NBSIR 73-291

A Systematic Study of Vibration Standards - Mounting Effects -

Robert S. Koyanagi, James D. Pollard, John D. Ramboz

Vibration Section, Mechanics Division
Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

September 1973

Final Report

Prepared for
Department of Defense
Calibration Coordination Group

NBSIR 73-291

A SYSTEMATIC STUDY OF VIBRATION STANDARDS – MOUNTING EFFECTS –

Robert S. Koyanagi, James D. Pollard, John D. Ramboz

Vibration Section, Mechanics Division
Institute for Basic Standards
National Bureau of Standards
Washington, D. C. 20234

September 1973

Final Report

Prepared for
Department of Defense
Calibration Coordination Group

U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

A SYSTEMATIC STUDY OF VIBRATION STANDARDS

- MOUNTING EFFECTS -

by
Robert S. Koyanagi
James D. Pollard
John D. Ramboz

ABSTRACT

The purpose of this study was to determine the extent of the sensitivity change of laboratory quality piezoelectric accelerometers for various mounting conditions. The mounting variables included the material upon which the accelerometer was mounted, geometry, the use of commercial insulated studs, and the use of mounting stud thread size adaptors. For the stated test conditions, the effect of different materials and geometry was insignificant below about 3000 Hz. For stainless steel, beryllium, alumina, and tungsten, the deviations were less than 0.5 percent up to 10,000 Hz. The aluminum alloy base showed an increase of about 2 percent by 10,000 Hz. The effect of insulated studs showed deviations beginning at about 3,000 Hz. No significant deviation was found between the different stud thread size adaptors.

Note: In this study, units of acceleration are expressed in gravitational units of g. All screws employed were fine-thread series and are designated in this paper by their screw size number of fractional diameter in inches and the pitch in numbers of threads per inch. This was done to facilitate communication with the intended reader. Conversion to SI units may be accomplished using the following relationships:

1 inch = 2.540 cm; and, 1 g = 980.7 cm/s^2

Keywords: Accelerometer calibration; mounting variable; vibration.

1. INTRODUCTION

This report describes a study of the effects of some mounting variables on the sensitivity of selected piezoelectric accelerometers. The frequency range was from 100 Hz to 10,000 Hz. The mounting variables studied were:

(1) material upon which the accelerometer is mounted,

(2) material geometry,

(3) mounting with insulated studs, and

(4) the use of thread size adaptors.

Some accelerometers exhibit a change of their sensitivity when mounting conditions are varied. In recent years, the sensitivity to mounting torque and to dynamic pressure has been made negligible by improved design of the accelerometers. However, base strain sensitivity and temperature sensitivity have remained problems for certain accelerometers. These responses may be different in some cases even among accelerometers having the same manufacturer and model.

Past experience shows that some accelerometers exhibit a change of sensitivity when mounted on different materials, for example, aluminum, stainless steel, or ceramic. These accelerometers are generally of the compression design and are known to have base strain sensitivity. Reasonably repeatable results can be obtained when mounted on any one material, but no good explanation is available to explain why this shift occurs. The shift is noticed even at relatively low frequencies of the order of 10 to 400 Hz, well below the range where the resonance phenomenon begins. Shifts of the order of 0.5 to 1.5 percent have been observed. When this large, a one percent calibration uncertainty is rather meaningless unless the mounting conditions are carefully specified. Even then, one cannot be certain that the conditions can be duplicated from laboratory to laboratory. Good practice for laboratory standards would be simply to avoid the use of such pickups as standards.

This study concentrated mainly on one model of accelerometer that is widely accepted and used as a laboratory standard. It is important to verify that this particular model does not suffer from the above described problems, or if it does, to what extent. Six accelerometers of the same manufacturer and model were chosen for this work.

2. TEST SYSTEM DESCRIPTION

All the tests for this study were conducted using the Dimoff Vibration Standard 201/203 as the vibration exciter.[1] This exciter has a reference standard accelerometer built into the moving element. The reference standard was calibrated by a reciprocity method during June 1971.[2]

The heart of the test system is a small digital computer.[3] A software program in the computer controlled the entire test process. The program controls the frequencies and voltages generated by a programmable oscillator which in turn feeds a power amplifier and then the vibration exciter. At each test frequency there is a predetermined acceleration which is controlled by the computer to insure constant measuring conditions through a closed-loop process. All base material and insulated stud tests were done at 10 g peak amplitude and at 100 Hz frequency increments between 100 and 1000 Hz, and in 500 Hz increments between 1000 and 10,000 Hz. (An additional frequency of 1700 Hz was included because of other program considerations.) The tests for the thread size adaptors were done at an acceleration of 5 g peak because of increased mass of the test accelerometers.

Accelerometer sensitivity measurements were made by comparing the voltage output of the test accelerometer system to the voltage output of the reference standard accelerometer system. The automated system is capable of measuring these ratios to within a few tenths of one percent.

The waveform of each of the accelerometers' charge amplifier outputs was monitored by an oscilloscope. The waveform harmonic distortion generally did not exceed one percent. The transverse motion ratio, although not monitored, was believed to be less than a few percent over the entire frequency range.

[1] Numerals in brackets refer to reference found at the end of this report.

3. TEST HARDWARE

3.1 Mounting Base Materials

To study the effects of the type of material the accelerometer is mounted on, six washer-like mounting bases were fabricated. Table I shows the five materials, the dimensions of the bases and gives the approximate elastic modulus of each. The inside clearance hole was 0.490 cm diameter, sufficient to clear a 10-32 threaded mounting stud. Each of the base mounting surfaces were ground flat with a surface finish of approximately 0.23×10^{-6}m rms. The materials are listed in their order of increasing modulus.

This geometry was selected because of symmetry, ease of fabrication and because of past experience with similar washer-like bases. Accelerometer sensitivity changes had been previously noted using a very similar configuration. Figure 1 shows the bases.

The static stiffness of each of the bases was calculated using the relationship

$$k = \frac{F}{e} = \frac{SE}{\ell} \quad , \qquad (1)$$

where k = static stiffness, N/m,

F = force, N,

e = elongation, m,

S = cross-section area, m^2,

E = elastic (Young's) modulus, N/m^2, and

ℓ = thickness, m.

Substituting the dimensions into eq. 1, k_1 = 0.2016E and k_2 = 0.1008E for the 0.356 cm and 0.711 cm thick bases, respectively. The static stiffnesses are shown below for each of the bases. The values for stiffness were rounded to the nearest whole billion and are listed in order of increasing stiffness. (A value of $E = 279 \times 10^9\ N/m^2$ was used for beryllium.)

Material	Static Stiffness, $\times 10^9$ N/m
Aluminum	15
Beryllium (0.711 cm thick)	28
Stainless Steel	38
Beryllium (0.356 cm thick)	56
Tungsten	56
Alumina	70

3.2 Insulated Studs

Insulated mounting studs are frequently used to electrically insulate the accelerometer case from the mounting surface. Three models of commercially available studs were tested. All were of a 10-32 stud size on both ends. The general construction is that of a "sandwich" of a relatively stiff insulator such as fiber glass and epoxy, between the two studded ends. Figure 2 shows typical items used. The three studs were designated as α, β, and γ .

3.3 Thread Size Adaptors

Frequently it becomes necessary to mount an accelerometer having a 10-32 threaded hole in its base onto a surface which contains a 1/4-28 threaded hole. This is true of several of the commonly available "piggy-back" type transfer standards. In order to accommodate several thread sizes, adaptor studs and adaptor bushings are used.

The adaptor stud selected was made of 17-4 stainless steel with 0.343 cm length of 10-32NF2A external thread on one end and 0.635 cm length of 1/4-28NF2A external thread on the other end.

The adaptor bushing was also made of 17-4 stainless steel and was 0.686 cm in overall length. The outside of the bushing was a 1/4-28NF2A external thread. Concentrically along the length axis, an internal 10-32 NF2B thread was used.

Both the adaptor stud and bushing are commercially available items. Figure 3 shows the items used. A "piggy-back" vibration transfer standard provided the surface having a 1/4-28 mounting hole. The transfer standard output was used to control the acceleration level. This transfer standard was calibrated at NBS during December 1972.

3.4 Test Accelerometers

Six accelerometers were selected to be used on the six different mounting bases. These were a precision compression type using preloaded quartz as the piezoelectric sensing material. The accelerometers have a mounted resonance frequency of nominally 40 kHz and weigh about 22 grams. The diameter of their mounting surface was 1.27 cm. The mounting hole is 10-32 which is nominally 0.356 cm deep. These accelerometers are designated A, B, C, D, E, and F for purposes of discussion.

