Servo Motor Driven Shake Tables for Multi-Axis Testing

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Multi-axis vibration excitation systems using servo motor drives are described. Applications include seismic, squeak and rattle, stress screening, packaging, and service simulation testing.

A unique new design of independent multi-axis vibration tables was created by using programmable servo motors. This is exemplified in test systems recently delivered by ANCO Engineers to two laboratories performing seismic qualification testing of nuclear power plant components. Vibration tables constructed utilizing these principles can be used in seismic testing, squeak and rattle testing, packaging testing, stress screening, road and aircraft simulators, and similar applications. Using servo motors, these tables achieve the low frequency long stroke capacity of servo hydraulic systems, while having the convenience and relative quietness of an electromagnetic vibrator. For payloads of one ton or less, and for frequencies under about 200 Hz, servo motors offer an attractive alternative to servo hydraulic actuators.

An independent triaxial implementation is shown in Figure 1. Six servo motors are used, in three pairs. Each pair is connected by a torque tube. The three torque tubes serve to prevent table pitch, roll, and yaw. The servo motors act directly on the torque tubes, to which are attached six arms, using Teflon lined rod ends, to actuate the table. A Pentium PC controller serves to transform the desired orthogonal motions of the table (surge, sway, and heave) into the required independent rotations of the torque tubes. A constant force air cylinder and reservoir are placed under the table to support the table/test object dead weight and relieve the servo motors from the need to vertically support this dead weight. The air cylinder reacts against the polished bottom of the table with a Teflon slip plate.

The triaxial table capacity is shown in Figure 2. Peak table displacement of ±5 in (±13 cm) and peak table velocity of 100 in/sec (2.5 m/sec) are possible. With a payload of 50 lbs (22 kg), peak table acceleration in excess of 6 g is achieved. With a payload of 200 lbs (90 kg) the peak table acceleration is 3 g. These can be reached simultaneously or individually, in all three axes. Payloads up to 800 lbs (360 kg) can be accommodated. The table has good fidelity and control up to 50 Hz, and excitation capability to 200 Hz. Sine, sine sweep, sine beat, random, and previously measured waveforms can be reproduced.

These capabilities are sufficient for qualifying equipment to the most severe seismic requirements specified for nuclear power plants and telecommunication facilities, according to industry specifications such as IEEE-Std-344-1987 and Bellcore TR-NWT-000063.[1,2] Typical performance is shown in Figure 3, where the table achieves a close fit to the required response spectrum. That is, the Test Response Spectrum (TRS) closely envelopes the Required Response Spectrum (RRS). This is a good fit, especially in the high frequency region (zero period acceleration) where servo hydraulic tables typically over test by 100% or more. The table can also meet IEEE-344 requirements for independence between orthogonal motions (coherence under 0.5 between each of the three orthogonal table motions).

Servo Motors and Controllers

The table actuators used in this implementation are hybrid servo motors which are available from Parker Compumotor.[3] These brushless servo motors have a microprocessor based drive and power supply with built in test modes, and a

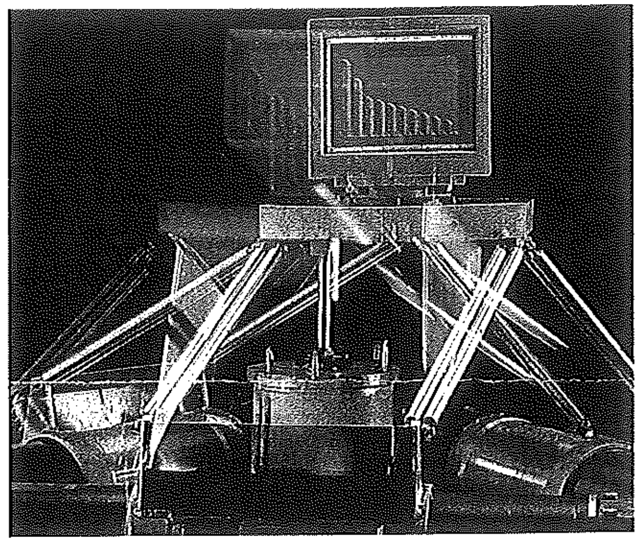

Figure 1. Servo motor driven triaxial table.

