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A SECOND GENERATION EARTHQUAKE SIMULATION SYSTEM IN CANADA: DESCRIPTION AND PERFORMANCE

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ABSTRACT

The recently acquired earthquake simulator facility at Ecole Polytechnique in Montreal, Canada, includes an advanced digital control system which incorporates a Three-Variable-Control (TVC) together with Adaptive Inverse Control (AIC) and On-Line Iteration (OLI) techniques. An experimental study has been performed to evaluate the performance of the different control algorithms. A 15 ton, two-story steel frame model was mounted on the shake table and subjected to two earthquake ground motions. The acceleration response spectra of the feedback and desired accelerograms are compared for different control schemes. It is shown that the TVC control algorithm is a very robust and stable technique for accurately reproducing earthquake ground motions. Iterative techniques based on full scale amplitude signals have been found to be more appropriate than low amplitude signals for achieving proper table movement. OLI and AIC techniques are particularly efficient in the high frequency range, typically above 10 Hz.

KEY WORDS

Adaptive Inverse Control, Earthquake simulator, On-Line Iteration, Shake table, Three Variable Control.

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 realties of mechanical compliance's, 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 system. A new seismic earthquake simulation facility has been built at Ecole Polytechnique in Montreal, Canada. This seismic system is the first one to incorporate digital signal processing technology, which retains all the required control algorithms of the older analog controller with the promise of newer adaptive and iterative control procedures that are only available with digital technology.

In this paper, the performance of this new system is examined through a series of tests with dynamically varying specimens, different earthquake ground motions and various control algorithms. The acceleration response spectrum computed from the feedback signal measured on the shake table during the tests is used as the basis of comparison to assess the capability of the simulator to accurately reproduce earthquake ground motions.

DESCRIPTION OF THE EARTHQUAKE SIMULATOR

Physical characteristics

The Earthquake Simulator of Ecole Polytechnique is operational since August 1, 1995. It is a uniaxial shaking table mounted on four hydrostatic linear bearings. The table itself weighs 6,9 tons and is an all-welded multicell steel construction. It has plan dimensions of 3,4 m x 3,4 m with a specimen payload capacity of 15 tons. The hydrostatic bearings of the table and the buttress of the actuator are anchored to the 1,5 m thick, 450 ton testing floor of the Structures Laboratory of Ecole Polytechnique. The simulator was manufactured by MTS Systems Corp., Minneapolis, Minnesota.

The table is driven by a 250 kN fatigue-rated actuator activated by a 730 l/min hydraulic power supply. The oil flow in the actuator is controlled by a three-stage 680 l/min servo-valve. The usable peak-to-peak stroke of the table is 250 mm. The flow rate of the hydraulic system allows a peak sinusoidal velocity of 800 mm/sec. The actuator can induce peak accelerations equal to 3,0 g and 1,0 g for the empty and fully loaded conditions, respectively. The workable frequency range of the simulator spans from 0 to 50 Hz.

Control algorithms

Three control algorithms are available with the digital control system of the simulator to reproduce earthquake ground motions. The first technique is a fixed form of compensation known as Three-Variable Control (TVC). The second control algorithm, which operates in conjunction with TVC, is a frequency response compensation technique known as Adaptive Inverse Control (AIC). The third control algorithm is an On-Line Iteration (OLI) which operates with both TVC and AIC when the control system causes significant tracking errors that TVC and AIC cannot cope with alone. AIC and OLI are proven techniques in dynamic testing. These techniques are used herein for the first time on a seismic shake table system.

TVC provides simultaneous control of displacement, velocity and acceleration, emphasising displacement at low frequencies, velocity at intermediate frequencies and acceleration at high frequencies. These combine to provide flat response over a broad frequency range. Furthermore, TVC linearizes the nonlinear flow gain characteristics of the hydraulic servo-valve to reduce distortion.

AIC involves compensating for residual frequency response irregularities of the fixed control system by placing a digital compensation filter between the program source and the control system. An integral system identification algorithm determines the frequency response of the control system, thereby achieving an overall response that is almost perfectly flat. The system identifier can be switched off after initial determination of the inverse frequency response function (IFRF), or can be left on during a test to adapt the digital compensation filter to frequency response changes.

