three control variables to provide the needed system performance, emphasizing displacement at low-range frequencies, velocity at middle-range frequencies, and acceleration at high-range frequencies.

Before the start of the tests, the TVC system of the bare table was tuned to reach, as close as possible, a wide band unit response when excited by a 0-50 Hz flat white noise acceleration input signal. This tuning process involves adjusting the various displacement, velocity, and acceleration lead terms of the control system, as well as implementing some user-defined resonance canceling notch filters. Two significant mechanical resonances were identified and compensated for by the notch filters. The first resonance, at a period of approximately 0.029 s (35 Hz), is associated with the oil column of the hydraulic system. The second resonance, at a period of approximately 0.04 s (25 Hz), represents a mechanical resonance of the foundation system. Finally, an AIC compensation filter was constructed to further improve the frequency response function of the system towards a unit value across a wide frequency band.

PERFORMANCE EVALUATION OF THE CONTROL ALGORITHMS

Performance Indicators

In view of their key importance in earthquake engineering, the acceleration response spectrum and time-history were chosen as performance indicators of the simulator in reproducing seismic ground motions. The acceleration time-histories and associated response obtained from the acceleration feedback signals measured during the tests were compared to those of the reference ground motion signals. All spectra were computed for 5% damping and for the mean spectral values of three similar runs.

Because of the wide dissimilarities observed in the frequency contents of the three earthquake ground motions, only the period of interest of each accelerogram was considered in the computation of the spectra: 0.01 – 1.0 s for the El Centro record, 0.01-3.0 s for the Mexico City record, and 0.01 – 0.5 s for the Saguenay accelerogram. All spectra were computed at a period increment of 0.01 s.

The error in % between the feedback and the reference spectra was computed for each period. Two parameters were selected as performance indicators for the system: 1) the RMS error computed over the complete period range and 2) the maximum error observed for periods above the oil column resonance (> 0.05 s).

Response Spectra Results

Figures 3 to 5 compare the acceleration response spectra, at 5% damping, obtained from the recorded acceleration time-histories of the shake table with the reference response spectra of the three earthquake accelerograms considered. The results are presented for the two different control algorithms considered and for the bare shake table, as well as for the shake table loaded with the test structure.

The results clearly indicate the shortcomings of the original analog control system over a wide frequency band. For the El Centro earthquake, the performance of the original analog controller is adequate, except for the strong amplification at the oil column resonance. For the Mexico City earthquake, the analog controller overestimates the spectral accelerations by as much as 60% in the 2-second period range (0.5 Hz). For the high frequency Saguenay earthquake, on the other hand, the spectral accelerations are underestimated by as much as factors of 2.5 in the 0.1- second period range (10 Hz).

The results indicate also that the OLI algorithm provides a significant performance improvement across all spectra. As shown in Tables 1 and 2, the performance of the OLI algorithm is particularly impressive for the Saguenay earthquake, where the RMS errors are 8% and 24 % for the bare and loaded table, respectively.

Table 1: RMS Spectral Acceleration Errors in % Over Complete Period Range.

Record	Bare Table		Table Loaded with Test Structure	
	Analog Controller	OLI	Analog Controller	OLI
El Centro	24	13	31	29
Mexico	68	27	54	33
Saguenay	274	8	186	24

Table 2: Maximum Spectral Acceleration Errors in % for Periods Longer than 0.05 s.

Record	Bare Table		Table Loaded with Test Structure	
	Analog Controller	OLI	Analog Controller	OLI
El Centro	66	19	51	28
Mexico	150	76	149	93
Saguenay	594	35	361	86

