INSTRUCTION FOR ACCELEROMETER SHOCK CALIBRATION*

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Biography

Mr. Kelley received his BS in Electrical Engineering from the University of Colorado in 1953 and his MS in Electrical Engineering from the University of New Mexico in 1965. He spent two years in the Quality Assurance Department at Sandia Corporation prior to entering the U. S. Navy in 1955, where he served for three years as Nuclear Officer with the Nuclear Weapons Unit, Pacific. Since his return to Sandia Corporation in 1959, he has worked as an Instrumentation Engineer in the Environmental Test Department. At present he is the Project Leader of the Calibration Development Group working on instrumentation, facilities and techniques for calibration and measurement.

Abstract

An instrumentation system has been developed for use with a ballistic pendulum shock accelerometer calibrator. The system provides readout and display of the peak amplitudes from a strain-gage load cell and from the shock accelerometer being tested. This instrumentation system is not limited to use with a ballistic pendulum, however, but can be adapted to systems which require measurement, display, and recording of transient pulses. Following the discussion of the instrumentation development, the results of an accuracy study of the system are presented. This study is still underway to obtain information on long-term accuracy and repeatability. The computations for obtaining values for overall system accuracy are shown, and an overall accuracy figure for the complete system is given.

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Introduction

For the past 4 years, the Environmental Testing Calibration Group of Sandia Corporation's Albuquerque Laboratory has been using a prototype ballistic pendulum device of that shown in Fig. 1, to obtain accelerometer shock calibrations. The operation of this device is based on Newton's Second Law, Force = Mass x Acceleration.

The accelerating force is applied by the impact of an accelerometer-carrying mass, or bullet, onto a stationary strain indicator (strain gage load cell), the details of which are shown in Fig. 2. The accelerometer-carrying mass, or bullet, is made of hardened steel and weighs approximately 3/4 pound. The front of the bullet is a hemispherical shape with a 3/4-inch radius.

The theory associated with the ballistic pendulum device and the justification for using this method is given by Palmer.[1] In his paper, Palmer includes a search of current literature regarding dynamic behavior of strain gages and discusses questions such as the following:

1. Does the strained material, itself, follow the same stress-strain curve for static and dynamic loads?

2. Does a measurement of surface strain give a true representation of the average cross-sectional strain?

3. Does the strain gage react in the same way for static and dynamic loads?

4. Are there other effects, such as, for instance, magnetostriction and magnetoresistance?

Palmer concludes that the use of strain gages to measure shock pulses is justified and describes a pendulum device based on the strain gage principle.

