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MODIFIED VIBRATION TRANSDUCER CALIBRATION SYSTEM WHICH DIRECTLY YIELDS A PLOT OF SENSITIVITY VERSUS FREQUENCY

by William C. Nieberding, Edward F. Miller, and David L. Wright

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

A commercially available vibration transducer calibration system was modified to directly produce an output plot of transducer sensitivity versus frequency over the range of frequencies from 10 to 10 000 Hz. This was accomplished by the insertion of a readily programmed automatic attenuation in the exciter control-system feedback loop to maintain constant vibration amplitude versus frequency. National Bureau of Standards primary calibration data are repeated to within ±0.5 percent over the frequency range of 10 to 9000 Hz and within ±1 percent from 9000 to 10 000 Hz. Calibrations are obtained in 15 minutes.

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SUMMARY

A commercially available vibration transducer calibration system was modified to directly produce an output plot of transducer sensitivity versus frequency over the range of frequencies from 10 to 10 000 hertz. This was accomplished by the insertion of a readily programmed automatic attenuation in the exciter control-system feedback loop to maintain constant vibration amplitude versus frequency. National Bureau of Standards primary calibration data are repeated to within ±0.5 percent over the frequency range of 10 to 9000 hertz and within ±1 percent from 9000 to 10 000 hertz. Calibrations are obtained in 15 minutes.

INTRODUCTION

Calibration of sensitivity versus frequency is required for accelerometers used for vibration measurement since many must be operated over a frequency range within which variations in their sensitivity are 15 to 20 percent. The calibration systems that are commercially available test the accelerometers typically from 5 to 10 000 hertz on an electrodynamic shaker (ref. 1). However, the frequency plots that result from these tests are not directly usable, since the resulting curves are not of sensitivity versus frequency. This report describes a commercially availably calibration system which was modified at the Lewis Research Center to directly produce the desired plot of sensitivity versus frequency.

The system to be described and analyzed is based on the use of a vibration transducer in the vibration-system feedback loop to maintain constant vibration amplitude during a frequency sweep. Since the actual system uses an accelerometer for the transducer and maintains constant acceleration, the discussion and analysis are based on acceleration. This type of system control, however, applies equally well to velocity or displacement systems if the proper transducers and/or electrical integrators are used.

The basic operation of both the conventional and modified systems consists of vibrating two accelerometers mounted on the same electrodyanamic shaker. One of these accelerometers is the one to be calibrated and together with its amplifier and connecting cable is referred to as the test system. The other accelerometer together with its amplifier and cable is electrically a part of the vibration-system feedback loop and is referred to as the comparison system. The comparison system is initially calibrated against a third accelerometer system, referred to as the standard system, which was previously calibrated absolutely by the National Bureau of Standards (NBS). A plot is made of the test-system output versus frequency on an X-Y plotter as the frequency of the signal driving the shaker is swept from the minimum to the maximum of interest.

In the conventional calibration system, shown in figure 1, the vibration amplitude is servocontrolled to maintain constant output voltage from the comparison system throughout the frequency sweep. Either the test-system output voltage or its deviation from the comparison-system output voltage is then plotted versus frequency on the X-Y plotter. Since the comparison-system sensitivity, in general, is not constant over the frequency range, the vibration is not at a constant acceleration level; thus, the test plot is not sensitivity versus frequency nor is it deviation from constant sensitivity versus frequency.

