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Copper-ball accelerometer operation and utility as a shock spectrum measuring device are discussed. The results of dynamic and static tests of copper balls are recorded. A comparison is made of the dynamic and static properties of copper balls. In order to arrive at a more accurate calibration of copper-ball accelerometers, correction is made for the non-linear deformation characteristics of the copper balls. Corrected accelerometer functions are presented in easy-to-use curves and nomographs for velocity change, peak g, and associated natural frequency.

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CALIBRATION OF NOL COPPER-BALL ACCELEROMETERS

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NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NOLTR 72-67 7 March 1972

CALIBRATION OF NOL COPPER-BALL ACCELEROMETERS

The information in this report updates the calibration of copper-ball accelerometers that use 0.1553 inch nominal diameter annealed copper balls. More detailed information on the general description and use of copper-ball accelerometers is reported in NOLTR 67-151 and NOLTR 63-279. The results of static calibration tests on copper balls are used as a standard of comparison for dynamic tests.

The opinions and conclusions expressed are those of the Environmental Evaluation Department.

Calibration of NOL copper-ball accelerometers for this report was conducted in support of the Torpedo MK 48 Mod 1, Task NOL-'55/ORD-054, and the Transponder Set AN/WQX-1, Task A370-5330/W4639.

The identification of commercial equipment implies neither criticism nor endorsement by the Naval Ordnance Laboratory.

ROBERT WILLIAMSON II
Captain, USN
Commander

V. M. Korty

V. M. KORTY
By direction

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REFERENCES

(a) NOLTR 67-151, "Shock Spectra Measurements Using Multiple Mechanical Gages (A Feasibility Study)," 20 Sep 1967

(b) NBS Test Report 213.04/645-72-C, "Copper Balls," 23 Aug 1971

INTRODUCTION

1. Although many advances have been made in the continuous recording of acceleration data, there are still certain recording situations in which these data are difficult or impossible to obtain. In these instances, a simple mechanical gage can generally be used to obtain the peak acceleration response to shock input. The copper-ball (CB) accelerometer is one of the most widely used gages for this purpose. Copper-ball accelerometers are used in laboratory and field tests to measure shock spectrum. A single CB accelerometer will give an acceleration response at its natural frequency to the acceleration input. Multiple CB accelerometers with different natural frequencies will give the overall shock-spectrum response.

2. The copper-ball accelerometer was developed during World War II. It, basically, consists of four principal parts. They are a housing, an inertia weight, a copper ball, and an anvil or base. Figure 1 shows five basic CB accelerometer designs currently in use at NOL. The inertia weight responds to the acceleration input at the base by deforming the copper ball between the inertia weight and the anvil. Once the copper ball has been deformed, the spring-loaded wedge on top of the inertia weight prevents the inertia weight from "hammering" on the copper ball. A permanent record of the peak acceleration response to the shock input is obtained in the form of the deformation of the copper ball. The difference between the original ball diameter and its final height gives the maximum deflection of the simulated mass-spring system. Accurate measurements can be made by a micrometer or dial indicator.

3. Copper-ball accelerometers are a valuable tool in measuring impulsive shocks. In some NOL facility tests the high g, short duration pulse exceeds the capabilities of piezoelectric accelerometers that are presently available. Such is the case for the impact phase shock level of two-phase air gun tests. Attempts to measure the steel-on-steel shock of the impact phase of these tests with high frequency piezoelectric accelerometers have been unsuccessful. For this type shock, copper-ball accelerometers give reliable shock pulse integration records in the form of velocity change.

4. Recently, certain discrepancies came to light between the dynamic calibration data for copper balls of reference (a) and dynamic test data from drop tests at NOL. These discrepancies appeared for

copper balls of the same general issue (1956 Hartford lot) as were used for the tests in reference (a). Because of this uncertainty, an extensive effort was initiated to determine the correct dynamic calibration of the copper balls used in copper-ball accelerometers. The purpose of this report is to document the results of this effort. Since the supply of 1956 Hartford lot balls was almost depleted, the major effort centered on calibrating a new supply of copper balls. Checks on the dynamic characteristics of the old ball supply (1956 Hartford lot) and the new ball supply (1965 Hartford lot) revealed only minor differences. Static calibration tests were carried out on both the old and the new ball supply at the National Bureau of Standards. In comparing the new static calibrations, it was found that there was little difference between the static calibration results from reference (a) for the 1956 ball lot, and the recent calibration of 1965 lot balls. The results of these tests indicated that the discrepancies in dynamic calibration tests could not be attributed to differences in the copper balls.

5. It is recognized that a source of discrepancy in interpreting calibration data could be attributed to the fact that no allowance was made in reference (a) for the nonlinearity of the copper ball's force-deformation characteristics. In this work, the copper ball's spring rate is determined as a function of permanent set. All corrections for dynamic and nonlinear effects are incorporated in nomographs that allow the peak g and natural frequencies to be read directly from the measured permanent set of the copper balls. For clarity of presentation, only data for the new 1965 Hartford ball lot will be presented in this report.

STATIC CALIBRATION OF COPPER BALLS

6. Most copper-ball accelerometers in use at NOL use the same material specification and size of copper balls. Different accelerometer natural frequencies are obtained by varying the mass of the inertia weight. Since the same copper ball is used in different accelerometers, a single calibration of the balls applies to all accelerometers in service with this given ball. Static calibration tests were conducted at the National Bureau of Standards on 0 1553 inch nominal diameter annealed copper balls (1965 production lot 300R from Hartford Steel Ball Co.) during August 1971 at NOL's request. Test balls were removed from four boxes of 10,000 units each and identified as lots 1, 2, 3, and 4 respectively. The results of the NBS static tests are recorded in reference (b). Figure 2 shows the static calibration test fixture. A copper-ball accelerometer inertia weight was used as the ram to compress the balls. The compression load was provided by a Baldwin hydraulic testing machine.

7. Eight tests were conducted for each load level with two tests per lot per load level. Tests were carried out at even increments of 100 pounds from 100 pounds through 800 pounds. The increments were increased to 200 pounds for tests from 1000 pounds through 2000 pounds. The span of permanent set results for each compression force level is

plotted in Figure 3. This span is bracketed by the minimum and maximum permanent set values for all eight tests with the four ball lots at each load level. The curve was drawn through the median point of the spans. Figure 3 is characteristic of the non-linear traces that have been observed from static calibration tests of previous ball lots.

DYNAMIC CALIBRATION OF COPPER BALLS IN COPPER-BALL ACCELEROMETERS

8. It was decided to determine the copper ball's dynamic characteristics using the IMPAC 66 drop tester at NOL. Figure 4 shows copper-ball accelerometers mounted on the carriage of this tester. The IMPAC 66 drop tester produces highly repeatable, high g, short duration shock pulses. Tests with 1/16-inch thick felt shock pads result in pulse shapes that approximate a haversine with amplitudes as high as 15,000g. The pulse durations range from 0.13 ms to 0.37 ms. The purpose of testing the copper-ball accelerometers with short duration pulses was to check the velocity-meter effect of the accelerometers. The importance of the accelerometers as velocity meters was discussed in paragraph 3. Accelerometers were selected with nominal natural frequencies that gave a product of the shock-pulse duration and the natural frequency of the accelerometer of less than 0.3. When this condition is met, then the velocity change for the shock pulse can be approximated as

$$\Delta V \approx \omega\delta = \sqrt{\frac{K_D g}{W}}\ \delta . \qquad (1)$$

See description of symbols for definitions.