brushless resolver for position feedback. They have a flat torque/speed curve and smooth rotation at slow speed, and an external rotor with no speed reducers required. The model used is capable of producing 370 ft-lbs (500 N-m) torque, at up to 1.5 radians/sec, with 30 arc-second positioning accuracy. In typical configurations these drives can produce up to 1,000 lbs (4,400 N) of linear force, with up to ±5 in (±13 cm) stroke. They can be connected in series for additional torque or force. These servo motors are highly reliable, having been developed for robotics and assembly line applications such as welding stations in automobile manufacturing. Their normal maintenance time is after 20,000 hours of continuous operation. They can operate at 60% of full power indefinitely, without cooling, and at 100% for over 5 minutes. Each servo motor is powered by up to 7.5 kVA of three phase 200 VAC power. The servo motors used are among the largest available commercially. A variety of units with lower peak torque, but otherwise equal dynamic capacities, are also available.

The servo motors can be operated in the displacement, velocity, or torque control mode, using analog or digital inputs. For higher frequency shake table operation the torque control mode has the best performance characteristics when coupled with a rotary feedback signal to complete a servo control loop, using servo controllers from Gardner Systems.[4] This analog servo control loop provides for both velocity and acceleration feed forward. In this configuration the Parker servo motors control well under displacement command at lower frequencies. In this lower frequency range the servo motors are similar to a servo hydraulic actuator. At higher frequencies the Parker servo motors can be controlled as an acceleration (force) control system, similar to an electromagnetic vibration exciter. The controlling PC is used to preprocess the servo motor signal in the frequency domain, to accommodate both these control regimes simultaneously. The triaxial table implementation discussed herein has been successfully controlled up to 100 Hz. Servo motors can potentially be used as high as about 300 Hz, but this will require very rigid and gap free design of the multi-axis table structure. For example, in the triaxial configuration discussed here, both a COSMOS finite element model and operational test data place the first table/servo motor arm/torque tube mode at approximately 65 Hz.

MULTI-AXES SERVO-MOTOR DRIVEN SHAKE TABLES

by

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A unique new design of independent multi-axes vibration tables is created by using programmable servo-motors. This is exemplified in test systems recently delivered by ANCO Engineers to two laboratories performing seismic qualification testing of nuclear power plant components. Vibration tables constructed utilizing these principles can be used in seismic testing, squeak and rattle testing, packaging testing, stress screening, road and aircraft simulators, and similar applications. Using servo-motors, these tables achieve the low frequency long stroke capacity of servo-hydraulic systems, while having the convenience and relative quietness of an electromagnetic vibrator. For payloads of one ton or less, and for frequencies under about 200 Hz, servo-motors offer an attractive alternative to servo-hydraulic actuators.

Triaxial Implementation

An independent triaxial implementation is shown in Figure 1 (and also on the cover of this issue). Six servo-motors are used, in three pairs. Each pair is connected by a torque tube. The three torque tubes serve to prevent table pitch, roll, and yaw. The servo-motors act directly on the torque tubes, to which are attached six arms, using Teflon-lined rod ends, to actuate the table. A control Pentium PC serves to transform the desired orthogonal motions of the table (surge, sway, and heave) into the required independent rotations of the torque tubes. A constant force air cylinder and reservoir are placed under the table to support the table/test object dead weight and relieve the servo-motors from the need to vertically support this dead weight. The air cylinder reacts against the polished bottom of the table with a Teflon slip plate.

The triaxial table capacity is shown in Figure 2. Peak table displacement of ± 5 inches (± 13 cm) and peak table velocity of 100 inches/sec (2.5 m/sec) are possible. With a payload of 50 pounds (22 kg), peak table acceleration in excess of 6 g is achieved. With a payload of 200 pounds (90 kg) the peak table acceleration is 3 g. These can be reached simultaneously or individually, in all three axes. Payloads up to 800 pounds (360 kg) can be accommodated. The table has good fidelity and control up to 50 Hz, and excitation capability to 200 Hz. Sine, sine sweep, sine beat, random, and previously measured time histories are possible.