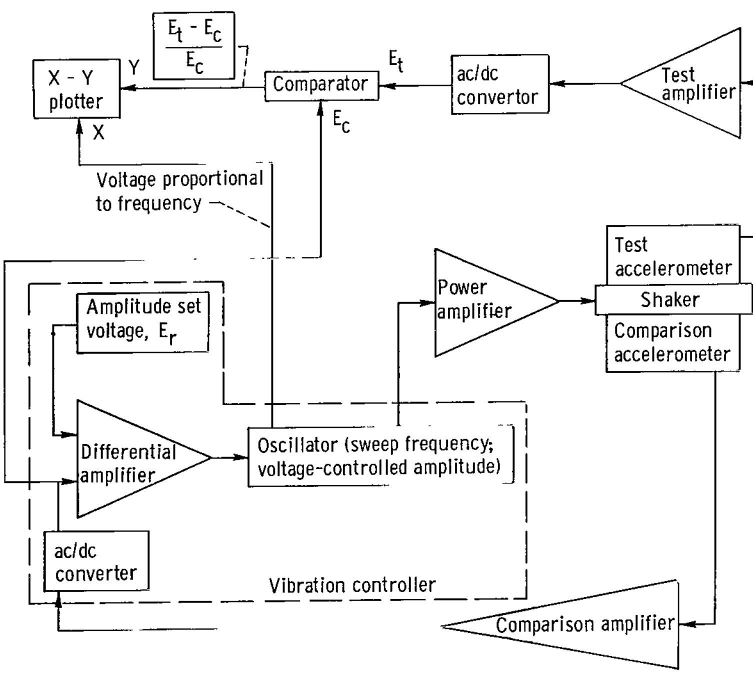

Figure 1. - Conventional calibration system.

The user of an accelerometer, calibrated by the conventional method, is forced to refer to two plots to obtain the sensitivity versus frequency for his accelerometer system. The first plot is the calibration provided as the output of the conventional calibration system; the second is the sensivitity versus frequency plot for the comparison accelerometer system. The comparison accelerometer system plot is then used to make point by point corrections to the original calibration curve. This procedure is tedious and time consuming.

If the shaker system were controlled to maintain a constant acceleration level throughout the frequency range of the calibration, a plot of the test accelerometer output versus frequency would produce automatically, on a single curve, and with no corrections required, the sensitivity versus frequency information that the user desires. The acceleration throughout the frequency range could be kept constant by building an electrical network which compensates for variations in the comparison-system sensitivity. However, such a system is not as flexible as the one described herein. Any change in the comparison-system sensitivity requires a redesign of the compensating network, which proves in practice to be time consuming.

This report presents a more usable method of obtaining calibrations at a constant acceleration level over the frequency range of the test. A conventional calibration system is modified by the addition of a variable attenuator in the feedback loop of the acceleration level servocontrol. This system has the advantage that the program for the variable attenuator is easily changed in case changes occur in the transfer characteristics of elements in the calibration system. The overall system can be quickly checked to determine whether these changes have occurred. Both the general principles and the detailed implementation of the modified system are presented herein.

SYSTEM DESCRIPTION

Conventional System

A block diagram of the conventional system as it operated before modification is shown in figure 1. The basic operation is such that the swept frequency ac output of the vibration controller (dashed box in fig. 1) drives a power amplifier which, in turn, drives the moving element of the shaker. On the shaker are mounted two accelerometers, the test and comparison accelerometers, which are assumed to move in unison. Each accelerometer signal is amplified by either a voltage amplifier or charge amplifier and then converted to a dc level. The dc level from the comparison system E_c is subtracted in the differential amplifier from the set point voltage E_r which represents the desired acceleration level (g-level). This difference or error signal ($e = E_r - E_c$) is used to control the amplitude of the vibration controller output; thus, the resulting servoaction holds

E_c constant in spite of the frequency dependence of the transfer functions of the vibration controller, power amplifier, and shaker.

The output of this system is obtained by forming the ratio $(E_t - E_c)/E_c$ where E_t is the dc output of the test system and E_c is constant because of the servoaction. A voltage proportional to this ratio is applied to the y-axis of the X-Y plotter while the x-axis is driven by a voltage (formed in the vibration controller) proportional to vibration frequency.

The operating procedure begins with the standard accelerometer system (calibrated by the NBS) in place of the test system. With the frequency set to a fixed value (usually 100 or 200 Hz), the gain of the comparison amplifier is varied until E_c equals E_s, the dc output of the standard system. This sets the comparison-system sensitivity equal to the standard-system sensitivity at this reference frequency. At this time the plotter pen is set to a convenient location on the y-axis. With the servoloop closed, a frequency sweep is then initiated. A plot results which is the deviation of the comparison-system sensitivity from the standard-system sensitivity as a function of frequency. (The plot will show no deviation at the reference frequency.) A plot of the comparison-system sensitivity can then be obtained by using the standard-system sensitivity plot (obtained from NBS) and a point by point correction obtained from the deviation plot. This information is needed to begin calibrating test accelerometers.

A test accelerometer can now be calibrated by replacing the standard system with the test system. At the reference frequency the test amplifier gain is adjusted so that $E_t = E_c$. The test system is then calibrated by the same procedure used to calibrate the comparison system.

