DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Calibration and Acceptance Testing of the DR-200 Digital Seismograph with S-6000 and L-4C Seismometers

by

David L. Carver[1], David R. Cunningham[1] and Kenneth W. King[1]

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Denver, Colorado

1986

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INTRODUCTION

The Urban Hazards Program of the U.S. Geological Survey (USGS) had a need for portable digital seismographs to record earthquakes and manmade seismic sources in a wide range of environmental conditions. The seismic data will be used to document site response values, free-field and induced motions in structures, and earthquake source parameters. A rugged and reliable recording system is needed that has a large dynamic range, low internal noise, and the capability to be reconfigured to suit the project at hand.

The Sprengnether DR-200 digital recorder was selected to fill this need. The recorder consists of a signal conditioning module, an analog-to-digital conversion module, power and timing module, and a cassette recording module all enclosed in a sealed case. The recorder can be controlled by a hand-held terminal without opening the case. Three channels of data (a fourth channel is an option) are recorded simultaneously on standard 1/4-in. magnetic tape cassettes. Gain, high-pass filter, and low-pass anti-aliasing filters are selectable for each channel. Other operating parameters such as sample rate, pre- and post-event memory, and trigger options are entered via the hand-held terminal. The DR-200 has a real time clock with provisions for synchronization to standard time. When a record is written, the header includes all of the operating parameters along with the time of the first sample of pre-event memory. Taken as a system the DR-200 is a very flexible seismograph that is able to adapt to a wide range of applications.

The first six DR-200's purchased were accepted at the Sprengnether factory. At that time we made extensive tests to determine that the instruments operated as specified. Results of that work are reported in this paper after a brief description of the DR-200 system characteristics. Later the DR-200's were taken to the U.S. Bureau of Mines' Operating Parameter Simulation Laboratory to calibrate the DR-200's with the S-6000 and L-4C seismometers on shaking tables. Results of that work are also presented here.

RECORDING SYSTEM DESCRIPTION

The Sprengnether DR-200 is a portable digital seismic-recording system. It is enclosed in a rugged, air-tight case weighing about 22 kg (50 lbs). A hand-held external controller is provided so that control parameters can be checked and changed without exposing the electronics to the environment. Input connectors are provided for a triaxial seismometer, as many as four single-channel seismometers, force-balance accelerometers, external timing, external synchronization, and external power supplies.

Data is recorded on 1/4-in. cassette magnetic tape. Each cassette is capable of recording 34 minutes of data at 200 samples per second per channel from three channels. Three data channels can be recorded on the standard system but an additional channel can be added as an option. Sample rate is selectable from 1 to 200 samples per second for either three- or four-channel recordings. A seven-pole Butterworth filter (42 dB/octave) is used for the low-pass anti-aliasing filter; the corner frequency can be set to 6.25, 12.5, 25, or 50 Hz. Low-frequency signal conditioning can be set either to D.C. response (no filtering) or to filter with a 0.1 Hz corner frequency. Amplifier gain is selectable at X1, X10, X100, or X1000. The analog-to-digital converter can be operated at X1, X4, X16, or X64 multiple gains in fixed gain mode or in automatic gain mode. The DR-200 automatic gain operates in an instantaneous floating point mode where the gain is varied from X1 to X64 for each data sample. The automatic gain mode provides 108 dB of dynamic recording range.

The DR-200 can be triggered either externally or internally. Internal triggering can be based on either exceedance of a specified absolute signal amplitude threshold or exceedance of a specified short-term/long-term average ratio. The long-term average can be held fixed during a record or it can be allowed to rise as a function of the post-trigger signal. External triggering can be manual, from a +5-volt pulse, or from another DR-200. Several systems can operate in synchronization when operated in a master-slave triggering mode. The DR-200 can also be turned on and off at several preset dates and times.

The system is capable of sampling rates of 1-800 samples per second in single channel mode, 1-400 samples per second in 2-channel mode and 1-200 samples per second in 3- or 4-channel mode. The system can record as many as 4,000 samples of pre-event memory and from 1 to 1,000 seconds of signal after the event.

The data on each channel is sampled at the same identical rate but the signal of each channel is conditioned separately. Gain, high-pass filter, and low-pass anti-aliasing filter corner frequency are independently selectable. Signal conditioning, date, time, and all other selectable parameters are recorded on tape in the header information at the beginning of each record. A 16-bit data word is written with 2,044 data words per data block.

Timing is provided by a temperature-controlled crystal oscillator with short-term stability of $\pm 1 \times 10^{-7}$ at constant temperature. The clock can be synchronized with a time standard either by automatic starting on an input time pulse or by manually advancing or retarding the clock until it comes into synchronization with the time standard. Time is recorded on each record header to the nearest 0.10 ms and a time bit in the data record flips state each second.

Seismometers

The DR-200 can record signals from many different transducers. For this study we use Sprengnether S-6000 three-component seismometers and Mark Products L-4C horizontal seismometers. The S-6000 is a suspended coil, fixed magnet seismometer. It uses annular suspensions to constrain the seismic mass to respond as a translating pendulum. The three orthogonal components are housed in an 18x18x20-cm weatherproof, cast-aluminum case. The S-6000 has an undamped electrodynamic constant of 282 volts per meter per second, a natural period of 0.62 sec and is damped 60 percent of critical.

The L-4C seismometer, a moving dual-coil design, is housed in a weatherproof cylinder 13 cm high by 7.6 cm in diameter. It has a period of 1, is damped 69 percent of critical, and has an undamped electrodynamic constant of 275 volts per meter per second.

ACCEPTANCE TESTING

Each DR-200 seismograph system was subjected to extensive testing during the acceptance test procedure to determine if the systems met their design specifications. The initial testing centered on the newly developed DR-200 recorder itself and not the seismometers as they have been in use for several years. All test equipment, oscilloscopes, and function generators were either shown to have a recent standard factory calibration or were checked with calibrated instruments.

Signal Conditioning

The DR-200's capability to reproduce a known input signal was tested through a wide range of frequencies. A calibrated input signal of ±5 volts was used to check the oscilloscope and function generators to maintain calibration standards. A calibrated function generator (Wavetek 191) was used to input ±5.0-volt sine waves from 1 to 60 Hz to each of the DR-200's for a calibration test. The recorded tapes from the tests were played back and the system response was found to be flat within the experimental accuracy in the frequency range of 1 to 60 Hz.

The systems' anti-aliasing filters were tested with a known signal input to the system. The anti-aliasing filters have 3 dB corner frequencies at 50, 25, 12.5, and 6.25 Hz and were shown to drop off at the specified 42 dB/octave.

The rate of digital sampling was tested by documenting the time between samples on a calibrated oscilloscope with a 100-ms sweep. The test was done at the 200 samples per second rate and was found to have a variance of less than ±0.5 ms (the maximum precision available from the oscilloscope).

Internal-Clock

The internal clocks of two DR-200's were compared to a time standard over a period of 48 hours. During that period, the DR-200's were undergoing thermal tests in which they were repeatedly taken from a 120 °F temperature controlled room and placed in a 12 °F to 20 °F cold chamber. The DR-200 clocks showed no more than 10-ms deviation from the standard clock at any time during the 48-hour testing period despite the wide variation in operating temperatures.

Thermal and Environmental Testing

Sprengnether Instruments Company provided a room that was kept at a constant air temperature of 120 °F and a cold chamber capable of temperatures as low as -20 °F. Two DR-200 systems were alternately placed in the hot and cold chambers for 8-12 hours at a time over a 48-hour test period. One instrument was inadvertently left in the cold chamber with its case unsealed. Ice formed on the circuit boards and the instrument failed to operate. After the recorder was brought to room temperature and dried off, it operated normally. The systems were cooled from 120 °F to 0 °F in five steps. No problems occurred when the instruments were operated within their specified limits (+120 °F to +32 °F), however, the system's tape drives failed to operate correctly at and below +12 °F due to variance in tape-transport speed. One hand-held remote-control terminal of three tested failed after several hours at 120 °F.

Check of Other System Features

The DR-200's preprogramming feature was tested over two 24-hour periods to turn the system on and off during the thermal testing. The preprogramming feature allows the DR-200 to turn itself on and off at preset times and dates. Wild-card conventions are available to allow the instrument to turn itself on, record in either continuous or short-term/long-term average trigger mode, and turn itself off again on the same minute of each hour or day. The feature was found to operate as the vendor specified.

Triggering of a record can come from either an external or internal signal. The external trigger capability allows several DR-200's to be networked together so that they are triggered by a master system and all begin recording at the same time with the sampling rates in synchrony. We tested this feature by checking the synchronization on a split-beam oscilloscope (on 100-ms sweep) and found the feature to be within vendor specifications.

Internal triggering is accomplished by either a long-term/short-term average ratio or by having the input signal exceed a specified level. We tested the former method with a taped input of earthquakes and earthquake-like signals in the magnitude 3-4 range with S-P's of less than 5. The DR-200 tested functioned according to specification. Level triggering was tested by inputting various amplitude signals and noting the level of triggering. The feature worked as specified.