Conversely, if the velocity change of the pulse is known, then the effective dynamic spring constant of the copper ball can be determined from

$$K_D \approx \frac{W}{g}\frac{\Delta V^2}{\delta^2} . \qquad (2)$$

9. Tests were conducted to calibrate the drop tester for impact velocity change. The drop tester carriage was instrumented with a 2225 Endevco piezoelectric accelerometer. The output of the accelerometer was connected to an Endevco charge amplifier. The output of the charge amplifier was run through an electronic integrator and then into the oscilloscope. A parallel line from the charge amplifier output was run directly to the oscilloscope. Both signals were put into the oscilloscope simultaneously so that a dual trace was generated. Two calibration tests per drop height were conducted at drop heights in 20-inch increments. Two shock pulses were recorded for each drop height confirming the high level of repeatability of the drop tester for the entire test range. Figure 5 gives typical oscilloscope traces for the drop tester calibration tests. The top trace of each picture gives the velocity-change integration of the shock pulse on the bottom trace. The velocity change was obtained by

electronically integrating the shock pulse. As a check, the shock pulses were integrated with a planimeter and good agreement found.

10. With the drop tester calibrated for velocity change, it was decided to conduct a series of tests with copper-ball accelerometers to determine the copper-ball permanent set for the calibrated drop heights. Four copper-ball accelerometers with 80.4-gram inertia weights were tested to check variations among accelerometers. Copper balls were selected from the same four lots that were used in the NBS static calibration tests. The results of the dynamic tests with the 80.4-gram accelerometers are recorded in Table 1. Each set of readings is the result of a separate drop test. As can be seen, the variation in permanent set between the four 80.4-gram accelerometers for any given drop height is small. The variation between readings for the different copper-ball lots is also small. In order to extend the permanent set range for the dynamic tests, an accelerometer with a 225-gram inertia weight was tested at two of the higher drop heights. The results of these tests are recorded in Table 2.

DETERMINATION OF EFFECTIVE DYNAMIC SPRING CONSTANT (K_D)

11. Average permanent set values from Tables 1 and 2 were used to compute effective dynamic spring "constant" values from Equation (2). These values are plotted as a function of copper-ball permanent set in Figure 6. Figure 6 shows that the dynamic spring "constant" does not remain constant for varying permanent set.

12. A review of Figure 3 shows that the static force versus permanent set trace is nonlinear as well. For any given permanent set value of Figure 3, the effective static spring constant can be interpreted in two ways. The effective static spring constant can be taken as the static force divided by the permanent set. This effective static spring constant is denoted as K_A in the illustration of Figure 7. K_A would be applicable to long duration input shock pulses where the peak response acceleration of the inertia mass is approximately the same as shock input peak acceleration. Another interpretation of the effective static spring constant would be to assume that it averages the energy under the static force versus permanent set curve. This effective spring constant is illustrated as K_V in Figure 7. K_V would be applicable to very short duration input shock pulses where the peak response acceleration of the inertia weight occurs at a significant time after the input shock. The mathematical interpretations of K_V and K_A are

$$K_V = \frac{2\sum_{i=0}^{n} \bar{F}_i \; (\Delta\delta_i)}{\delta_n^2} \qquad (3)$$

$$K_A = \frac{F_n}{\delta_n} \; . \qquad (4)$$

Table 3 records the computed values of K_V and K_A as functions of permanent set from the data of Figure 3.

13. The values of K_V and K_A are plotted in Figure 6. It can be seen in Figure 6 that the K_V and K_A curves, from static calibration, bracket the dynamic calibration curve of K_D. This shows that the copper ball's dynamic deformation characteristics are approximately the same as its static deformation characteristics. It also shows that the dynamic response of the copper-ball accelerometer is influenced by both the static velocity meter and peak force effects. It should be noted that the dynamic calibration tests were conducted with short duration pulses; whereas, the static calibration tests were conducted with a long-duration pulse. Since the effective spring constants for the dynamic and static tests are essentially the same, it may be assumed that the effective dynamic spring constant applies to all shock pulses.

APPLICATION OF DYNAMIC CALIBRATION RESULTS TO COPPER-BALL ACCELEROMETER READINGS

14. The effective dynamic spring "constant" is too variable with permanent set to be treated as a constant. Greater accuracy in the interpretation of data can be achieved if K_D is allowed to vary with δ. This can be done by selecting the appropriate values of K_D for each accelerometer reading from Figure 6. With this value of K_D determined, the shock spectrum functions of peak acceleration and natural frequency can be mathematically determined from

$$a = \frac{\delta K_D}{W} , \qquad (5)$$

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K_D g}{W}} \qquad (6)$$

15. The mathematical conversion of K_D into working functions of peak g and natural frequency have been carried out for the reader's convenience. Data from Figure 6 are used in Equation (5) to determine peak g nomographs of Figures 8 and 9. Figure 8 gives peak g for copper-ball accelerometers with deformation on the top and bottom surface of each ball. This is the most common type accelerometer in use. In order to increase the effective spring constant for high g readings, the Mod 8 copper-ball accelerometer was developed. This accelerometer gives nine individual spectrum readings. The balls in this accelerometer are supported so that deformation occurs on only the top surface of each ball. Reference (a) gives details on the characteristics and operation of this accelerometer. Figure 9 is a peak g nomograph for the masses of the Mod 8 accelerometer. Accelerometer natural frequencies associated with the peak g response for shock spectrum are presented in nomograph form in Figures 10 and 11. Figure 10 is for accelerometers with deformation on two sides of the ball. Figure 11 is for the Mod 8 accelerometer with deformation on one side of the ball.

16. Velocity change for low frequency accelerometers has already been given as Equation (1). By use of the values of K_D from Figure 6 in Equation (1), Figure 12 was evolved. Figure 12 gives velocity change as a function of copper-ball permanent set. Dynamic test data from Tables 1 and 2 are included in Figure 12 for comparison with the computed curves.

CONCLUDING REMARKS

17. Dynamic tests show that copper-ball accelerometers are remarkably consistent in results for different stock accelerometers with copper balls picked at random for the same shock input. The dynamic spring rate of copper balls tested at NOL was basically the same as the static spring rate of copper balls tested at NBS. Since the copper balls were unaffected by load rate, the effective dynamic spring constant is applicable to all shock pulses. A more accurate shock spectrum can be determined by allowing for the nonlinearity of the effective dynamic spring rate. Easy-to-use shock-spectrum parameter nomographs are presented that automatically allow for the variations of the effective dynamic spring constant with copper-ball permanent set. By allowing for the copper-ball non-linear characteristics, the accuracy of copper-ball shock spectrum is enhanced.

DESCRIPTION OF SYMBOLS

ΔV - velocity change	- in./sec
K_D - effective dynamic spring constant	- lb/in.
K_V, K_A - effective static spring constants	- lb/in.
g - acceleration caused by gravity	≈386 in./sec^2
δ - permanent set	- in.
$\Delta\delta$ - increment of permanent set	- in.
W - weight of accelerometer inertia weight	- lb
F - static force on copper ball	- lb
a - response acceleration of accelerometer inertia weight	- g units
f_n - natural frequency of accelerometer	- Hz
ω - natural frequency of accelerometer	- rad./sec
$\bar{F}$ - average force	- lb
E - energy consumed by crushed copper ball	- in.-lb

Table 1

PERMANENT SET FROM DYNAMIC TESTS OF HARTFORD COPPER BALLS
FROM PRODUCTION LOT 300R OF 11/8/65
WITH FOUR 80.4-GM ACCELEROMETERS

Accelerometer No.	Drop Height (in.)	Permanent Set - in. Lot 1	Lot 2	Lot 3	Lot 4	
1	20	.0230	.0225	.0223	.0213	
2	↓	.0220	.0227	.0220	.0226	
3	↓	.0220	.0225	.0222	.0220	
4	↓	.0210	.0220	.0217	.0212	Avg = .0221 in.
1	40	.0365	.0360	.0360	.0362	
2	↓	.0370	.0360	.0370	.0350	
3	↓	.0390	.0370	.0370	.0375	
4	↓	.0360	.0360	.0350	.0360	Avg = .0364 in.
1	60	.0475	.0470	.0470	.0460	
2	↓	.0473	.0470	.0485	.0470	
3	↓	.0470	.0470	.0470	.0467	
4	↓	.0460	.0460	.0460	.0460	Avg = .0468 in.
1	80	.0557	.0556	.0550	.0560	
2	↓	.0557	.0556	.0563	.0560	
3	↓	.0547	.0555	.0560	.0560	
4	↓	.0540	.0549	.0554	.0560	Avg = .0555 in.
1	100	.0615	.0622	.0637	.0623	
2	↓	.0645	.0639	.0645	.0640	
3	↓	.0630	.0630	.0630	.0635	
4	↓	.0630	.0622	.0622	.0625	Avg = .0631 in.