In addition, a shear type accelerometer was also used. Preliminary measurement revealed that "drift" due to its temperature sensitivity masked the effects of mounting. This accelerometer was designated as G.

The same six quartz accelerometers, A through F, were used for the insulated stud test. Several of these accelerometers, however, could not be used because the 10-32 stud "bottomed" in the accelerometer prior to its proper seating.

A "piggy-back" type transfer standard accelerometer was selected to test the thread size adaptor stud and bushing. It was designated as H. Several of the test accelerometers could not be tested because the stud adaptor "bottomed" in the accelerometer prior to proper seating.

3.5 Charge Amplifiers

In all instances, the accelerometers were fed into charge sensing amplifiers. For the test accelerometers A through F, the same amplifier was used throughout. Amplifier gain was nominally 20 mV/pC. Separate amplifiers were used for accelerometers G and H.

The frequency-gain response of the amplifier was not important, because only changes in the test responses were being examined. Short term stability (for the duration of the testing) was of critical importance. It was estimated that the gain stability with time was better than ±0.05 percent.

4. TEST PROCEDURE

4.1 General Precautions

When making a test assembly, all mating surfaces were thoroughly cleaned with alcohol and coated with a thin film of medium weight petroleum lubricating oil (viscosity of 240-500 S.U.S. at 100 degrees F). The entire assembly, consisting of test accelerometer, base, stud, or bushing was mounted onto the vibration exciter. The assembly was mounted with a torque of nominally 2 Nm (18 lbf-in.). The testing of each of the test accelerometers and each base or stud combination was done in a random manner. After the completion of a test, the entire assembly was removed and the next base selected at random was used. It was anticipated that randomizing the test order would help minimize any effect due to temperature or time drift.

The electrical connections for each accelerometer were cleaned using dry industrial paper wipers only and the connector was securely attached. The cable was taped to the vibration exciter base as near as possible to the moving element without interfering with the motion. Sufficient time was allowed to permit all the electronic equipment to warm up.

4.2 Test Matrix

Table II shows the overall test matrix for the eight accelerometers used, the materials, insulated studs, and the thread size adaptors.

Each of the six precision quartz accelerometers A through F were tested on all six bases. The results using accelerometer G were unreliable because of temperature sensitivity. Accelerometer H was a "piggy-back" type used only for the thread size adaptor test.

Accelerometers D and E could not be used because certain of the 10-32 insulated studs "bottomed" into the accelerometer before it was properly seated. This is shown by the absence of an "x".

Accelerometers A, D, and E also could not be used with the adaptor stud because of "bottoming". This is shown by the absence of an "x" in the "stud" column.

5. ANALYSIS

5.1 General Analysis Approach

Accelerometers A through F had a nominal sensitivity of 1 pC/g. Using a single charge amplifier for each of these six accelerometers, the output of the amplifier was nominally 20 mV/g. It was necessary to remove the effects of both the intrinsic frequency response of the accelerometer and charge amplifier from the results. Only the changes in response due to the mounting variable were sought. A scheme of taking percentage differences of the response of the same accelerometer under different mounting conditions and group averaging was selected. Standard deviations were also computed for the data to obtain a measure of quality for the test. Because slightly different analysis operations had to be used for the three different tests (i.e., materials, insulated studs, and thread adaptors) each is discussed individually below. Data taken at frequencies below 100 Hz were not considered. At these frequencies, the effects of the mounting variables under investigation might be masked by other effects.

5.2 Analysis of Mounting Base Materials Data

The response when mounted on the tungsten base was selected as a reference condition and was used in order to calculate the desired percentage difference of each accelerometer's response when mounted on another material. Experience had indicated that this could be expected to yield the most stable and least change in response of all the materials. Thus, each difference is the difference between the stated material base and the tungsten base. The percentage difference was determined from the following expression.

$$\delta_n (M, f) = \left[\frac{S_n (M,f)}{S_n (W,f)} - 1 \right] \times 100 , \qquad (2)$$

where δ_n (M, f) = percentage difference of response between material M and tungsten,

S_n (M, f), S_n (W, f) = system sensitivity of accelerometer n,

n = accelerometer A, B, C, D, E, or F,

M = mounting base material, for example, Al, SS, Be1, Be2, Al_2O_3, and W, and

f = test frequency, in Hz.

It is important to note that the differences are determined for the different materials, M, at specific frequencies, f, for each of six accelerometers. Twenty-nine frequencies were selected from 100 to 10,000 Hz. Additionally, it can be seen from eq. 2 that as long as the accelerometer charge amplifier gain remains the same value from the time S_n (M, f) is measured to the time S_n(W, f) is measured, the gain effectively divides out. Also, as long as the intrinsic characteristics of the accelerometer remain constant with time, the frequency response divides out. Thus, ideally all that remains is the difference due to mounting material. Under perfect conditions, δ_n (M, f) = 0.

Because random errors exist in the measurement process, multiple measurements were made. Also, because any one accelerometer of a particular model exhibits characteristics unique to itself, a group of six were used. The group average was determined from

$$\bar{\delta}(M,f) = \frac{\sum_{n=1}^{N} \delta_n(M,f)}{N} , \qquad (3)$$

where $\bar{\delta}$ (M,f) = group average for material M at frequency f, and

N = number of accelerometers tested.

The standard deviation of N measurements for any one material and frequency was computed from

$$\pm\sigma(M, f) = \left[\frac{\sum_{n=1}^{N} \xi_n^2(M, f) - (1/N)\left[\sum_{n=1}^{N} \xi_n(M, f)\right]^2}{N - 1} \right]^{1/2} , \qquad (4)$$

where $\pm\sigma(M, f)$ = standard deviation, and

$$\xi_n(M, f) = \delta_n(M, f) - \bar{\delta}(M, f).$$

$\xi_n(M,f)$ is the difference between the normalized response and the group average response.

If the measurement process were perfectly repeatable, $\pm\sigma(M, f) = 0$.

5.3 Analysis of Insulated Stud Data

The same basic approach in the analysis of the insulated stud data was used as for the base materials discussed in Section 5.2. It was decided that the response of the accelerometers where mounted on tungsten would be employed as a reference condition. Therefore, the percentage differences were calculated from an equation very similar to eq. 2, except for the notation shown in eq. 5.

$$\delta_n(I, f) = \left[\frac{S_n(I, f)}{S_n(W, f)} - 1 \right] \times 100 , \qquad (5)$$

where $\delta_n(I, f)$ = percentage difference of response between stud I at frequency f, and the response on tungsten at the same frequency,

$S_n(I, f)$, $S_n(W, f)$ = system sensitivities of accelerometer n,

n = accelerometers as shown by Table II and the data below eq. 6.

The group averages were computed from eq. 6 below.

$$\bar{\delta}(I, f) = \frac{\sum_{n=1}^{N} \delta_n(I, f)}{N} , \qquad (6)$$

where $\bar{\delta}(I, f)$ = group average for the insulated stud, I, tested at frequency, f, and

N = number of accelerometers tested for a given mounting condition.

For $I = \alpha$, n = A, B, C, D, F, and N = 5

For $I = \beta$, n = A, B, F, and N = 3

For $I = \gamma$, n = A, B, C, D, F, and N = 5

} See Table II

The standard deviations were computed similar to that done for the base material analysis. Changes had to be made for the different number of accelerometers tested. Equation 7 shows the generalized form.

$$\pm\sigma\ (I,\ f) = \left[\frac{\sum_{n=1}^{N}\xi_n^2(I,\ f) - (1/\ N)\left[\sum_{n=1}^{N}\xi_n(I,\ f)\right]^2}{N - 1}\right]^{1/2}, \tag{7}$$

where n and N are given for the different studs below eq. 6.

5.4 Analysis of Thread Adaptor Data

In order to compare the performance of the adaptor bushing and adaptor stud, the percentage difference was calculated between the response when using the bushing and when using the stud. This is expressed by eq. 8 below.

$$\delta_n\ (Q,\ f) = \left[\frac{S_n\ (Q_B,\ f)}{S_n\ (Q_S,\ f)} - 1\right] \times 100 \quad , \tag{8}$$

where $\delta_n\ (Q,\ f)$ = percent difference of response between bushing and stud adaptors at frequency f,

$S_n\ (Q_B,\ f)$ = sensitivity when using the adaptor bushing, Q_B, and

$S_n\ (Q_S,\ f)$ = sensitivity when using the adaptor stud, Q_S.