SHAKE-TABLE CALIBRATION

The shake-table testing was done at the U.S. Bureau of Mines, Twin Cities Research Center (TCRC), Minneapolis, Minn. The vibration-test laboratory there has two separate devices that were used for shaking the S-6000 seismometers in both vertical and horizontal planes and L-4C seismometers in the horizontal plane. Figures 1, 2, and 3 show the vibrating system configurations and list the equipment used. Seismometers were rigidly fixed to the tables with "Super Glue." The device used for horizontal shaking was manufactured by Unholtz-Dickie and is capable of shaking two S-6000 (fig. 4) or four L-4C seismometers (fig. 5) from 1 to 60 Hz. Shake-table motion was measured by two Bruel & Kjaer model 4370 accelerometers mounted parallel to the driven direction (longitudinal). A third accelerometer was mounted perpendicular to the driven direction (transverse) to record any ellipticity in the motion of the table; a fourth accelerometer was mounted on the top surface of the table to measure vertical motion. One of the two longitudinal accelerometers was calibrated by the U.S. National Bureau of Standards (see app. A) and the second (uncalibrated) accelerometer provided a check on the first. At no time during the testing did the two longitudinal accelerometers differ by more than 1.0 percent nor was the lateral or vertical motion of the table greater than 1.0 percent of the driven direction motion. Table motion was determined by

S-6000 HORIZONTAL & TRANVERSE SET-UP
SMALL TABLE

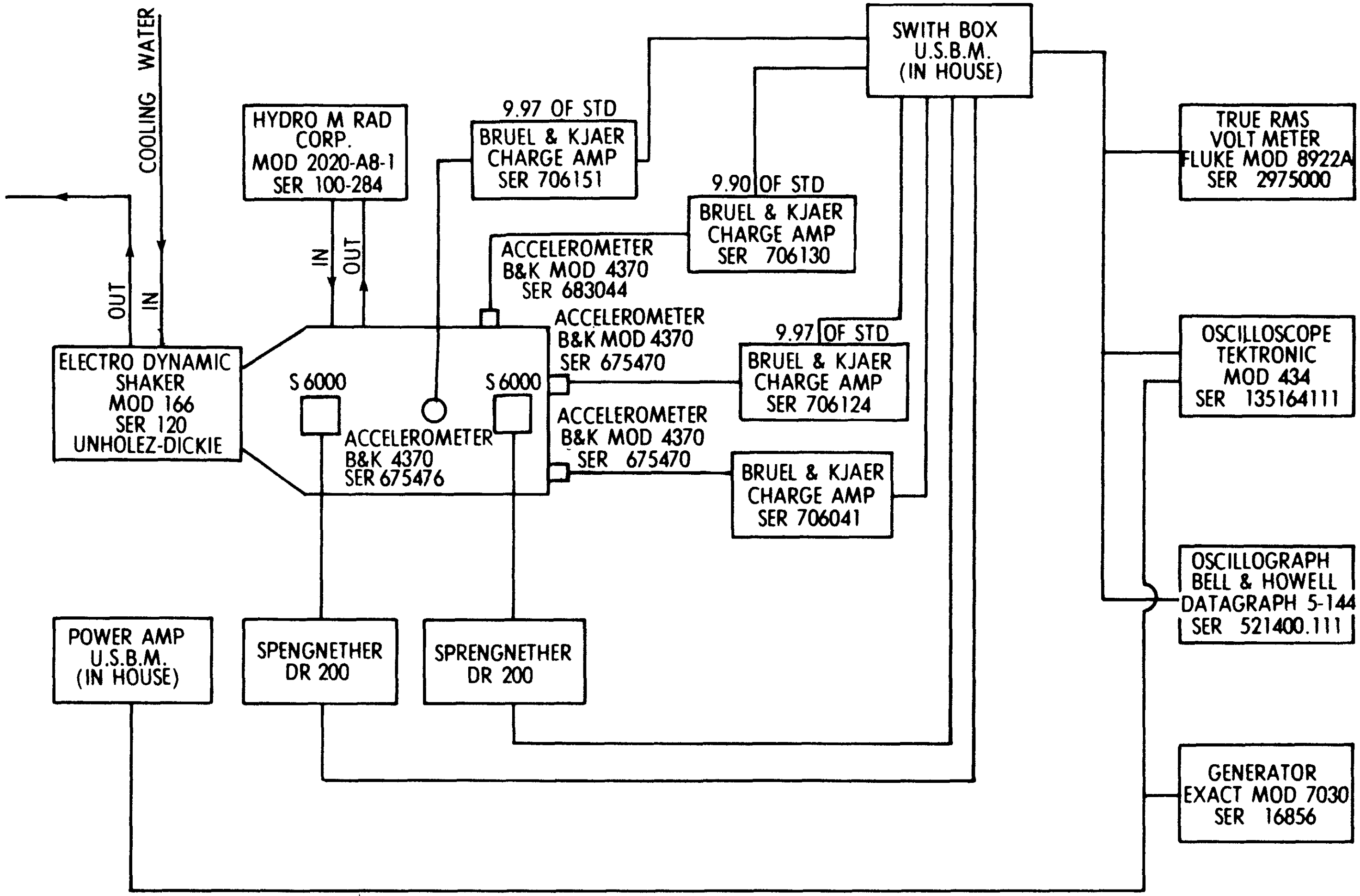

FIGURE 1.--System configuration for shaking S-6000 seismometers in the horizontal plane using the Unholtz-Dickie.

L-4c HORIZONTAL SET UP
SMALL TABLE

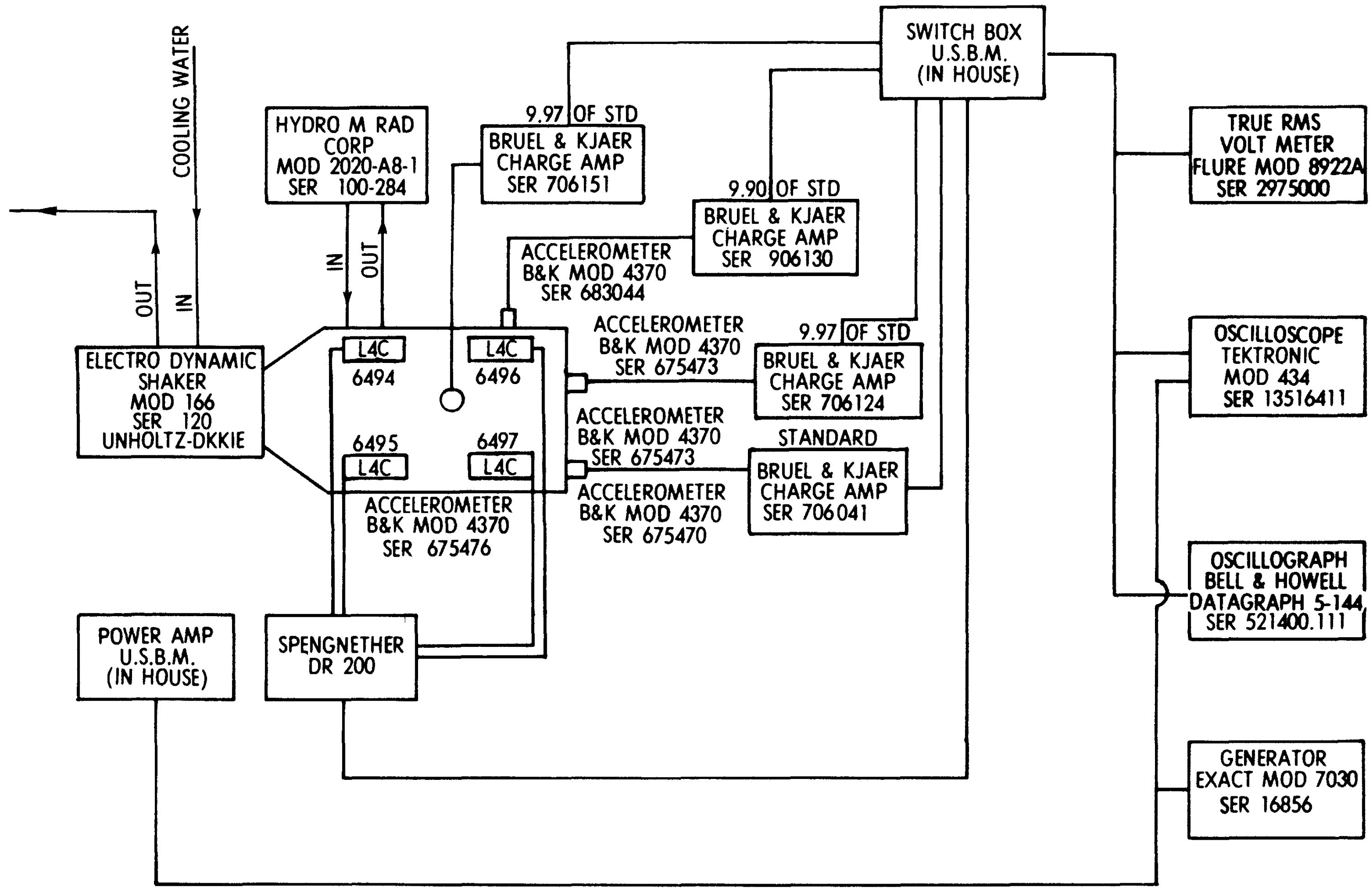

FIGURE 2.--System configuration for shaking L-4C seismometers in the horizontal plane using the Unholtz-Dickie shake table.