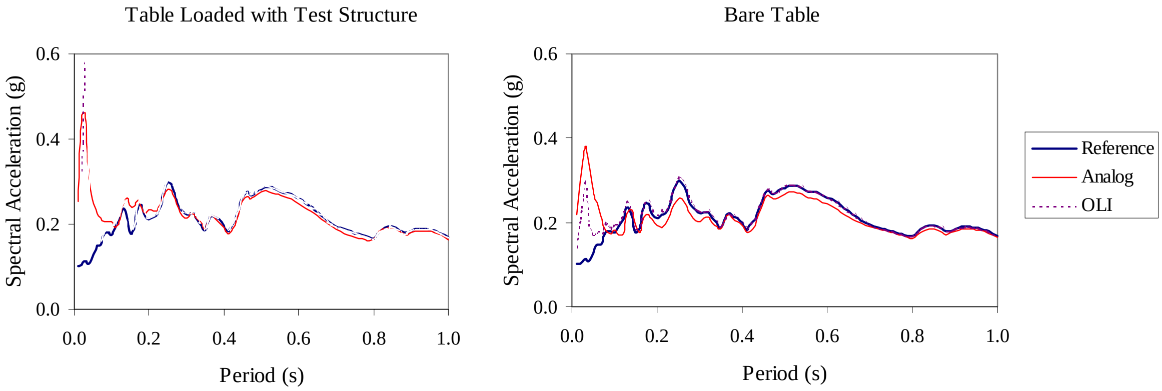

Figure 3: Absolute Acceleration Response Spectra, 5% Damping, El Centro Record, 32% Span.

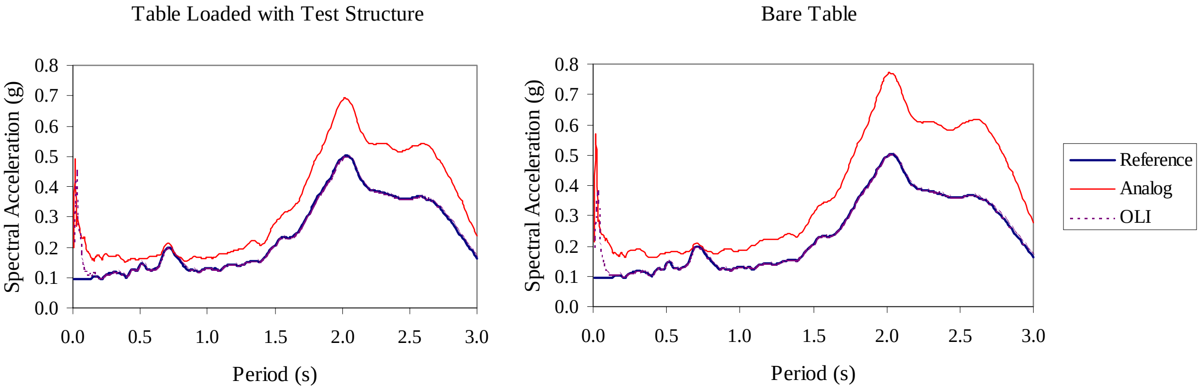

Figure 4: Absolute Acceleration Response Spectra, 5% Damping, Mexico Record, 50% Span.

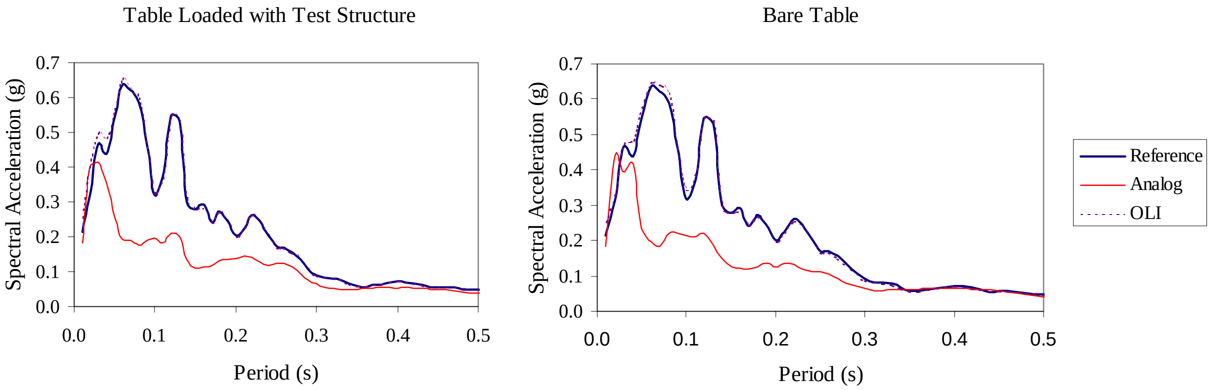

Figure 5: Absolute Acceleration Response Spectra, 5% Damping, Saguenay Record, 188% Span.