Table 2

PERMANENT SET FROM DYNAMIC TESTS OF HARTFORD COPPER BALLS
FROM PRODUCTION LOT 300R OF 11/8/65
WITH ONE 225-GM ACCELEROMETER

Accelerometer No.	Drop Height (in.)	Permanent Set - in. Lot 1	Lot 2	Lot 3	Lot 4	
5	60	.0756	.0757	.0773	.0760	
↓	↓	.0758	.0763	.0750	.0754	
		.0736	.0747	.0755	.0730	Avg = .0757 in.
	80	.0832	.0856	.0847	.0870	
	↓	.0843	.0840	.0845	.0836	
		.0844	.0848	.0870	.0861	Avg = .0849 in.

Table 3

K_V AND K_A AS FUNCTIONS OF PERMANENT SET FROM NBS STATIC CALIBRATION

δ in.	F lb	$\overline{F}$ lb	ΔE in.-lb	E in.-lb	K_V lb/in.	K_A lb/in.
		50				
.005	100		.250	.250	20,000	20,000
		135				
.010	170		.675	.925	18,500	17,000
		195				
.015	220		.975	1.900	16,890	14,670
		245				
.020	270		1.225	3.125	15,620	13,500
		297				
.025	324		1.485	4.610	14,760	12,970
		352				
.030	380		1.760	6.370	14,170	12,670
		410				
.035	440		2.050	8.420	13,770	12,580
		468				
.040	496		2.340	10.760	13,430	12,400
		528				
.045	560		2.640	13.400	13,230	12,450
		595				
.050	630		2.975	16.375	13,100	12,610
		668				
.055	706		3.340	19.715	13,020	12,830
		753				
.060	800		3.765	23.480	13,050	13,330
		850				
.065	900		4.250	27.730	13,110	13,850
		955				
.070	1010		4.775	32.505	13,270	14,420
		1070				
.075	1130		5.350	37.855	13,470	15,080
		1205				
.080	1280		6.020	43.875	13,720	16,000
		1365				
.085	1450		6.820	50.695	14,040	17,070
		1555				
.090	1660		7.770	58.465	14,430	18,450
		1790				
.095	1920		8.940	67.405	14,950	20,200

$$\Delta V \approx \sqrt{\frac{K_V g}{W}}\,\delta \;; \qquad K_A = \frac{F}{\delta} \;; \qquad K_V = \frac{2E}{\delta^2}$$