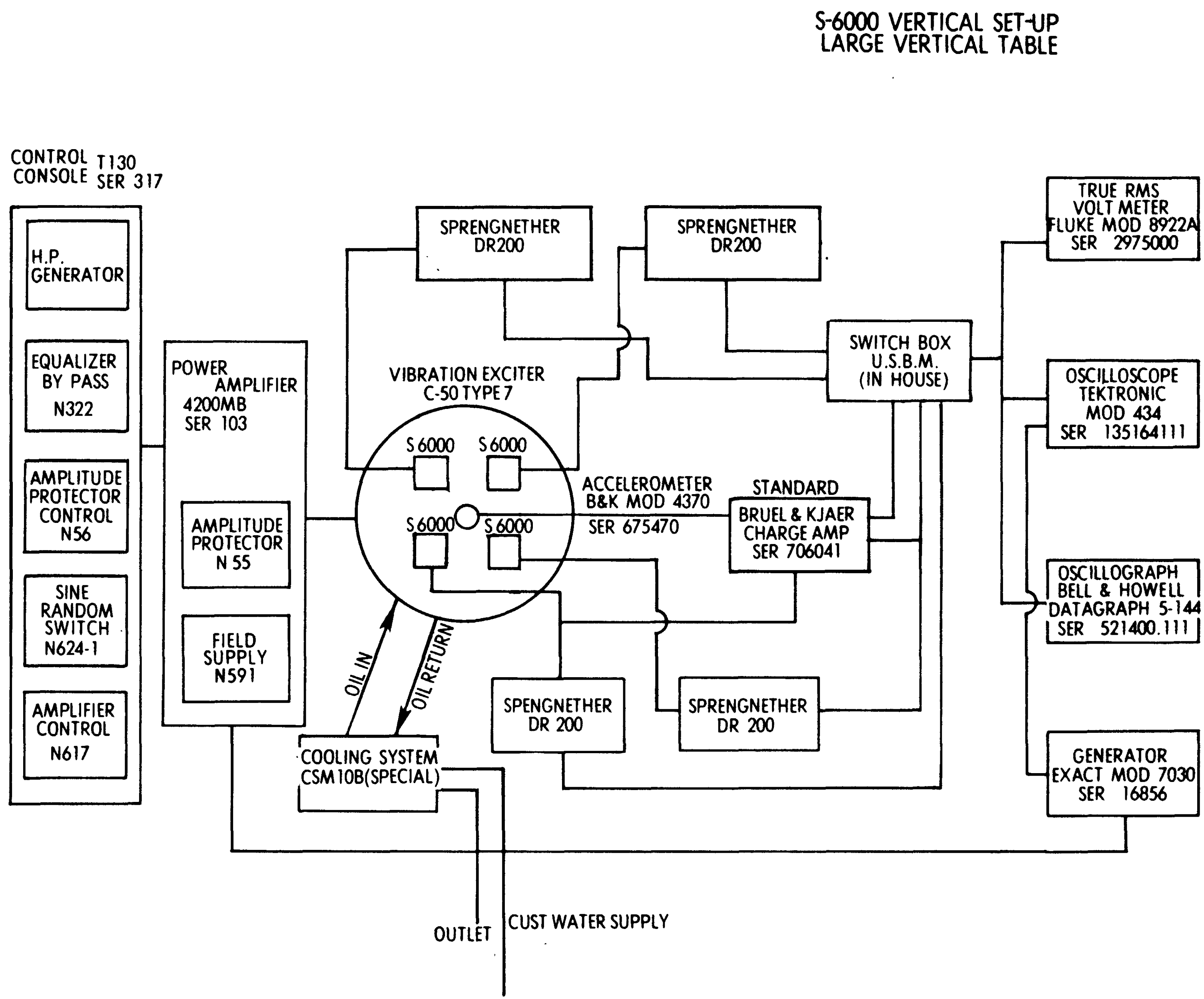

FIGURE 3.--System configuration for shaking S-6000 seismometers in the vertical plane using the MBIS vertical shake table.

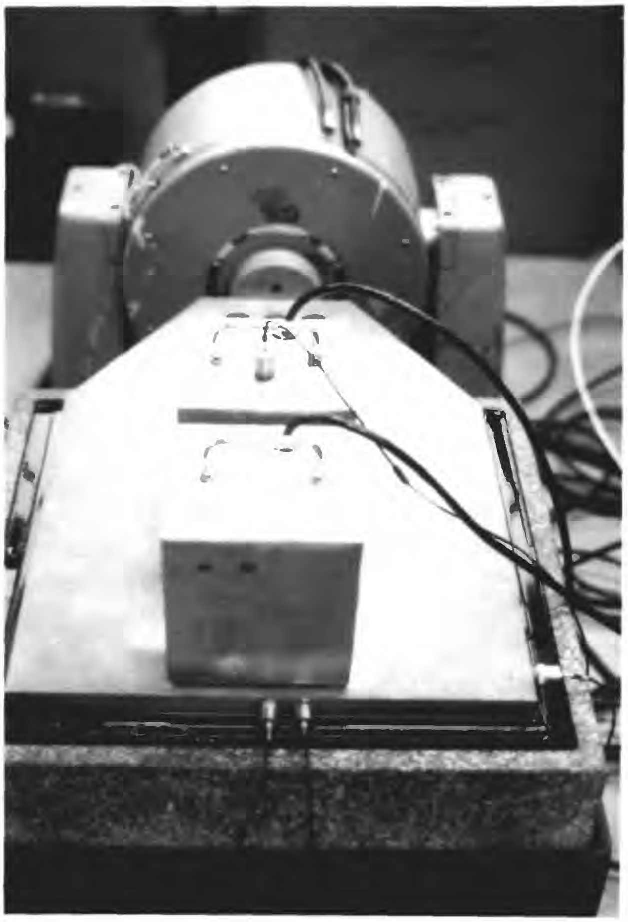

FIGURE 4.--Photograph of the horizontal shake table with two S-6000 seismometers mounted. Also visible are three B&K accelerometers attached to the edge of the shaking table. They were used as described in the text to determine actual table motion.

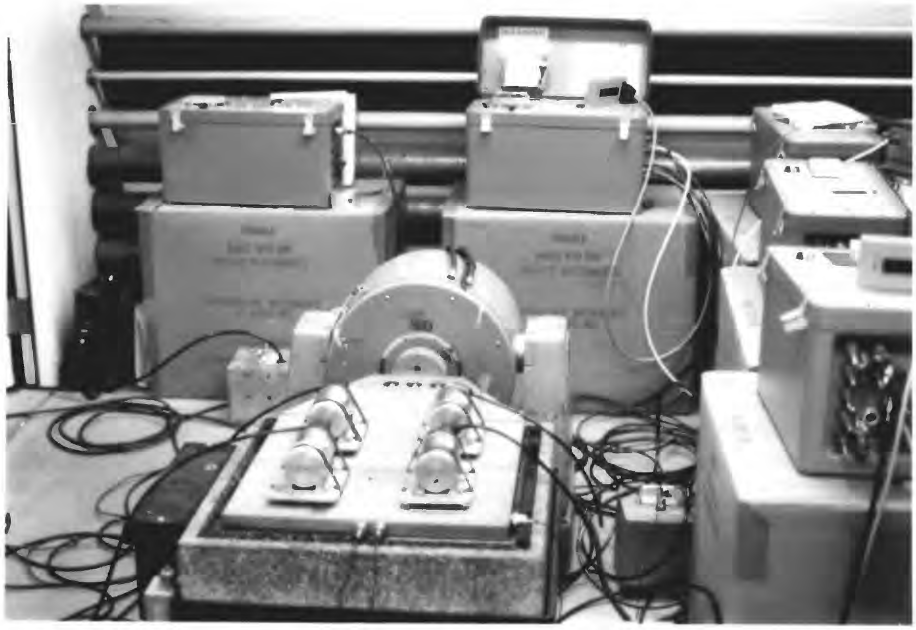

FIGURE 5.--Photograph of the horizontal shake table with four L-4C seismometers mounted. Also visible are three B&K accelerometers attached to the edge of the shaking table. They were used as described in the text to determine actual table motion.

measuring the peak voltage output by the standard accelerometer. The frequency of the signal was measured with a calibrated frequency counter for each of the test frequencies. The horizontal-shaking-table tests were recorded by the DR-200's with a 50-Hz low-pass filter, fixed gains of X10, and a sample rate of 200 samples per second per channel.

The S-6000 seismometers were shaken at frequencies from 1.5 to 30 Hz in both their longitudinal and their transverse directions. The L-4C seismometers were shaken at frequencies from 1 to 50 Hz in their longitudinal direction. A total of 20 frequencies was recorded.

The vertical shaking table used in the experiment was built by MBIS, Inc. and is an electromechanical type. The table is shown in figure 6 with four S-6000 seismometers mounted with "Super Glue." Two Bruel & Kaer accelerometers were used to record actual table motion as was previously described for the horizontal-shaking tests. The S-6000 seismometers were shaken at frequencies from 2 to 25 Hz. A total of 18 frequencies was recorded at a fixed gain of X1.

The cooling system for the vertical shaking table produced an interfering vibration at approximately 28 Hz; therefore, a 25-Hz low-pass filter was used in the DR-200 for the tests. Amplifier gains were set at one (X1) and analog to digital converter gains were held fixed at X1 for all of the tests.

CALCULATION OF SYSTEM RESPONSE

Several methods are available for determining seismograph system response. We have calculated the theoretical response and experimentally determined the system response via both the shake-table method and the calibration coil method.

Theoretical Calculation of Response

The instrument specifications given by the manufacturer can be used to calculate and construct a theoretical seismometer reponse curve. This method generally gives results that closely approximate those obtained from shake-table and calibration coil tests.

The generator constant, natural frequency, coil resistance, and the critical damping are all required for the computation. The theoretical output voltage of the seismometer (E) for 1 μ of sinusoidal earth motion can be calculated for any frequency as follows:

$$\frac{E}{\mu} = \left(\frac{G2\pi f_1 R_o}{(R_c+R_o)\times 10^6}\right) \times \left(\frac{1}{\sqrt{\left(1-\left(\frac{f_o}{f_1}\right)^2\right)^2 + \left(2\lambda_o \frac{f_o}{f_1}\right)^2}}\right)$$

FIGURE 6.--Photograph of the vertical shake table with four S-6000 seismometers mounted. Two B&K accelerometers were mounted in the center.

where: G = effective generator constant, v-sec/meter
f_1 = frequency of input table motion, in Hertz
f_o = natural frequency of the seismometer, in Hertz
R_o = load resistance, in ohms
R_c = coil resistance, in ohms
λ_o = ratio of seismometer damping to critical damping

The theoretically determined response values are shown in figures 7 and 8 for both S-6000 and L-4C seismometers.

Shake-Table Determination of System Response

Seismograph system response is best determined by the shake-table method because shake tables produce the actual equivalent of earth motion. Shake-table tests can disclose nonlinearities caused by spurious modes and help locate sources of spurious vibration within the seismometer. Shake-table experiments test the entire recording system from seismometer feet through the playback.