Likewise, the average deviation was calculated from eq. 9 below.

$$\bar{\delta}\ (Q,\ f) = \frac{\sum_{n=1}^{N}\delta_n\ (Q,\ f)}{N} \quad , \tag{9}$$

where n = B, C, F, and N = 3.

The standard deviation was calculated by

$$\pm\sigma\ (Q,\ f)\ =\ \left[\frac{\sum_{n=1}^{N}\xi_n^2(Q,\ f)\ -\ (1/N)\left[\sum_{n=1}^{N}\xi_n(Q,\ f)\right]^2}{N\ -\ 1}\right]^{1/2}\ , \tag{10}$$

where $\xi_n\ (Q,\ f)\ =\ \delta_n\ (Q,\ f)\ -\ \bar{\delta}\ (Q,\ f)$,

and n is the same as for eq. 9.

5.5 Standard Deviations for Small Data Samples

Certainly the statistical meaning of standard deviation when only a few measurements are made is open to question. Any validity at all must be considered rather lightly. It does, however, give some measure of the quality of the measurement in a vague way. As the number of measurements approach one pair of measurements in a set, it can be shown that the standard deviation equals the absolute difference between the two measurements divided by the square root of 2,

$$\pm\sigma\Big|_{N\ =\ 2}\ =\ \frac{|\xi_1\ -\ \xi_2|}{\sqrt{2}}\ . \tag{11}$$

6. MEASUREMENT RESULTS

6.1 General Comments on Measurement Results

In all instances, the measured data were analyzed as stated in Section 5 and percentage deviations from a selected reference were determined. It was necessary to select different reference quantities for different tests. These reference quantities have been discussed in Section 5.

The data is grouped according to the test performed. The following groupings are presented in the order shown below:

(1) reference response on tungsten,

(2) mounting base materials,

(3) insulated studs, and

(4) thread size adaptors.

Each group contains a table of data, a plot showing percentage deviation from the reference condition versus frequency, and a plot showing the standard deviation of the group data versus frequency.

Plots were made in order to present the final data in a readily readable manner. These show the extent and nature of the mounting effect as determined by these test methods and hardware, and provide certain assessments of the overall quality of the data.

The "FREQUENCY" axis of each plot is a two-decade logarithmic scale from 100 Hz to 10,000 Hz. The ordinates, "AVERAGE PERCENT DEVIATION", "PERCENT REFERENCED TO TUNGSTEN", "PERCENT REFERENCED TO ADAPTOR STUD", of the above listed groups were plotted with the same span of -1 to +5 percent. The ordinates "PERCENT STANDARD DEVIATION" for all the plots range from -0.5 to +2 percent. As such, the data can be more easily intercompared between the results of the different tests.

The tabular data are given to rounded hundredths of one percent. Usually, variations of vibration data of less than several tenths of one percent are considered excellent. The extra digits are given to indicate the repeatability of data obtained. The control, stability and averaging process of these tests indicate variations are generally very small and in order of a few tenths of one percent. Exceptions are noted in the ensuing discussions.

6.2 Reference Response on Tungsten

The responses of accelerometers A through F were measured on the base materials given in Table I and shown in Figure 1. The data thus obtained was then treated such that the responses on the tungsten base were used as the reference quantity. This is shown by the denominator of eq. 2 as $S_n(W, f)$. Because the response on tungsten was used as a reference condition, it is desirable to examine the nature and quality of the reference tungsten data.

Table III gives the measured response of accelerometers A through F for the tungsten base mounting condition. This data was normalized by dividing the measured sensitivity by the average of the sensitivity for the five frequencies from 100 to 500 Hz for each accelerometer, as

$$\Delta_n (W, f) = \left[\frac{S_n (W, f)}{(1/5) \sum_{f=100}^{500} S_n (W, f)} - 1 \right] \times 100 , \qquad (12)$$

where $\Delta_n (W, f)$ = percent difference of normalized accelerometer response. The other terms have been previously described.

The eighth column of Table III gives the average normalized response of the six accelerometers at each frequency and was derived by

$$\bar{\Delta} (W, f) = \frac{\sum_{n=1}^{N} \Delta_n (W, f)}{N} , \qquad (13)$$

where $\bar{\Delta} (W, f)$ = average of the normalized sensitivities, and

n = accelerometer A, B, C, D, E, or F , and

N = 6.

The ninth column of Table III gives the standard deviation of columns A through F for each frequency.

Figure 4 is a plot of $\overline{\Delta}$ (W, f) versus frequency. The deviation of the plotted data from zero is less than +0.25 percent up to a frequency of 3500 Hz. At frequencies greater than 3500 Hz, the frequency response of the accelerometers causes the average to increase to about +1.15 percent at 9500 Hz due to resonant rise.

Figure 5 is a plot of the standard deviation as given in Table III. At frequencies less than about 3500 Hz, the values are near zero. The rise at the higher frequencies is smooth and not excessive.

A small anomaly is noted at a frequency of 4000 Hz. This was solely due to an irregularity in the data for accelerometer D. As given in Table III, S_D (W, 4000) = 0.95 percent, which is about 0.5 percent or so greater than the adjacent data of S_D (W, 3500) = 0.26 and S_D (W, 4500) = 0.41 percent. If this point had been removed from the analysis, then $\overline{\Delta}$ (W, 4000) would have equaled 0.32 rather than 0.43.

The probable cause of why the value of S_D (W, 4000) was higher than expected is not known. It was not removed from the data because its effect on the average was small and its subsequent effect on the analysis can be accounted for.

Of greater concern is the anomaly noted at 10,000 Hz. The value of S_n (W, 10,000) for all six accelerometers suddenly decreased by about one percent. The reason for this is unknown, but could have been the result of poor motion or an irregularity of the sensitivity of the internal reference standard accelerometer at 10,000 Hz.

Based on the above discussion and observations, good test results are expected with the possible exception of tests performed at 4000 and 10,000 Hz.

6.3 Results of Different Mounting Base Materials

This test was performed using accelerometers A through F as shown by Table II and discussed in Section 3.1. The data was analyzed as described in Section 5.2.

The results are shown in Table IV and Figures 6 and 7. All the relative responses were smooth and near zero as desired for all frequencies up to about 3500 Hz. Above this frequency, the response when mounted on aluminum, $\bar{\delta}$ (Al, f), begins to rise. It ultimately achieves an average rise of about 2 percent above the reference condition of tungsten mounting. The remaining materials indicate a fairly flat response to 6000 Hz or so where they begin to "fan" out to about ±0.5 percent at 10,000 Hz.

Similarly the standard deviation is low, not exceeding 0.25 percent below 6000 Hz. Above 6000 Hz, scatter in the data is indicated by an increasing standard deviation of about ±0.5 percent at 10,000 Hz.

It is interesting to note the small anomaly at 4000 Hz. This is the direct result of the irregularity of the tungsten reference response (as previously discussed in Section 6.2) of about the same magnitude. Additionally, there may be an indication of problems at 10,000 Hz. Note the large range of standard deviations at 10,000 Hz from Figure 7.

6.4 Results of Different Insulated Studs

This test was performed using the accelerometers and insulated studs as shown by Table II. The procedure is discussed in Section 3.2 and the analysis approach in Section 5.3.

The results are shown in Table V and Figures 8 and 9. The differences between the response when mounted on tungsten and on the insulated studs are generally small, less than about 0.25 percent up to approximately 3000 Hz. Above 3000 Hz, the rise becomes significant. Stud γ has the highest rise of about 4 percent at 10,000 Hz. Examining the standard deviation as plotted in Figure 9, the overall values are higher than for the previous test on different base materials. This is true especially at the high frequencies where the values clearly rise.

6.5 Results of Thread Size Adaptors

This test was performed using the accelerometers and adaptors shown by Table II. The procedure is discussed in Section 3.3 and the analysis approach in Section 5.4.

The results are shown in Table VI and Figures 10 and 11. The difference in the response between the adaptor bushing and the adaptor stud are small. Except at frequencies of 4500 and 6500 Hz, the average difference did not exceed 0.15 percent. It is thought that poor motion was the cause of the apparent anomalies at 4500 and 6500 Hz. The difference should ideally be zero. Moreover, the column average for all frequencies of the average differences should be zero. As shown in Table VI, there was a slight negative bias of -0.07 percent when averaging over all the frequencies. If the anomalies at 4500 and 6500 Hz are removed from the column average, then the bias decreases insignificantly from -0.07 to -0.06 percent. In consideration of the average standard deviation for this test of about ±0.20 percent, the data appears to be well within an acceptable limit.