These capabilities are sufficient for qualifying equipment to the most severe seismic requirements specified for nuclear power plants and telecommunication facilities, according to industry specifications such as IEEE Std-344-1987 (1) and Bellcore TR-NWT-000063 (2). Typical performance of the table is shown in Figure 3, where the table achieves a close fit to the required response spectra (shock spectra). That is, the Test Response Spectra (TRS) closely envelopes the Required Response Spectra (RRS). This is a good fit, especially in the high frequency region (zero period acceleration) where servo-hydraulic tables typically over test by 100% or more. The table can also meet the IEEE Std-344-1987 requirements for independence between orthogonal motions (coherence under 0.5 between each of the three orthogonal table motions).

Servo-Motors and Controllers

The table actuators used in this implementation are hybrid servo-motors, shown in Figure 4, which are available from Parker Compumotor (3). These brushless servo-motors have a microprocessor-based drive and power supply with built in test modes, and a brushless resolver for position feedback. They have a flat torque/speed curve and smooth rotation at slow speed, and an external rotor with no speed reducers required. The model used is capable of producing 370 foot-lbs (500 N-m) torque, at up to 1.5 rps, with 30 arc-second positioning accuracy. In typical configurations these drives can produce up to 1,000 pounds (4,400 N) of linear force, with up to ± 5 inches (± 13 cm) stroke. They can be connected in series for additional torque or force. These servo-motors are highly reliable, having been developed for robotics and assembly line applications such as welding stations in automobile manufacturing. Their normal maintenance time is after 20,000 hours of continuous operation. They can operate at 60% of full power indefinitely, without cooling, and at 100% for over 5 minutes. Each servo-motor is powered by up to 7.5 kVA of three-phase 200 VAC power. The servo-motors used are among the largest available commercially. A variety of units with lower peak torque, but otherwise equal dynamic capacities, are also available.

The servo-motors can be operated in the displacement, velocity, or torque control mode, using analog or digital inputs. For higher frequency shake table operation the torque control mode has the best performance characteristics when coupled with a rotary feedback signal to complete a servo-control loop, using servo-controllers from Gardner Systems (4). This analog servo-control loop provides for both velocity and acceleration feed forward. In this configuration the Parker servo-motors control well under displacement command at lower frequencies. In this lower frequency range the servo-motors are similar to a servo-hydraulic actuator. At higher frequencies the Parker servo-motors can be controlled as an acceleration (force) control system, similar to an electromagnetic vibrator. The controlling PC is used to preprocess the servo-motor signal in the frequency domain, to accommodate both these control regimes simultaneously. The triaxial table implementation discussed herein has been successfully controlled up to 100 Hz. Servo-motors can potentially be used as high as about 300 Hz, but this will require very rigid and gap free design of the multi-axes table structure. For example, in the triaxial configuration discussed here, both a COSMOS finite element model and operational test data place the first table/servo-motor arm/torque tube mode at approximately 65 Hz.

In addition to the analog real time control discussed above, the table motion is digitally-batch equalized using a transfer function measurement and correction procedure. In this procedure, the table is excited with random noise, in turn, in each of its axes, and the response is measured in all axes. This allows the table/test object frequency domain transfer function to be computed. The desired table motion is then multiplied, during digital preprocessing, by the inverse of this transfer function, so as to compensate for the table/test object impedance and produce a much closer fit to the desired table response. Typical performance reproduces the desired time history root-mean-square and peak value to about 5% - 10%.

Low Acoustic Signature

A significant advantage of servo-motor actuators is their low acoustic signature. In certain applications, such as automotive buzz, squeak and rattle testing, conventional table noise can interfere with the test, and may require construction of an insulated chamber on or around the table. The need for an "on-table" chamber reduces table payload weight and size. Even an "off-table" chamber increases the complexity and cost of the table and of the instrumentation setup. For example, typical noise levels on a multi-axes servo-hydraulic table are 75-80 dB ("A" weighted scale). To perform squeak and rattle testing, the noise level just above the table top typically needs to be under 60-65 dB. On a servo-hydraulic table, elaborate methods (including an insulated chamber, a remote well insulated pump room, and low noise ball joints), are needed to reduce the 75-80 dB to 60-65 dB. Reducing the noise below 60 dB is nearly impossible using a servo-hydraulic system.