The problem is that since the comparison-system sensitivity is not constant over the frequency range, a constant g-level is not held. The plots resulting from the calibration of the test accelerometer systems must each be corrected, point by point, for the variations in the sensitivity of the comparison system.

Modified System

Modification of the system just described by the insertion of a programmed attenuator in the comparison-system feedback loop enables a constant g-level to be maintained throughout the frequency range. Figure 2 is a block diagram of this modified system with a curve follower used as the programmed attenuator. Operation is identical to the conventional system except that E_t is plotted directly and E_c is attenuated by a factor b whose frequency dependence is such that constant g-level is maintained (see ANALYSIS).

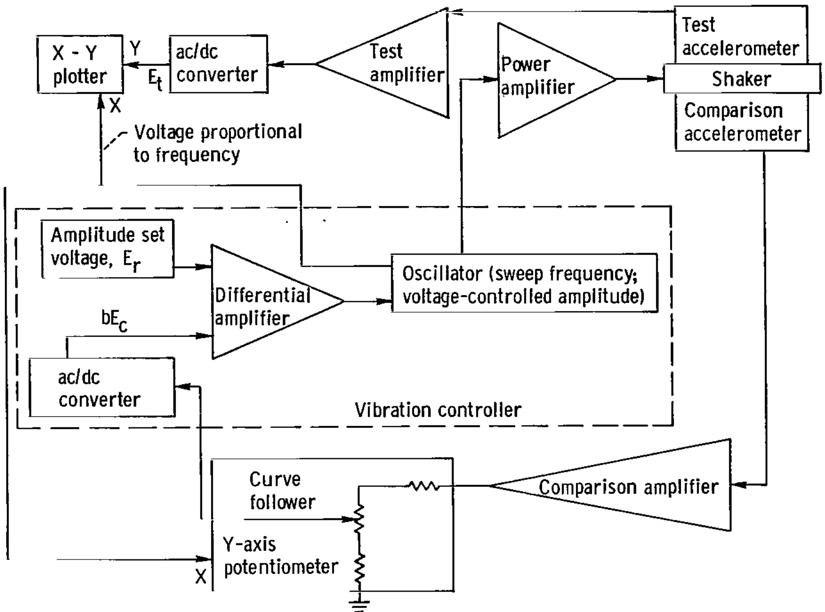

Figure 2. - Modified calibration system.

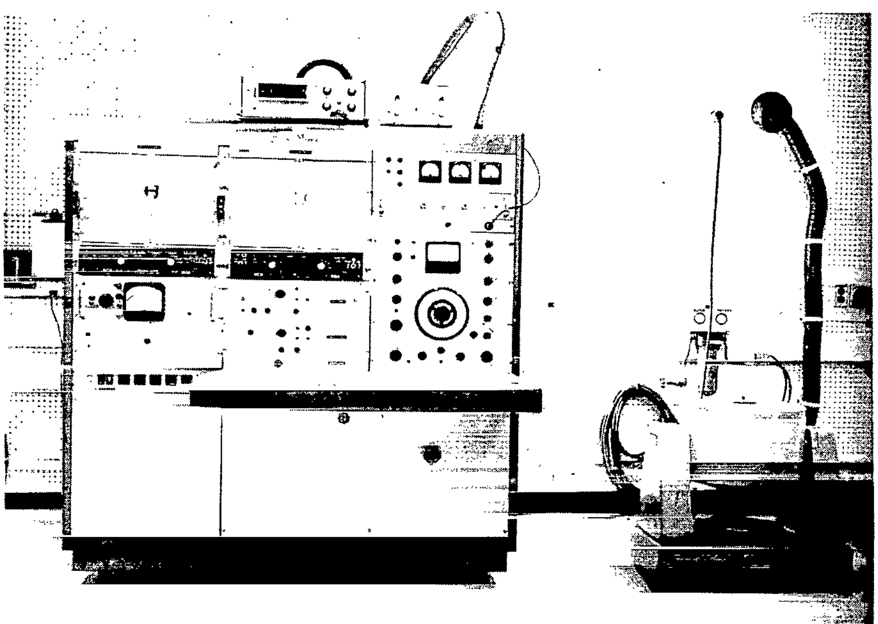

Figure 3. - Modified calibration system.

