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Overview:

The acceptance tests were performed during the months of June, July and August of 2004. MTS and CABR personnel performed the tests. The tests were performed in the spirit of co-operation. The following results were performed per the protocol- 'Final Acceptance Procedure for Earthquake Simulation System' dated June 6,2002.

1.0 Static test Index:

1.1 Static stroke position holding accuracy at all axes $< \pm 0.15\%$

CABR supplied external displacement transducers which monitored the position of the table over a 50-minute time period. It was verified that the table could hold a position within the required tolerance and the 50-minute time period.

1.2 Static stroke resolution within $\pm 0.1\%$ of full stroke.

It was verified for the X, Y and Z-axes that the table had a resolution within 0.15 mm for the X-axis, 0.25 mm for the Y-axis, and 0.10mm for the Z-axis.

1.3 Static stroke repeatability for all axes within $\pm 0.1\%$ of full stroke

The table was moved from a defined location and returned to that location 10 times and the average was within the required repeatability.

1.4 Static Noise level of system less than 0.01 g.

The background noise level the table was measured the system off, hydraulics on with table in park position, and with table in normal position with hydraulics on at high pressure. The measured results for X, Y and Z are 0.007g, 0.008g and 0.007g respectively.

1.5 Maximum Performance Tests.

These tests are to verify the power of the system and are run under two cases; bare table and 60 ton specimen. All tests under acceleration control were done using the AHC control to eliminate any harmonics and APC to maintain the required amplitude. The fundamental frequency was measured. The tests were run with 7 of the 8 pumps available but in all cases the pumping capacity was

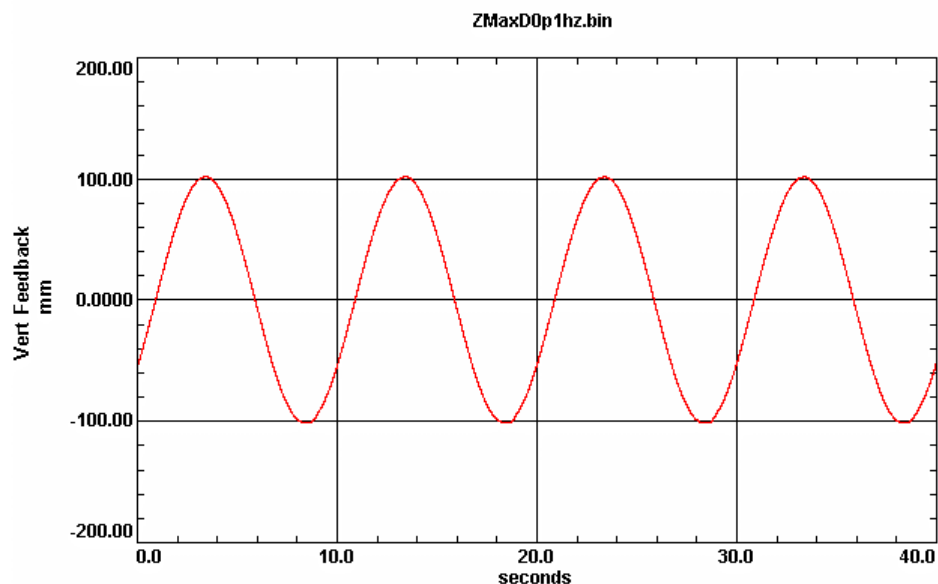
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sufficient to complete the tests. The 8th pump was repaired at a later date. This shows that the system has a reserve capacity of one pump or about 14%.