In examining the standard deviation as plotted in Figure 11, it is reasonably low and consistent up to a frequency of 3500 Hz. At frequencies between about 4000 and 8000 Hz, the standard deviation more than doubles the lower frequency values. It is suspected that poor motion is the cause of this poorer performance and that it is not related to the adaptor bushing or stud.

7. CONCLUSIONS

7.1 General Comments

The tests performed were under tightly controlled laboratory conditions and extra care was taken to ensure repeatable results. As such, the results should generally be considered as the best obtainable, not particularly typical. Furthermore, the averaging of data tends to reduce the random component of errors and "smoothes" the results. This would not occur for single tests.

The standard deviations derived herein were based on statistically small samples. Additionally, statistical methods were used which presupposes that certain independence exists in the measured data; this may not be true. However, in the lack of a more thorough and more costly test, the results herein establish approximate bounds and limits of performance which can be expected under similar conditions.

The standard deviations given herein are for confidence limits of $\pm 1\sigma$. When single sets of measurements are made under less controlled conditions, a better estimate of measurement uncertainty would probably be $\pm 3\sigma$. It is therefore recommended that although $\pm\sigma$ values are given, that the reader mentally triple the standard deviation values to develop a "feel" for a reasonable range of measurement uncertainty. Past experience indicates that the measurements were probably no better than $\pm 1\sigma$, but no worse than $\pm 3\sigma$.

Over the frequency range from 100 to 3000 Hz, the frequency response was virtually flat, i.e., having less than a few tenths of one percent difference for all mounting conditions. Because of this, it was possible to more fully intercompare the different mounting conditions.

Table VII shows the summary of all the tests performed. It is divided into two parts. Part A deals with the average of the differences over the frequency range. It was derived by averaging each of the "Average" columns of Tables III, IV, V, and VI. The frequency range for the averaging for the base mounting materials and the insulated studs was from 100 to 3000 Hz where the response was "flat". For the thread size adaptors, the different test permitted averaging over two frequency intervals, from 100 to 3000 Hz and 100 to 10,000 Hz.

Part B of Table VII deals with the average of the standard deviations over the indicated frequency ranges. It was derived by averaging each of the "Standard Deviation"($\pm\sigma$) columns of Tables III, IV, V, and VI. Because the standard deviation is not a direct function of the frequency response, averaging could be done over the whole range. It was, however, subdivided into ranges of 100 to 3000 Hz, 3500 to 10,000 Hz, and the whole range of 100 to 10,000 Hz. (The exception was for the tungsten mounting base material where it was a function of the frequency response. See Section 5.2 for a description of the analysis.)

7.2 Conclusions for Mounting Base Materials

The measured differences were small for all the materials tested over a frequency range from 100 to 3000 Hz. The aluminum alloy base showed an increase of about 2 percent at 10,000 Hz. The other materials showed deviations of less than 0.5 percent up to 10,000 Hz. The largest mean values of the average difference in the frequency range of 100 to 3000 Hz was about +0.10 percent. This is shown in Table VII, Part A.

The mean value of the average standard deviation was about ±0.10 percent over the frequency range from 100 to 3000 Hz and about ±0.20 percent over the frequency range from 3500 to 10,000 Hz. This is shown in Table VII, Part B.

A conservative estimate of the change of accelerometer sensitivity in the frequency range from 100 Hz to 3000 Hz is ±0.30 percent and for the frequency range from 3500 to 10,000 Hz is ±0.6 percent (excluding the aluminum base material from the latter). These numbers represent a $\pm 3\sigma$ standard deviation envelope.

7.3 Conclusion for Insulated Studs

The measured differences in response were small in the frequency range from 100 to 3000 Hz. Above 3000 Hz, the response begins to rise. For stud γ, the rise was approximately 4 percent at 10,000 Hz. The other two studs were somewhat less. The standard deviation also increased with an increasing frequency. This is generally true for instances where measurements are made on the "skirts" of a mechanical resonance.

In the frequency range from 100 to 3000 Hz, the standard deviation was about ±0.20 percent and in the range from 3500 to 10,000 Hz was about ±0.35 percent. This is shown in Table VII. It is expected that accelerometers of the type tested could be calibrated on a specific insulated stud to within an additional uncertainty of ±0.6 percent from 100 to 3000 Hz and ±1.0 percent from 3500 to 10,000 Hz. These uncertainties would be due to the insulated stud and should be added to other sources of error. Any phenomena (such as aging, temperature change, or fracture of the epoxy) which changes the dynamic characteristics of the insulated stud increases the uncertainty. A study of the stability of the insulated stud was beyond the scope of this investigation.

7.4 Conclusions for Thread Size Adaptors

The measured difference between the response when using adaptor studs and adaptor bushings was small and within expected measurement uncertainties. This is shown in Table VII. The measured standard deviation for the frequency range from 100 to 3000 Hz was about ±0.11 percent and about ±0.31 percent over the frequency range from 3500 to 10,000 Hz.

In consideration of the test conditions, no measureable difference is thought to exist between the use of a 10-32 to 1/4-28 adaptor bushing and adaptor stud.

8. REFERENCES

1. Dimoff, T., "Electrodynamic Vibration Standard With a Ceramic Moving Element", Journal of the Acoustical Society of America, Vol. 40, No. 3, Sept. 1966, pp. 671-676.

2. Payne, B. F., "Absolute Calibration of Vibration Generators With Time Sharing Computer as an Integral Part of System", Shock and Vibration Symposium Bulletin No. 36, Part 6, February 1967, pp. 183-194.

3. Payne, B. F., "An Automated Precision Calibration System for Accelerometers", Instrument Society of America 17th National Aerospace Instrumentation Symposium, May 1971 (Las Vegas, Nevada).

TABLE I. Characteristics of the Mounting Bases

Material	Symbol	Alloy or Composition	Dimension, cm. (Dia., thickness)	Elastic Modulus, N/m^2	
Aluminum alloy	Al	2024ST	1.588 x 0.356	73.1×10^9	(a)
Stainless steel	SS	303	1.588 x 0.356	$190. \times 10^9$	(b)
Beryllium alloy	Be1	Brush N50-B	1.588 x 0.356	$255-303 \times 10^9$	(a, b)
Beryllium alloy	Be2	Brush N50-B	1.588 x 0.711	$255-303 \times 10^9$	(a, b)
Tungsten alloy	W	Mallory 1000	1.588 x 0.711	276×10^9	(c)
Alumina ceramic	Al_2O_3	Coors AD-99	1.588 x 0.711	345×10^9	(a)

(a) Materials Engineering, Vol. 68, No. 5, pp 30, October 1968; Reinhold Publishing Corp.

(b) Mark's Mechanical Engineer's Handbook, Seventh Edition, pp 6-67 and 6-68; McGraw-Hill Book Co.

(c) Engineering Alloy Digest, Inc., Upper Montclair, N. J., Mallory 1000 Tungsten Alloy, filing code W-2, Nov. 1954. Composition in 0.9W, 0.06 Ni, 0.04 Cu.

TABLE II. Overall Test Matrix

		Mounting Base Materials[a]						Insulated Studs			Thread Size Adaptors[c]	
		Al	SS	Be 1	Be 2	Al_2O_3	W	α	β	γ	Bushing	Stud
Test Accelerometers	A	X	X	X	X	X	X	X	X	X	[X]	
	B	X	X	X	X	X	X	X	X	X	X	X
	C	X	X	X	X	X	X	X	(X)[b]	X	X	X
	D	X	X	X	X	X	X	X		X	[X]	
	E	X	X	X	X	X	X				[X]	
	F	X	X	X	X	X	X	X	X	X	X	X
	G[b]	(X)	(X)	(X)	(X)	(X)	(X)					
	H										X	X

[a] See Table I for material symbols.

[b] Values obtained by the tests in parenthesis were not used in the final results because of unreliable data. See text for explanations.

[c] Values obtained by the bushing tests in brackets were not used because corresponding data was not available for the stud. See text for explanations.

TABLE III. Normalized Response of Six Accelerometers Mounted on Tungsten Base Material (Data derived from eq. 12 and 13.)