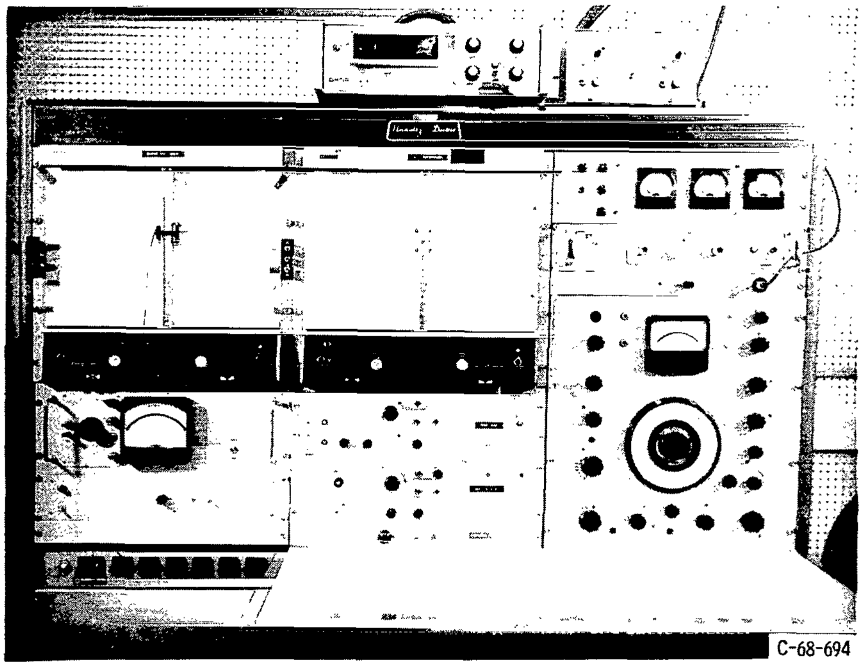

Figure 4. - Closeup of control console showing X-Y plotter and curve follower.

The curve follower is identical to the X-Y plotter (see figs. 3 and 4) except that its y-axis has been modified to follow a predrawn curve placed on its bed. The moving element on the y-axis is attached to the wiper of a potentiometer. As the x-axis is driven (as a function of frequency in this case), the y-axis follower action causes the potentiometer wiper to move up and down according to the curve. The factor b is thus proportional to the position of the wiper on the y-axis potentiometer of the curve follower.

Setup of the system begins by hand plotting the NBS data for the sensitivity versus frequency of the standard system (fig. 5) and placing this plot on the curve follower. The

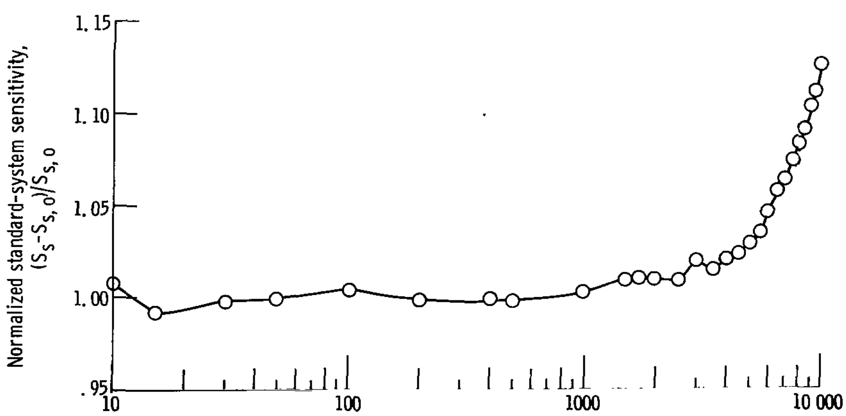

Figure 5. - Normalized standard-system sensitivity as function of frequency.