The shake-table frequency is varied over the frequency range of interest, with the amplitude and frequency of the table motion carefully measured. For these tests, the actual table motion was determined using the following formula:

$$\text{Table velocity} = \frac{A_o\ (\sqrt{2})}{A_s}$$

where: A_o = standard accelerometer output, mV (peak)
A_s = standard accelerometer sensitivity, mV/cm/sec (as determined by National Bureau of Standards at the given frequency)

Table velocity is expressed in cm/sec peak to peak.

The relative response of the seismograph system can then be determined by:

$$\text{System sensitivity} = \frac{E_o\ (\sqrt{2})}{(\text{Table velocity})}$$

where: System sensitivity = V/cm/sec

E_o = system output voltage, V peak at a given frequency.

Results of these calibrations are shown in figures 9 through 15.

Calibration Coil Determination of System Response

In the third calibration method we used the calibration coil. This technique drives the seismometer's internal calibration coils with a sinusoidal signal having variable amplitude and frequency generated by a Geotech PC-200 field calibrator. The motor constant of the calibration coil

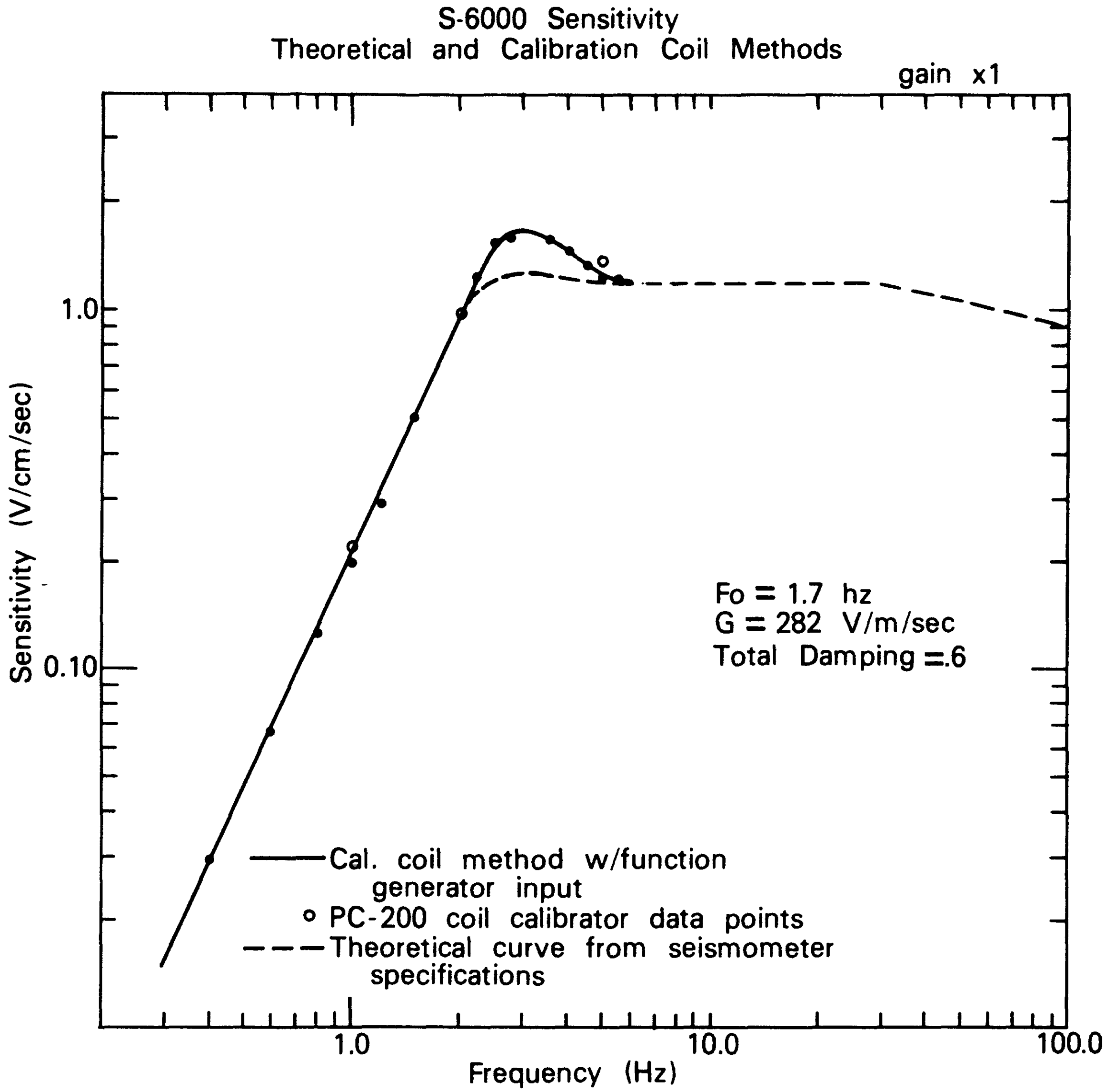

FIGURE 7.--S-6000 seismometer sensitivity.

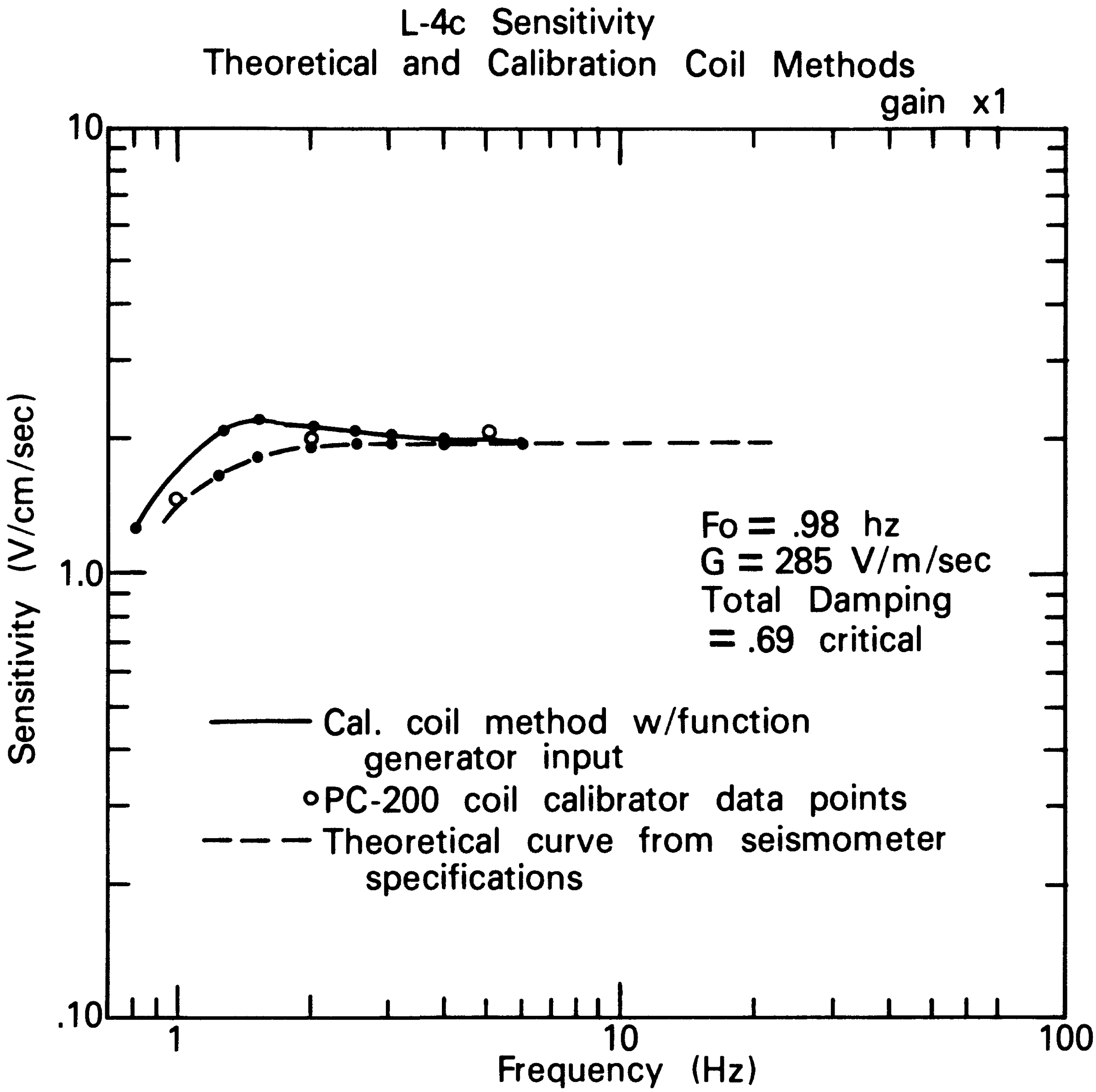

FIGURE 8.--L-4C horizontal seismometer sensitivity.