DISCLAIMER

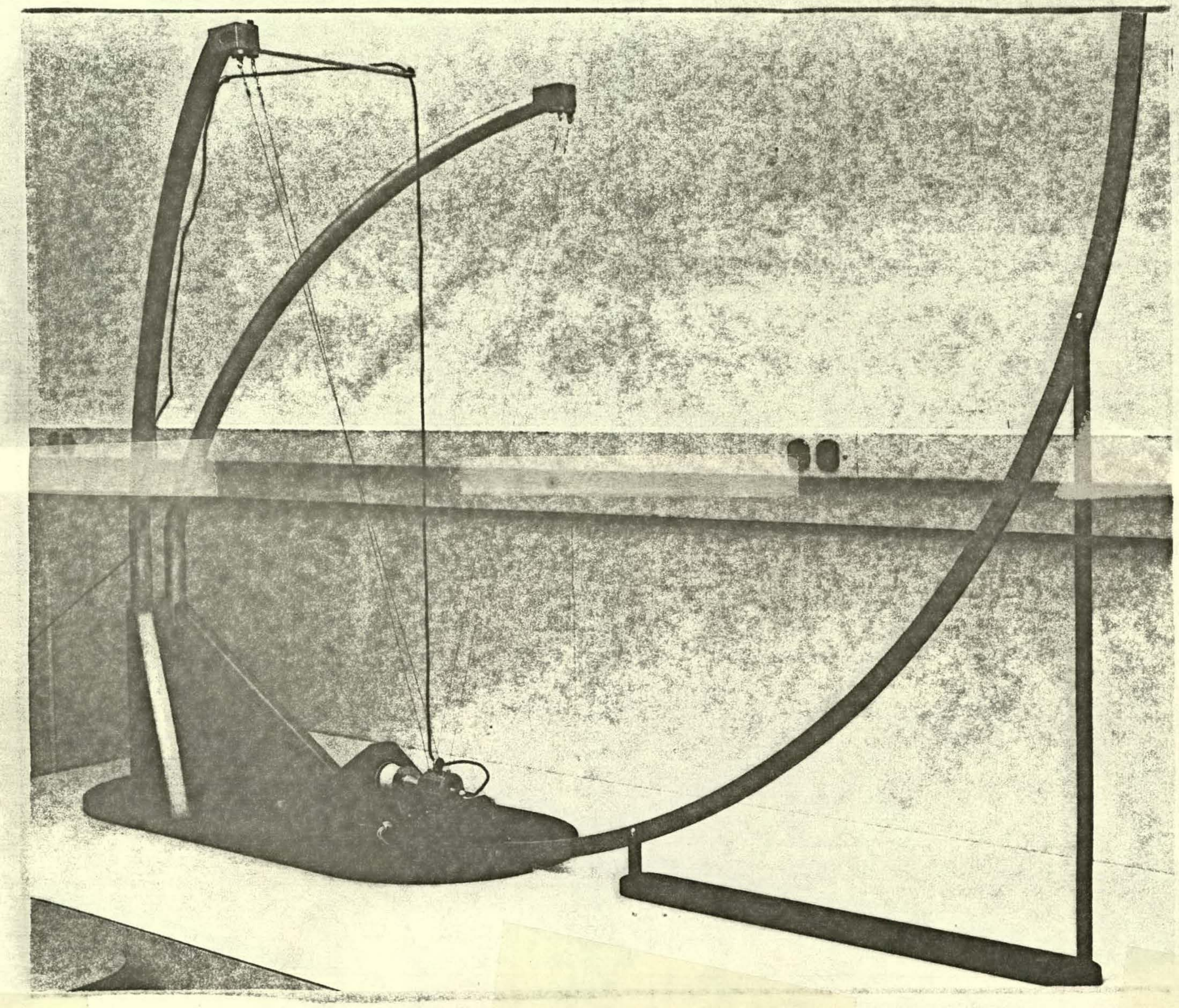

Fig. 1. Complete ballistic pendulum device

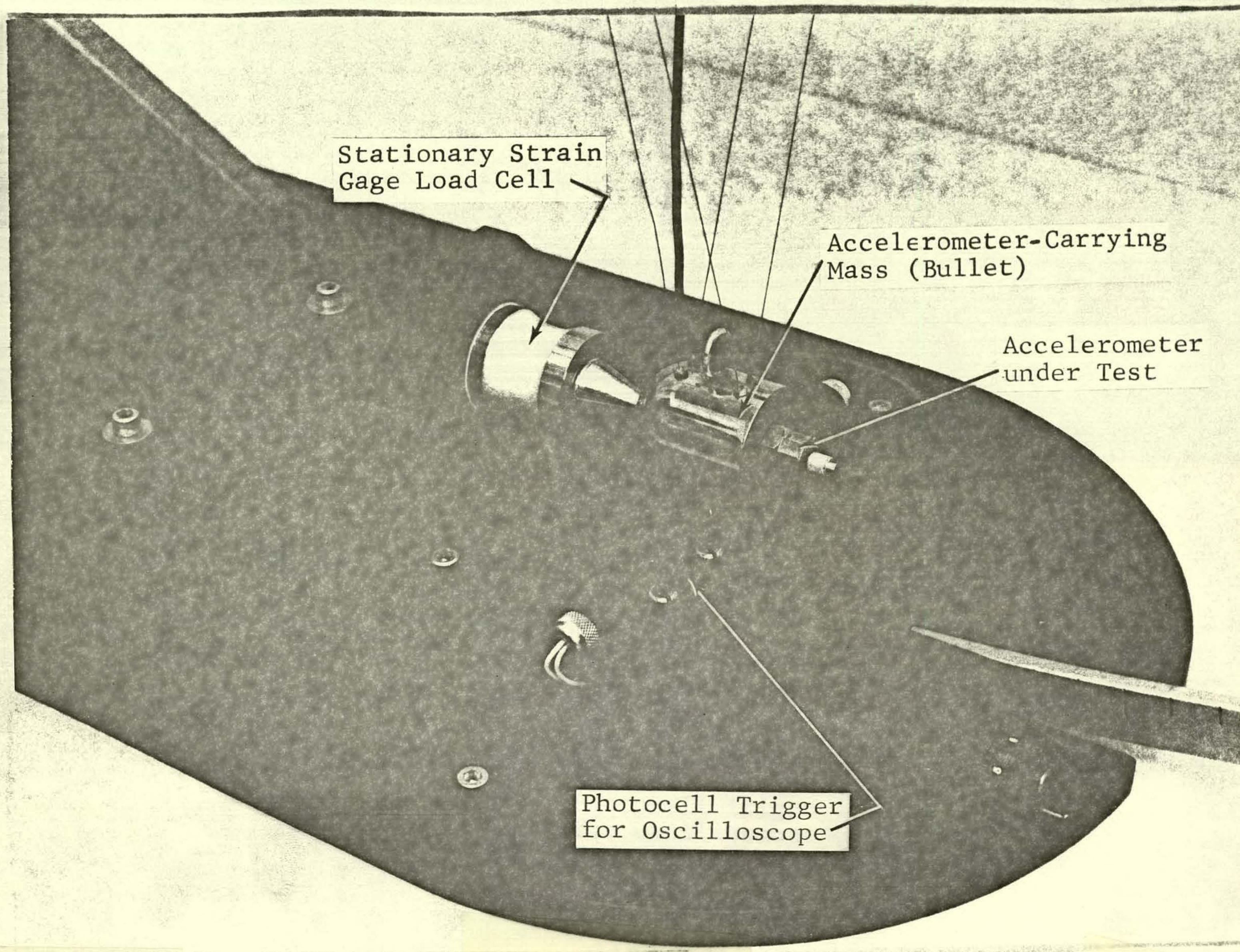

Fig. 2. Detailed view of accelerometer-carrying mass and stationary strain indicator (load cell)

A load cell manufactured by Lockheed Electronics Company was selected for use in the pendulum system.[1,2] The unit, spool-shaped with four 1/4-inch open-grid strain gages arranged in a full Wheatstone bridge, had the following specifications:

1. Resonant frequency greater than 65 kcps
2. Sensitivity of 2mv/v at 5000-pound load
3. Excitation voltage of 10 volts
4. Linearity and hysteresis of 1 percent
5. Repeatability of 1 percent.

Over the extended use period of the pendulum device, its calibrations have compared favorably with those obtained with the vibration system, the difference between the two systems being rarely more than ± 4 percent, and in most instances being less than ± 2 percent.

Ballistic Pendulum

The original prototype calibration device designed by Mr. Palmer, with only minor improvements, was used as a calibration facility until the spring of 1966. At this time the problems associated with the ballistic pendulum mechanism were investigated. Because of structural instability, misalignment of the bullet frequently occurred which caused the bullet to impact the load cell off-center and resulted in inaccurate data. Since the mounting hole size of the various test accelerometers varies, the bullet was frequently changed; this was awkward and time-consuming with the prototype pendulum. Also the support cables for the mass were made of cord, and stretched with time and use resulting in further misalignment. The prototype system was redesigned and the resulting ballistic pendulum is the one shown in Figure 1. This pendulum has been in operation for approximately 8 months. The difficulties encountered during the use of the prototype have been eliminated by increasing the rigidity of the entire structure. The use of metal support cables has provided greater versatility and maintains the original alignment of the system. In addition the bullets can be easily interchanged.

This ballistic pendulum covers an acceleration range from about 500 to 2000 G. The acceleration pulses used for calibration approach a haversine and have durations ranging from about 150 to 300 microseconds. Longer durations can be obtained but at reduced acceleration levels.

For a complete description of the redesigned ballistic pendulum, including complete drawings for the device, see Reference 3.

Original Readout Instrumentation

A schematic of the instrumentation originally used on the pendulum is given in Fig. 3, and the two unfiltered pulses obtained during a typical shock calibration are shown in Fig. 4.

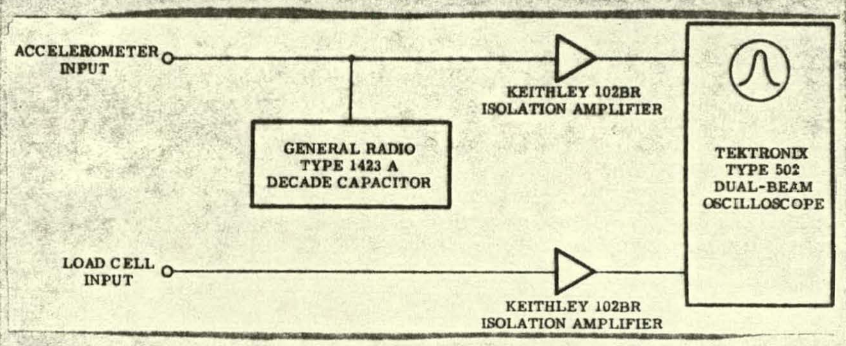

Fig. 3. Original pendulum instrumentation

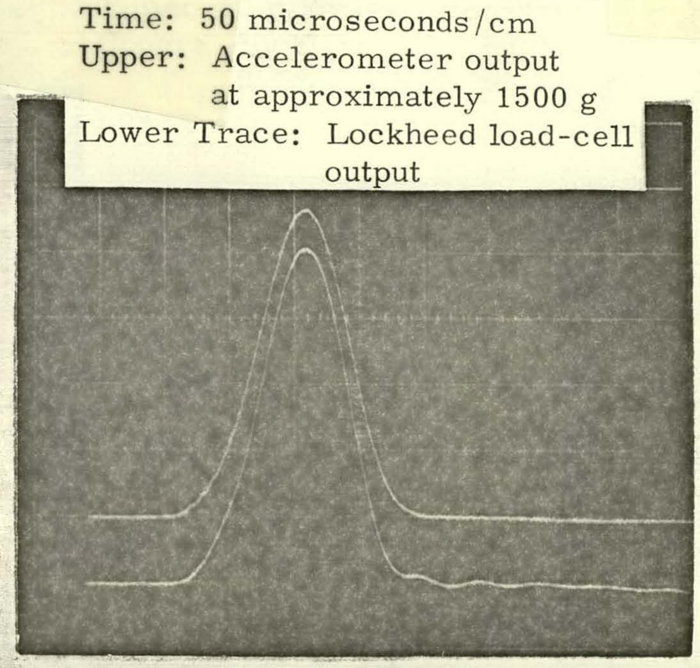

Fig. 4. Typical unfiltered shock pulses obtained from the pendulum calibrator

The normal procedure was to take three oscilloscope pictures on each accelerometer. The peak on each pulse as determined from the photographs was then inserted into two standard equations for calculation of the basic sensitivity of the accelerometer. Most of the errors resulted from misreading the Polaroid picture or from inherent inaccuracies such as parallax and linearity. Some of these errors were minimized by applying a sine-wave calibrate signal through the system and photographing the calibrate signal at about the same voltage level as the actual shock pulses. But this procedure was time-consuming from the standpoint of data reduction, and it did not eliminate the necessity for human judgment. The next step was to find a way to modify the system so that both human error potential and data reduction time were reduced.