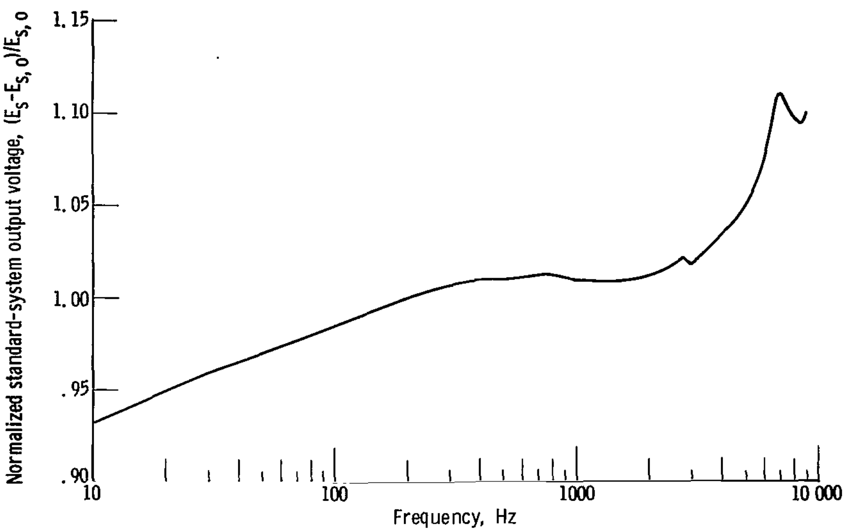

Figure 6. - Normalized standard-system output voltage as function of frequency obtained on X-Y plotter with figure 5 on curve follower.

standard system is then installed in place of the test system. With the oscillator set at the reference frequency (200 Hz in this case), the comparison-amplifier gain is adjusted until the signal from the comparison amplifier equals that from the standard amplifier. The frequency is then swept, with E_s being plotted on the X-Y plotter. This plot (fig. 6) is placed on the curve follower for calibration of test accelerometer systems. The ANALYSIS section shows that this is the curve-follower plot required to servocontrol the shaker to a constant g-level.

Calibration of test systems is now initiated by replacing the standard system with a test system, setting the oscillator to the reference frequency, and adjusting the test-amplifier gain until the test-amplifier output equals the comparison-amplifier output. The dc voltage from the test system E_t is then plotted during a frequency sweep; the resulting plot directly yields test-system sensitivity versus frequency since constant g-level is maintained during the sweep.

Figure 7 is an example of such a calibration plot taken from the actual system. The two curves shown in figure 7 result from the fact that the actual system sweeps from 10 to 10 000 hertz in two segments, 10 to 5000 hertz and 5010 to 10 000 hertz. The curves corresponding to figures 5 and 6 that are used in the system are also plotted in two segments for this reason. It is worth pointing out here that in practice these curves (figs. 5 and 6) are put on Mylar since they are to be used over an extended period of time. The use of Mylar avoids the distortion associated with environmental effects on paper.

An overall system checkout can be readily performed by calibrating the standard system as if it were a test system. The result will agree, within system accuracy, with the NBS standard data if the system is still operating properly.

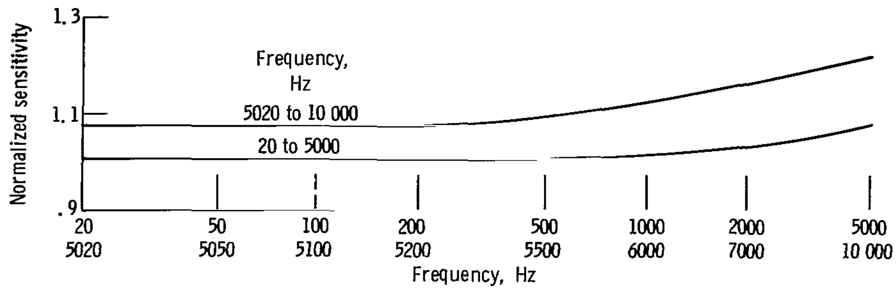

Figure 7. - Typical plot from modified calibration system. Sensitivity, 17.7 rms millivolts per peak g and 10 peak picocoulombs per peak g; accelerometer capacitance, 100 picofarads; total external capacitance, 300 picofarads; sensitivity measured at 200 hertz; calibrated at 10-g peak.