Measurements made on the six servo-motor triaxial table indicate table top noise levels of 60-65 dB (made with an MSA PN 695090 hand-held sound meter in a reverberating room) without any acoustic insulation. The noise can be reduced to less than 55 dB with minimal acoustical insulation around the servo-motors.

Alternate Configurations

The triaxial system described herein can be operated with full six axes independent motion (surge, heave, sway, pitch, roll, and yaw) by removal of the torque tubes and independent control of each of the six servo-motors. The servo-motors can be connected together to achieve higher torque (acceleration), longer arms can be used for greater displacement and velocity, shorter arms can be used for greater acceleration. Orthogonal orientation of the servo-motors are possible, as well as the implementation of 8 or more independent axes. Hence the technology of servo-motors can be applied to almost every area of motion base simulation and testing.

Conclusions

Servo-motors are reliable, quiet, and easily integrated prime movers that have numerous applications in vibration testing systems. The advent of larger and more sophisticated servo-motors and control systems opens up the field of application and allows servo-motors to take their place alongside servo-hydraulic actuators and electromagnetic vibrators.

Acknowledgments

The author wishes to thank Ralph Purugganan and his staff at Parker Compumotor, and Joe Gardner and Rick Reeves at Gardner Systems for their invaluable contribution during the development of the servo-motor control system. At ANCO, John Stoessel and Jim Sherrick contributed greatly to the multi-axes table design, assembly, and check out. The author also thanks Bob Jabs and his staff at Westinghouse (Pittsburgh), and Heinrich Melinz and his staff at Science Applications International (Huntsville), for their suggestions and cooperation during installation of the triaxial tables at their facilities.

References

1. IEEE Std-344-1987, "*IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Generating Stations.*"

2. Bellcore TR-NWT-000063, "*Network Equipment-Building System, Generic Equipment Requirements*", Issue 5, September 1993.

3. Parker Compumotor, Rohnert Park, California.

4. Gardner Systems, Santa Ana, California.

Biography of Dr. Paul Ibanez

Dr. Ibanez received his engineering degrees at UCLA, completing his dissertation in 1972 on parameter identification techniques using experimental data from sinusoidal and transient testing of civil structures. Since then he has worked at ANCO Engineers using, and delivering to clients, eccentric mass vibrators to identify dynamic properties of structures and equipment, and designing servo-hydraulic servo-motor multi-axes shake tables to perform seismic qualification on telecommunication and nuclear power plant equipment. Dr. Ibanez has assembled over twenty multi-axes vibration test systems using electromagnetic, servo-hydraulic, and servo-motor actuators, and including PC-based data acquisition, processing, and control systems. He is currently President of ANCO Engineers, Inc.