OLI involves rehearsing the test repeatedly, while updating and storing a corrective drive signal to the control system until acceptable fidelity is achieved. For tests where the specimens are driven in the nonlinear range, the iteration is usually processed at a low, non-destructive amplitude. The iterated drive is then scaled up to full amplitude for the actual test, with the hope that the response will scale up accordingly. OLI uses AIC's system identifier and compensation filter. The compensation filter is used in a different way: it filters the response error to compute a correction to the program input, rather than filtering the program input itself.

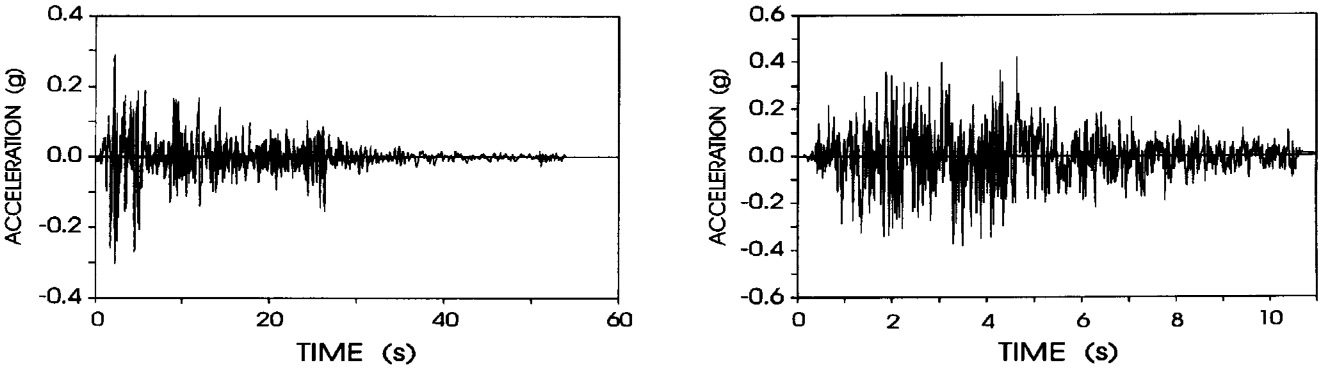
TEST PROGRAM

The scope of the test program included two different earthquake accelerograms using five different control schemes. A structural model was mounted on the shake table during the tests. The model was designed so that its lateral resistance could be changed without altering its dynamic properties. Thus, two series of tests could be performed: one with the model responding linearly during the entire earthquake motion and one where the structure responded in the nonlinear range.

Earthquake ground motions

The first accelerogram is the well-known S00E component of the ground motion recorded at El Centro, California, during the 1940 Imperial Valley earthquake. The second accelerogram is an artificially generated ground motion which simulates a probable strong ground shaking scenario for eastern North America (Atkinson 1992[1]). Both signals were applied unscaled in all tests but were processed through a high-pass filter with a cut-off frequency of 0.2 Hz to limit peak displacements. In this paper, these filtered earthquake accelerograms are referred to as the "desired signals", as opposed to the table acceleration signals recorded during the tests, which are designated as "feedback signals".