ANALYSIS

Both the conventional and modified systems can be analyzed by using the simplified block diagram shown in figure 8. The difference in the two systems is in the curve-follower attenuation factor b which is equal to 1 for the conventional system but which is the programmed attenuation required to maintain constant g-level in the modified system. In figure 8, E_r represents the dc set point signal proportional to the desired g-level. The voltage e is the difference or error between E_r and bE_c. The quantity A is the overall forward transfer function, g/e, in g's at the shaker per volt of error signal. It includes the shaker response to power input (including resonances), power amplifier gain, and vibration controller gain. The quantity S_c is the overall sensitivity of the comparison system in dc volts per g (i.e., S_c includes the transfer function of the ac/dc con-

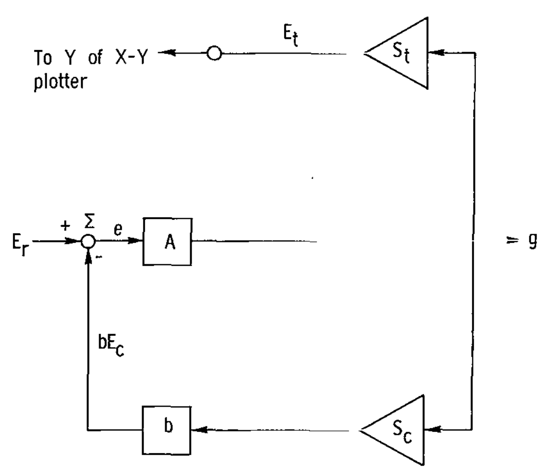

Figure 8. - Simplified block diagram of modified system. For generation of final control curve b_2, S_t becomes S_s, E_t becomes E_s, and b becomes b_1 (i.e., standard accelerometer system is substituted for test accelerometer system).

verter). The quantities S_t and S_s have identical definitions for the test and standard systems, respectively. The standard system replaces the test system when the standard system is being used in the modified calibration system.

The closed-loop transfer function for this system is

$$\frac{g}{E_r} = \frac{1}{bS_c + \frac{1}{A}} \tag{1}$$

The usual approximation made for a proportional control system is that the magnitude of the forward transfer function is large compared with that of the feedback transfer function. This approximation can be stated for this case in the form

$$A \gg bS_c \tag{2}$$

so that the transfer function becomes

$$\frac{g}{E_r} = \frac{1}{bS_c} \tag{3}$$

This result, which is valid for both the conventional and modified systems, shows that the system is independent of variation of A with frequency as long as A remains large. The significant feature of equation (3) is the dependence on S_c. With the conventional system, $b = 1$ and the g-level is thus not constant over the frequency range. The modified system uses variation in b to keep bS_c constant and, therefore, to keep g constant.

Figure 9 is a schematic of the attenuator circuit where R_p is the total resistance of

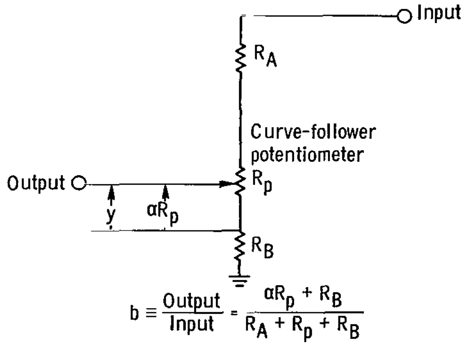

Figure 9. - Programmed attenuator circuit.

the curve-follower potentiometer and R_A and R_B are fixed resistors. A general expression for b is then

$$b = \frac{\alpha R_p + R_B}{R_A + R_p + R_B} = \frac{\text{Output}}{\text{Input}} \tag{4}$$

where α is the fraction of the potentiometer included between the wiper and the lower end.

For the first frequency sweep the standard system is used in place of the test system and the curve follower tracks a curve of the standard-system sensitivity which was hand plotted according to

$$y_s = K_p g_o (S_s - S_{s,o}) + y_{s,o} \tag{5}$$

where y_s is the wiper displacement from the lower end, $y_{s,o}$ is a convenient origin, K_p (cm/V) is the scale factor used in plotting the NBS data and the X-Y plotter sensitivity that will be used, and g_o is the acceleration level selected at the reference frequency. Equation (5) is the hand-plotted NBS data and represents the curve-follower wiper position as a function of S_s which is a function of frequency. A normalized form of this curve is shown in figure 5 (p. 6). The resulting attenuation factor b_1 can now be derived.

$$y_s = \frac{y_{s,o}\alpha_s R_p}{R_{s,o}} \tag{6}$$

$$b_1 = \frac{\dfrac{R_{s,o} y_s}{y_{s,o}} + R_B}{R_A + R_p + R_B} \tag{7}$$

where

$$R_{s,o} = \alpha_{s,o} R_p$$

Substituting equation (5) into equation (7) yields

$$b_1 = \frac{R_{s,o}\left[\frac{K_p g_o}{y_{s,o}}(S_s - S_{s,o}) + 1\right] + R_B}{R_B + R_p + R_A} \tag{8}$$