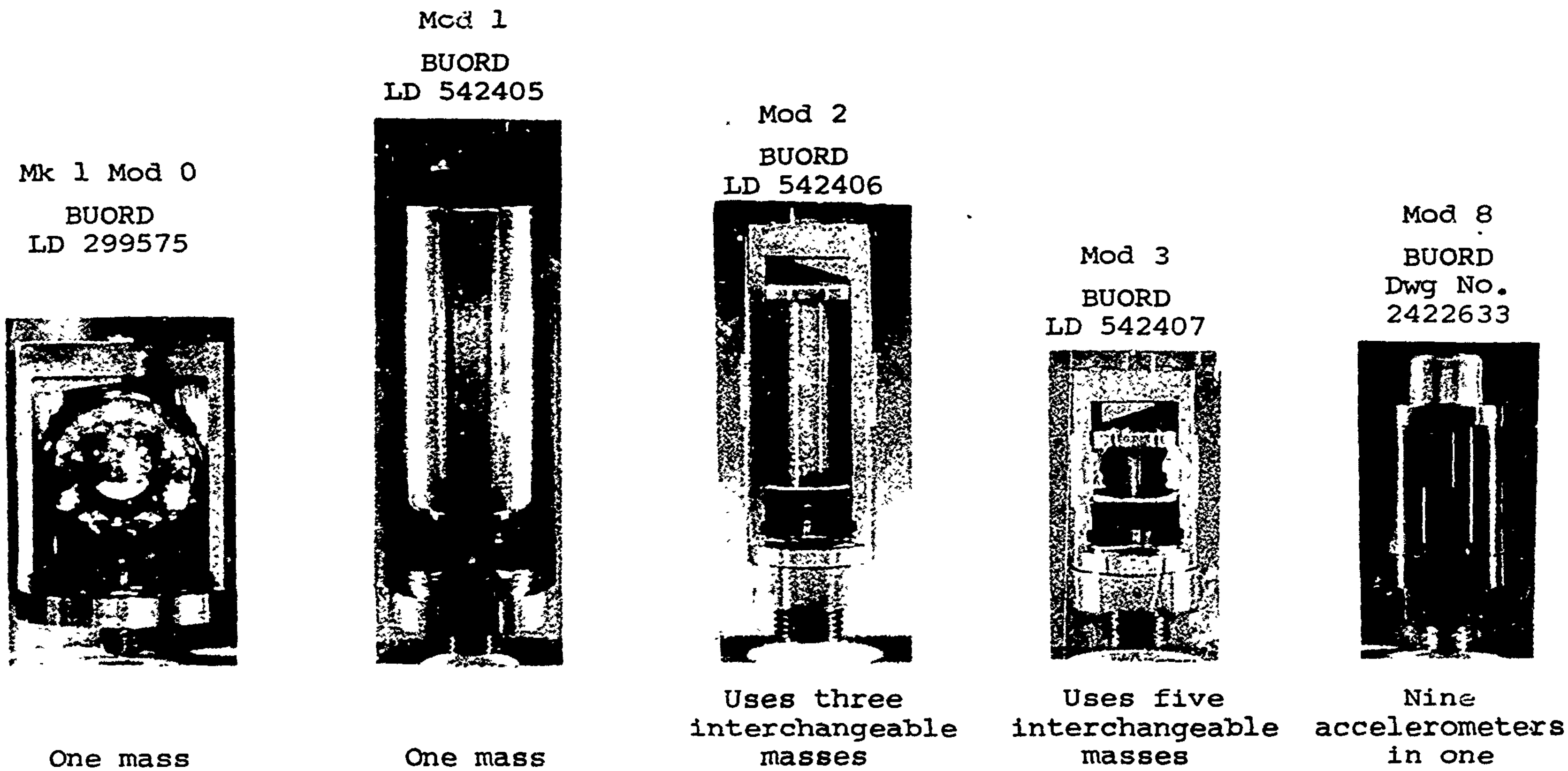


Fig. 1. Conventional Accelerometers

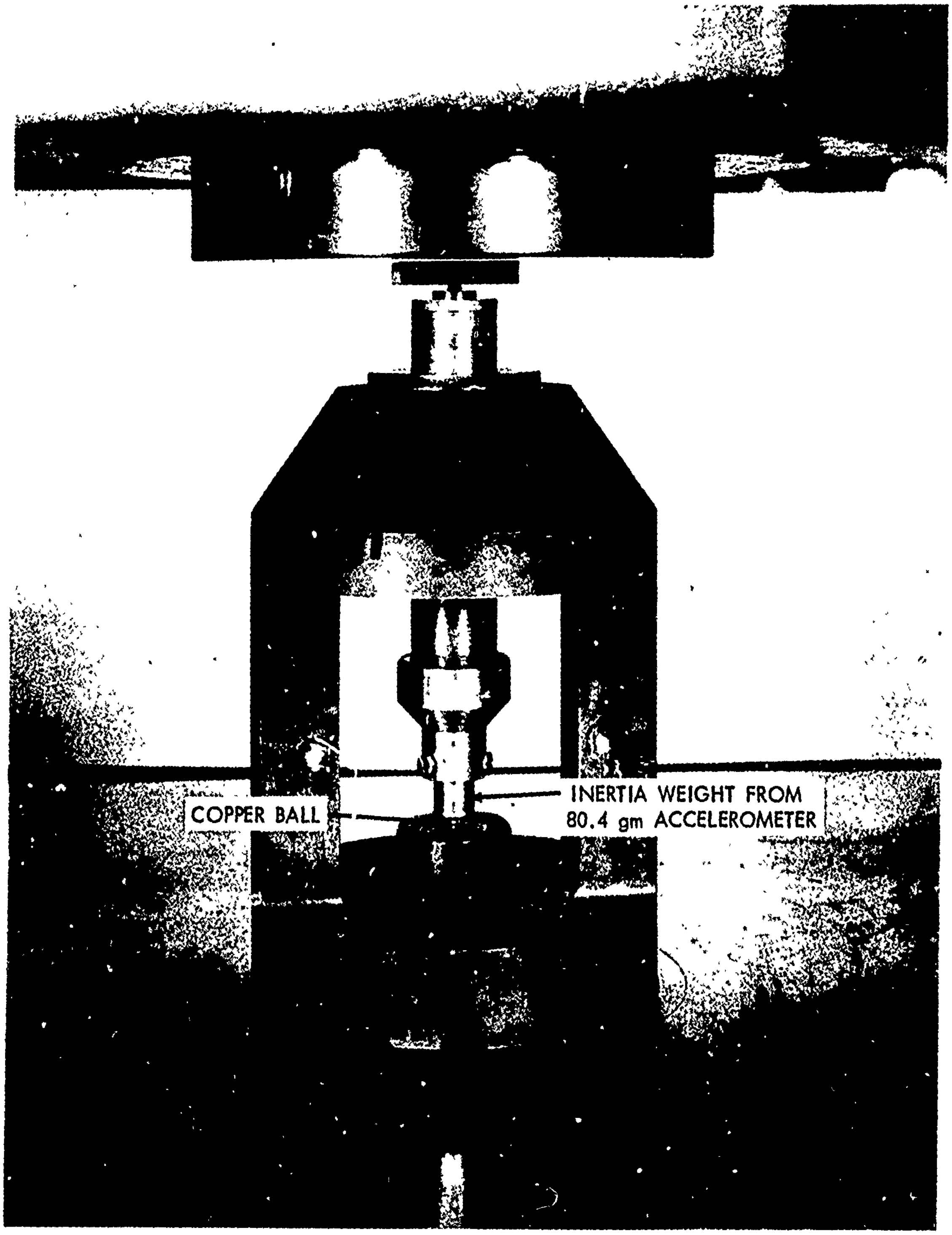


FIG. 2 COPPER-BALL TEST SETUP FOR STATIC CALIBRATION

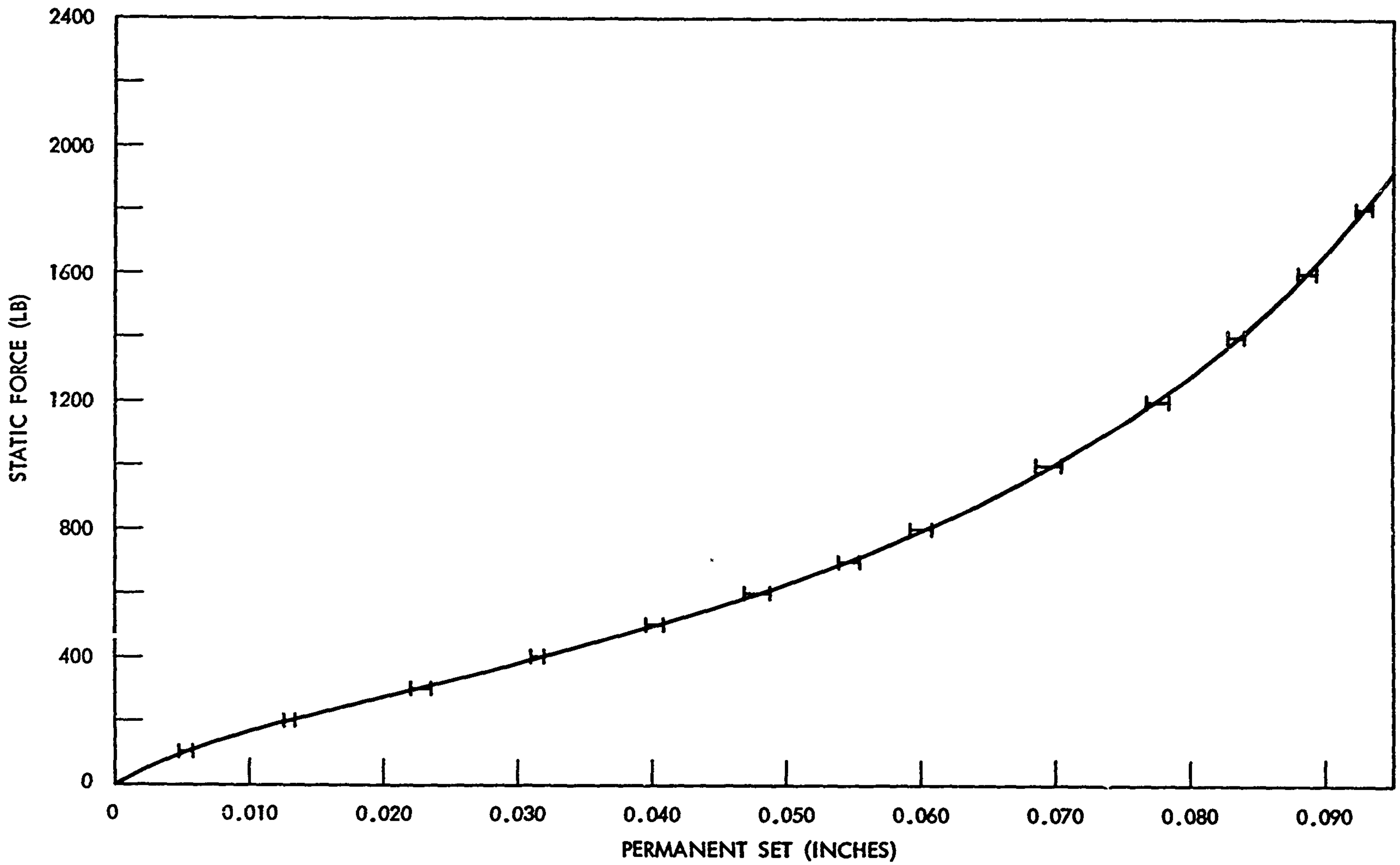


FIG. 3 STATIC FORCE VS COPPER BALL PERMANENT SET FOR STATIC CALIBRATION OF COPPER BALLS (NBS DATA, AUGUST 1971)