Time-History Results

Figures 6 and 7 compare the acceleration time-histories with the reference accelerograms for two particular test series involving the El Centro record on the bare table and the Saguenay record with the table loaded by the test structure. The superior performance of the OLI scheme is clearly observable. The original analog control system is unable to compensate for the frictional distortion.

For the El Centro record (Fig. 6), the frictional resistance of the bearing system introduces overshoots at peak acceleration values when the shake table suddenly changes direction and the velocity crosses over at zero. This phenomenon is better illustrated in Fig. 8, where time-history windows between 1.2 and 3.2 s are shown for the same test series. The original analog controller is unable to compensate for the frictional overshoots around the peaks. The iteration scheme of the OLI process allows the system to learn the repeatable frictional distortions, to anticipate them during the next iteration and ultimately to under-program the drive signal around the peaks to virtually annihilate the overshoots in the feedback signal.

The frictional resistance has a completely different effect on the Saguenay record, as shown in Fig. 7. Because of the high frequency signal and small displacement amplitudes, the static friction of the bearing system prevents the table from moving for most of the record. For this case, the OLI algorithm over-programs the drive signal to force the table to overcome the static frictional resistance and ultimately to accurately reproduce the reference signal.

CONCLUSIONS

The new digital control system implemented on the existing uniaxial seismic simulation system of the University of California in San Diego (UCSD) represents a significant step forward in the development of digital control systems for shake table testing.

The On-Line Iteration (OLI) technique has allowed to overcome the major shortcoming of the existing system caused by the high frictional resistance of the bearing system. Since the frictional distortion originates from a repeatable mechanical Coulomb-type phenomenon, the OLI algorithm is able to learn about the frictional disturbances and to anticipate them during subsequent iterations. OLI over- or under-programs the drive signal ahead of the frictional disturbances to, ultimately, annihilate them in the feedback signal.

The results of this test program demonstrates that second-generation digital control technology can be, by itself, a technically sound and cost-efficient retrofit solution to older first-generation seismic systems without the need to upgrade the mechanical hardware. In the case of the high-friction UCSD system, the level of fidelity now available with the new digital controller is comparable to recent seismic systems equipped with low-friction hydrostatic bearings.

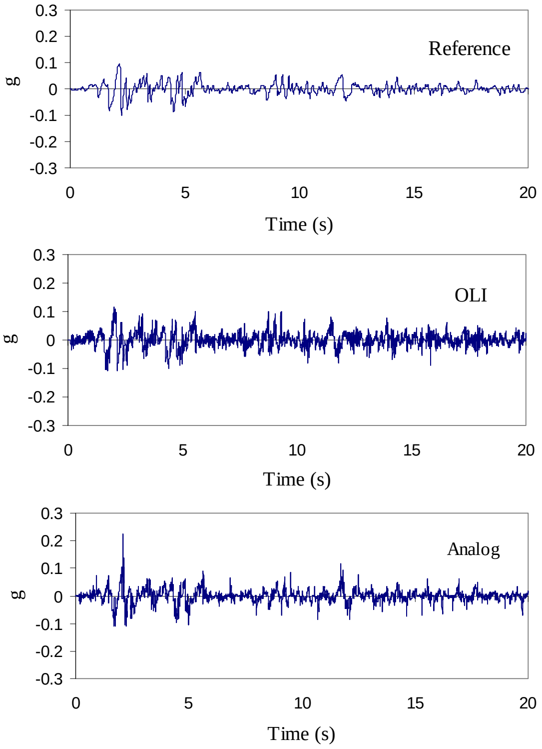

Figure 6: Acceleration Time-Histories, Bare Table, El Centro Record, 32% Span.