X direction (bare table)				X direction (60 ton payload)			
Frequency (hz)	Control Variable	Amplitude	Pass/Fail	Frequency (hz)	Control Variable	Amplitude	Pass/Fail
0.1	disp.	± 15 cm	Pass	0.1	disp.	± 15 cm	Pass
0.5	disp.	± 15 cm	Pass	0.5	disp.	± 15 cm	Pass
1.0	disp.	± 15 cm	Pass	1.0	disp.	± 15 cm	Pass
1.5	vel.	± 70 cm/s (cont)	Pass	1.5	vel.	± 70 cm/s (cont)	Pass
2.0	vel.	± 70 cm/s (cont)	Pass	2.0	vel.	± 70 cm/s (cont)	Pass
5.0	vel.	± 70 cm/s (cont)	Pass	5.0	accel.	± 1.5 g	Pass
1.5	vel.	± 100 cm/s (>10sec)	Pass	1.5	vel.	± 100 cm/s (>10sec)	Pass
2.0	vel.	± 100 cm/s (>10sec)	Pass	2.0	vel.	± 100 cm/s (>10sec)	Pass
5.0	vel.	± 100 cm/s (>10sec)	Pass	5.0	accel.	± 1.5 g	Pass
10.0	accel.	± 3.7 g	Pass	10.0	accel.	± 1.5 g	Pass
30.0	accel.	± 3.7 g	Pass	30.0	accel.	± 1.5 g	Pass
50.0	accel.	± 3.7 g	Pass	50.0	accel.	± 1.5 g	Pass

Some typical results for a displacement, velocity and acceleration test are listed below:

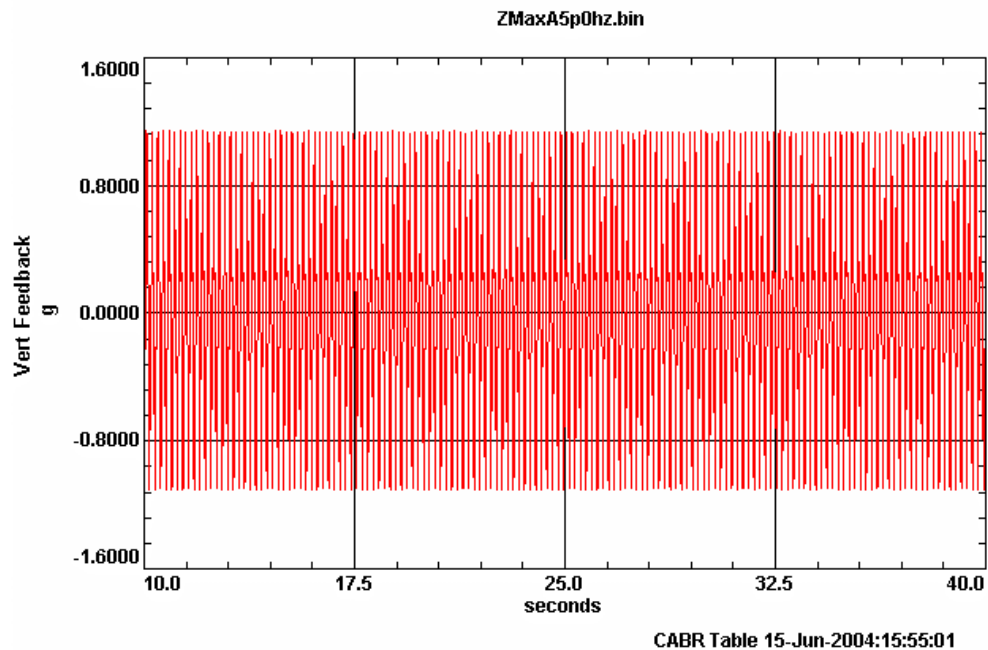
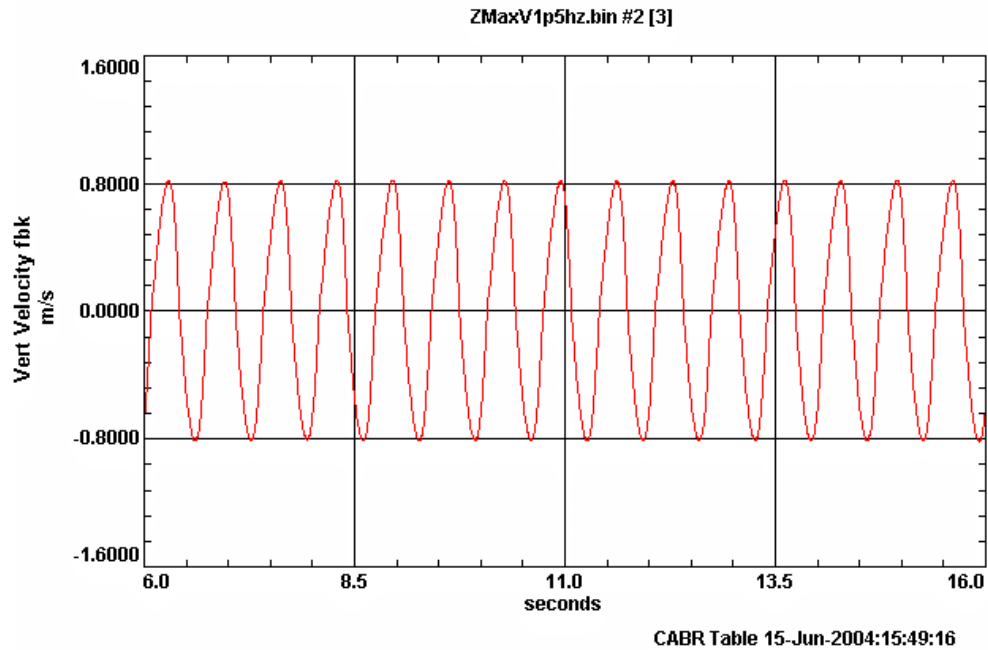
Displacement plot for vertical axis.