Freq.	Sensitivity, Percent Deviation From Low Frequency Response							
Hz	A	B	C	D	E	F	Average	σ
100	-.04	-.02	-.08	.02	.02	.07	-.01	05
200	.06	.07	.12	.12	.12	.15	.10	.03
300	-.09	-.02	-.08	-.08	-.08	-.08	-.07	.03
400	.06	-.02	.07	.02	-.03	-.03	.01	.04
500	.01	-.02	-.03	-.08	-.03	-.08	-.04	.03
600	.06	.03	.07	.02	-.03	-.02	.03	.03
700	.16	.13	.18	.07	.02	-.03	.08	.07
800	.16	.13	.12	.02	.07	-.03	-.08	.07
900	.16	.13	.12	.07	-.03	.07	.09	.07
1000	.16	.12	.07	.07	.02	.02	.08	.06
1500	.26	.18	.17	.17	.07	.12	.16	.06
1700	.26	.18	.21	.17	.12	.07	.17	.07
2000	.30	.18	.22	.17	.12	.12	.18	.07
2500	.35	.18	.27	.21	.16	.16	.22	.08
3000	.30	.08	.17	.21	.21	.16	.19	.07
3500	.35	.08	.36	.26	.16	.07	.22	.13
4000	.55	.18	.41	.95	.26	.21	.43	.29
4500	.65	.13	.36	.41	.26	.21	.34	.18
5000	.89	.27	.41	.75	.45	.31	.52	.25
5500	.84	.32	.56	.51	.41	.26	.48	.21
6000	1.1	.32	.41	.56	.41	.26	.51	.30
6500	1.2	.32	.31	.46	.41	.21	.49	.37
7000	1.5	.42	.31	.61	.45	.26	.59	.45
7500	1.5	.42	.51	.51	.41	.21	.59	.45
8000	2.0	.42	.61	.70	.31	.07	.69	.69
8500	2.4	.71	1.00	.95	.74	.36	1.02	.70
9000	2.6	.76	1.05	1.00	.79	.40	1.09	.75
9500	2.9	.76	.86	.65	1.23	.50	1.15	.89
10000	1.8	-.12	.17	.07	.02	-.46	.24	.78

TABLE IV. Measurement Results for Different Mounting Base Materials (Data derived from eqs. 3 and 4.)

Frequency Hz	Mounting Base Materials									
	Al		SS		Be 1		Be 2		Al_2O_3	
	Ave.	σ	Ave.	σ	Ave.	σ	Ave.	σ	Ave.	σ
100	.08	.06	.04	.16	.11	.14	.10	.11	.08	.16
200	-.01	.15	.03	.13	.13	.10	.09	.11	.09	.11
300	.00	.05	.07	.17	.16	.15	.13	.11	.10	.13
400	.04	.06	.02	.19	.12	.10	.05	.09	.08	.09
500	.03	.05	.03	.14	.11	.10	.06	.08	.06	.09
600	.06	.04	.02	.15	.08	.08	.04	.08	.04	.09
700	.01	.02	-.01	.13	.10	.08	.04	.07	.03	.07
800	.05	.08	.03	.14	.11	.07	.07	.07	.04	.11
900	.03	.03	.03	.14	.11	.06	.07	.11	.04	.09
1000	.05	.03	.06	.16	.11	.09	.08	.08	.07	.11
1500	.04	.04	.01	.21	.11	.08	.06	.11	.07	.09
1700	.05	.05	.03	.16	.13	.07	.05	.06	.07	.08
2000	.03	.10	.01	.16	.05	.05	.03	.08	.06	.08
2500	.11	.04	-.01	.16	.06	.08	.01	.07	.02	.07
3000	.12	.09	.03	.18	.05	.09	.05	.09	.06	.10
3500	.19	.08	.04	.15	.01	.04	.02	.07	.01	.05
4000	.27	.11	-.14	.27	-.09	.22	-.06	.26	.10	.24
4500	.32	.18	.09	.08	.01	.08	.05	.06	.03	.01
5000	.36	.29	.08	.17	-.08	.10	-.01	.10	-.01	.11
5500	.45	.27	.06	.09	-.06	.06	.02	.10	.00	.07
6000	.46	.19	.08	.17	-.06	.06	.05	.06	.01	.08
6500	.57	.35	.12	.26	-.10	.11	.02	.13	.00	.10
7000	.71	.34	.14	.30	-.12	.11	.00	.11	.00	.10
7500	.97	.38	.18	.18	-.18	.14	-.02	.20	-.06	.17
8000	.97	.32	.16	.21	-.28	.18	-.11	.23	-.11	.16
8500	1.11	.41	.26	.28	-.36	.24	-.10	.30	-.11	.20
9000	1.21	.33	.28	.35	-.43	.28	-.14	.39	-.19	.23
9500	1.34	.16	.44	.40	-.43	.38	-.05	.49	-.05	.27
10000	2.01	1.92	.42	.45	-.18	.48	-.02	.67	-.04	.23

TABLE V. Measurement Results for Different Insulated Studs (Data derived from eqs. 6 and 7)

Frequency Hz	Insulated Studs					
	Stud α		Stud β		Stud γ	
	Ave.	σ	Ave.	σ	Ave.	σ
100	.05	.20	.16	.27	.05	.30
200	-.05	.17	.18	.23	-.02	.23
300	.02	.18	.28	.28	.04	.27
400	-.13	.16	.18	.14	-.09	.24
500	-.07	.18	.18	.19	-.02	.26
600	-.12	.15	.13	.19	-.13	.24
700	-.11	.15	.13	.12	-.10	.24
800	-.09	.14	.18	.17	-.06	.26
900	-.11	.14	.20	.17	-.05	.23
1000	-.09	.16	.19	.18	-.04	.25
1500	-.02	.15	.21	.16	.05	.25
1700	-.01	.12	.24	.18	.04	.24
2000	.04	.15	.18	.15	.10	.24
2500	.07	.13	.24	.13	.21	.24
3000	.23	.18	.29	.17	.40	.25
3500	.36	.09	.37	.15	.56	.24
4000	.33	.30	.40	.16	.62	.29
4500	.71	.12	.48	.13	.86	.19
5000	.68	.24	.52	.07	.98	.32
5500	.87	.11	.61	.22	1.34	.30
6000	1.04	.21	.72	.12	1.61	.40
6500	1.25	.27	.87	.12	1.92	.48
7000	1.46	.35	1.05	.16	2.24	.50
7500	1.89	.29	1.21	.32	2.71	.53
8000	2.14	.42	1.49	.37	3.07	.70
8500	2.42	.42	1.63	.33	3.51	.75
9000	2.73	.71	1.72	.41	3.95	.92
9500	3.62	.66	2.41	.30	3.79	1.06
10000	2.79	.60	2.08	.52	4.40	.97

TABLE VI. Measurement Results for Thread Size Adaptors
(Data derived from eqs. 9 and 10.)

Frequency Hz	Ave.	σ
100	-.02	.17
200	.00	.20
300	.02	.10
400	-.07	.11
500	-.06	.12
600	-.05	.08
700	-.08	.14
800	-.05	.10
900	-.05	.08
1000	-.06	.07
1500	-.05	.05
1700	-.03	.14
2000	-.06	.07
2500	-.07	.07
3000	-.06	.10
3500	-.05	.13
4000	-.13	.53
4500	.14	.71
5000	-.13	.27
5500	-.08	.49
6000	-.06	.48
6500	-.34	.51
7000	-.15	.36
7500	-.07	.24
8000	-.07	.16
8500	-.10	.13
9000	-.10	.09
9500	-.08	.10
10000	-.10	.13

TABLE VII. Summary of Measurement Results, all values given in percent. (See Sections 5 and 7 for explanation of the derivation of values. Table I gives materials description.)