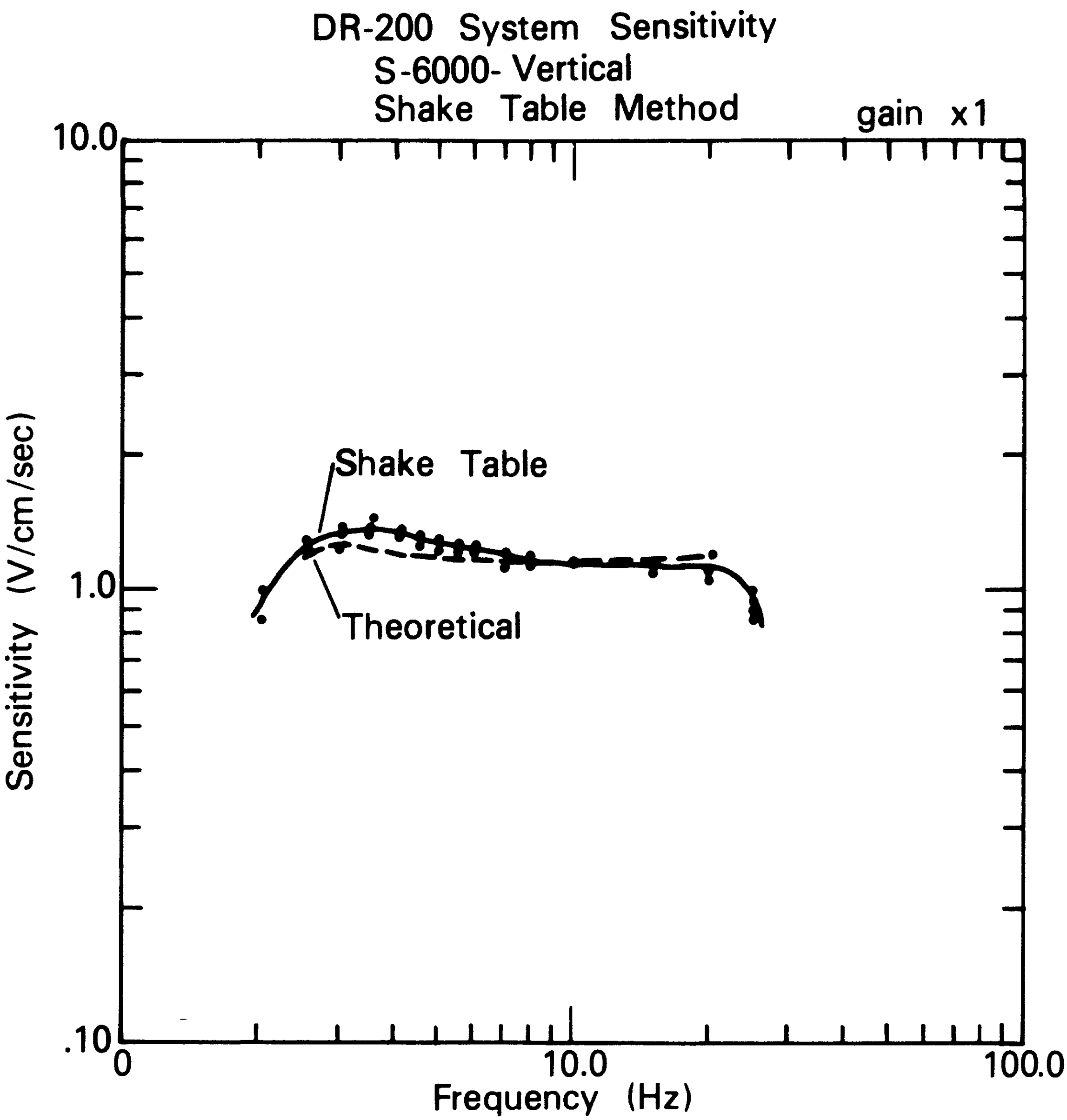

FIGURE 9.--Sensitivity of four DR-200/S-6000 (vertical) seismograph systems using the shake-table method.

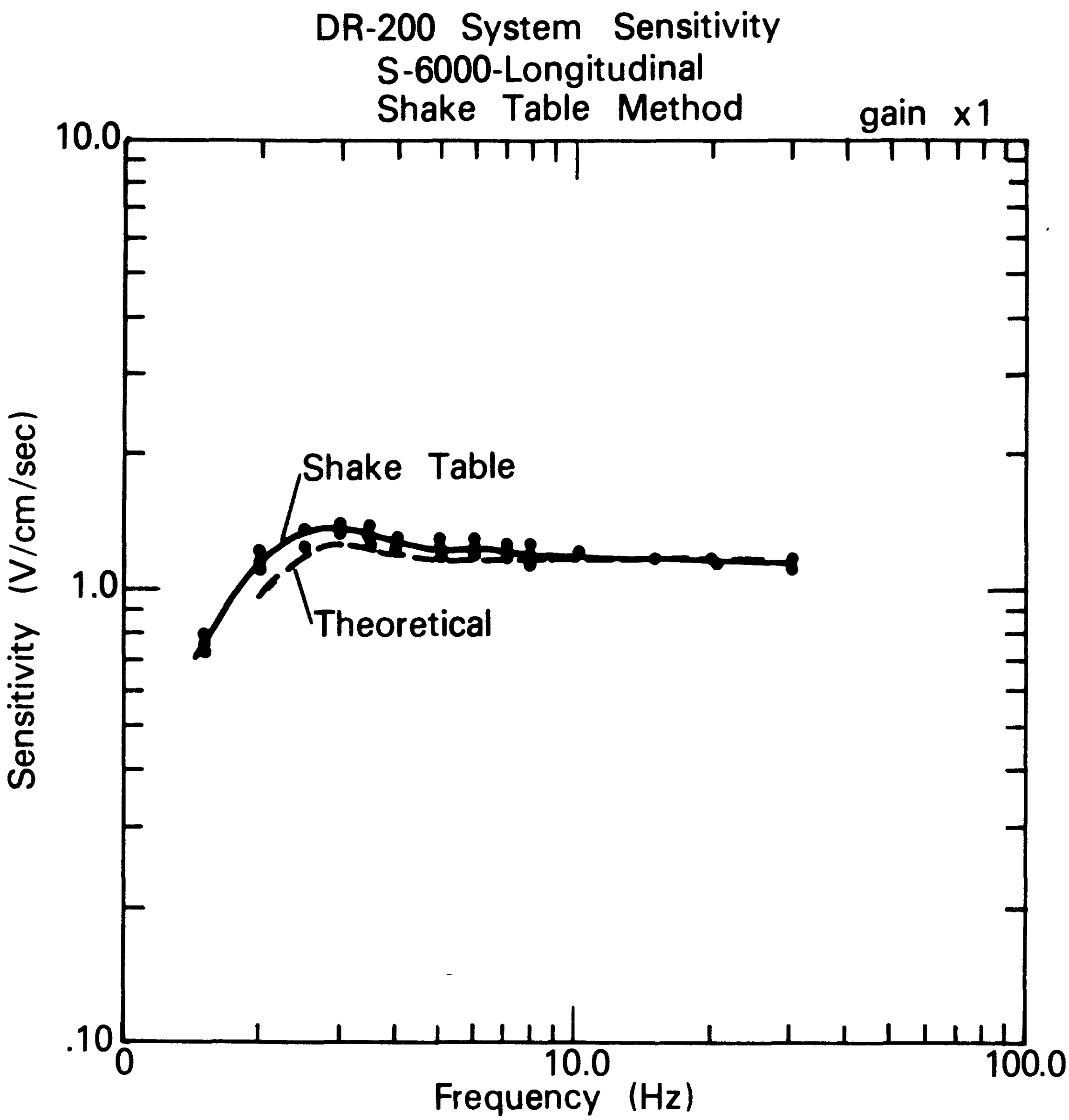

FIGURE 10.--Sensitivity of four DR-200/S-6000 (longitudinal seismograph systems using the shake-table method.

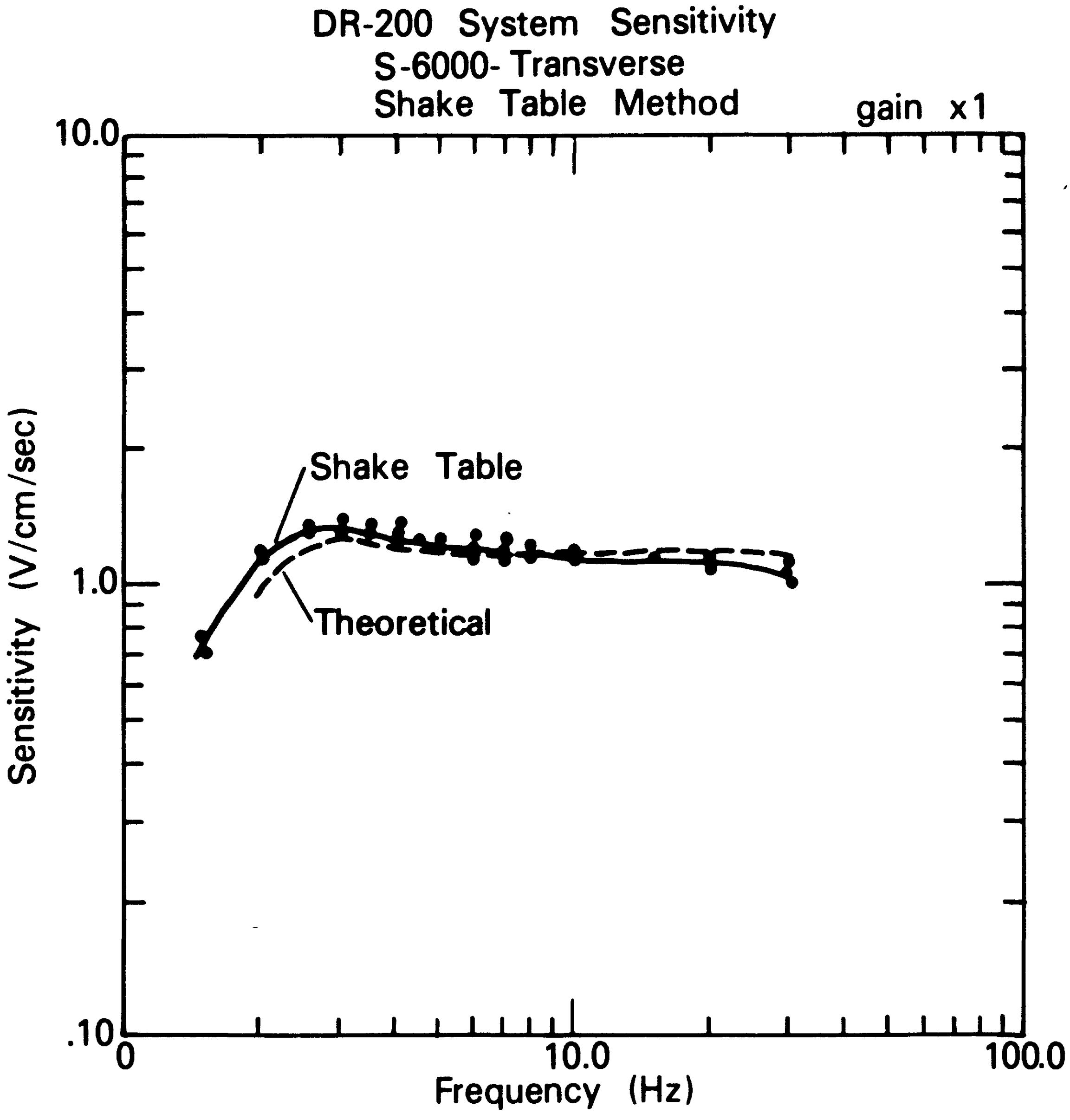

FIGURE 11.--Sensitivity of four DR-200/S-6000 (transverse) seismograph systems using the shake-table method.