Modification with Peak Reading Voltmeters

Since the peak value of the accelerometer and load-cell pulses were of primary interest, it was felt that the addition of devices which would electronically indicate and hold the peak values would be advantageous. Accordingly, several instruments were evaluated for use with the pendulum system. For the particular application at Sandia, the Adcomp, Model 440A, was selected. Some of the main reasons are as follows:

1. Accuracy better than ±1-1/2 percent of reading over required voltage range (upper 20 percent of scale)
2. Sensitivity down to 100-mv full scale
3. Bandwidth from DC to over 1 megacycle
4. Indefinite holding time on peak reading
5. Analog output suitable for digital readout
6. Capability of calibration with a sine-wave input.

The peak-reading voltmeters were included in the system, as shown in Fig. 5. With this modification, it is now possible to calibrate the system by feeding a sine-wave calibrate signal into each channel and setting the attenuator so that the DVM reads the peak value directly. The DVM in the accelerometer channel reads the peak output of the accelerometer directly in volts, and the DVM in the load-cell channel reads the peak output of the load cell directly in millivolts.

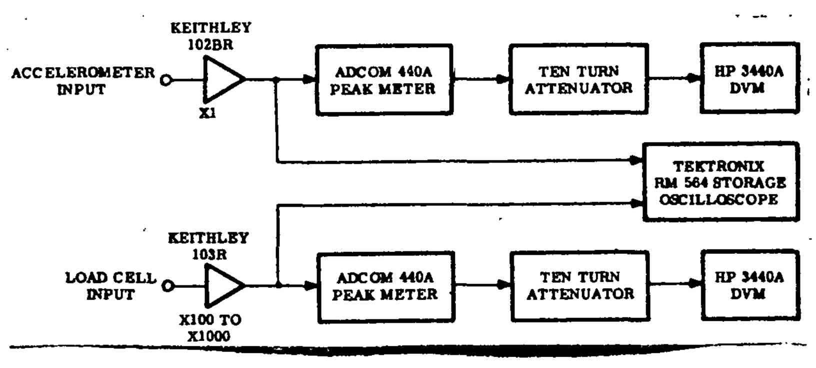

Fig. 5. Pendulum instrumentation with peak meters

A control chassis was designed to allow an operator to control all functions of the system by back-lighted pushbutton switches. This includes zeroing both peak meters, applying calibrate signals to each channel, controlling the power to the lamp and photodiode in the scope trigger circuit, balancing the strain-gage load cell, and reading the bridge voltage on one of the existing DVM's. (See Fig. 6 for a block diagram and Fig. 7 for a photograph of the overall instrumentation.) To keep the system noise within acceptable limits, it was necessary to use coaxial relays in the control chassis, since the signals in the load-cell channel were in the range of 1 to 5 mv.

Although the peak meters obviate the requirement for taking oscilloscope pictures, it is still a good idea to observe the pulse shape of the accelerometer output. Zero shift, undershoot, discontinuities, or excessive ringing could indicate a bad accelerometer, but these problems would not be obvious from the peak meter readings. Therefore, a Tektronix (Model RM 564) storage oscilloscope was included in the system. This oscilloscope provides a way to observe the accelerometer output quickly without having to take Polaroid pictures. Moreover, the use of the oscilloscope does not add significantly to the time required for calibration.

Error Analysis of Pendulum Calibration System

Comparison Between Oscilloscope Pictures and Peak Meters

The first check on the system was accelerometer calibration with simultaneous use of both the original oscilloscope photography method and the peak-meter method. For this test, four groups of shock accelerometers were used. A summary of the data obtained with the four groups of accelerometers is given in Table I. This table gives, for each accelerometer type, the number of accelerometers calibrated, and for E_p, the mean value, standard deviation, maximum and minimum values, and range.

For each type of accelerometer calibrated, a statistical test of significance was performed to determine whether the mean value difference between the peak meters and the vibration was statistically different from that of the pictures and the vibration. It was found that the mean value of the group 1 and group 4 accelerometers was statistically different at the $\alpha = 0.05$ level,* and not statistically different for the other models. It can be seen, therefore, that with the group 1 and group 4 accelerometers there was better correlation between the peak meters and the vibration than there was from the pictures. But on the other groups of accelerometers, there was no better correlation between the peak meters and the vibration than is normally obtained with the pictures.

TABLE I

Data Summary on Basic Sensitivity

Group	Type of Calibration	No.	Mean	Standard Deviation	Max. Value	Min. Value	Range
#1	Peak meter and picture	7	+2.00	0.76	+2.95	+0.99	1.96
	Peak meter and vibration	7	+0.97	0.66	+2.14	+0.24	1.90
	Picture and vibration	7	+2.55	1.21	+4.98	+1.00	3.98
#2	Peak meter and picture	18	+0.84	0.60	+1.68	0.00	1.68
	Peak meter and vibration	16	+1.21	0.70	+2.97	+0.27	2.70
	Picture and vibration	16	0.97	0.72	+2.33	0.00	2.33
#3	Peak meter and picture	6	+0.89	0.39	+1.35	+0.32	1.02
	Peak meter and vibration	6	+2.87	0.75	+4.21	+1.89	2.32
	Picture and vibration	6	+3.43	0.33	+3.93	+3.10	0.84
#4	Peak meter and picture	6	+2.23	1.09	+3.46	+0.32	3.14
	Peak meter and vibration	6	+0.69	0.27	+1.02	+0.37	0.66
	Picture and vibration	6	+2.12	0.75	+3.09	+1.00	2.08

*The α level of significance is the probability of stating that the two means are different, when in fact they are not. When $\alpha = 0.05$, this probability is 5 percent.