CABR Table 15-Jun-2004:15:38:48

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Velocity and acceleration plots for vertical axis



1.6 Hydraulic system continuous working hours: 72 hours

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All pumps were run continuously at high pressure until the test was successfully terminated by CABR. No shutdowns occurred. System maintained correct operation temperature.

1.7 Maximum Rotation angle of actuator test.

The table was operated in roll, pitch and yaw. For the roll and pitch it was required to meet ± 2.3 degrees and for yaw ± 3.0 degrees. Achieved results were ± 2.8 degrees for pitch and roll, and ± 4.1 degrees for yaw.

2.0 Static test Index:

2.1 Frequency control accuracy for all waveforms within 0.1to 50hz : <0.1%

Frequency control was verified by CABR to be within limits.

2.2 Acceleration unevenness along main actuated axis of table: <10%

Table system was driven in each axis at a given acceleration and frequency. Measurements were made at each of four locations on table top using data acquisition system are referenced to the average table acceleration calculated by the 469D controller. Results are listed below.

Acceleration uniformity on Table top - 60 ton specimen							
Axis	Acceleration (g's)	Frequency (hz)	Uniformity (%)				
			1	2	3	4	Max
X	1.0	3	-0.3	0.1	0.1	-0.1	0.3
	1.0	5	-0.1	0.0	-0.1	0.0	0.1
	1.0	10	0.3	1.2	0.3	1.2	1.2
	1.0	20	3.0	4.3	4.0	3.9	4.3
	1.0	30	5.7	12.4	7.9	11.4	12.4
	1.0	50	19.0	17.6	27.9	16.9	27.9
Y	1.0	3	1.3	-5.9	-5.4	-6.5	6.5
	1.0	5	1.4	-5.7	-5.2	-6.5	6.5
	1.0	10	2.1	-5.0	-4.5	-5.8	5.8
	1.0	20	6.1	-0.5	-3.0	-4.4	6.1
	1.0	30	9.6	3.8	3.1	1.3	9.6
	1.0	50	18.9	15.0	21.1	11.5	21.1
Z	0.6	3	-1.3	-5.0	-0.6	-0.3	5.0
	0.6	5	-0.8	-4.3	-0.2	0.2	4.3
	0.6	10	2.6	-1.1	2.8	3.7	3.7
	0.6	20	12.3	13.5	16.9	13.6	16.9
	0.6	30	29.9	37.1	39.7	30.5	39.7
	0.6	50	82.5	86.0	90.3	84.5	90.3

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In general the X and Y axes met specification except for the 50 hz condition. The Z axis did not meet specification at 20 hz and higher. The main results are quite uniform within all the accelerometers but deviate when compared to the average acceleration calculated by the 469D. This is most likely due to the table experiencing an oil can mode due to the compliance of the table and the four 15 ton concrete blocks.