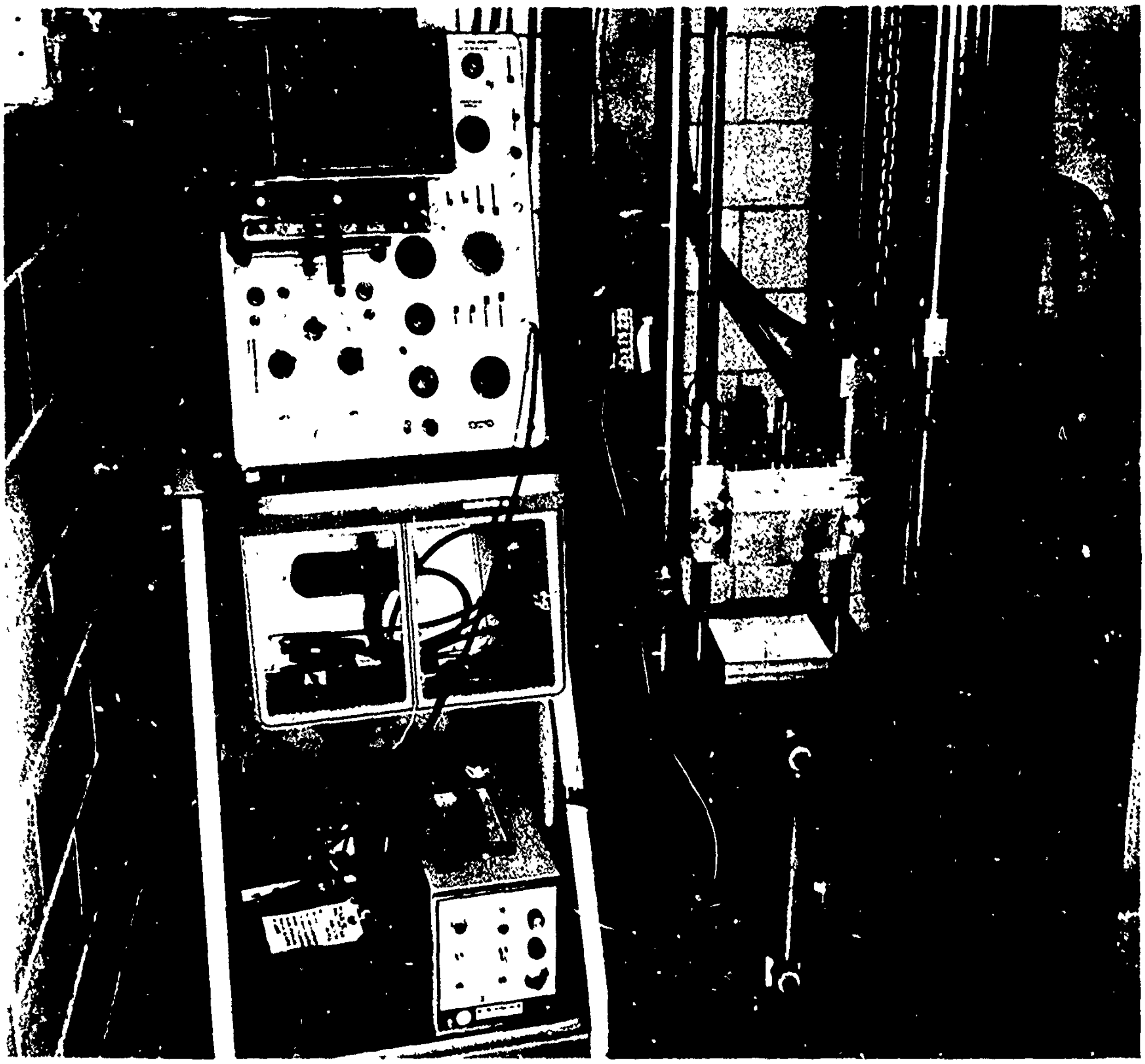
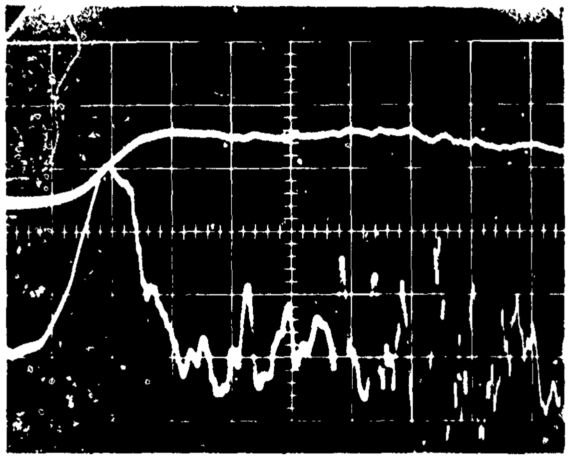
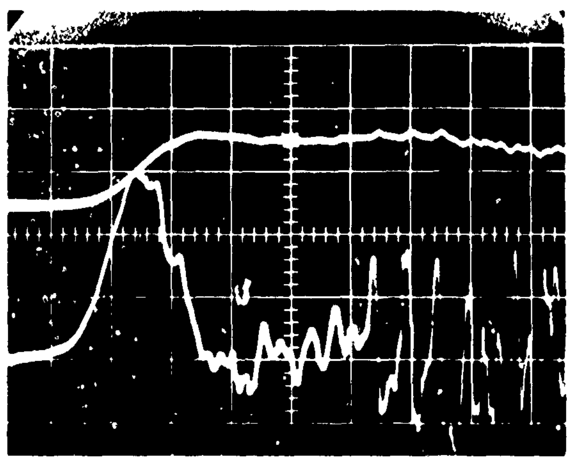


FIG. 4 DYNAMIC CALIBRATION TEST SETUP OF COPPER BALLS ON MONTEREY IMPAC 66 DROP TESTER.