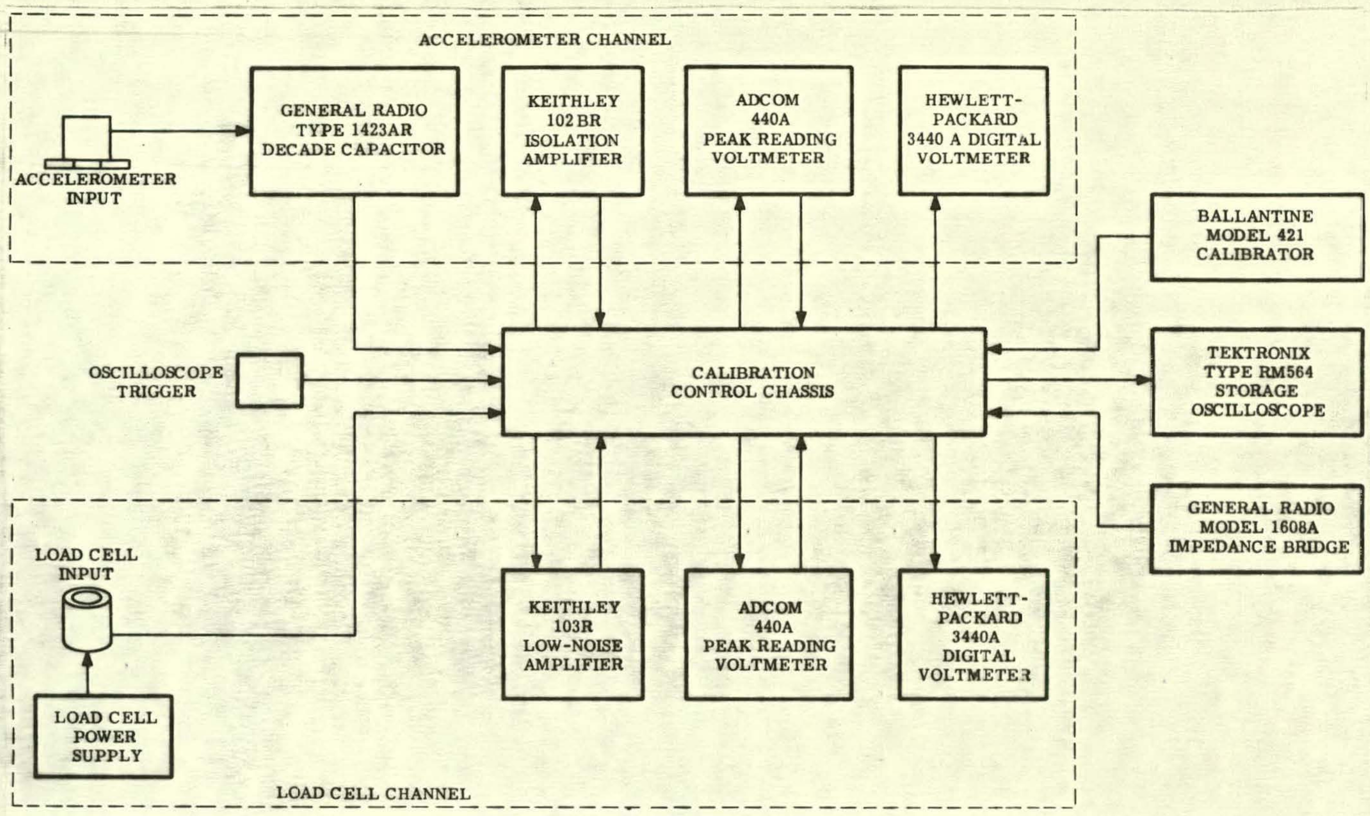

Fig. 6. Complete pendulum calibration system

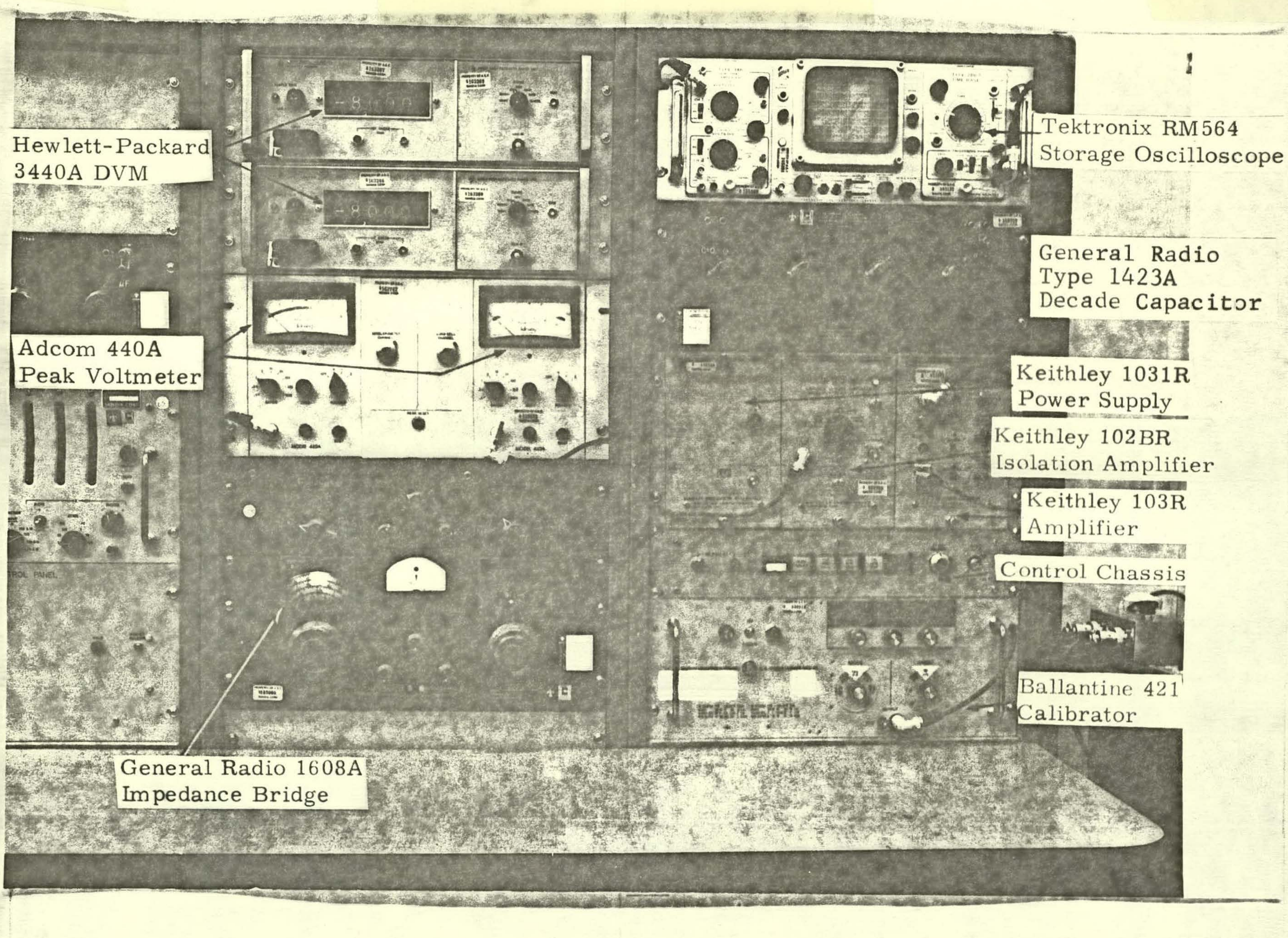

Fig. 7. Overall instrumentation console

Detailed data show the percent difference between the values obtained with the peak meters and with the oscilloscope pictures for both the accelerometer and load-cell channels. It is interesting to note that these percent differences between the peak meters and the oscilloscope pictures are fairly large for most of the accelerometers tested, running often as high as 5 to 6 percent and in some cases over 8 percent. Assuming that the peak meter is correct and serving as the standard, then the error in the peak reading taken from the oscilloscope picture is often in excess of 5 percent, or too much for purposes of determining basic sensitivity. The values given in the tables showing the large percent of difference are based on the reading of the peak of only one voltage signal. Data analysis has shown that better results are obtained if readings of the peaks of two signals on the same picture are taken and the ratio of these two voltages used in the computations. This two reading-ratio method reduces the overall error, with the percent difference of the E_p values between peak meters and oscilloscope pictures generally averaging only 2 percent.