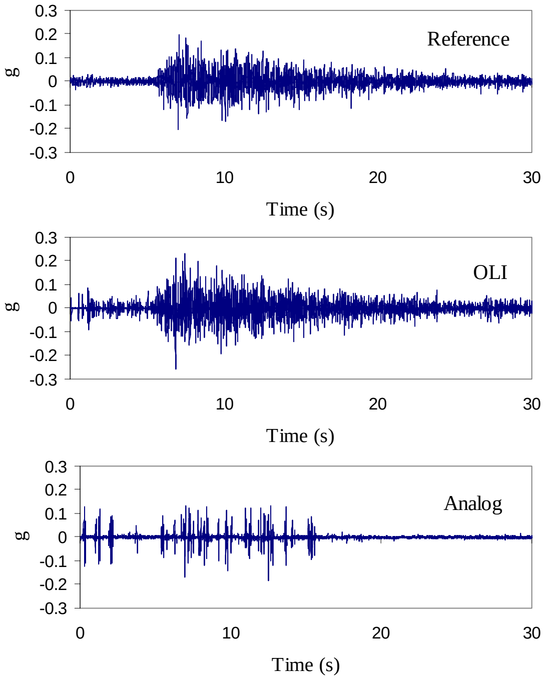

Figure7: Acceleration Time-Histories, Table Loaded with Test Structure, Saguenay Record, 188% Span.

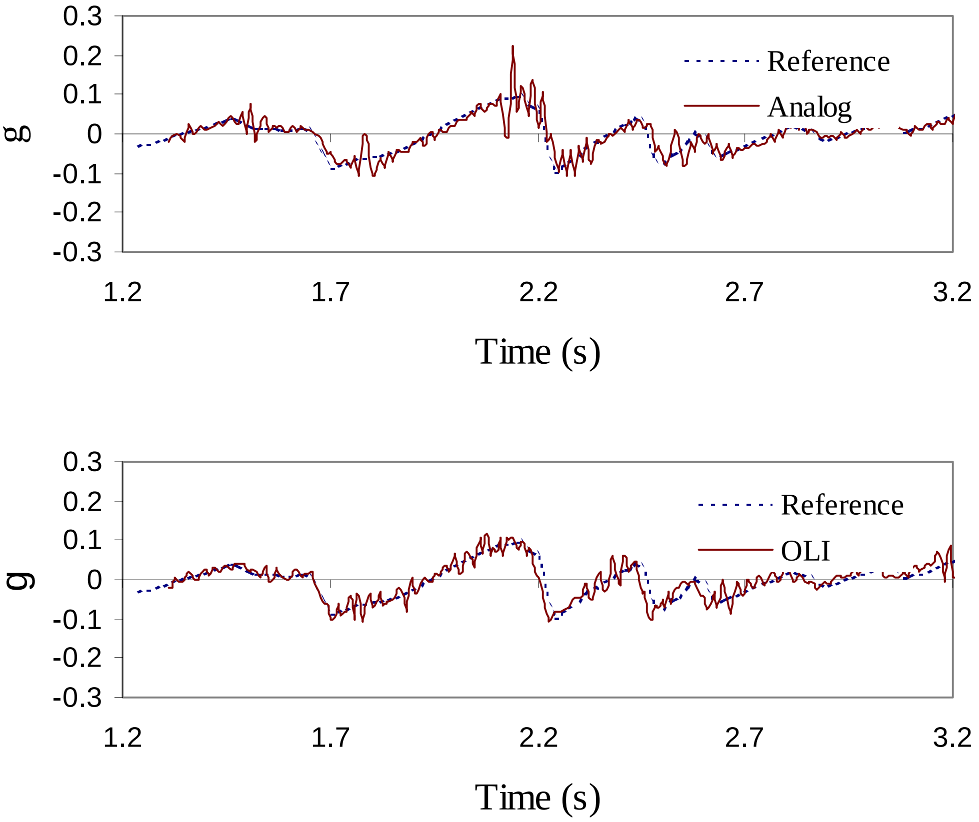

Figure 8: Details of Acceleration Time-Histories, Bare Table, El Centro Record, 32% Span.

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