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COMPUTER-CONTROLLED MULTIPLE-ACTUATOR SHAKER
OFFERS VERSATILE TEST CAPABILITIES

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COMPUTER-CONTROLLED MULTIPLE-ACTUATOR SHAKER OFFERS VERSATILE TEST CAPABILITIES

ABSTRACT

The Laboratory's multiple-actuator shaker facility at Site 300, developed for weapons testing, is now also being used for such studies as shock and vibration tests of rocket motors, seismic qualification of a turbine-generator set, and performance analysis of the rock bolts used in mine-tunnel construction. Rigid loads exceeding 9 tonnes can be tested over a wide frequency range (dc to 500 Hz) with up to 120 channels of real-time data acquisition and display. Capabilities include the safe testing of hazardous materials and explosives exceeding 90-kg TNT equivalent. The computerized control system permits the shaker to be easily adapted to nonstandard shock and vibration tests. The shaker can be used for a wide variety of projects, such as materials testing, aerospace structural-response studies, seismic proof testing, and conventional ordnance work.

INTRODUCTION

Development of the shaker facility at Site 300, near Livermore, began in July 1968 in response to weapons-program requirements for a high-force, high-amplitude, low-frequency shock and vibration test capability. The first stage of construction was completed in the fall of 1970 at a cost of \$2,374,836 (see Table 1). A 0.62-MN-thrust electrohydraulic shaker with four portable, base-mounted actuators was brought on line then under an interim analog control system. A year later we began developing the digital-computer control system¹ that now operates the facility. Various technical problems have been solved, such as actuator cross-coupling (undesirable responses of one actuator to the motions of the other actuators). The facility is now unique in its sophistication, versatility, and test capabilities.

Table 1. Total capital value of the test facility.

Building No.	Building value	Equipment value	Total
863A	\$183 997	\$1 116 819	\$1 300 816
863B	274 927	80 697	355 624
863C	650 001	68 395	718 396
	\$1 108 925	\$1 265 911	\$2 374 836

TEST FACILITY

Figure 1 shows the arrangement of the test facility's three units: a control building for data-acquisition and control equipment, an equipment building for hydraulic power supply, and the test cell in which the shaker is located. The test cell, physically isolated from the control and equipment buildings, has sufficient overpressure design to permit safe testing of specimens exceeding 90-kg TNT equivalent. It also has air scrubbers and a containment system for radiation hazard control.

The hydraulic power supply consists of 11 individually controlled, pressure-compensated, 0.11-MW pumps running in parallel. Their combined continuous output is $0.043 \text{ m}^3/\text{s}$ (680 gpm) at a nominal supply pressure of 20.7 MPa. Peak flows to the four electrohydraulic actuators are $0.014 \text{ m}^3/\text{s}$ (225 gpm). We use a fire-retardant synthetic oil for safety.

Each actuator has a maximum thrust capability of 0.155 MN and a total stroke of 127 mm. Integral hydrostatic guide bearings can support cross-axis loads up to 0.04 MN without actuator damage. The high-performance, two-stage servovalves have a response time of $2.6 \times 10^{-4} \text{ s}$, resulting in a nominal actuator bandwidth of 500 Hz and a peak velocity of 2 m/s. Stroke length, peak velocity, force output, and valve response combine to give the single-actuator performance characteristics shown in Fig. 2.

Because the actuators are free-standing and relocatable, they can be bolted either to the top surface (for z-axis motion) or to the vertical abutments (for x- and y-axis motion) of the 680-tonne reinforced-concrete reaction mass. As shown in Fig. 3, threaded attachment sockets are provided for this purpose in the abutments and in the heavy steel plate that covers the reaction mass. This versatility gives us great latitude in fixturing (attaching a specimen to the actuators) and also in accommodating unusual specimen/actuator configurations.

In the most common test configuration (z-axis vibration), the actuators drive a rigid table to which the test specimen is secured. Two tables are available: a 3.8 m by 1.9 m unit weighing 1814 kg for four-actuator testing and a 1.6 m by 1.5 m unit weighing 640 kg for three-actuator testing. In both cases, the maximum clearance between the table surface and the overhead crane hook (10.7-tonne capacity) is 3.9 m. By securing the actuators against the

Fig. 1. Site 300 dynamic test facility arrangement.

Fig. 2. Sinusoidal performance characteristics of a single actuator.

Fig. 3. Typical test configurations for z-axis motion (top), where the specimen is a shipping container, and y-axis motion (bottom), where the specimen is an upper-stage missile structure.

abutments and placing the test specimen on hydrostatic guide bearings, we can accommodate very massive specimens for x- or y-axis testing (see Fig. 3).

We have installed a wide range of signal-conditioning and data-acquisition equipment. The general instrumentation equipment includes 24 channels of strain-gage conditioning, 12 channels of thermocouple reference junctions, 24 channels of dc differential amplifiers, and 12 channels of piezoelectric-transducer signal conditioners. Recording equipment includes a 32-track FM tape recorder and a 24-channel light-beam oscillograph. For unusual test requirements, we can easily integrate additional equipment into the system. In the past, as many as 120 data channels have been conditioned and recorded for a single test.

Computerized Control System

Figure 4 shows the configuration of the computerized control system. We have three hardware groupings: digital control hardware, hybrid interface components, and the analog process. The analog process can be either the actuators and test specimen (actual test hardware) or a dynamic simulation on a small, general-purpose analog computer. The simulation capability, originally needed to develop the computerized system, is now used for operator instruction and developing new-application software.