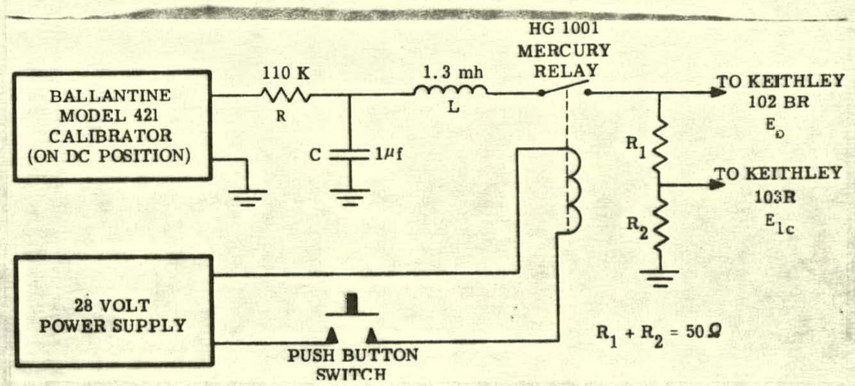

Fig. 8. Pulse shaping circuit

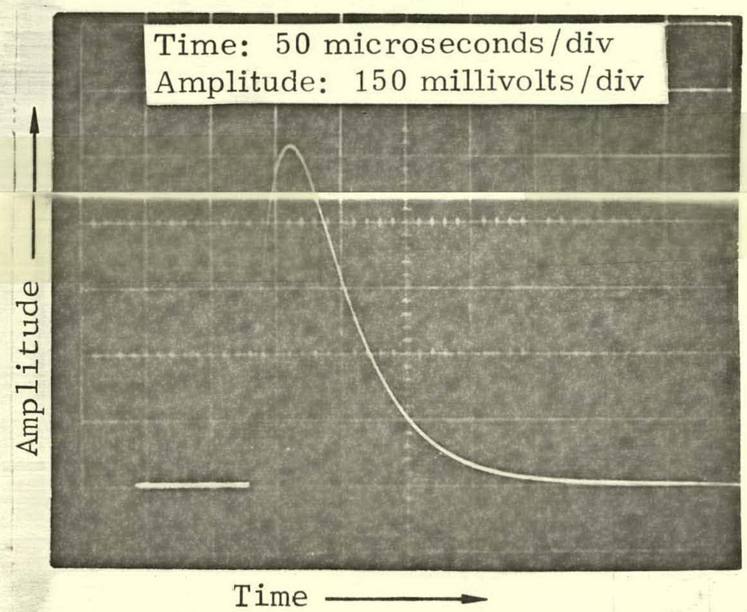

Fig. 9. Signal from pulse shaping circuit

Instrumentation System Accuracy

Although the first test series indicated that correlation between vibration and the peak meters was better than that obtained from the picture reduction method, this still tells us very little about the system accuracy with the peak meters because there is presently no way of determining which shock sensitivity value is the correct one. Since the calibrations were performed by the same technicians who normally perform shock calibrations, these tests showed that data reduction time could be reduced by using the peak meters and allowed the system to be calibrated and operated with relative ease.

The next group of tests was performed to provide accuracy data on the instrumentation system, exclusive of the error in the basic load-cell calibration. For this error analysis, a pulse shaping circuit, shown in Fig. 8, was used.

This is basically an RLC series circuit, which is almost critically damped. The circuit also includes a mercury relay to minimize noise caused by contact bounce. The initial charge on the capacitor is provided by the Ballantine calibrator. The resulting pulse (Fig. 9) is extremely clean and repeatable. The amplitude and duration of this pulse is basically fixed by the parameters of the circuit and the voltage level set on the Ballantine calibrator. Two outputs, as shown in Fig. 8, were provided: a high output pulse for the Keithley 102BR (~ 1 to 5 volts), and a low output pulse for the Keithley 103R (~ 10 to 50 millivolts).

For the pulse test, the system arrangement was essentially the same as the modified pendulum instrumentation depicted in Fig. 5. The system was initially calibrated by applying the Ballantine calibrator (set on 1000 cps and peak-to-peak voltage) to each channel and setting the attenuator so that the DVM indicated the correct peak level of the sine-wave signal. The pulse circuit was then applied simultaneously to both input channels of the peak reading system. The peak amplitude of the high output pulse, E_o, was determined with a Tektronix Type W plug-in, a high-gain calibrated differential comparator which has a comparison voltage accuracy and drift of less than ± 0.2 percent of reading and a resolution of 100 microvolts/mm at the maximum sensitivity. The true peak amplitude of the low output pulse, E_{1c} was taken as 0.010 (E_o) and was determined by the ratio

$$\frac{R_2}{R_1 + R_2}$$

(see Fig. 8).

The results of this test are shown in Table II. The input pulse levels were regulated to provide for peak-meter operation between 70 and 100 percent of full-scale level, since this is the range used during the calibration of accelerometers.

Five individual readings were taken at each voltage level on both the accelerometer and the load-cell channels. Twenty-three different pulse levels, ranging from 0.983 to 0.736 volt peak, were chosen, on the high output, whereas the range on the low output side was 9.83 to 7.36 millivolts. The first step in the analysis was to compute the mean of the five E_o and E_{lc} readings, where E_o and E_{lc} are the peak-voltage readings from the accelerometer and load-cell channels, respectively. Next the values were reduced to relative errors in this manner:

Relative error =

$$\frac{\text{True value of } E_o - \text{mean observed value of } E_o}{\text{True value of } E_o}$$

The relative errors for E_{1c} were found in a similar manner.

A summary of the relative error data is as follows:

	E_o	E_{1c}
Number of observations:	23	23
Mean relative error:	-0.00433	-0.00550
Standard deviation:	0.00282	0.00380
Maximum relative error:	0.00057	0.00134
Minimum relative error:	-0.00895	-0.01635

Analysis of the data indicated that the relative errors were normally distributed for both E_o and E_{lc}. Tolerance values were computed based on a normal distribution to determine limits on the population of relative errors. Based on these limits, 95 percent of the population of relative errors will fall between -1.18 percent and +0.32 percent for E_o and between -1.56 percent and +0.46 percent for E_{lc}. Both of these limits are with a confidence of 95 percent.

For general interest, a similar analysis was performed on only the first reading obtained on the accelerometer channel. The data computed would indicate the accuracy possibly attainable when the peak-reading system is used on a mechanical shock test. For this analysis, this is the summary of the relative error data:

Number of observations:	23
Mean relative error:	-0.00381
Standard deviation:	0.00368
Maximum relative error:	0.00265
Minimum relative error:	-0.01157

Again the error limits, based on a normal distribution, were computed. With these limits, 95 percent of the population of relative errors will fall between -1.36 percent and +0.60 percent with a confidence of 95 percent. These figures take into account the error in the Keithley 102BR isolation amplifier and the Adcomp 440A peak meter, assuming only one reading by the operator. Also, this accuracy will only be obtained when the analog DC voltage output of the Adcomp 440A is used; if the meter on the Adcomp 440A is used, the error will be somewhat larger, generally on the order of ± 2.5 percent.

Overall System Accuracy

The data obtained during the test series were reduced and computations were made to determine the overall system accuracy. These computations, step-by-step, to determine the basic sensitivity, E_p, of accelerometers, are as follows.

First, the load-cell output is found with this equation:

$$E_{1c} = \left[\left(\frac{M_b + M_{ac}}{453.59}\right) G\right] S_{1c} E_b , \qquad (1)$$

where

E_{1c} = peak-output voltage of load cell

M_b = mass of bullet in grams

M_{ac} = mass of accelerometer in grams

G = peak-acceleration level in g's

S_{1c} = load-cell sensitivity in microvolts/volt/pound force

E_b = load-cell bridge voltage

453.59 = number of grams in 1 pound.