Frequency Range, Hz	Mounting Base Materials						Insulated Studs			Thread Size Adaptors
	Al	SS	Be1	Be2	Al_2O_3	W	α	β	γ	
	Part A. Mean value of the average differences.									
100 - 3000	+.05	+.03	+.10	+.06	+.06	+.07	-.03	+.20	+.03	-.05
3500 - 10,000	--	+.16	-.17	-.03	-.03	--	--	--	--	-.09
	Part B. Mean value of the average of standard deviation									
100 - 3000	±.05	±.16	±.09	±.09	±.10	±.06	±.16	±.18	±.25	±.11
3500 - 10,000	±.38	±.24	±.18	±.21	±.14	--	±.34	±.24	±.48	±.31
100 - 10,000	±.21	±.20	±.13	±.15	±.12	--	±.25	±.21	±.36	±.20

F I G U R E S

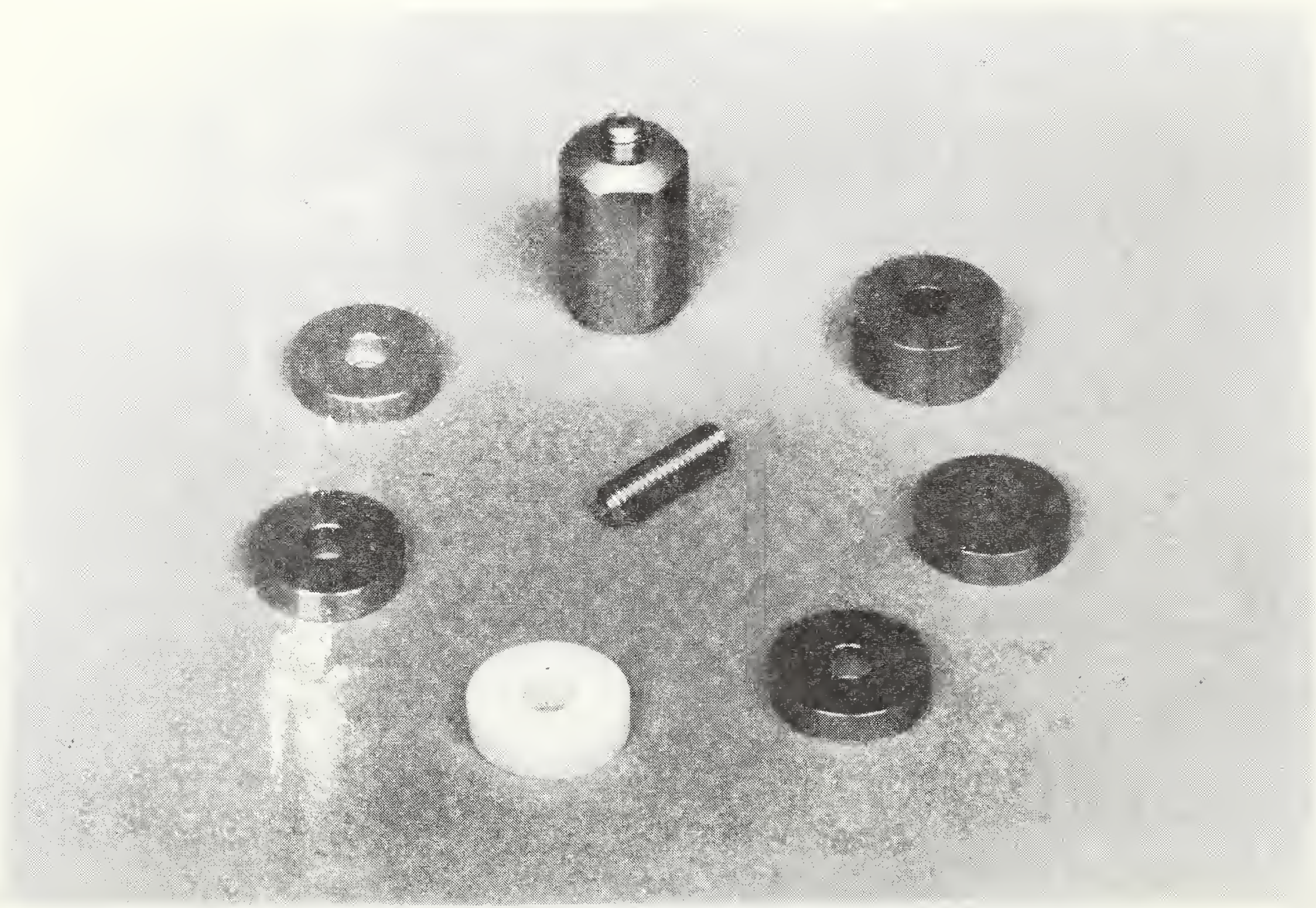


FIGURE 1. Different mounting base materials shown with a typical accelerometer and mounting stud. Materials counter-clockwise from the left of the accelerometer are aluminum, stainless steel, alumina, tungsten, and two beryllium bases.

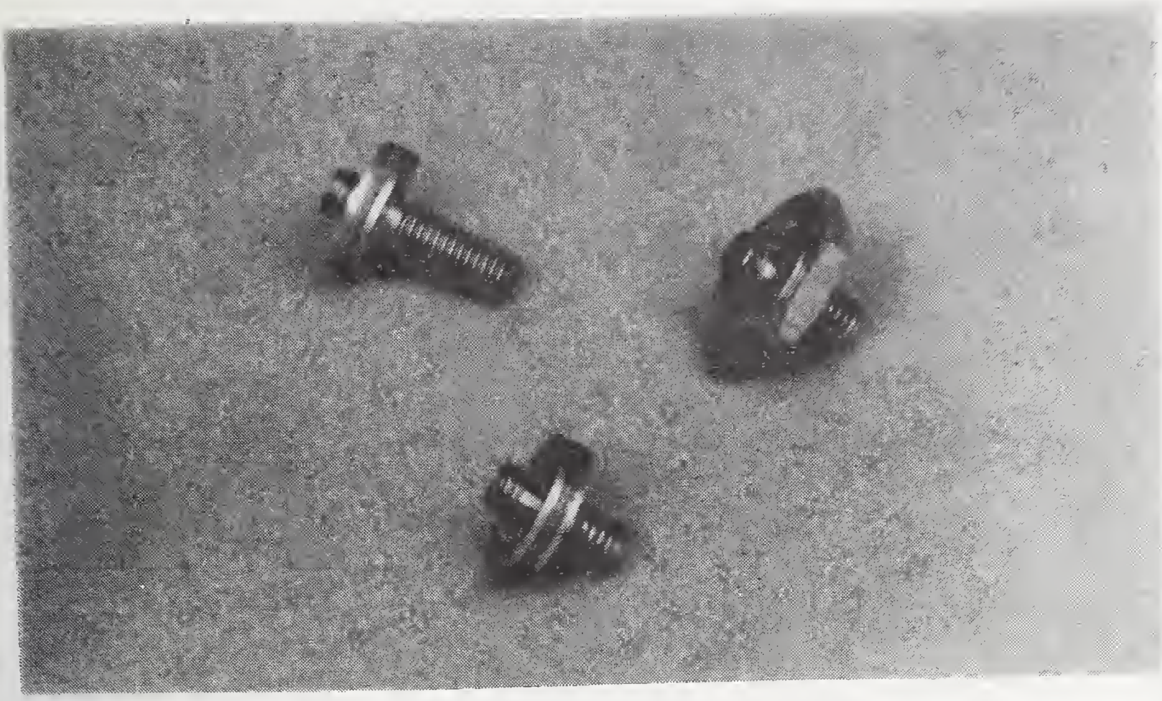


FIGURE 2. Three typical insulated studs used. Threads are all 10-32.

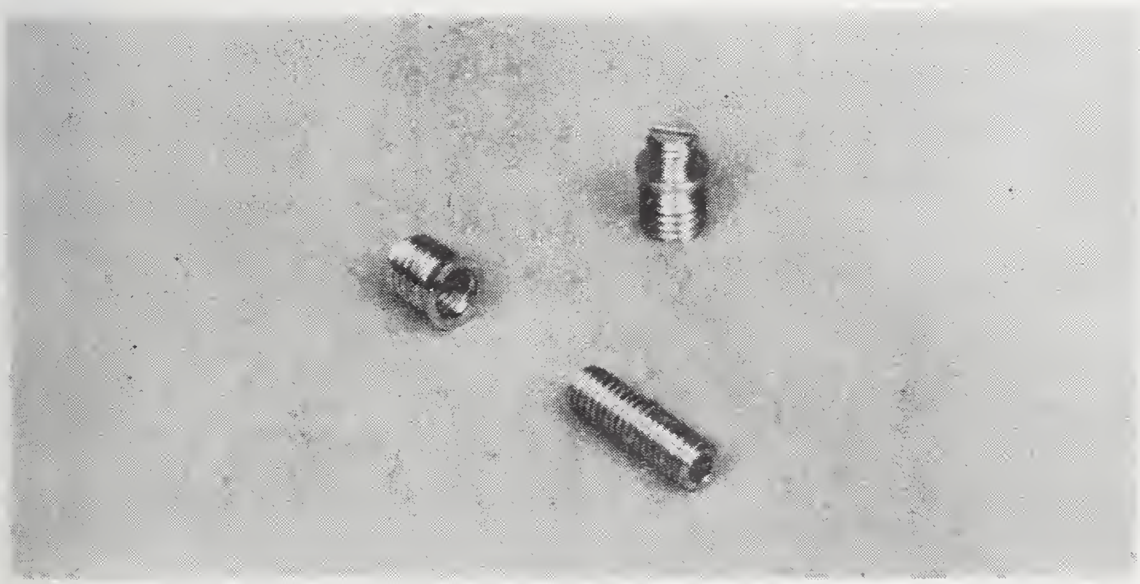


FIGURE 3. The thread size adaptor bushing (left) and adaptor stud (shown in the rear). The smaller thread is 10-32 and the larger is 1/4-28. A typical 10-32 stud is shown in the foreground.