2.3 Acceleration unevenness component on orthogonal non-actuated axis of table: <5%

Table system was driven in each axis at a given acceleration and frequency. Measurements were made at the table center for the other two orthogonal axis. These results were then compared to the table acceleration as calculated by the 469D controller in the actuated direction. The table system accelerometers within the table were also compared to the drive axis. Results are listed below.

Cross Coupling				
Axis	Frequency Hz	Test level (g's)	MTS (%)	CABR 5s (%)
X	3	1.0	0.6	5.3
	5	1.0	0.7	5.1
	10	1.0	1.1	5.2
	20	1.0	2.9	6.1
	30	1.0	3.1	7.0
	50	1.0	8.3	18.2
Y	3	0.8	0.7	1.8
	5	0.8	0.4	1.7
	10	0.8	0.8	2.0
	20	0.8	1.6	2.7
	30	0.8	1.9	3.6
	50	0.8	4.9	10.7
Z	3	0.6	0.8	7.0
	5	0.6	0.7	6.8
	10	0.6	1.2	6.7
	20	0.6	2.7	7.0
	30	0.6	5.1	7.9
	50	0.6	8.6	8.6

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In general, the acceleration as measured by the system accelerometers within the table meet the 5% except for the X and Z axis at 50 hz. The accelerometer mounted on the table top has worse results. This is most likely due to; slight pitch and rolling of the table, small differences in the calibration of the accelerometers.

2.4 Stroke wave distortion along each axis of the table : < 3% with 60 ton specimen

Table system was driven in each axis at a 0.1hz, 0.5hz, 1.0 hz and 5 hz near full displacement. In all cases the distortion was extremely low and less than 1.0%.

2.5 Acceleration wave distortion along each axis of the table with 60 ton specimen 20-80%

The table was tested at 2,4,8,10,15, 20, 30, 40 and 50hz. Tests were conducted at a low level and a high level. The specification was less than 10% for frequencies 8 hertz and lower, and 5% for frequencies 10 hz and higher. The table was operated with AHD function in the 469D which is very effective for removing harmonics up to 120hz. The results are listed in the chart below.

Acceleration waveform distortion - THD (%)									
	X axis			Y axis			Z axis		
Frequency	Test level	System accel.	Table top accel.	Test level	System accel.	Table top accel.	Test level	System accel.	Table top accel.
hz	(g's)	(%)	(%)	(g's)	(%)	(%)	(g's)	(%)	(%)
2	0.1	0.7	0.8	0.1	1.6	1.6			
4	0.2	0.5	0.5	0.2	2.3	2.5	0.2	0.7	0.8
8	0.2	0.3	0.3	0.2	0.9	1.1	0.1	1.2	1.9
10	0.3	0.6	0.9	0.3	0.7	0.5	0.2	2.2	2.5
15	0.3	0.3	0.6	0.3	1.2	1.3	0.2	0.6	1.1
20	0.3	0.5	0.7	0.3	0.9	0.8	0.2	2.6	2.4
30	0.3	1.8	1.4	0.3	0.7	1.3	0.2	2.9	3.8
40	0.3	4.0	4.1	0.2	3.3	2.8	0.2	7.7	5.8
50	0.3	4.6	3.2	0.2	2.1	2.1	0.2	17.7	23.0
2	0.4	1.3	1.4	0.4	1.4	1.4	0.3	1.7	1.9
4	0.6	0.5	0.6	0.6	0.8	0.8	0.4	0.7	0.9
8	0.6	0.3	0.4	0.6	0.4	0.5	0.4	1.0	1.9
10	1.0	0.4	0.4	1.0	0.7	0.7	0.6	0.9	3.4
15	1.0	0.5	0.6	1.0	0.5	0.7	0.6	0.8	2.1
20	1.0	1.3	1.7	1.0	0.5	1.0	0.6	1.5	4.7
30	1.0	1.3	3.7	1.0	2.2	5.1	0.6	2.5	7.1
40	1.0	6.9	6.9	0.8	6.7	3.6	0.6	6.5	11.5
50	0.6	12.8	12.3	0.8	4.2	8.1	0.6	11.0	12.8

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Comments: For frequencies 8 hertz and lower the THD was much better than the specification. Typical values were less than 1% for the X and Y axis and less than 2% for the Z axis versus the specification of 10%. At higher frequencies the THD increased due to table/specimen modes in the Z direction.