By rearranging Eq. (1), computation can be made for peak-acceleration level as follows:

TABLE II

Pulse Test Results

Ballantine Calibrator	Actual Accel. Channel Input (volts)	Acceleration Channel Peak Meter Readings 1	2	3	4	5	Actual Load-Cell Channel Input (mv)	Load Cell Peak Meter Readings 1	2	3	4	5
1.740	0.9836	0.989	0.989	0.989	0.989	0.989	9.836	9.906	9.906	9.906	9.906	9.906
1.720	0.9723	0.978	0.978	0.978	0.978	0.978	9.723	9.806	9.806	9.806	9.806	9.806
1.700	0.9610	0.967	0.967	0.967	0.967	0.967	9.610	9.612	9.710	9.710	9.710	9.612
1.680	0.9497	0.956	0.956	0.956	0.956	0.956	9.497	9.514	9.514	9.514	9.514	9.612
1.660	0.9384	0.946	0.946	0.946	0.946	0.946	9.384	9.416	9.514	9.416	9.416	9.416
1.640	0.9271	0.935	0.935	0.935	0.935	0.935	9.271	9.320	9.320	9.320	9.320	9.320
1.620	0.9158	0.924	0.924	0.924	0.924	0.924	9.158	9.222	9.222	9.222	9.222	9.222
1.600	0.9044	0.902	0.913	0.902	0.913	0.902	9.044	9.124	9.124	9.124	9.124	9.124
1.580	0.8931	0.892	0.892	0.902	0.902	0.892	8.931	9.026	9.026	8.928	9.026	8.928
1.560	0.8818	0.892	0.881	0.892	0.892	0.881	8.818	8.830	8.830	8.830	8.928	8.928
1.540	0.8705	0.870	0.870	0.870	0.870	0.870	8.705	8.732	8.732	8.732	8.732	8.732
1.520	0.8590	0.859	0.859	0.859	0.859	0.859	8.590	8.636	8.636	8.636	8.636	8.636
1.500	0.8479	0.848	0.848	0.848	0.848	0.848	8.479	8.538	8.538	8.538	8.538	8.538
1.480	0.8366	0.837	0.848	0.837	0.837	0.837	8.366	8.440	8.440	8.440	8.440	8.440
1.460	0.8257	0.826	0.826	0.826	0.826	0.826	8.257	8.244	8.244	8.342	8.244	8.244
1.440	0.8140	0.816	0.816	0.816	0.816	0.816	8.140	8.146	8.146	8.146	8.146	8.244
1.420	0.8032	0.805	0.805	0.805	0.805	0.805	8.032	8.050	8.050	8.050	8.050	8.050
1.400	0.7918	0.794	0.794	0.794	0.794	0.794	7.918	7.950	7.950	7.950	7.950	7.950
1.380	0.7809	0.783	0.783	0.783	0.783	0.783	7.809	7.854	7.854	7.854	7.854	7.854
1.360	0.7696	0.773	0.773	0.773	0.773	0.773	7.696	7.756	7.756	7.756	7.756	7.756
1.340	0.7585	0.762	0.762	0.762	0.762	0.762	7.583	7.858	7.560	7.560	7.858	7.560
1.320	0.7472	0.751	0.751	0.751	0.751	0.751	7.472	7.462	7.462	7.462	7.462	7.560
1.300	0.7359	0.740	0.740	0.740	0.740	0.740	7.359	7.364	7.364	7.364	7.364	7.364

$$G = \left[\frac{453.59}{\left(M_b + M_{ac}\right)S_{lc}E_b}\right]E_{lc} . \quad (2)$$

The equation for accelerometer basic sensitivity is given by

$$E_p = \frac{E_o}{G}\left[\frac{C_p + C_s}{C_p}\right] , \quad (3)$$

where

E_p = basic sensitivity in pmv/pg

E_o = peak-output voltage of test accelerometer

G = peak-acceleration level in g's

C_p = crystal capacitance in pfd

C_s = total shunt capacitance in pfd.

Next, by substituting Eq. (2) into Eq. (3), then

$$E_p = \left[\frac{\left(M_b + M_{ac}\right)S_{lc}E_b}{453.59}\right]\left[\frac{C_p + C_s}{C_p}\right]\frac{E_o}{E_{lc}} . \quad (4)$$

For a calibration on any one accelerometer, M_b, M_{ac}, S_{lc}, E_b, C_p, and C_s are all constants. Therefore, the equation for basic sensitivity is given by

$$E_p = K\frac{E_o}{E_{lc}} , \quad (5)$$

where

$$K = \left[\frac{\left(M_b + M_{ac}\right)S_{lc}E_b}{453.59}\right]\left[\frac{C_p + C_s}{C_p}\right] .$$

Observe in Eq. (5) that the ratio of the two peak readings (E_o and E_{lc}) and not the single reading is used to calculate for basic sensitivity.

It is necessary when determining overall system accuracy to consider the variance of each of the independent variables in Eq. (5). In general, if $y = f(X_1, X_2, \ldots X_n)$, then the approximate variance of y, namely V(y), as given by Deming,[4] is calculated in this manner:

$$V(y) = \sum_{i=1}^{n}\left(\frac{\partial f}{\partial X_i}\right)^2 \sigma^2_{X_i} , \quad (6)$$

where $\sigma^2_{X_i}$ is the variance of X_i. The partial derivatives $\partial f/\partial X_i$ are all evaluated at a set of nominal values.

By using Eq. (6), it is found that the variance of E_p is

$$V\left(E_p\right) = \left(\frac{\partial E_p}{\partial M_b}\right)^2\sigma^2_{M_b} + \left(\frac{\partial E_p}{\partial S_{lc}}\right)^2\sigma^2_{S_{lc}} + \left(\frac{\partial E_p}{\partial E_b}\right)^2\sigma^2_{E_b} + \left(\frac{\partial E_p}{\partial C_p}\right)^2\sigma^2_{C_p} + \left(\frac{\partial E_p}{\partial C_s}\right)^2\sigma^2_{C_s} + \left(\frac{\partial E_p}{\partial E_o}\right)^2\sigma^2_{E_o} + \left(\frac{\partial E_p}{\partial E_{lc}}\right)^2\sigma^2_{E_{lc}} . \quad (7)$$

By taking the partial derivatives indicated in (7), we arrive at the following equation:

$$V\left(E_p\right) = \left[\frac{S_{lc}E_b}{453.59}\left(1 + \frac{C_s}{C_p}\right)\left(\frac{E_o}{E_{lc}}\right)\right]^2\sigma^2_{M_b} + \left[\frac{\left(M_b + M_{ac}\right)E_b}{453.59}\left(1 + \frac{C_s}{C_p}\right)\left(\frac{E_o}{E_{lc}}\right)\right]^2\sigma^2_{S_{lc}} + \left[\frac{\left(M_b + M_{ac}\right)S_{lc}}{453.59}\left(1 + \frac{C_s}{C_p}\right)\left(\frac{E_o}{E_{lc}}\right)\right]^2\sigma^2_{E_b}$$

$$+ \left[\frac{\left(M_b + M_{ac}\right)S_{lc}E_b}{453.59}\left(\frac{-C_s}{C_p^{\,2}}\right)\left(\frac{E_o}{E_{lc}}\right)\right]^2 \sigma^2_{C_p}$$

$$+ \left[\frac{\left(M_b + M_{ac}\right)S_{lc}E_b}{453.59}\left(\frac{1}{C_p}\right)\left(\frac{E_o}{E_{lc}}\right)\right]^2 \sigma^2_{C_s}$$

$$+ \left[\frac{\left(M_b + M_{ac}\right)S_{lc}E_b}{453.59}\left(1 + \frac{C_s}{C_p}\right)\left(\frac{1}{E_{lc}}\right)\right]^2 \sigma^2_{E_o} \qquad (8)$$

$$+ \left[\frac{\left(M_b + M_{ac}\right)S_{lc}E_b}{453.59}\left(1 + \frac{C_s}{C_p}\right)\left(\frac{-E_o}{E_{lc}^{\,2}}\right)\right]^2 \sigma^2_{E_{lc}}$$

The variance of M_{ac} is assumed to be zero, and, hence, the term

$$\left(\frac{\partial E_p}{\partial M_{ac}}\right)^2 \sigma^2_{M_{ac}}$$

does not enter into Eqs. (7) or (8).