25 fps/cm
ΔV = 28 fps

5000 g/cm
0.05 ms/cm



25 fps/cm
ΔV = 28 fps

5000 g/cm
0.05 ms/cm

FIG. 5 100-INCH DROP ON 1/16-INCH FELT SHOCK PAD FOR DYNAMIC CALIBRATION

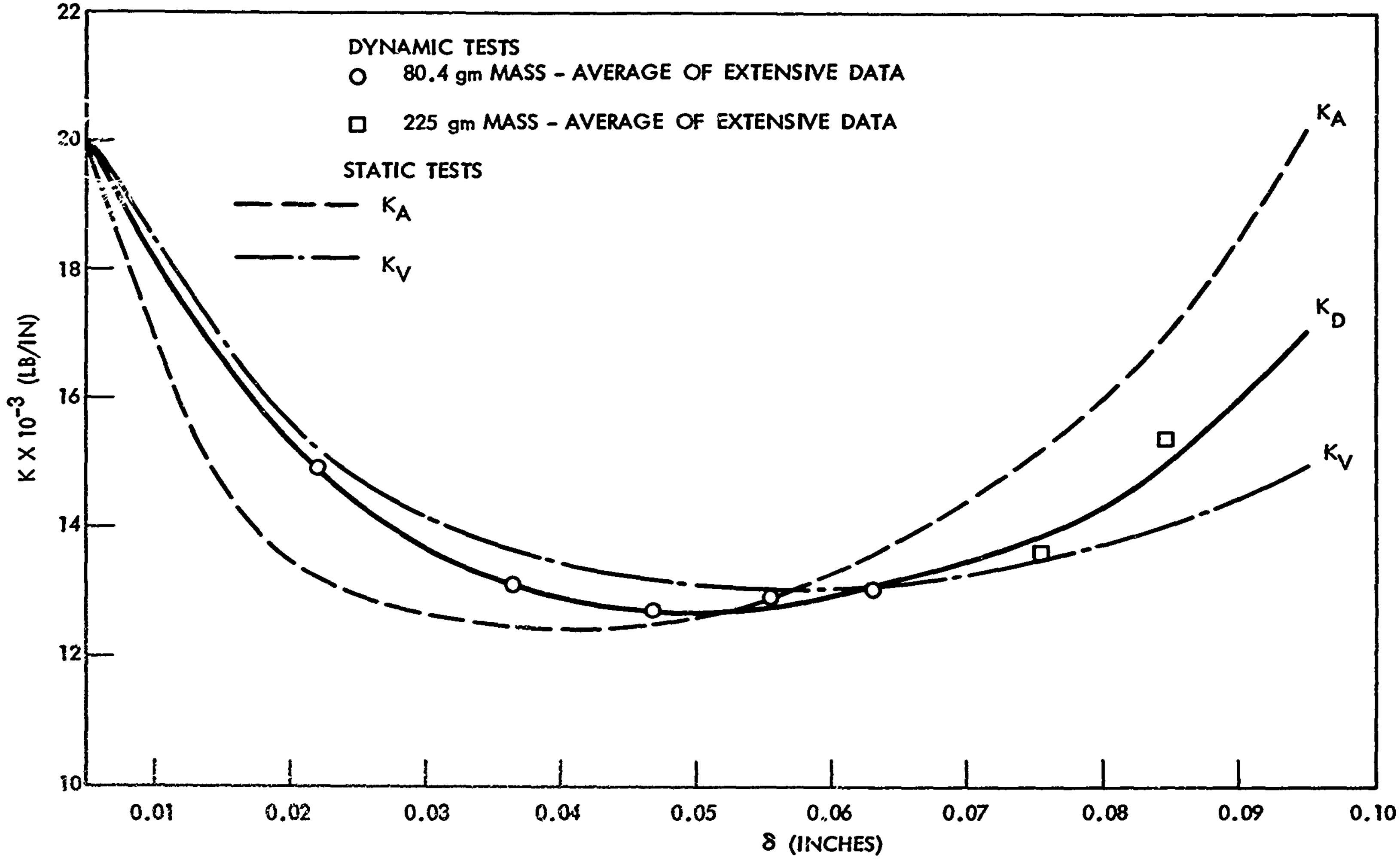


FIG. 6 EFFECTIVE SPRING CONSTANT VS COPPER-BALL PERMANENT SET FOR DYNAMIC AND STATIC CALIBRATION OF COPPER-BALL ACCELEROMETERS

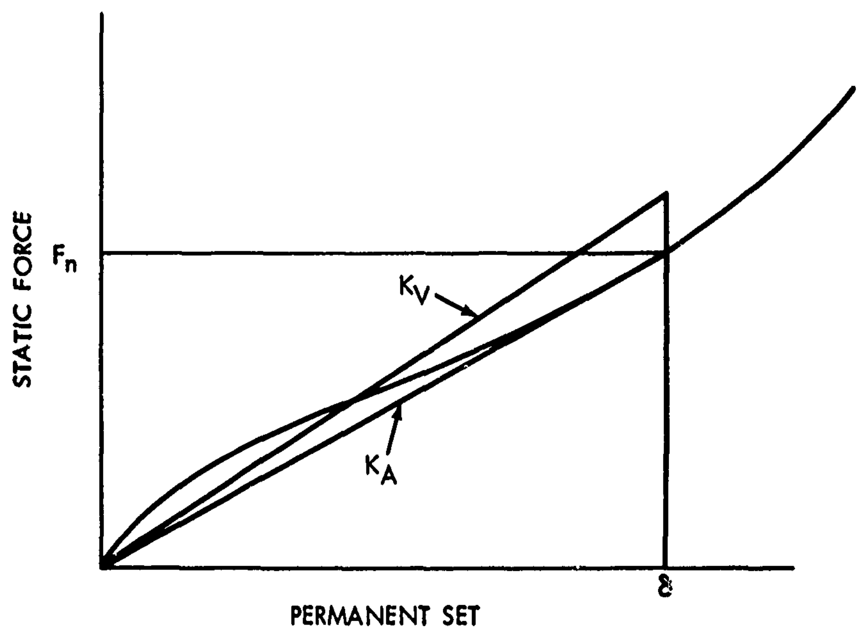


FIG. 7 SCHEMATIC OF K_V AND K_A FOR STATIC CALIBRATION CURVE.

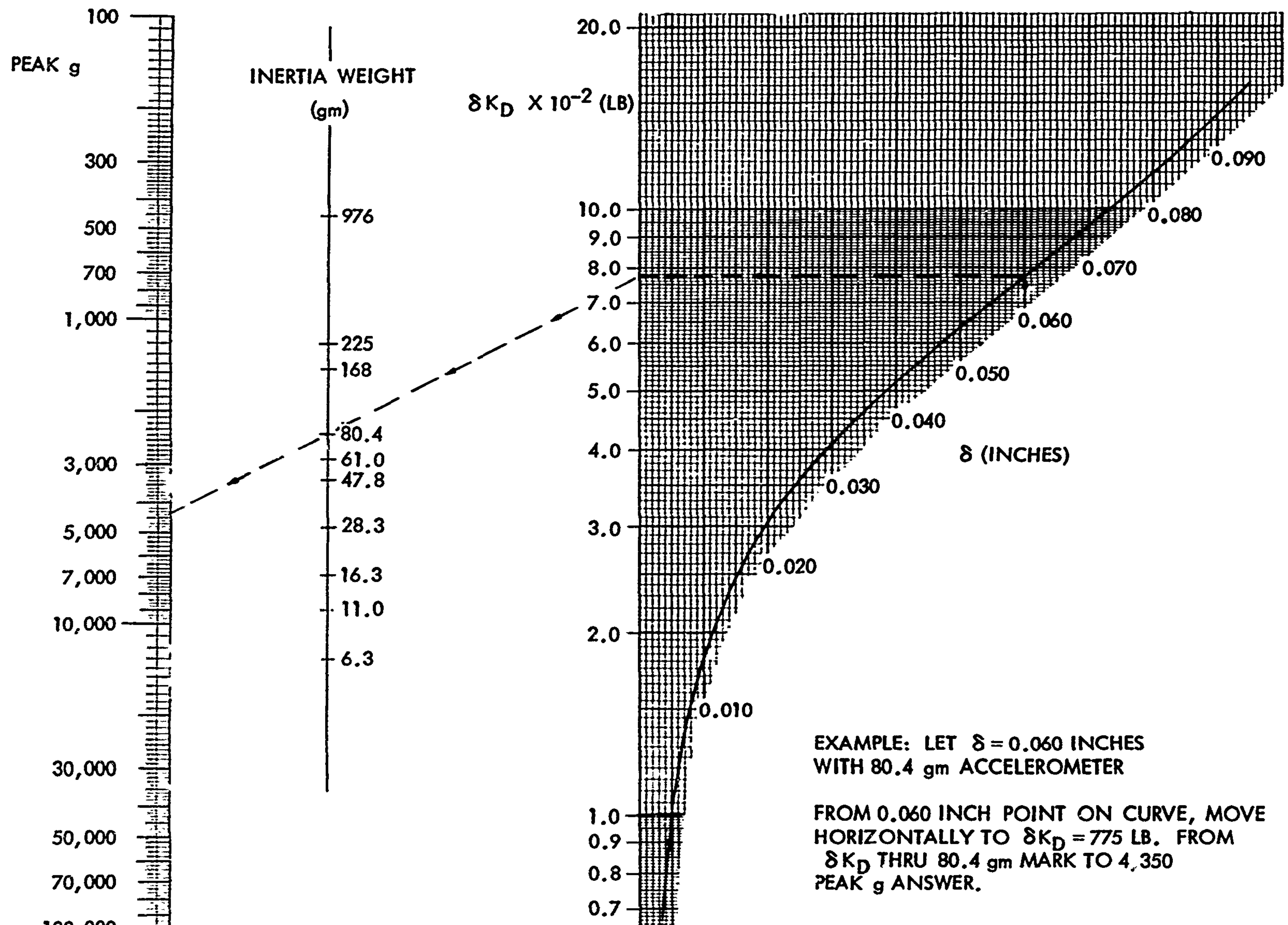


FIG. 8 PEAK g NOMOGRAPH FOR COPPER-BALL ACCELEROMETERS WITH DEFORMATION ON TWO SIDES OF COPPER BALL.