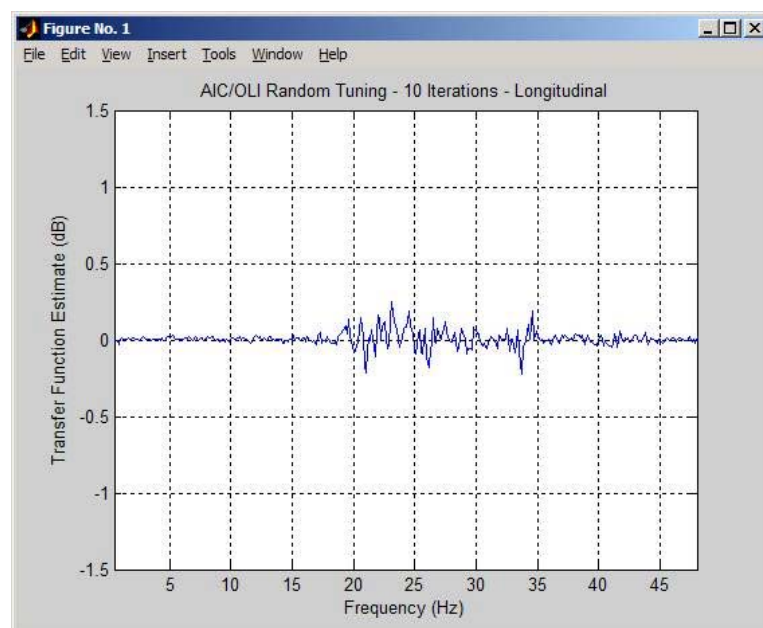
2.6 Permissible max. display accuracy of acceleration range : $< \pm 5\%$

System was tested at 2, 20 and 40 hz with no payload. At each frequency the shaking table was excited at 0.2, 0.4 and 0.8 g's in each axis. In all cases the external measuring device was within 5% of the system (table accelerometer) read out.

2.7 Within usable frequency range, unevenness of acceleration-frequency curve $< \pm 1.5$ db

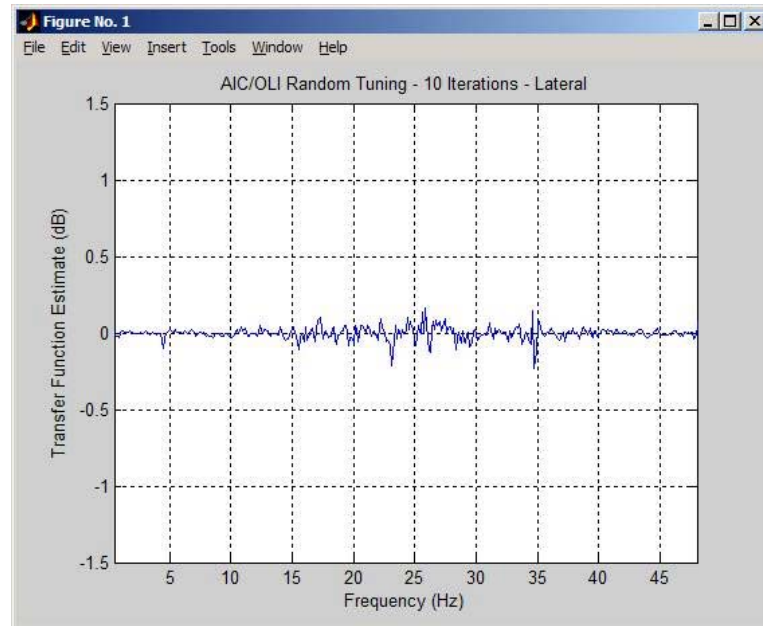
System was tested with the elastic specimen in X, Y and Z directions. In all cases the unevenness of the transfer function was much less than 1.5 db. (See below)

Transfer function for X axis:

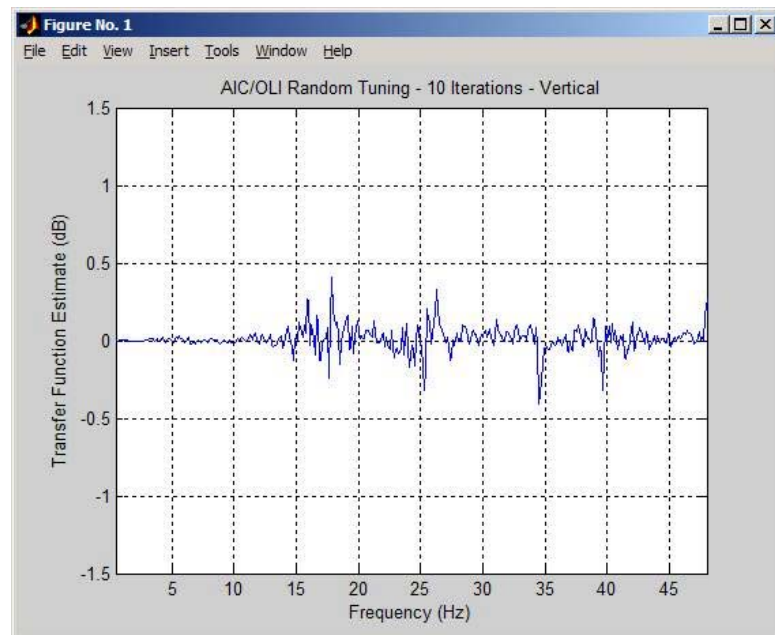


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Transfer function for Y axis:



Transfer function for Z axis:



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2.8 Within 60 minutes, the permissible max. stability of acceleration: $< \pm 5\%$

System was excited at 0.6 g and 5 hz, the amplitude of the center accelerometer was recorded for 60 minutes by the 469D data recorder. Variation was much less than 5%.

2.9 Power Spectrum repetitive error of random wave: $< 3\%$

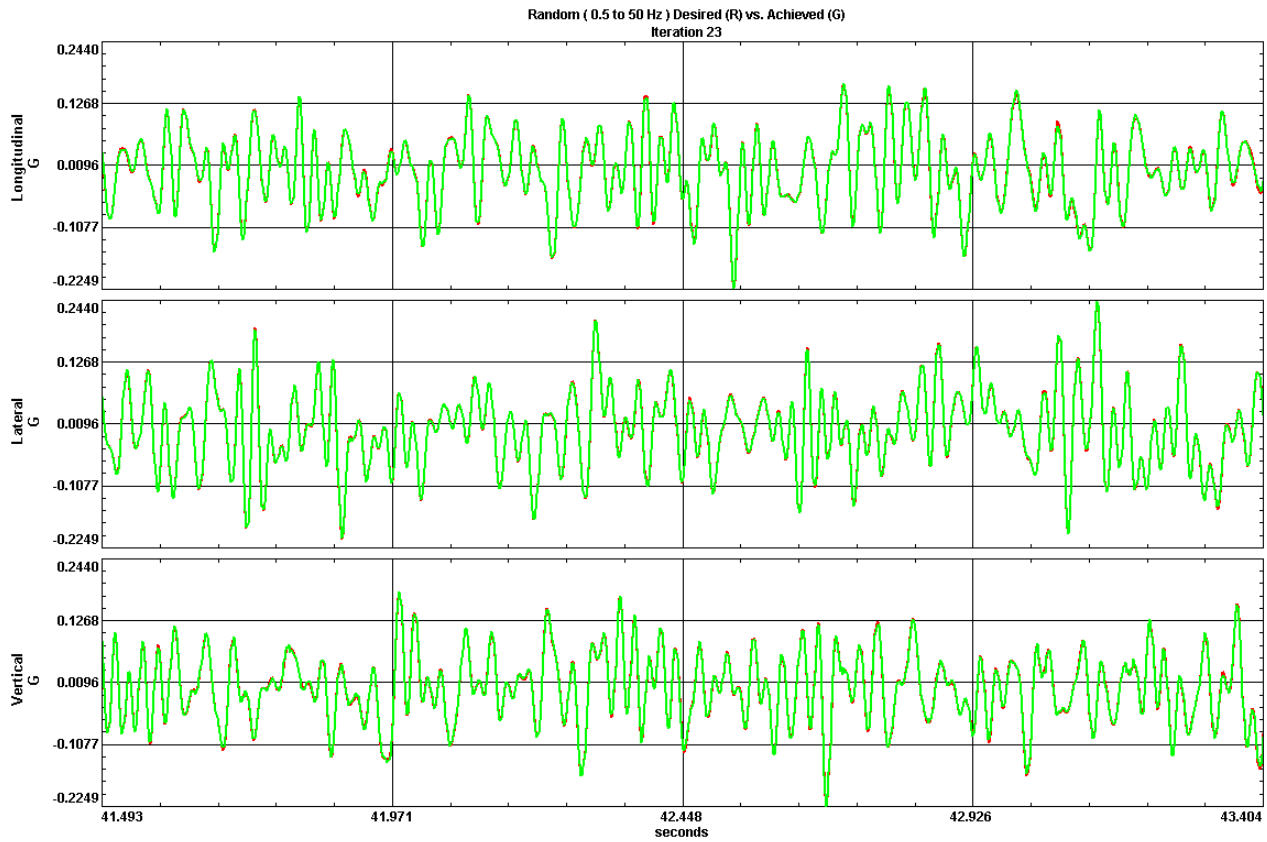
The table and elastic specimen were simultaneously excited tri-axially by a random signal with frequency content between 0.5 and 50 hz. The spectrum of the desired versus actual was compare in all cases the difference was much less than 1%. Tests were run with the 469D controller as well as the STEX off line system. See chart below.