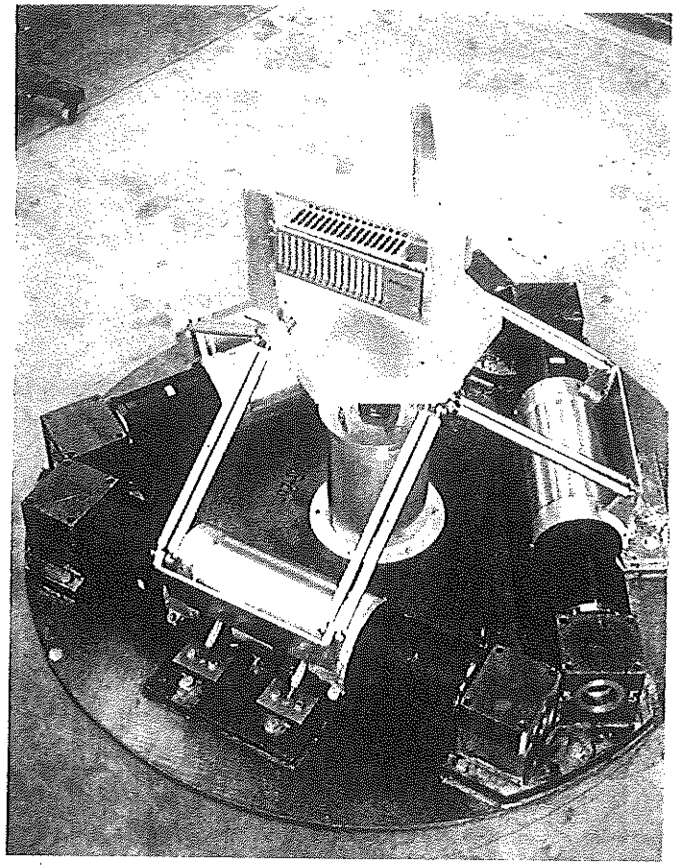

Figure 1: Independent Triaxial Implementation

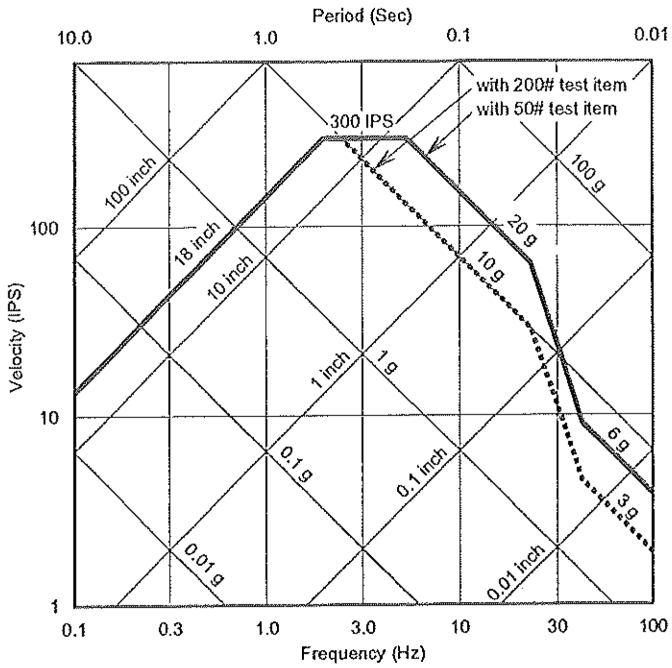

Figure 2: Triaxial Table Response (Shock) Spectra Capacity