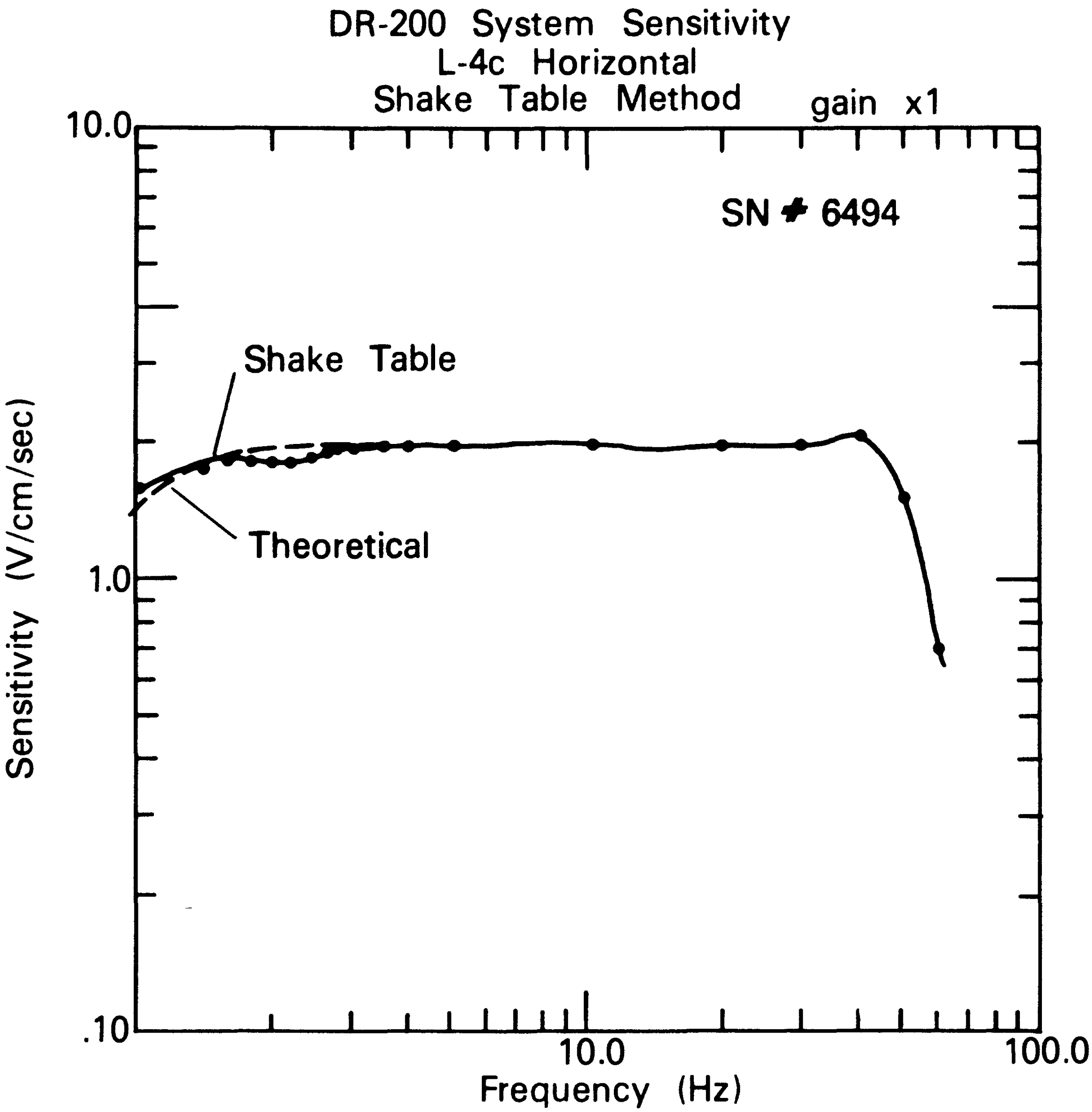

FIGURE 12.--Sensitivity of a DR-200 and L-4C seismograph system using shake-table method.

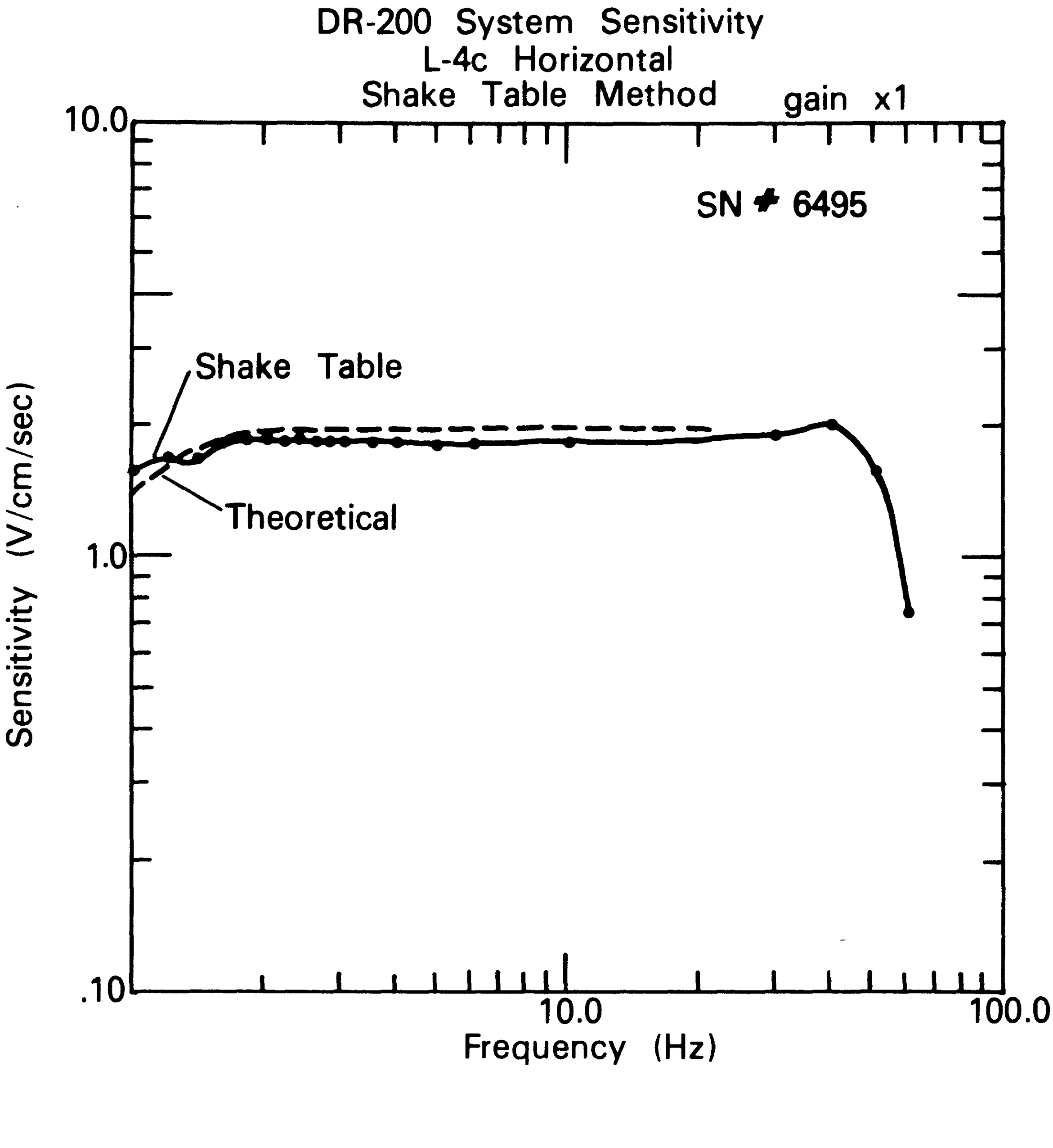

FIGURE 13.--Sensitivity of a DR-200 and L-4C seismograph system using shake-table method.