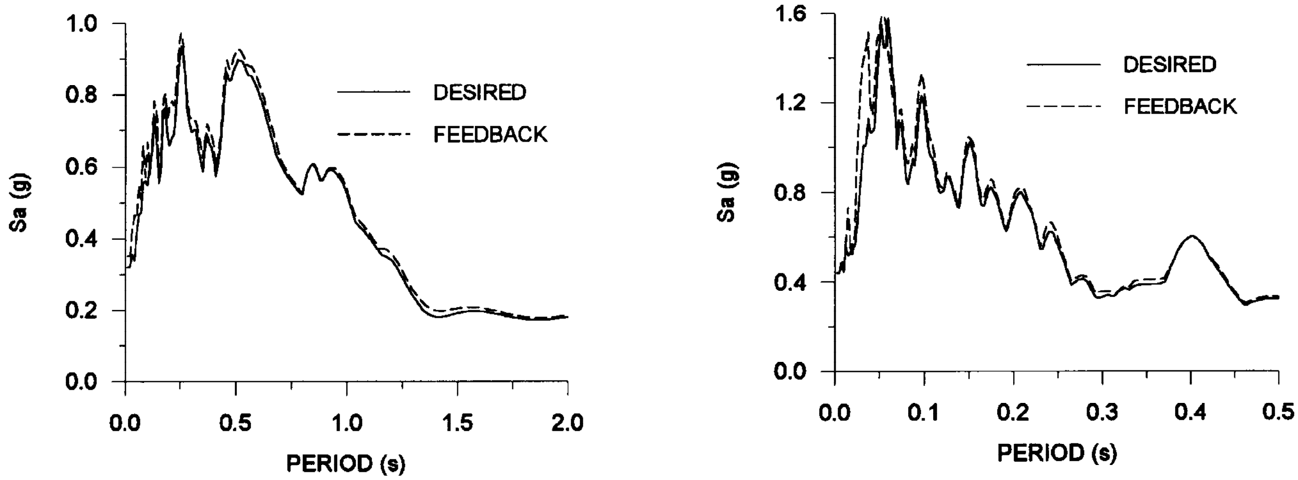
The time-histories of the desired signals are reproduced in Fig. 1. The peak ground acceleration is equal to 0,30 g and 0,43 g for the El Centro and the Atkinson S81 ground motions, respectively. The El Centro record is longer in duration than the Atkinson signal (54 s vs 11 s). The 5% damping absolute acceleration response spectra computed from the desired accelerograms are shown in Fig. 2. The figure indicates that the signals exhibit very different dominant period ranges: most of the energy of the El Centro record is concentrated within the 0.1-1.0 s range while the dominant period of the Atkinson ground motion is below 0.1 s.



a) El Centro signal

b) Atkinson S81 signal

Fig. 1 Time history of desired ground motion signals.



a) El Centro signal

b) Atkinson S81 signal

Fig. 2 Absolute acceleration response spectra, 5% damping (bare table).

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[1] Atkinson, G. 1992. Private communication.

Testing frame

The two-story steel moment resisting frame half-scale model shown in Fig. 3 was used in the study. Four 30 kN concrete blocks, supported on a separate peripheral gravity frame with no lateral resistance, were used to simulate the mass at the floor and roof levels. The members of the moment resisting frame were carefully selected to achieve realistic dynamic properties for a typical two-story steel building: the first and second natural frequencies of the model being equal to 2.3 Hz and 14.0 Hz, respectively. The measured first modal damping ratio was equal to 2.3% of critical.

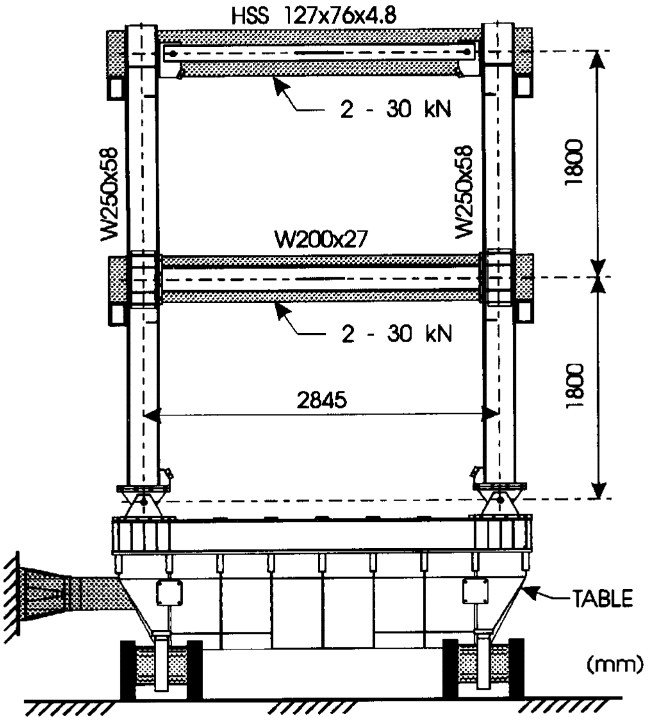


Fig. 3 Two-story structural model.