FIGURE 4. Reference Response on Tungsten Base Material
(Deviation derived from eq. 13, and column 8 of Table III.)

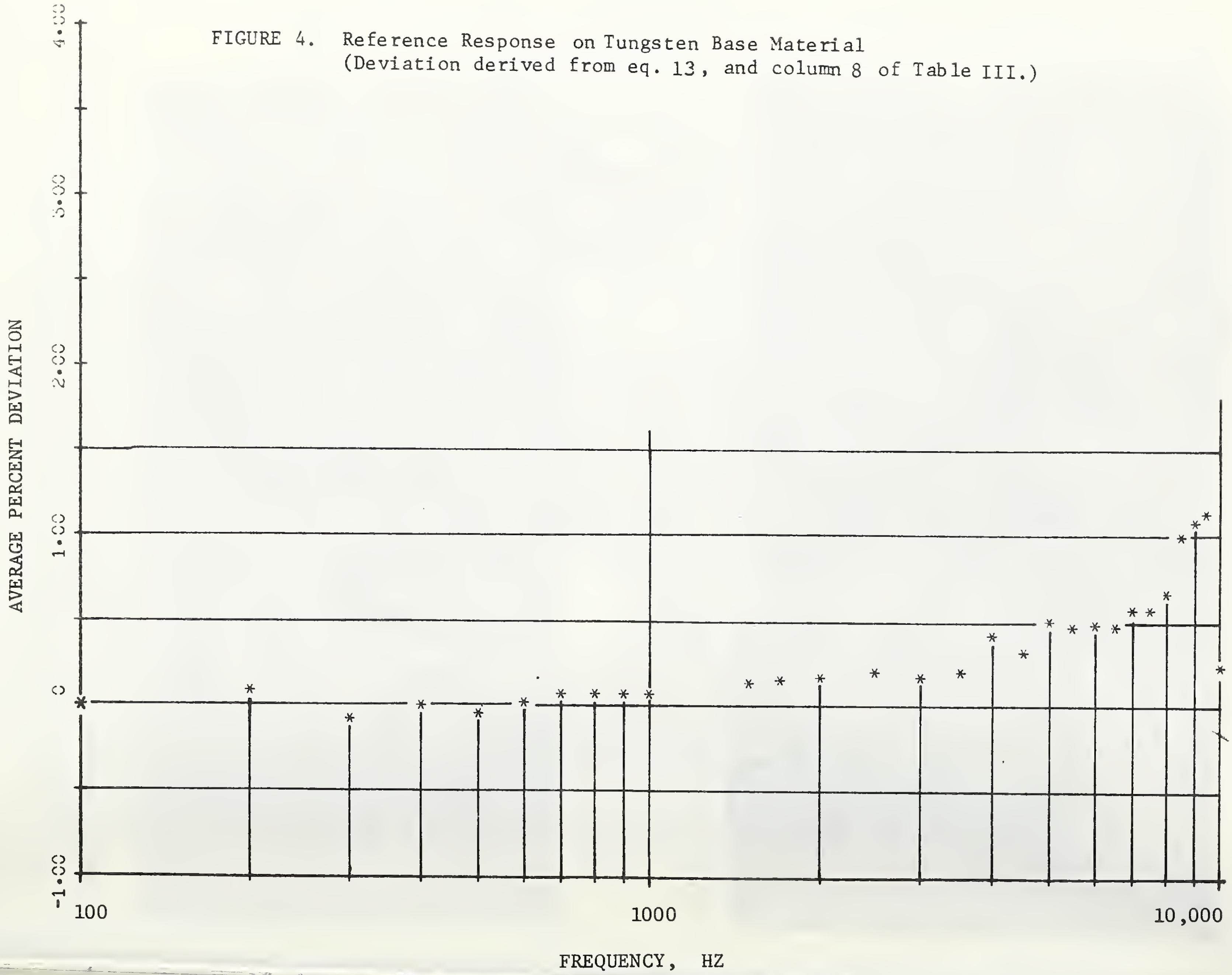
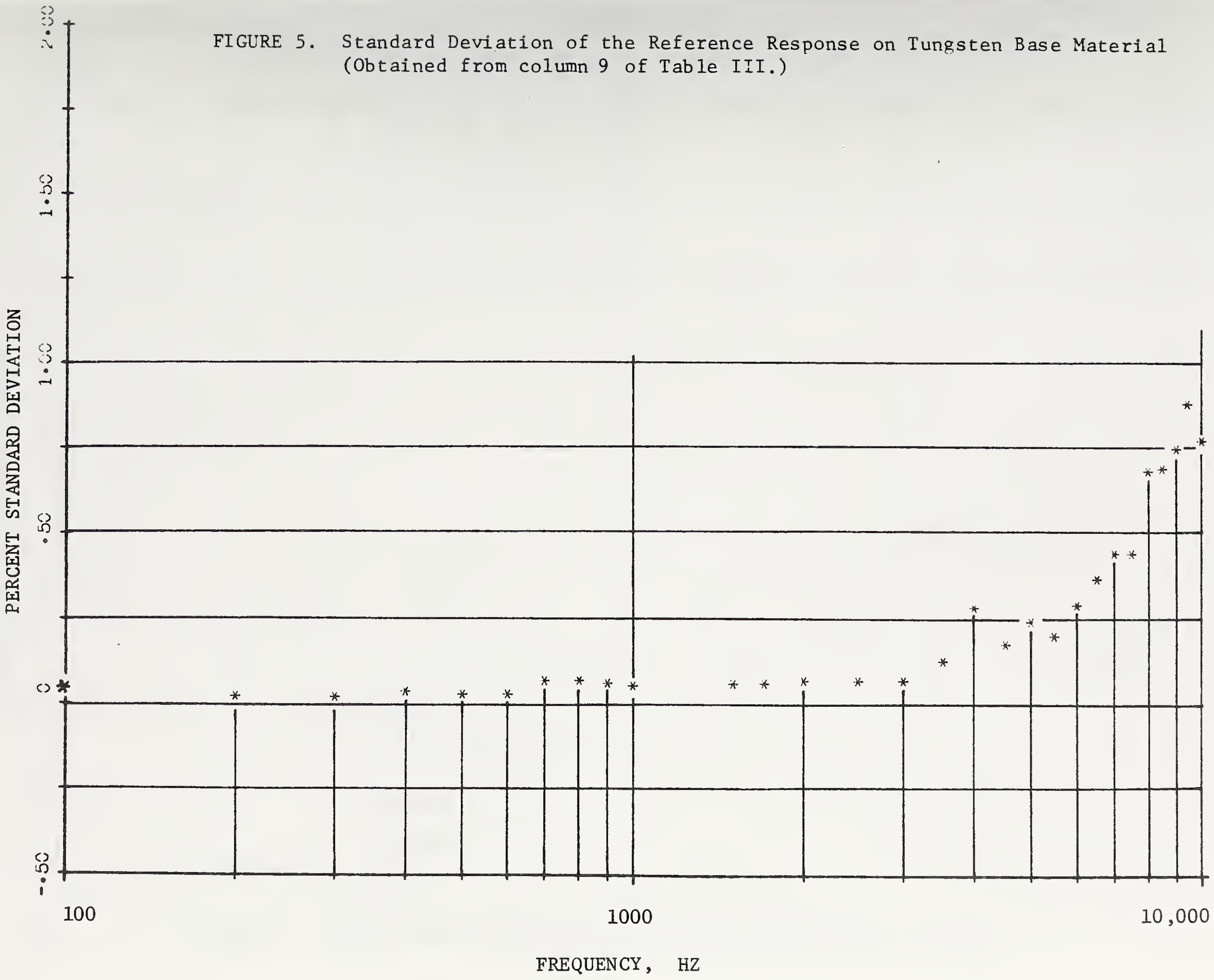


FIGURE 5. Standard Deviation of the Reference Response on Tungsten Base Material (Obtained from column 9 of Table III.)