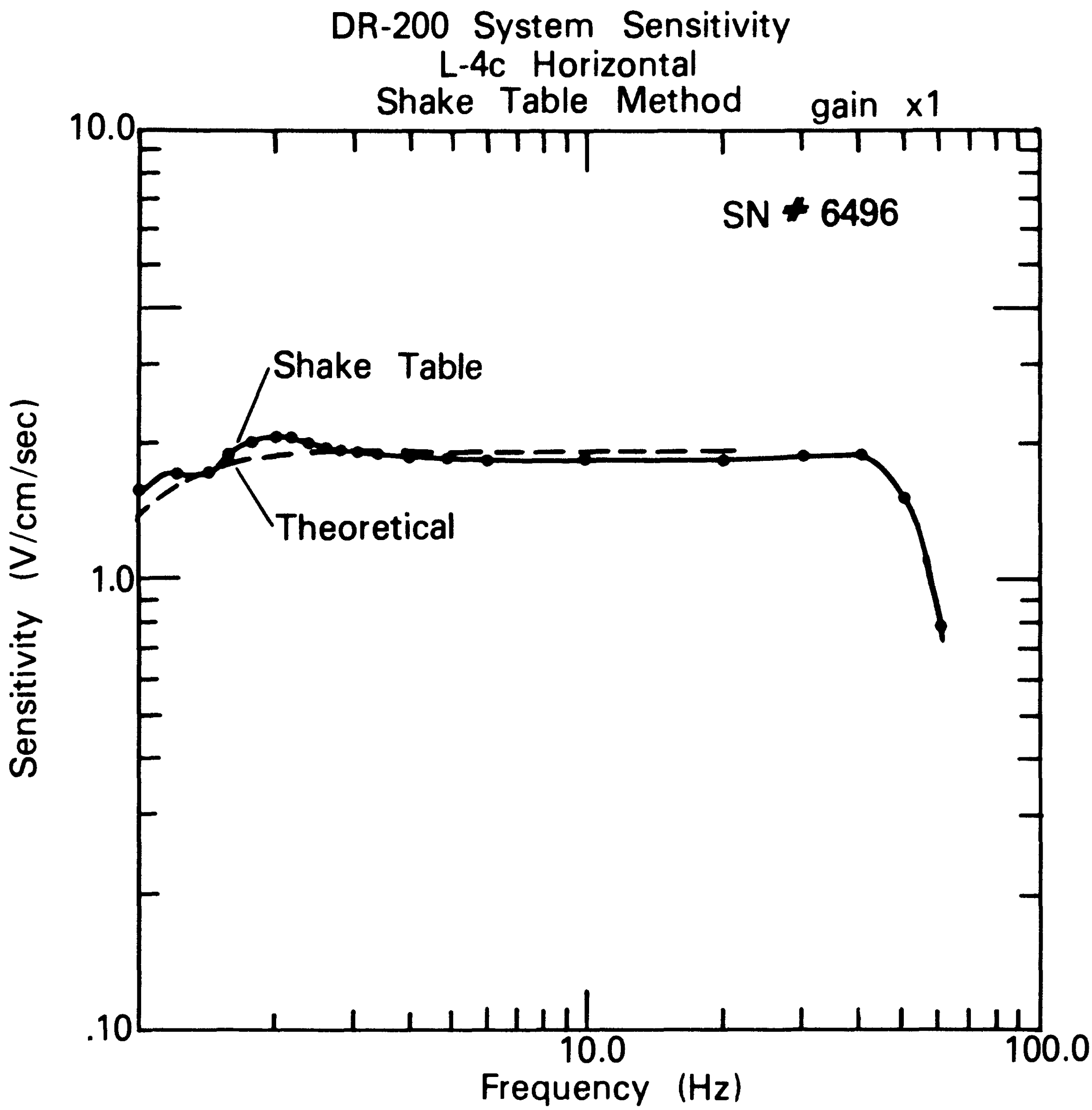

FIGURE 14.--Sensitivity of a DR-200 and L-4C seismograph system using shake-table method.

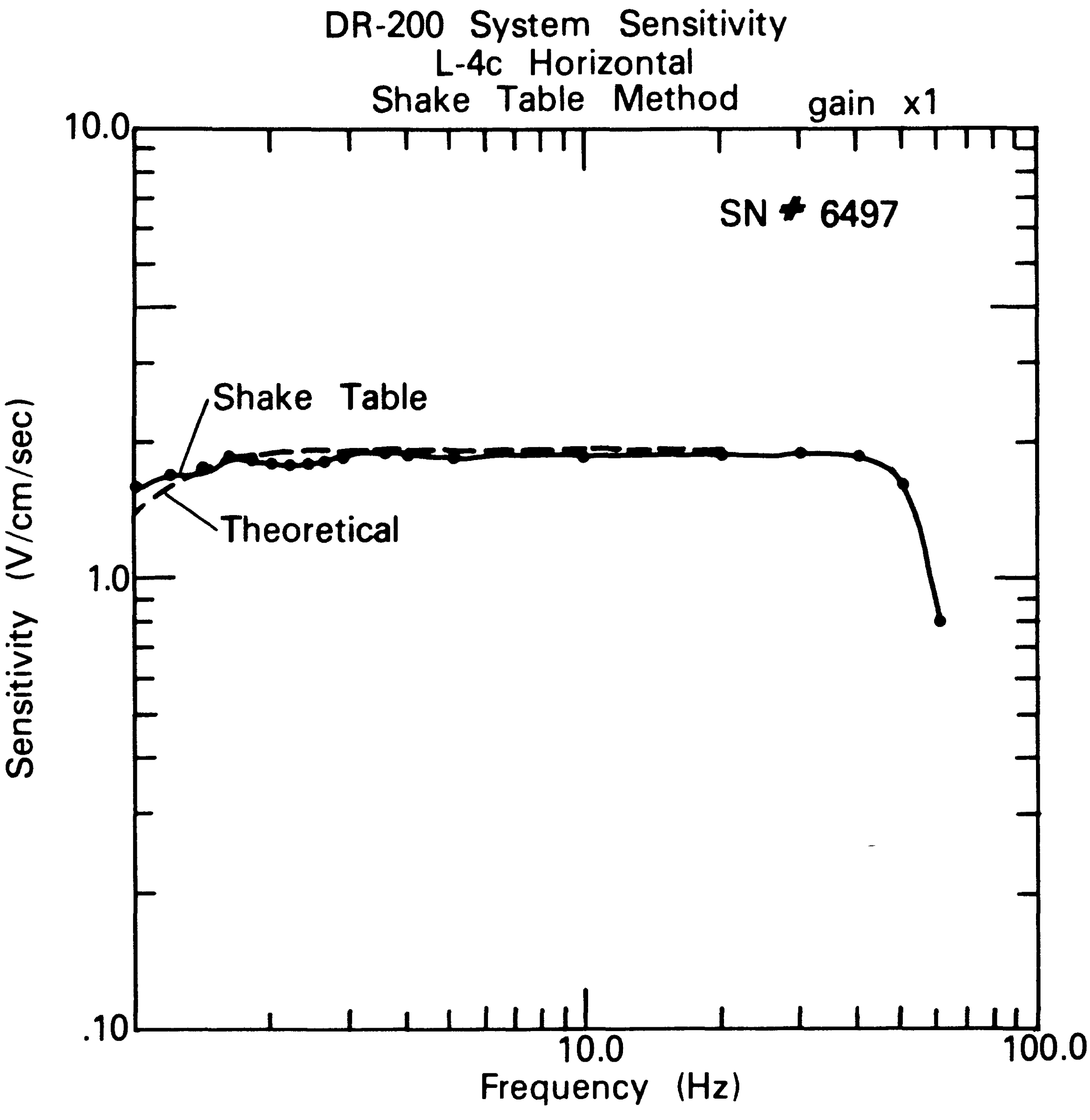

FIGURE 15.--Sensitivity of a DR-200 and L-4C seismograph system using shake-table method.

is given by the manufacturer. The equivalent earth motion produced by the signal through the calibration coil may be calculated using the formula:

$$y = \frac{g_i \times 10^6}{4\pi^2 f_1^2 M}$$

where: y = equivalent earth motion in microns, peak-to-peak
g = calibration coil motor constant, newtons/ampere
i = current through the calibration coil, amperes peak-to-peak
f_1 = frequency of calibration signal
M = weight of mass, kilograms

The seismograph output voltage is then divided by the equivalent earth motion for each data point and the result is plotted against frequency in figures 7 and 8. The PC-200's output was checked against a laboratory standard and was found to have an error in the range of concern of less than 1.0 percent. The PC-200 has the capability of generating 1.0-, 2.0-, 5.0-, and 10.0-Hz sine waves. However, the 10-Hz signal is not used because the seismometer output is contaminated by transformer coupled energy when driven by the calibration coil above 5 Hz.

Analog Playback Response

Many users of the DR-200 seismograph system may need to know actual ground velocity as recorded by the system and the Sprengnether DP-260 digital playback. Figures 16 and 17 show the full system response through the DP-260 playback for both the S-6000 and L-4C based system. The formula:

$$\text{Playback response} = \frac{A_R}{\text{Table velocity}}$$

was used to calculate the playback response where A_R is the peak-to-peak amplitude on the DP-260 playback paper.

SEISMOMETER SENSITIVITY TO TILT

An experiment was run to determine how sensitive the S-6000 and L-4C seismometers are to improper leveling (tilt). The test demonstrated that there is no measurable distortion in the recorded wave form until the L-4C's are tilted more than 4.6° between 1 and 60 Hz. The S-6000's were tested between 1 and 16 Hz in both the horizontal and vertical axes. They showed no visually discernable distortion of the wave form until 7° of tilt in the horizontal plane, and in vertical motion we found no distortion at tilts less than 7°. These tests indicate that accurate data can be retrieved from S-6000 seismometers mounted so that the leveling bubble is as much as one half on either side of the circle on the level case. The L-4C seismometer must be leveled as accurately as possible.