Power Spectrum repetitive error (%)		
Axis	469D controller	STEX
X	0.06	0.093
Y	0.025	0.065
Z	0.1	0.139

2.10 Time-history wave repetitive error of random wave $< 3\%$ (elastic specimen)

The table and elastic specimen were simultaneously excited tri-axially. The time history of the desired versus actual was compared. Tests were run with the 469D controller as well as the STEX off line system. See plots below. (red is desired, green is achieved).

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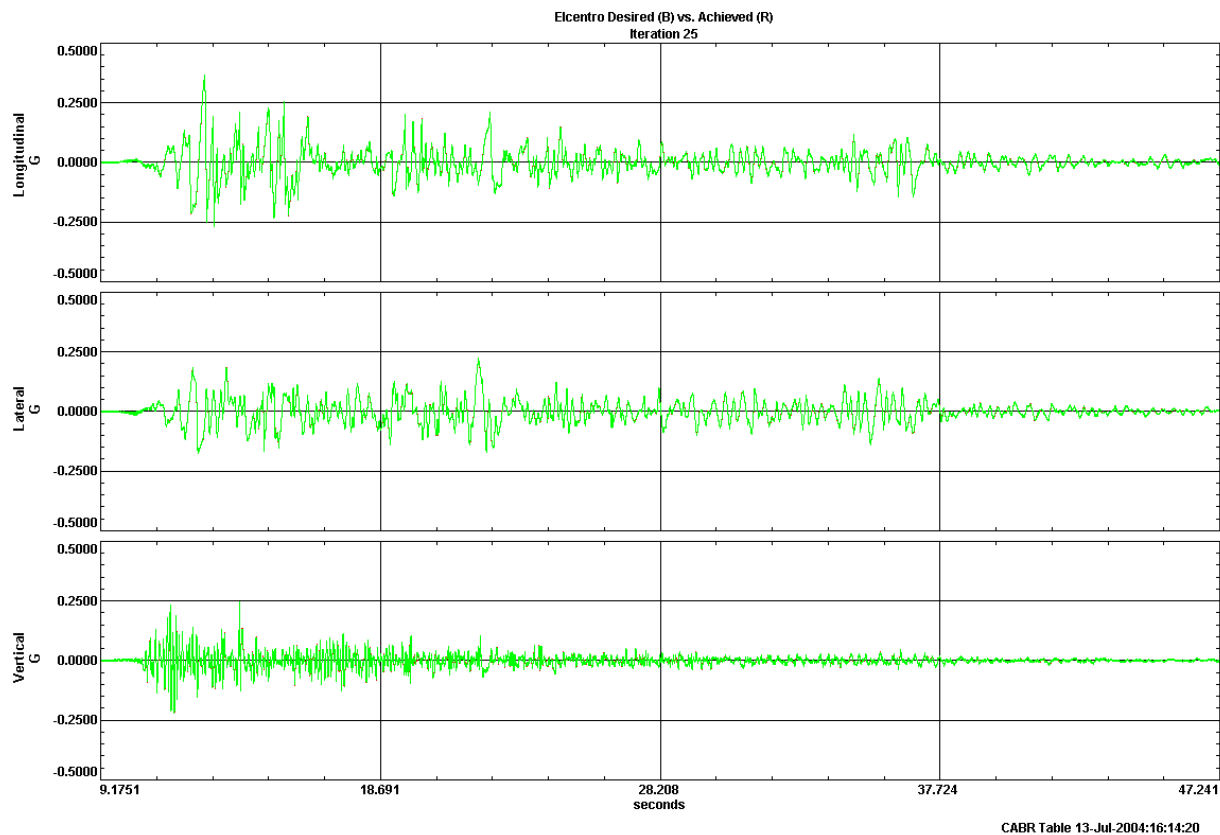
The actual measured error was close to 3 %. See chart below.