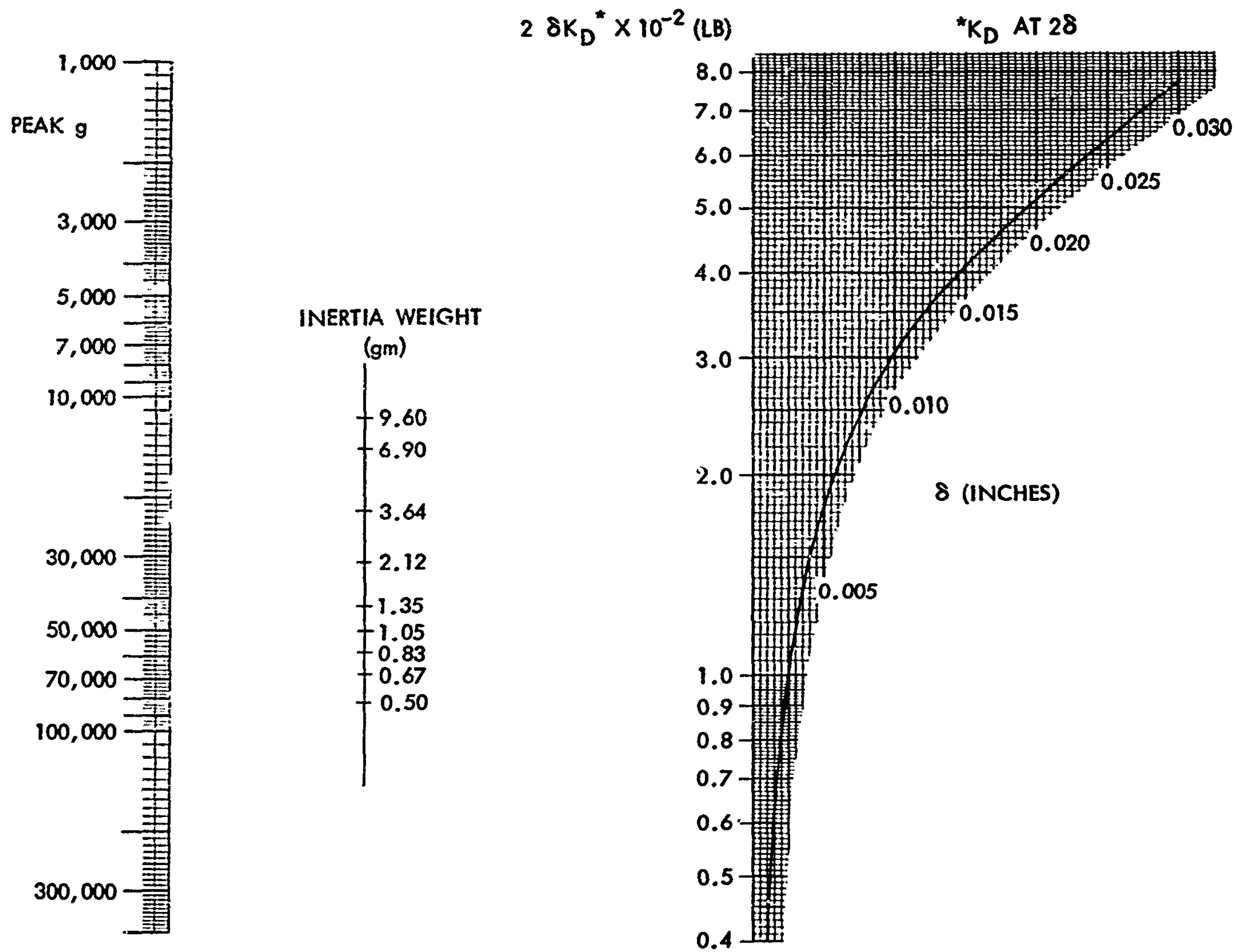
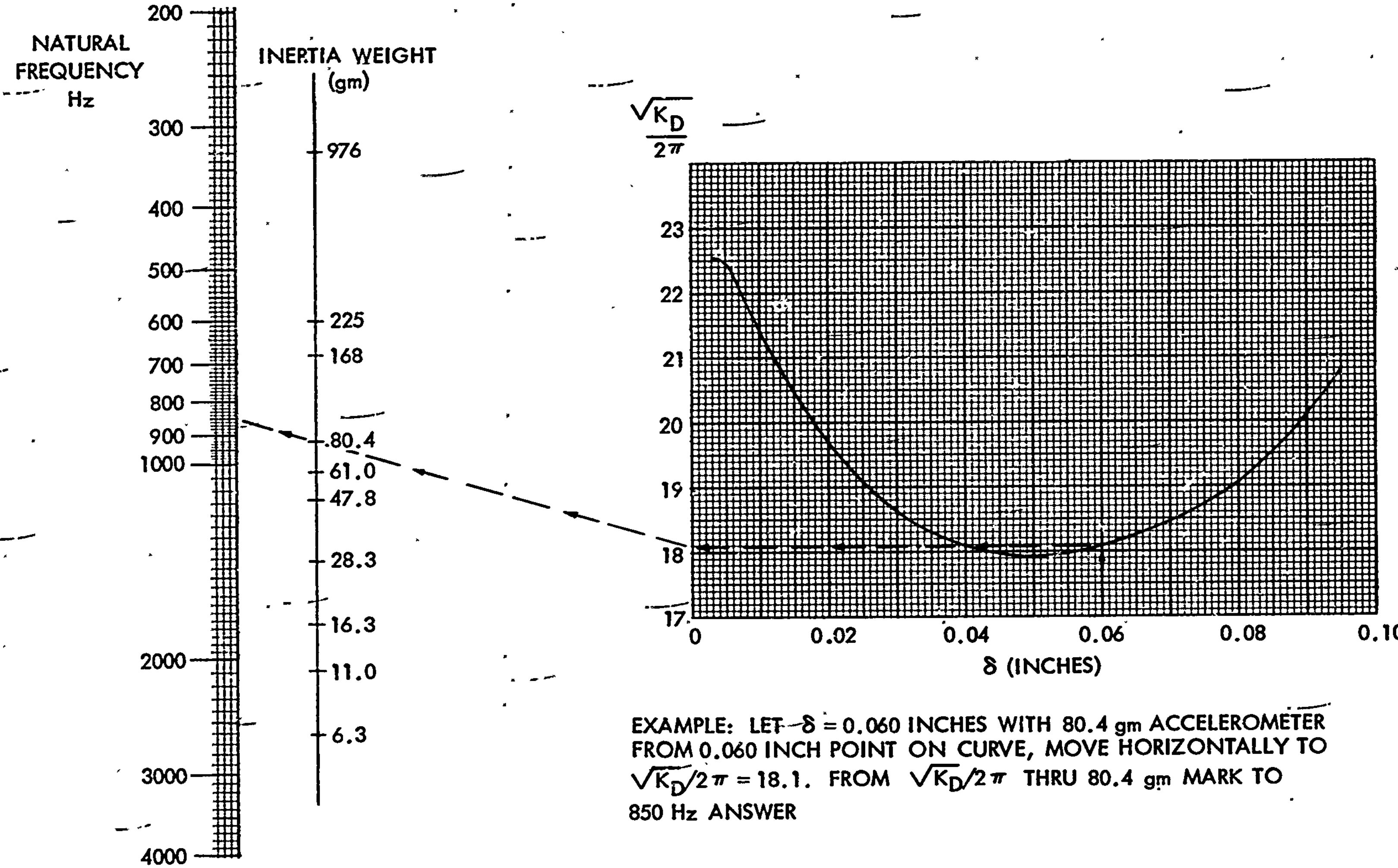


FIG. 9 PEAK g NOMOGRAPH FOR COPPER-BALL ACCELEROMETERS WITH DEFORMATION ON ONE SIDE OF COPPER BALL.



EXAMPLE: LET $\delta = 0.060$ INCHES WITH 80.4 gm ACCELEROMETER FROM 0.060 INCH POINT ON CURVE, MOVE HORIZONTALLY TO $\sqrt{K_D}/2\pi = 18.1$. FROM $\sqrt{K_D}/2\pi$ THRU 80.4 gm MARK TO 850 Hz ANSWER

FIG. 10 NATURAL FREQUENCY NOMOGRAPH FOR ACCELEROMETERS WITH DEFORMATION ON TWO SIDES OF COPPER BALL.