Nominal sets of values, relative errors, and variances of M_b, M_{ac}, S_{lc}, E_b, C_p, C_s, E_o, and E_{lc} are given in Table III. As shown in Table III, it is assumed that M_b, E_b, C_p, and C_s are uniformly distributed (Fig. 10), and that S_{lc}, E_o, and E_{lc} are normally distributed (Fig. 11).

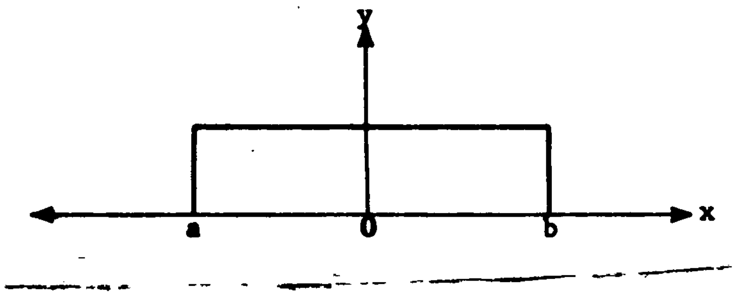

Fig. 10. Uniform error distribution

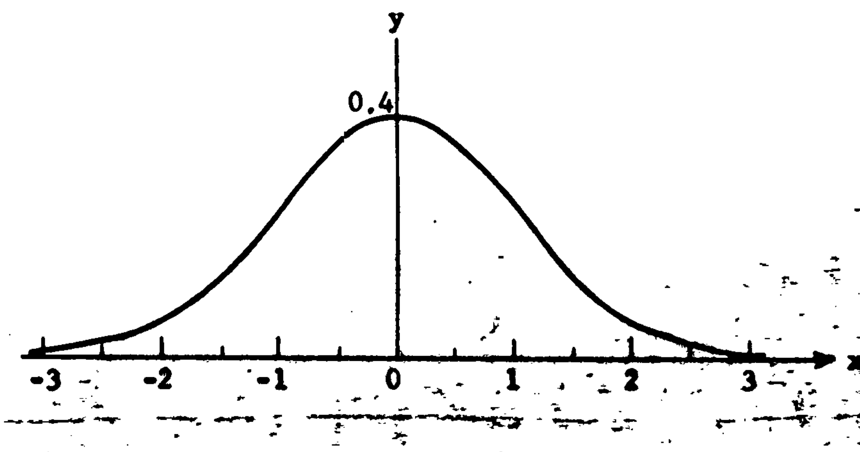

Fig. 11. Normal curve: $y = \frac{1}{\sqrt{2\pi}} \exp\left(-x^2/2\right)$

The relative error for S_{lc}, shown in Table III, is a combination of (1) linearity of $\pm$1.25 percent, (2) hysteresis of $\pm$0.50 percent, and (3) repeatability of $\pm$0.50 percent. These three conditions were assumed to be independent, normally distributed, and to include 99 percent of the error distribution (3x standard deviation) for each variable, resulting in a total standard deviation of $\pm$0.479 percent for S_{lc}.

The errors in E_o and E_{lc} were shown in the previous section to be normally distributed. Since the analog output of the Adcomp Model 440A peak-reading voltmeter is made up of 100 steps (each step being 50 millivolts out of the total full-scale output of 5.00 volts), an additional $\pm$0.50-percent error, having a uniform distribution, is included in the standard deviation for E_o and E_{lc} shown in Table III.

Table IV gives the nominal value and the approximate variance of E_p for various combinations of the variables listed in Table III. The approximate variance of E_p can be divided into the seven parts, as shown by Eq. (7). Table V shows the contribution of each part to the total variance, $V(E_p)$.

The last column in Table IV gives the estimated standard deviation of E_p for each of the six cases considered. It can be seen from Table IV that the resulting standard deviation of E_p did not vary significantly for any of the cases considered. To be conservative, the largest estimated standard deviation, 0.00848, is chosen.

Assuming the overall system error to be normally distributed, then the limits of error on E_p are $\pm$(3 x 0.00848) (100) = $\pm$2.54 percent of E_p. These limits will include approximately 99 percent of the system error distribution, and the true value of E_p will be outside of these limits less than 1 percent of the time. Under the same assumption that the errors in E_p are normally distributed, the limits of error which will include 95 percent of the error distribution would be ±1.70 percent.

Future Improvements in the Instrumentation

Load Cell Investigations

As previously mentioned, the Lockheed strain gage load cell provides shock calibration values which correlate very closely with vibration calibration values. This load cell does, however, have a sensitivity of approximately 0.5 microvolt per volt per pound. For a shock calibration at 1000 G, the load cell provides a peak output of only about 3 millivolts. Because of this low sensitivity it is necessary to use a battery for the bridge excitation for this application.

In an attempt to overcome this problem, several additional load cells have been evaluated. The first one to be evaluated was a 1500 pound capacity flat load cell. The linearity, repeatability and hysteresis proved to be exceptionally good on this unit and the output was about six times that of the previous Lockheed unit. The increased output makes it possible to use a strain gage power supply with the system and, therefore, to reduce the calculations necessary. When a sample of shock accelerometers was calibrated using this load cell, however, the sensitivities obtained were approximately 2.5 percent higher than the sensitivities obtained on the same sample with the Lockheed load cell.

Another load cell which was evaluated was a piezoelectric type quartz load cell. The sensitivity of this unit is nominally 800 millivolts/lb., and it has a resonant frequency, when mounted in the system, of about 50 kHz. This load cell has the additional advantage that no strain gage power supply is required and the computations are further simplified. When the same sample of shock accelerometers was calibrated using this load cell, the sensitivities obtained were approximately four percent higher than those obtained with the Lockheed load cell.

It appears that some of these differences between load cells are caused by the inability to obtain a sufficiently accurate and repeatable static calibration of the load cells. To remedy this, a more accurate static force calibration system has been ordered. It is felt that this should bring all of the results into closer agreement.

Readout Instrumentation

If either of the load cells evaluated prove satisfactory, this will allow the readout system to be simplified considerably. It is anticipated that a digital ratiometer and a digital voltmeter will be used for presentation of the calibration data to the operator. For each drop of the ballistic pendulum, the operator will receive a direct readout, on the digital voltmeter, of the acceleration level obtained in G's. The operator will also receive, on the digital ratiometer, a direct readout, of the sensitivity of the test accelerometer in millivolts/G, with a fixed cable length. The operator would then be required to perform only one simple calculation to obtain the basic sensitivity of the test accelerometer.

Summary

The former pendulum shock calibration system used by the Calibration Laboratory was an effective shock calibrator, but its readout instrumentation allowed for the possibility of human error and required long data reduction time. Therefore, a development was undertaken to improve performance. This modified instrumentation system has been in use in the Calibration Laboratory for almost 10 months, and it has performed its intended function, namely reducing the chance of human error during the calibration of shock accelerometers.