Time History repetitive error (%)		
Axis	469D controller	STEX
X	2.93	2.41
Y	2.48	1.58
Z	3.56	3.16

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2.11 Time-history wave repetitive error of earthquake wave <3% (elastic specimen)

The table and elastic specimen were simultaneously excited tri-axially using the El-Centro wave form. The time history of the desired versus actual was compared. Tests were run with the 469D controller as well as the STEX off line system. See plots below. (red is desired, green is achieved)



The actual error measured was larger than 3 % even though the time histories were extremely close. This larger % error is due mainly to the very low programming levels for much of the waveform. The signal to noise ratio is quite large at levels less than 0.005 g's. This is especially true for the vertical axis which has very low excitation levels.

El Centro Time History repetitive error (%)	
Axis	STEX
X	3.64
Y	3.96
Z	7.49

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2.12 System should be operated continuously for more than 8 hours (60 ton specimen)

System was programmed tri-axially and successfully run for more than 8 hours with no change in performance or any shutdowns.

2.13 Check safety –protection functions of the system one by one

While the system was being programmed and at full pump pressure various fail safes were successfully checked, these included:

Emergency stop: All E-stops were checked on console, main level, in pit and on pumps.

Main power failure: Control room power, pump power and PLC power were checked by disconnecting the power .

Control system failure: The control system was checked to make sure that the program was spanned down and the table was parked smoothly under the above shut down conditions.

System limits: All system limits were checked. These include program and feedback limits for displacement, velocity, acceleration and force. There are three modes: pump shutdown, program stop and indicator mode. These were all demonstrated.

Safety protection of pumps: Various functions such as low level, dirty filter, over temperature were checked to make sure the correct course of action was followed. The correct display of these events on the PLC screen was also verified.

Data acquisition and analysis system

3.1 128 Channel data acquisition system

32 channels of strain gages and accelerometers were mounted on system. These were monitored during the elastic specimen testing to demonstrate the set up and recording of data. Analysis tools were also demonstrated.

Computer Software Demonstration

During customer training all functions and features of software on both the 469D and STEx system was demonstrated. These included the generation and playback of random signals, artificial waveforms,

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earthquake waveforms from a data base. Analysis functions such frequency spectrum analysis, time-domain analysis, etc were demonstrated.

3.3 Control of remotely mounted specimen transducer

An accelerometer mounted on top of the elastic specimen was used as the control accelerometer. STEX was used to control as desired waveform at this location. The achieved results were similar to those for control of table accelerometers.

3.4 Sine Sweep

Control of the table was demonstrated using sine sweep on the 469D controller as well as sine sweeps generated by STEX off line.

3.5 Other software functions

All the various adaptive control features of the 469D were successfully demonstrated. These included the Adaptive Harmonic Cancellation (AHC), Adaptive Inverse Control (AIC), Amplitude/Phase Control (APC) and Online Iteration (OLI)>