The fixed resistor R_B is chosen such that

$$R_B + R_{s,o} = \frac{R_{s,o} K_p g_o S_{s,o}}{y_{s,o}} \tag{9}$$

Thus,

$$b_1 = \frac{R_{s,o}}{R_B + R_p + R_A}\left(\frac{K_p g_o S_s}{y_{s,o}}\right) \tag{10}$$

From equation (3)

$$g_s = \frac{g_o b_o S_{c,o}}{b_1 S_c} \tag{11}$$

and, thus,

$$g_s = \frac{S_{c,o} b_o y_{s,o}(R_B + R_p + R_A)}{S_c R_{s,o} K_p S_s} \tag{12}$$

Equation (12) is the g-level achieved as a function of frequency during this first sweep. During this sweep, E_s is plotted on the X-Y plotter according to the equations

$$\left.\begin{aligned} y_c &= K_p(E_s - E_{s,o}) + y_{c,o} \\ y_c &= K_p(S_s g_s - S_{s,o} g_o) + y_{c,o} \end{aligned}\right\} \tag{13}$$

where y_c is the pen displacement from the bottom of the plotter. A normalized form of this curve is shown in figure 6 (p. 7).

The subscript c is used in equations (13) because this plot will be used on the curve follower during the next (constant g) sweep. Substituting equation (12) into equations (13) yields

$$\frac{y_c}{y_{c,o}} = \frac{K_p}{y_{c,o}}\left[\left(\frac{S_{c,o}b_o y_{s,o}}{S_c R_{s,o} K_p}\right)(R_B + R_p + R_A) - S_{s,o}g_o\right] + 1 \tag{14}$$

Now $y_{c,o}$ is chosen equal to $y_{s,o}$ (i.e., the same reference location is picked for the curve follower and the plotter). Thus,

$$\frac{y_c}{y_{c,o}} = \frac{S_{c,o}b_o}{S_c R_{s,o}}(R_B + R_A + R_p) - \frac{S_{s,o}g_o K_p}{y_{c,o}} + 1 \tag{15}$$

This curve then generates the $b = b_2$ for the second sweep when it is placed on the follower.

$$b_2 = \frac{\dfrac{R_{c,o}y_c}{y_{c,o}} + R_B}{R_A + R_p + R_B} \tag{16}$$

Equation (16) is just equation (7) rewritten with y_c substituted for y_s and $R_{c,o}$ for $R_{s,o}$. Since $y_{s,o} = y_{c,o}$, then $R_{c,o} = R_{s,o} = R_o$ so that

$$b_2 = \frac{R_o\left[\dfrac{S_{c,o}b_o(R_A + R_B + R_p)}{S_c R_o} - \dfrac{S_{s,o}g_o K_p}{y_{c,o}} + 1\right] + R_B}{R_A + R_p + R_B} \tag{17}$$

From equation (9) and the fact that $S_{s,o}$ was set equal to $S_{c,o}$, equation (17) reduces to

$$b_2 = \frac{S_{c,o}b_o}{S_c} \tag{18}$$

With the curve follower on the y_c curve (fig. 6) the g-level is then (see eq. (11))

$$g_c = \frac{g_o b_o S_{c,o}}{b_2 S_c} \tag{19}$$

By combining equations (18) and (19)

$$g_c = g_o \tag{20}$$

which says that constant g_o is achieved. This is the desired result.

The determination of R_A is based on keeping the feedback path gain at the reference frequency in the modified system equal to that of the conventional system to minimize equipment modification. This is accomplished in practice by placing a constant gain amplifier between the curve-follower output and the vibration controller to compensate for the attenuation of the curve-follower circuit and then choosing R_A so that b_o times the amplier gain equals 1.