All connections in the frame were perfect hinges except for the beam at the first floor which was rigidly connected to the columns, providing lateral strength and stiffness to the frame. Two different beams were used at the first floor level. The beam shown in Fig. 3 had its flanges shaved at both ends to reduce its flexural resistance in the region of plastic hinging. Full plastic moment in that beam could be developed under 41% amplitude of the El Centro signal and 47% amplitude of the Atkinson S81 accelerogram.

The second beam was designed to achieve higher resistance while maintaining the dynamic properties of the frame unchanged. That beam was tapered and was made of high strength steel material. Its flexural resistance was four times higher than the beams of the first type. Hence, this beam could sustain both earthquake signals within the elastic range of the material.

Control schemes

Five different control schemes were investigated in the study. The first approach included only the basic TVC algorithm. The AIC and OLI techniques were, both, used twice.

The inverse frequency response functions (IFRFs) to be used with the AIC technique were shaped gradually while driving the simulator with successive applications of the full scale earthquake signals. Two sets of filters were obtained. In one case, the IFRFs were built by exciting only the bare table (AIC-B), before the installation of the structural model, while the second set of filters was built with the specimen attached to the table (AIC-S).

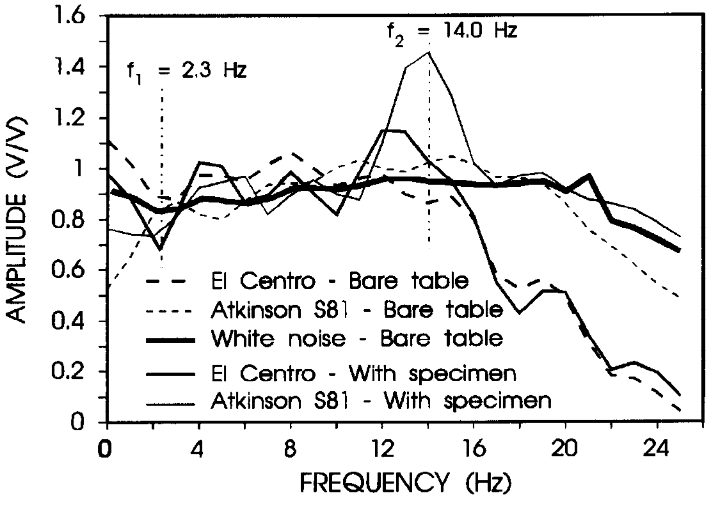


Fig. 4 Inverse frequency response functions.

Figure 4 shows the two different IFRFs obtained for each signal. For comparison purposes, the IFRF obtained for the bare table under a 0-25 Hz white noise with a RMS amplitude of 0,13 g is also given. The latter is very flat and close to unity, which indicates that the system is well tuned and that no particular resonance nor anti-resonance are present. The IFRFs derived with the bare table under the resonance nor anti-resonance are present. The IFRFs derived with the bare table under the two accelerograms are also flat and close to unity over the high energy frequency range of the signals. For the El Centro record, the IFRF drops sharply after 10 Hz (period of 0,1 s). The IFRF obtained under the Atkinson S81 accelerogram shows smaller amplitudes at low frequencies since this signal has little energy content below 2 Hz.

With the structural model attached to the table, the first resonance of the specimen was detected under the El Centro signal, which translates into a dip in the IFRF around 2.3 Hz. Under the Atkinson excitation, which exhibits higher frequencies than the El Centro record, the first natural period of the specimen did not show up as distinctly in the IFRF but an anti-resonance appeared near the second natural frequency of the model.

The OLI iteration technique was used in the last two control schemes. In both cases, the iteration was performed with the strong structural model mounted on the simulator. A first set of corrected drive signals (OLI-L) was obtained with the earthquake signals scaled down to 25% of their amplitude. These ground motions were scaled up to 100% before testing. The second set (OLI-H) was obtained while iterating with the full scale signals.