The command generation and data acquisition units (see Fig. 4) comprise the hybrid interface. The generation unit receives command data either directly from the computer or indirectly from the digital waveform synthesizer, which is used in sinusoidal-response testing to generate a repetitive waveform. Under control of the computer, the generation unit converts the digital commands to analog voltages, then combines, scales, and feeds the results to the actuator controllers. All four actuators can be commanded independently.

The data acquisition unit selects the appropriate response signals, converts them to digital form, and performs various preliminary data-processing functions. For each of the actuators, the unit can select the actuator displacement, load pressure, or associated specimen response as a feedback signal. The selected signal is scaled, filtered, sampled, and digitized with 12-bit precision at rates up to 50 000 samples/s. The data can then be fed directly into the computer or, in the case of sinusoidal-response testing, further processed to yield peak, coincident, and quadrature components of response that are input after a slight delay.

Fig. 4. Computer control system for the multiple-actuator shaker.

The computer system is configured about a 16-bit-word-size central processor having 64 000 words of 800-ns core memory, floating-point hardware, a 12-Hz real-time clock, and an interval timer. Peripherals include a 1.2×10^6 -word disk memory, seven-track magnetic tape unit, card reader, electrostatic printer, CRT graphics terminal and operator control console, and a hardware fast-Fourier-transform processor.

The control system operates as a closed loop, repetitively feeding response data to the computer from the acquisition unit and comparing the data with the desired test levels. New commands are computed and the results used to update the waveform synthesizer and/or command generation unit. The latter continuously feeds analog commands to each of the actuators, which in turn try to produce physical displacements in direct proportion to the command voltage levels. Appropriate transducers sense the resulting motion, returning the data to the acquisition unit to complete the loop.

Because of resonances in the table-specimen structure, the motion of one actuator may cause undesired response at any other actuator. Historically, this cross-coupling has been a severe problem in multiple-actuator systems. A cross-coupled control system can be represented by a transfer matrix where the nonzero, off-diagonal terms are the cross-coupling. Ideally, we would like all the off-diagonal elements to be zero. To achieve this, we introduce a compensation matrix, which is simply the product of the desired system-transfer matrix and the inverse of the measured transfer matrix. By knowing the response characteristics of the system (in this case the combination of actuators, fixturing, and test specimen), we then calculate the input signals needed to produce the desired response. In essence, the actuators, to do one thing, are commanded to do another.²

Our new multiple-actuator control system is the first attempt to control cross-coupled actuators digitally. We have succeeded because (1) the system transfer matrix is determined by perturbation techniques at the full test level to minimize nonlinear effects, and (2) general-purpose computer hardware permits the command compensation to be "tuned" to the system at an arbitrarily large number of frequencies. Thus implemented, our technique permits the same hardware to be used for a wide variety of tests.

Test Capabilities

Under computer control, the actuators are easily programmed to perform virtually any test within the fundamental mechanical/hydraulic performance limits defined in Fig. 5. General-purpose programs have been written for the most commonly performed tests. Each of these programs (see Table 2) features the CRT terminal and operator's console as the man-machine interface. By means of an interactive question-and-answer sequence, the operator defines the test to be performed. The test specification can be executed at once or stored for later use.

Table 2. Standard control and data processing programs.

Program	Description	Applications
SINE ^a	Swept-frequency sinusoidal testing	Resonance surveys, mechanical impedance studies, proof testing, fatigue tests
TRAN ^a	Transient response testing	Shock spectrum, fatigue tests, seismic simulations
RAND ^a	Random vibration testing	Transportation or flight environment proof testing
TEN/COM	Tension/compression testing	High-shear-rate material properties, impact tests
GPDAP	General-purpose data analysis and plotting	Post-test spectral and time-domain data analysis

^a Encompass classical shock and vibration tests.

During testing, the operator can interrogate the computer at any time to determine the test status. Data acquisition of all critical control parameters is performed by the computer, and the data are available for plotting immediately following the test. Also, data recorded on the 32-track FM tape recorder can be played back, digitized, and processed immediately. A typical plot resulting from on-line data acquisition and reduction is shown in Fig. 5.

The programs described in Table 2 encompass the bulk of testing done at the shaker facility. However, the real advantage of a computerized system becomes evident when unusual requirements are first encountered, as in the

Fig. 5. Results of on-line data acquisition and analysis during random vibration test.

case of high-shear-rate tension/compression tests. For these applications, no special hardware or long development programs are necessary. We need only write a short executive program calling the required functional subroutines. The resulting program then becomes one of our standard capabilities. This adaptability, combined with our flexibility in actuator positioning and fixturing, accommodates test criteria that would be impossible with conventional systems.

Applications

High performance and computer-controlled versatility distinguish our test facility from other such complexes. The principal features include:

- Capacity to handle large, rigid loads (in excess of 10.7 tonnes) over a wide frequency range (dc to 500 Hz).
- Real-time data acquisition and display during testing.
- Easy adaptability to nonclassical shock and vibration tests.

This combination permits the shaker facility to be used for a wide variety of projects, such as materials testing, aerospace structural response studies, seismic proof testing, and conventional ordnance work.

We are under contract to the U.S. Air Force Space and Missile Systems Organization to perform shock and vibration tests on two MX upper-stage rocket motors being developed by Aerojet Solid Propulsion Company, Sacramento, California. The investigation concerns the dynamic response characteristics of these motors and their ability to survive specified environments. Our shaker facility is the only test complex equipped to test live rocket motors of this size. We also completed a study for the Army Corps of Engineers to determine the high-stress-rate response characteristics of rock bolts used in mine-tunnel construction. Seismic qualification tests are now under way on an emergency power turbine-generator set to be installed at LLL's plutonium research facility. We are making the test facility available to such users and will become involved in other varied projects as its capabilities receive wider recognition.

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