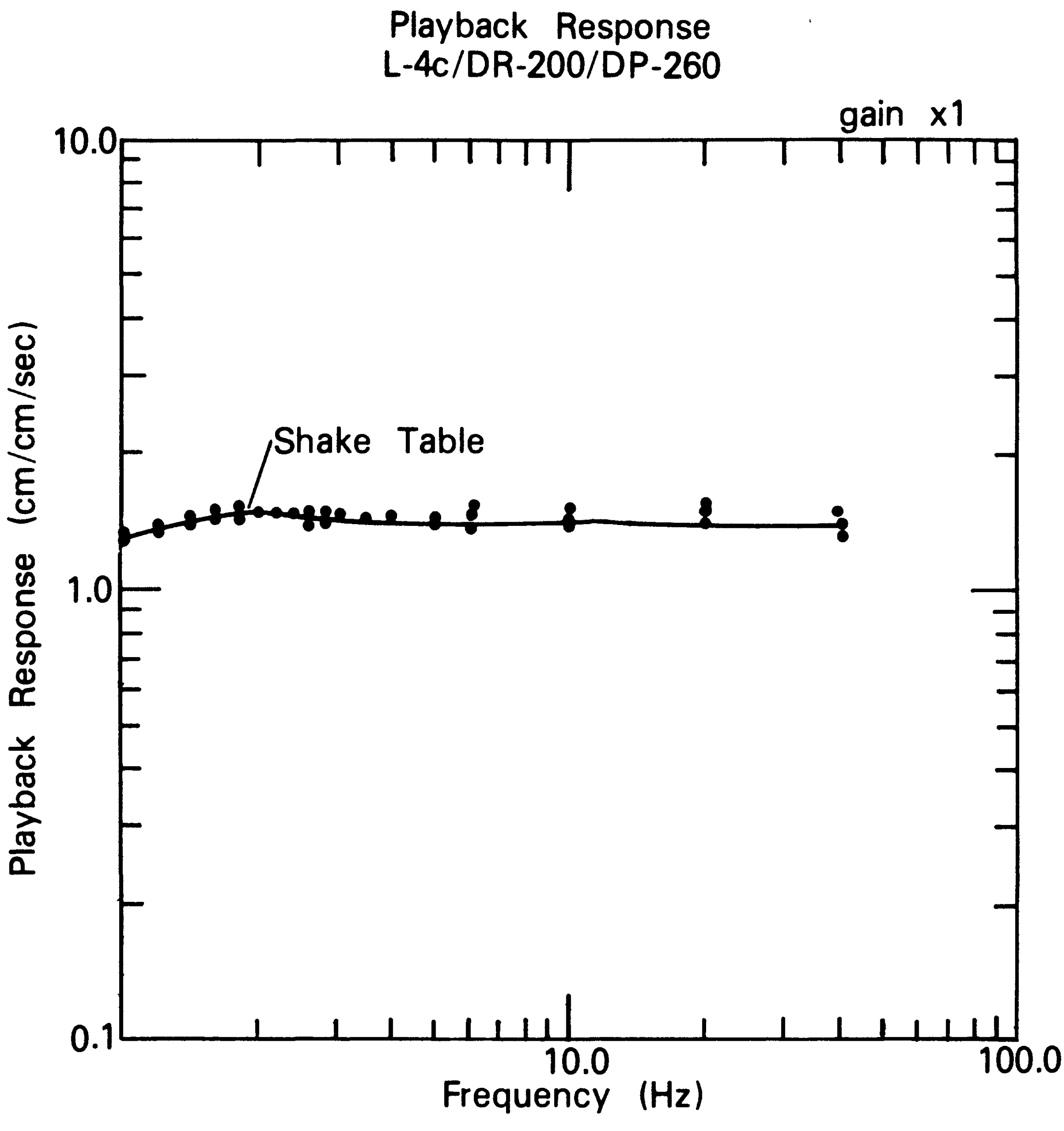

FIGURE 16.--Playback response of a DR-200/S-6000 recording system played back on a DR-260 strip chart .

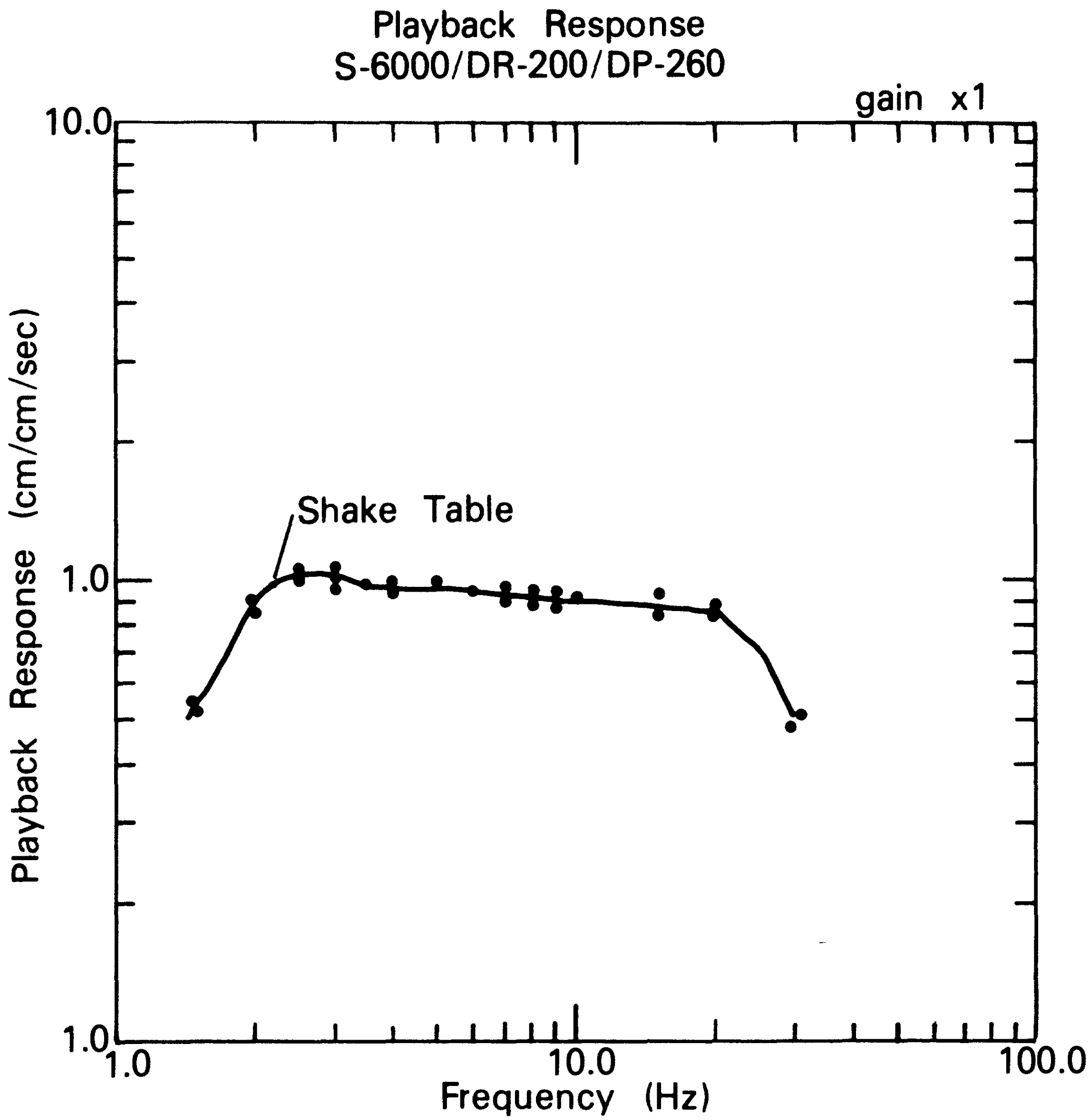

FIGURE 17.--Playback response of a DR-200/S-6000 seismograph system layed back on a DR-260 strip chart.

RESULTS

The results from the external calibrator and shake-table testing of both the S-6000 and L-4C seismometers recorded by the DR-200's agree within the experimental error with the theoretically determined system response. The shake-table calibrations agree within 10 percent and the external calibrator results are within 5 percent of the theoretical values.

APPENDIX A

U.S. NATIONAL BUREAU OF STANDARDS

REPORT OF ACCELEROMETER

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON D.C. 20234

NBS Test No.-737/G-44331
NBS Cost Center No.- 7374602
Customers PO Date-1/11/82
Customer Order No.-L3320501

February 11, 1982

8-921-2020

REPORT OF ACCELEROMETER CALIBRATION

B&K 4370 Accelerometer No. 675470

submitted by

Department of the Interior
Bureau of Mines Twin Cities Research Center
5629 Minnehaha Avenue South
Minneapolis, Minnesota 55417

B&K accelerometer model 4370 (serial number 675470) with accompanying cable and B&K charge amplifier model 2635 (serial number 706041) were calibrated at the National Bureau of Standards on 2/10/82 over a frequency range of 2 TO 100 Hz according to NBS special publication 250. The contacting surfaces of the accelerometer was coated with medium petroleum lubricating oil and attached to the vibration standard with a torque of nominally 2Nm (18 lbf-in).

The test accelerometer was calibrated on vibration standard LF-1 at frequencies of 2 to 100 Hz. This standard was calibrated at the National Bureau of Standards by a fringe counting method.

The sensitivity factors of the test accelerometer were determined by comparing the output voltage of the above accompanying amplifier to the output voltage of each of the vibration standards. The average results of the calibration are shown in the attached table.

921-3607

Calibration performed by:

B.F. Payne

B.F. Payne
Vibration Calibration Service

For the director,
National Engineering Laboratory

D R Flynn

Daniel R. Flynn, Chief
Mechanical Production Metrology Division
Center for Manufacturing Engineering

NBS TEST NO.-737/G-44331

Results of calibration of B&K accelerometer model 4370 (serial number 675470) with accompanying cable and B&K charge amplifier model 2635 (serial number 706041).

Frequency	Sensitivity	Applied Nominal Peak Velocity for Calibration	Estimated Accuracy of calibration
Hz	mV/in/sec	in/sec	%
2	254.3	1	2
4	253.9	1	2
5	253.5	1	2
8	252.3	1	1
10	251.9	1	1
15	251.9	1	1
30	250.7	1	1
50	249.5	1	1
100	244.8	1	1
500	209.1		

252.64

251.42 ± (2) = 2.92

The above sensitivity values can be converted to SI units by noting that 1g=9.80665 meter/second/second.

Amplifier settings: mV/unit out 100; upper freq. limit 1 KHz; lower freq. limit 1; vel. mode and unit out .01 m/s;trans. sen 9.97 with switch in 1-11 pos.

m = -.08899233

b 253.64

r = .9805

254.3 / 25.4

20Hz 251.86

.1V / M/S

1 in / 1000 mm

25.4 mm / in