In earthquake engineering research, iterating under full scale ground motions with the specimen mounted on the shake table to obtain filters (AIC) or corrected accelerograms (OLI) may require to temporarily reinforce the specimen. This reinforcement must be designed to avoid damaging the specimen during this preliminary phase of testing, while preserving its dynamic properties. In this study, the purpose of performing iterations at high excitation level with the strong moment resisting frame was to assess the gain in accuracy that could be achieved using this technique.

PERFORMANCE EVALUATION OF THE CONTROL ALGORITHMS

Performance indicator

In view of its key importance in earthquake engineering, the acceleration response spectrum was chosen to assess the performance of the simulator in reproducing seismic ground motions. The spectra obtained from the acceleration feedback signals measured during the tests were compared to those calculated from the desired ground motion signals. All spectra were computed for 5% damping.

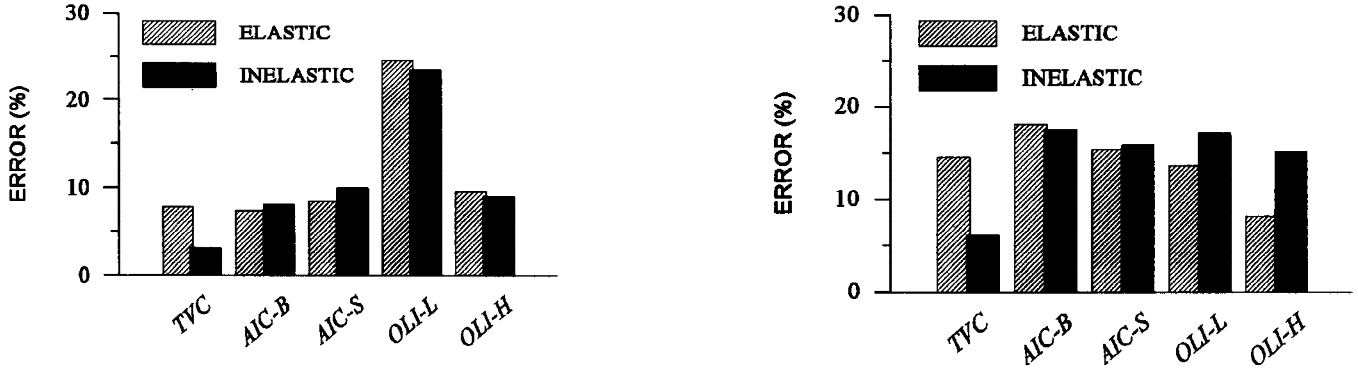
Because of the dissimilarity observed in the frequency content of the two earthquake ground motions, only the period range of interest of each accelerogram was considered in the computation of the spectra: 0.01-2.0 s for the El Centro record and 0.025-0.5 s for the Atkinson accelerogram. For both signals, however, the calculations were performed for 200 points evenly distributed over the period range.

The relative error in % between the feedback and the desired spectra was computed for each period. Two parameters were selected as performance indicators for the system: *i)* the average error computed over the period range and *ii)* the maximum error observed over the entire period range. The absolute value of the errors was considered in the calculations of both indicators.

Results

Before installing the structural model on the shake table, both earthquake ground motions were applied to the bare table using the TVC control algorithm alone. The response spectrum obtained from these two tests is shown in Fig. 2. These spectra compare very well with those obtained from the desired signals. This result demonstrates the efficiency of TVC alone in accurately reproducing earthquake ground motions. For the El Centro and the Atkinson S81 signals, respectively, the average errors are equal to 4,9% and 5,5%. For both signals, the highest errors were observed in a narrow period range near 0,04 s, which coincides with the oil column frequency of the shake table (25 Hz). Elsewhere, the errors were considerably lower.