Overall system accuracy has been determined by analyses of the equipment. The accuracy of the basic sensitivity, E_p, calibration of accelerometers was found to be ±2.5 percent, assuming a normal distribution and, therefore, the true value of E_p will be outside of these limits of error less than one percent of the time. The accuracy of performance appears to be consistent with that predicted by calculations, and the increased reliability from one calibration to the next is evident.

The system is very convenient to use, both from the standpoint of calibration and operation. The time required for overall calibration has been reduced approximately one-half. The new system has also eliminated the necessity for using an oscilloscope camera and polaroid film, although it still allows the operator to monitor the waveshape from the accelerometer during calibration. Should either of the load cells which have been evaluated prove satisfactory the system could be further simplified and the overall calibration time could again be reduced by approximately one-half. This would result in an overall reduction in calibration time of approximately 75 percent over the original system.

The accuracy study which has been discussed in this report is still being conducted, and the emphasis is currently on several models of shock accelerometers which are among those most commonly used by Sandia Corporation's Environmental Testing Organization at Albuquerque.

TABLE III

Nominal Values, Relative Errors, Type of Distribution Assumed and Variances of E_b, M_b, M_{ac}, S_{1c}, E_o, E_{1c}, C_s, and C_p

Variable	Nominal Value	Relative Error	Distribution	Variances
E_b	9.000 volts	±0.10% reading	Uniform	$(27.00)(10^{-6})$ volts
M_b	339.00 grams	±0.5% reading	Uniform	0.9578 gram
M_{ac}	3.0 to 33.9 grams	0		0.00
S_{1c}	$(0.432)(10^{-3})$mv/v/lb	S.D. = ±0.479%	Normal	$(4.277)(10^{-12})$mv/v/lb
E_o	0.890 volt 0.800 volt 0.885 volt	S.D. = ±0.404%	Normal	$(12.928)(10^{-6})$ volts $(10.446)(10^{-6})$ volts $(12.781)(10^{-6})$ volts
E_{1c}	$(4.50)(10^{-3})$ volts $(3.00)(10^{-3})$ volts $(1.50)(10^{-3})$ volts	S.D. = ±0.477%	Normal	$(4.607)(10^{-10})$ volts $(2.048)(10^{-10})$ volts $(0.5119)(10^{-10})$ volt
C_s	550 pf 2700 pf 70,700 pf	±0.16% reading	Uniform	0.258 pf 6.224 pf 4267.59 pf
C_p	800 pf 750 pf 9800 pf	±0.16% reading	Uniform	0.546 pf 0.480 pf 81.997 pf

TABLE IV

Mean and Variance of E_p for Various Values of E_b, M_b, M_{ac}, S_{1c}, E_o, E_{1c}, C_s, and C_p

	E_b (volts)	M_b (grams)	M_{ac} (grams)	S_{1c} (mv/v/lb)	E_o (volt)	E_{1c} (mv)	C_s (pf)	C_p (pf)	E_p (mv/g)	$V(E_p)$	$\sqrt{V(E_p)}$	$\frac{\sqrt{V(E_p)}}{E_p}$
Case 1	9.000	339.0	3.0	$(0.432)(10^{-3})$	0.890	4.50	550	800	0.978	$(64.678)(10^{-6})$	$(8.04)(10^{-3})$	$(8.22)(10^{-3})$
Case 2	9.000	339.0	33.9	$(0.432)(10^{-3})$	0.890	4.50	550	800	1.065	$(78.950)(10^{-6})$	$(8.89)(10^{-3})$	$(8.35)(10^{-3})$
Case 3	9.000	339.0	3.0	$(0.432)(10^{-3})$	0.800	3.00	2,700	750	3.593	$(9.238)(10^{-4})$	$(3.039)(10^{-2})$	$(8.458)(10^{-3})$
Case 4	9.000	339.0	33.9	$(0.432)(10^{-3})$	0.800	3.00	2,700	750	3.917	$(10.324)(10^{-4})$	$(3.213)(10^{-2})$	$(8.203)(10^{-3})$
Case 5	9.000	339.0	3.0	$(0.432)(10^{-3})$	0.885	1.50	70,700	9800	14.194	$(144.667)(10^{-4})$	$(12.03)(10^{-2})$	$(8.475)(10^{-3})$
Case 6	9.000	339.0	33.9	$(0.432)(10^{-3})$	0.885	1.50	70,700	9800	15.476	$(168.890)(10^{-4})$	$(13.00)(10^{-2})$	$(8.400)(10^{-3})$

TABLE IV

Mean and Variance of E_p for Various Values of E_b, M_b, M_{ac}, S_{1c}, E_o, E_{1c}, C_s, and C_p

	E_b (volts)	M_b (grams)	M_{ac} (grams)	S_{1c} (mv/v/lb)	E_o (volt)	E_{1c} (mv)	C_s (pf)	C_p (pf)	E_p (mv/g)	$V(E_p)$	$\sqrt{V(E_p)}$	$\frac{\sqrt{V(E_p)}}{E_p}$
Case 1	9.000	339.0	3.0	$(0.432)(10^{-3})$	0.890	4.50	550	800	0.978	$(64.678)(10^{-6})$	$(8.04)(10^{-3})$	$(8.22)(10^{-3})$
Case 2	9.000	339.0	33.9	$(0.432)(10^{-3})$	0.890	4.50	550	800	1.065	$(78.950)(10^{-6})$	$(8.89)(10^{-3})$	$(8.35)(10^{-3})$
Case 3	9.000	339.0	3.0	$(0.432)(10^{-3})$	0.800	3.00	2,700	750	3.593	$(9.238)(10^{-4})$	$(3.039)(10^{-2})$	$(8.458)(10^{-3})$
Case 4	9.000	339.0	33.9	$(0.432)(10^{-3})$	0.800	3.00	2,700	750	3.917	$(10.324)(10^{-4})$	$(3.213)(10^{-2})$	$(8.203)(10^{-3})$
Case 5	9.000	339.0	3.0	$(0.432)(10^{-3})$	0.885	1.50	70,700	9800	14.194	$(144.667)(10^{-4})$	$(12.03)(10^{-2})$	$(8.475)(10^{-3})$
Case 6	9.000	339.0	33.9	$(0.432)(10^{-3})$	0.885	1.50	70,700	9800	15.476	$(168.890)(10^{-4})$	$(13.00)(10^{-2})$	$(8.400)(10^{-3})$

TABLE V

Division of $V(E_p)$ Into Its Component Parts

$V(E_p)$	$\left(\frac{\partial E_p}{\partial E_b}\right)^2 \sigma^2_{E_b}$	$\left(\frac{\partial E_p}{\partial M_b}\right)^2 \sigma^2_{M_b}$	$\left(\frac{\partial E_p}{\partial S_{1c}}\right)^2 \sigma^2_{S_{1c}}$	$\left(\frac{\partial E_p}{\partial E_o}\right)^2 \sigma^2_{E_o}$	$\left(\frac{\partial E_p}{\partial E_{1c}}\right)^2 \sigma^2_{E_{1c}}$	$\left(\frac{\partial E_p}{\partial C_s}\right)^2 \sigma^2_{C_s}$	$\left(\frac{\partial E_p}{\partial C_p}\right)^2 \sigma^2_{C_p}$

This study should indicate the long-term repeatability of the shock calibration instrumentation system and will indicate the correlation with vibration calibration.

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