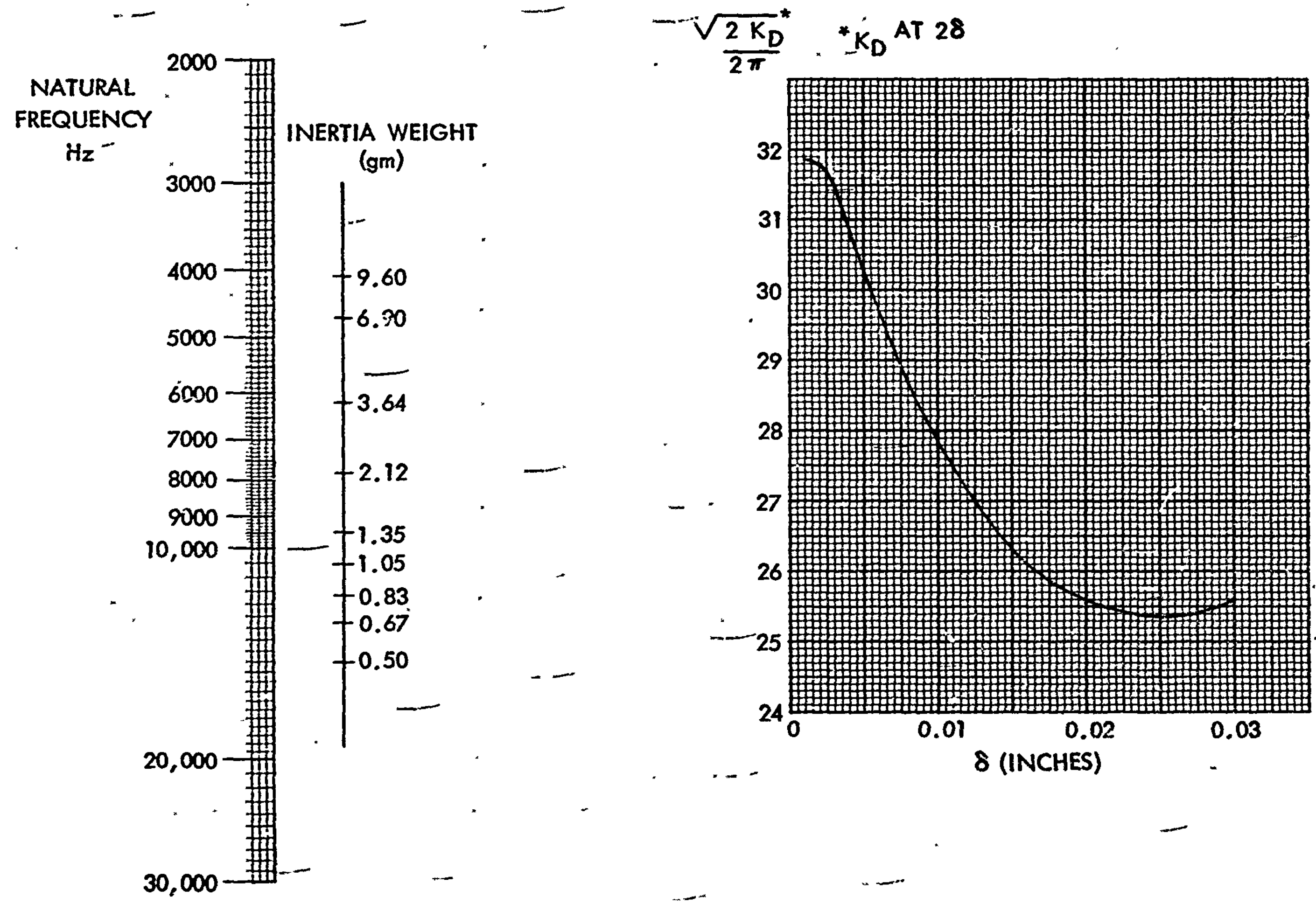


FIG. 11 NATURAL FREQUENCY NOMOGRAPH FOR ACCELEROMETERS WITH DEFORMATION ON ONE SIDE OF COPPER BALL.

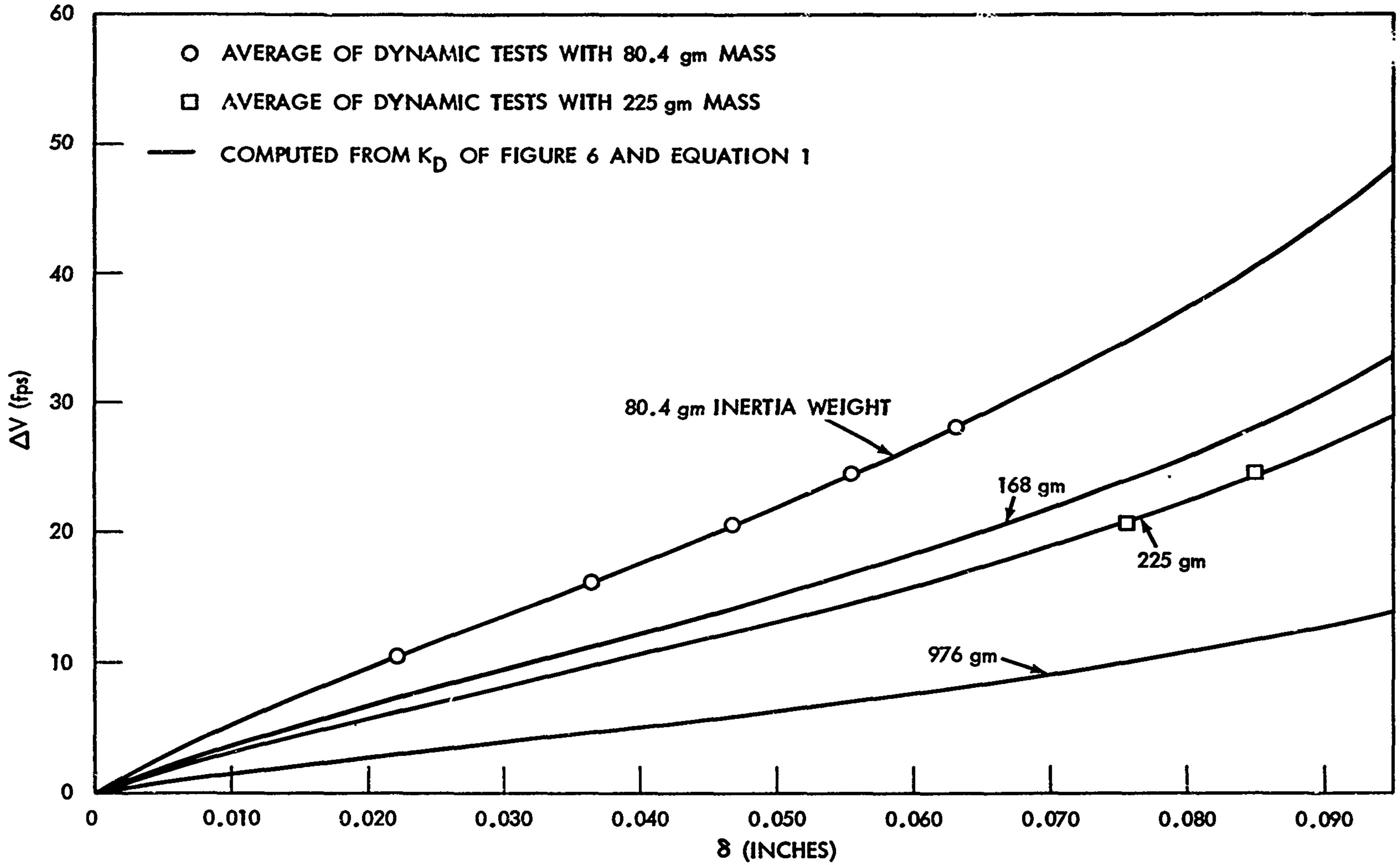


FIG. 12 VELOCITY CHANGE VS COPPER-BALL PERMANENT SET FOR FOUR ACCELEROMETERS COMMONLY USED AS VELOCITY METERS.