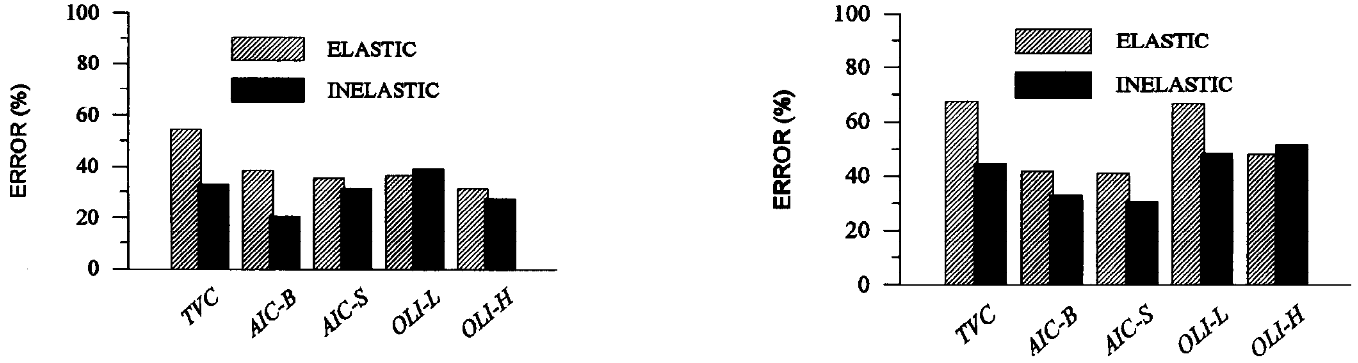
The computed average and maximum errors are summarised in Fig. 5 and Fig. 6, respectively, for the whole series of tests (two earthquake signals, five control schemes and two types of response: elastic and inelastic).



a) El Centro signal

b) Atkinson S81 signal

Fig. 5 Average error (absolute values) between feedback and desired response spectra.



a) El Centro signal

b) Atkinson S81 signal

Fig. 6 Maximum error (absolute values) between feedback and desired response spectra.

As shown, the average and maximum errors both vary depending upon the signal, the control algorithm and the type of response. The Atkinson S81 signal generally led to larger differences between the feedback and desired acceleration signals. This can be attributed to the fact that this signal excited more the shake table system near its resonance frequency, which represented a more challenging situation from a control point of view.

Figure 5a shows that all techniques, except OLI-L, present similar average errors for the strong (elastic) specimen under the El Centro record. The OLI-H technique, with the corrected drive obtained by iterating at high amplitude, resulted in a much better correlation between feedback and desired spectra than the OLI-L technique, for which the iteration is performed with the low amplitude signal. For the inelastic specimen, the measured average error with the TVC algorithm is considerably less than the corresponding error obtained with the elastic structure. The performance of the other control techniques did not seem to be affected by the nonlinearity of the specimen. Remarkably, for the inelastic model, the average error obtained with TVC (3,1%) is less than the average error measured with the bare table under the same signal (4,9%).

Similar observations can be made in Fig. 5b which shows the average errors measured under the higher frequency Atkinson S81 accelerogram. Again, the TVC algorithm performed extremely well (average error of 6,1%) with the specimen responding inelastically. In contrast with Fig. 5a, however, the average errors obtained with the OLI-L control approach were comparable to the ones obtained with the other control schemes. Moreover, with the elastic specimen, the OLI-H technique improved the fidelity of the feedback signal (error of 8,1%) when compared to the results obtained using TVC (14,5%).

For nonlinear specimens, the TVC algorithm thus appears to be the most appropriate to achieve accuracy, on average, over the frequency range of interest. The significant increase in accuracy observed with that control scheme when testing an inelastic specimen rather than an elastic one can be explained by the softening that takes place at peak ground accelerations when yielding mechanisms develop in the model. This softening mechanism reduces the inertia forces and, thus, the demand on the hydraulic system. For this situation, the motion of the simulator is easier to control. For the nonlinear case, AIC and OLI techniques, which rely on IFRF constructed based on the elastic properties of the undamaged model, were not as efficient as TVC.

As shown in Fig. 6, however, AIC and OLI techniques were found to be effective in reducing the maximum errors between the feedback and desired spectra. For both acceleration signals and model properties, using the AIC algorithm resulted in smaller maximum errors when compared to the performance obtained with the TVC technique. The same improvement could be achieved for the elastic model with the OLI algorithm.