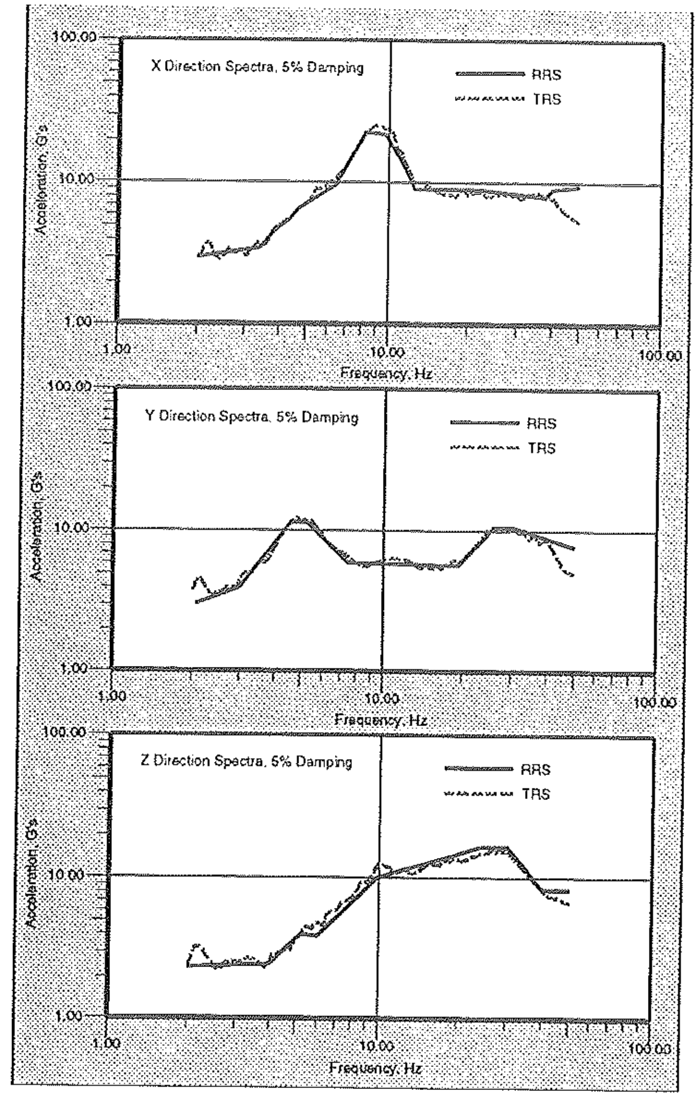

Figure 3: Fidelity of the Triaxial Table

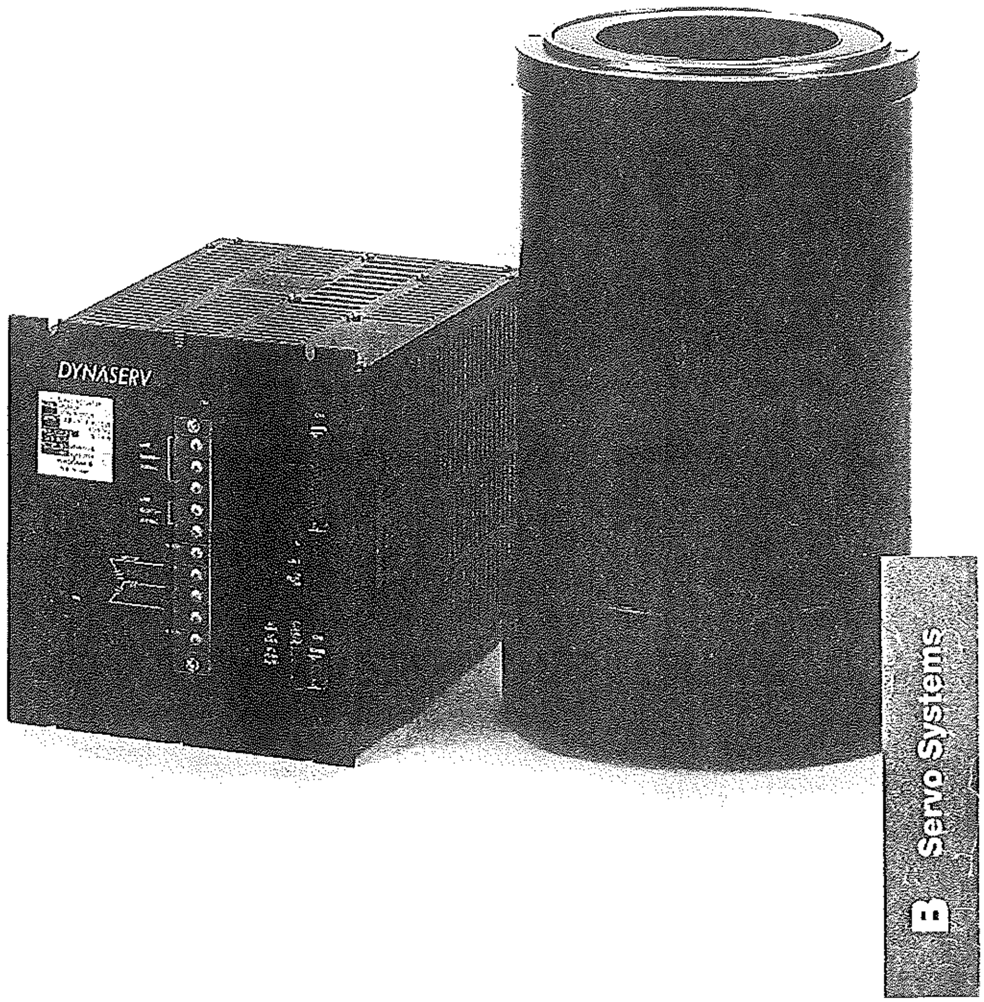

Figure 4: Brushless Servo-Motors From Parker Compumotor