RESULTS

The modified system was implemented as described. The system is shown in figures 3 and 4. The error contributed by the system was judged on the basis of ability to reproduce the NBS generated data (fig. 5) for the standard system. This error must be added to the error of the NBS data to obtain the absolute calibration error. A 10-minute time period was used to sweep from 10 to 10 000 hertz. The error achieved was ±0.5 percent for 10 to 9000 hertz and ±1 percent for 9000 to 10 000 hertz. This error or deviation from the standard data (fig. 5) is shown plotted against frequency in figure 10. The larger error at the higher frequencies can be reduced by use of a slower sweep rate. It is caused by lack of dynamic response of the control loop at these frequencies where the accelerometer sensitivities are increasing rapidly with frequency. The 10-minute sweep

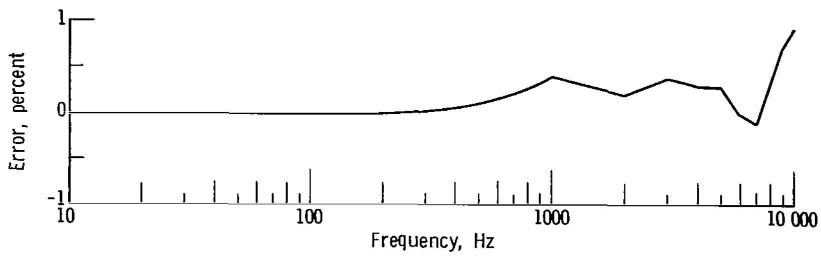

Figure 10. - Error in reproduction of standard data as function of frequency.

time was chosen as a compromise between speed and accuracy. A 2-percent error, in addition to the NBS data error, was considered acceptable.

Initial setup of the system takes about 2 hours, from the point where the NBS data are in tabular form to the point where the final control curve is on the curve follower. Most of this time is used to plot the NBS data in normalized form to obtain the first, intermediate control curve. The total time required to produce a test-system calibration or to check the operation of the whole calibration system with the standard system is about 15 minutes. The plot obtained is then directly usable without correction. A sample of an actual test-system calibration plot from 20 to 10 000 hertz is shown in figure 7 (p. 8).

Operational stability of the system has shown that a new control curve is required only when equipment breakdown causes major changes in the system. A new control curve has been required about once a year on the average with the system operating practically full time.

CONCLUSIONS

From the modification of a commercially available vibration transducer calibration system to directly produce an output plot of transducer sensitivity versus frequency over the range of frequencies from 10 to 10 000 hertz, the following conclusions were drawn:

1. Controlling to constant acceleration levels during frequency response testing of accelerometers by using a programmed attenuator is practical. (A working system was described herein.) A curve follower and its potentiometer were used as the programmed attenuator.

2. The calibration results in a directly usable plot of sensitivity as a function of frequency. All the required information is obtained on one plot in 15 minutes.

3. System accuracy can be easily checked by verifying the NBS calibration of a standard.

4. Calibrations using this system repeat National Bureau of Standards data to within ±0.5 percent over the frequency range 10 to 9000 hertz and within ±1 percent from 9000 to 10 000 hertz.

5. The control curve for the programmed attenuator is drawn automatically. Changes in the control curve can be made easily and quickly (2 hr).

6. The system is stable. New control curves are required infrequently, on the order of one per year.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 1, 1968,
125-24-03-22.

APPENDIX - SYMBOLS

A	transfer function of vibration controller, power amplifier, and shaker, g/e, g's/V
b	attenuation of curve-follower potentiometer and associated resistor network
b_1	attenuation obtained by placing normalized NBS data for standard system on curve follower
b_2	attenuation used for calibration of test systems
E	dc voltage, V
E_r	dc set point voltage proportional to desired g-level, V
e	dc error voltage, V
g	peak acceleration level normalized to earth's gravity
K_p	plotter sensitivity, cm/V
R_A	fixed resistor, ohms
R_B	fixed resistor, ohms
R_o	αR_p at reference frequency, ohms
R_p	curve-follower potentiometer resistance, ohms
S	transfer function of accelerometer, accelerometer amplifier, and ac/dc converter, V/g
x	abscissa of plotter or curve follower, cm
y	ordinate of plotter or curve follower, cm
α	fraction of potentiometer between wiper and lower end
α_s	α obtained by placing normalized NBS data for standard system on curve follower

Subscripts:

c	comparison system
o	reference frequency
s	standard system
t	test system

REFERENCE

1. Specifications and Operation Manual for Unholtz-Dickie Series 300 Vibration Calibration Systems. Unholtz-Dickie Corp., Hamden, Conn.

NASA-Langley, 1968 —— 14 E-4420

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