Although the TVC technique performed well on average over the period range of interest, it exhibited peak errors in the short period range, typically below 0,1 s (frequency higher than 10 Hz). For longer periods, the error was small, being generally less than 5%. This is illustrated in Fig. 7 for the inelastic specimen excited by the EL Centro record. For that particular case, the AIC and OLI techniques significantly improved the performance of TVC for periods less than 0.07 sec, as shown in Fig. 8. Note that the absolute value of the errors have been considered in the calculation of the ratios in Fig. 8. Similar behavior was also observed under the Atkinson S81 signal and for the elastic specimen.

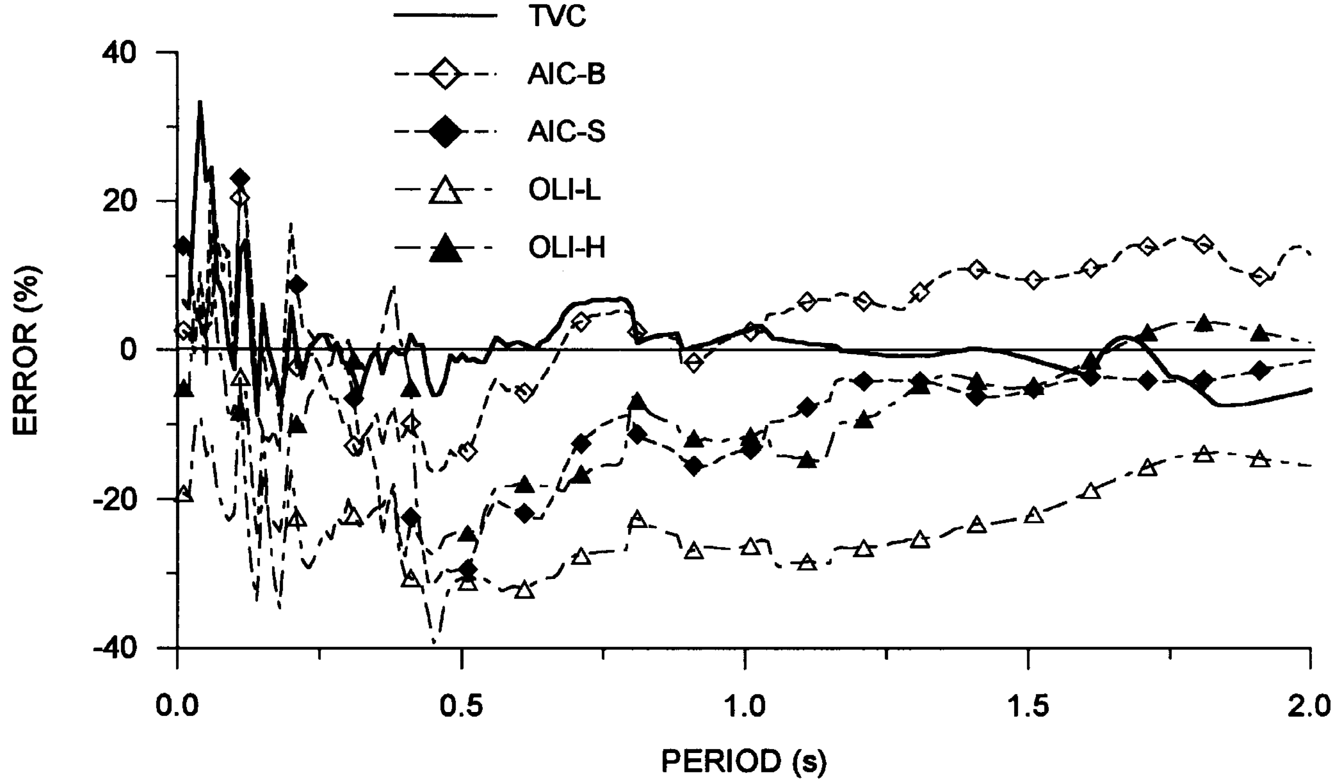


Fig. 7 Error between desired and feedback response spectra under El Centro record (inelastic response).

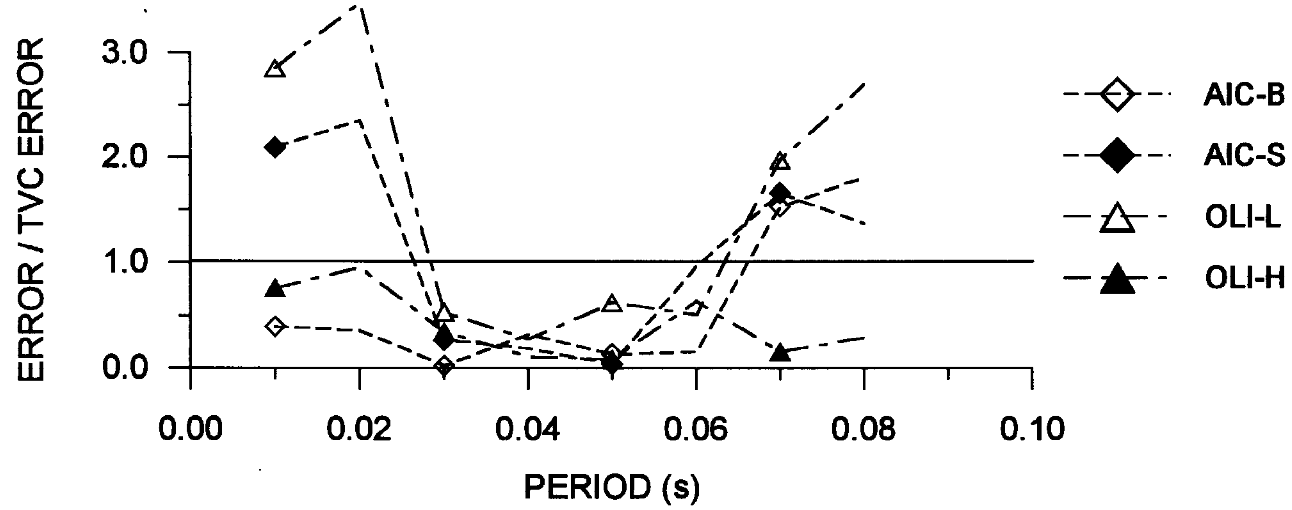


Fig. 8 Improvement of the TVC response spectrum under the El Centro record (inelastic response).

There is no definite general trends in the results that could indicate which one of the two control schemes (AIC-B or AIC-H) is the more appropriate for reducing peak errors. Conversely, for both elastic and inelastic specimens, the OLI technique generally yielded better results when iteration was performed with the full amplitude signal, which was also the case when comparing average errors in Fig. 5. This clearly indicates that the amplitude of the signal used during the iteration process must exhibit sufficient energy near the natural frequencies of the system in order to adequately capture its dynamic characteristics.

CONCLUSION

The digital control system implemented in the shake table at Ecole Polytechnique in Montreal, Canada, represents a significant step forward in the development of digital control systems for shake table testing.

For period ranges typically encountered in earthquake engineering testing of inelastic specimens (periods longer than 0,1 sec), the Three Variable Control (TVC) algorithm proved to be a very reliable tool for achieving high fidelity levels. The largest errors observed with TVC occured in a narrow period range near the oil column resonance. Adaptive Inverse Control (AIC) and On-line Iteration (OLI) techniques can be used in conjunction with TVC to improve the performance of the simulator in this high frequency range. This may be of significance in tests involving small scale specimens for which the time is scaled down and the frequency range of interest is shifted towards higher frequencies.

The test results indicate that the OLI should be performed at a sufficient drive signal level to ensure that the energy fed into the system is large enough to clearly identify the dynamic properties of interest of the system. This can be achieved by temporarily reinforcing the specimen, without modifying its dynamic characteristics, to increase the amplitude of the iterative drive signal.

The results of this test program have highlighted the main features and potential of these advanced control techniques. Further development is needed to tailor these techniques for seismic testing. The third and fourth authors are currently involved in this endeavour.

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