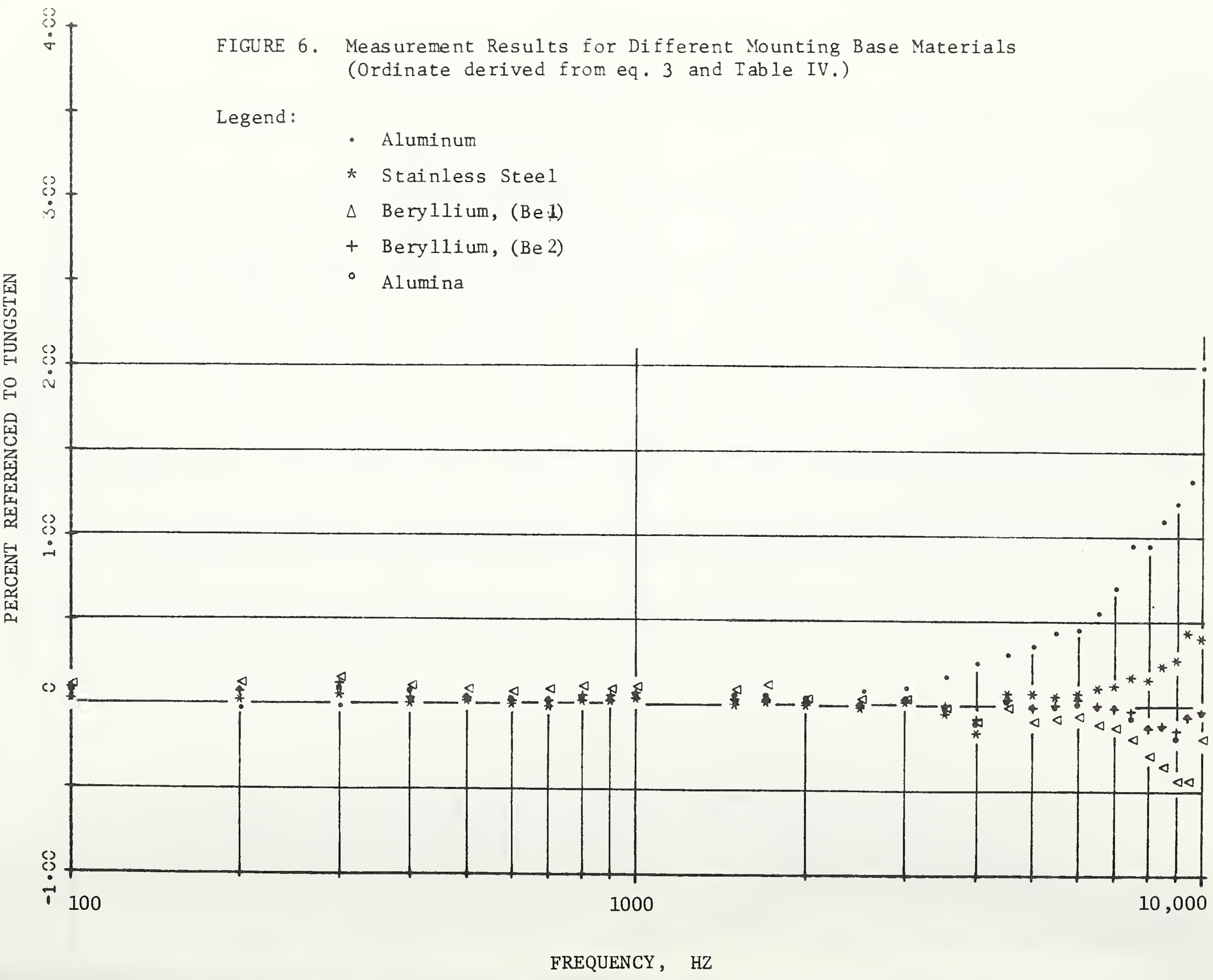


FIGURE 6. Measurement Results for Different Mounting Base Materials (Ordinate derived from eq. 3 and Table IV.)

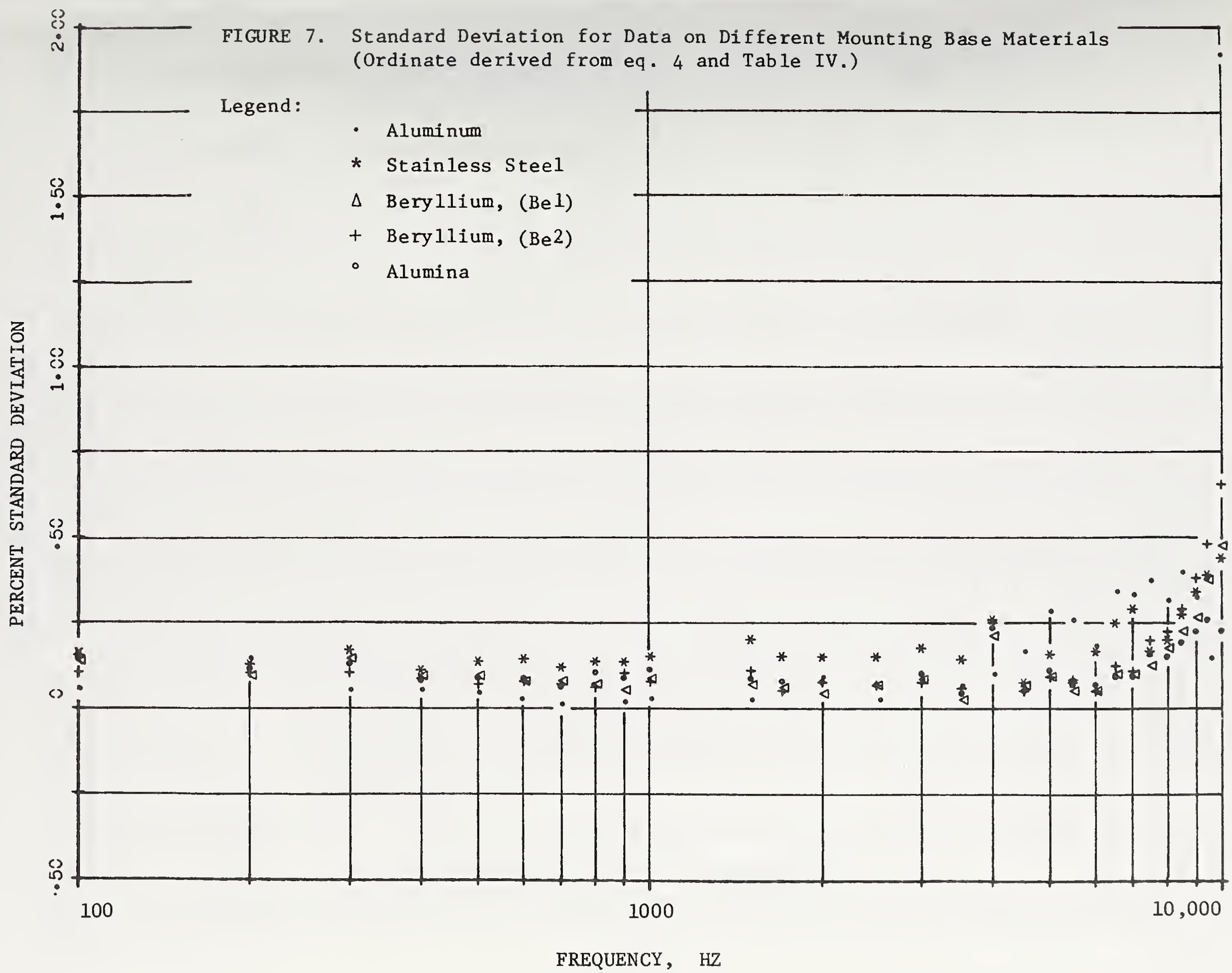


FIGURE 7. Standard Deviation for Data on Different Mounting Base Materials (Ordinate derived from eq. 4 and Table IV.)

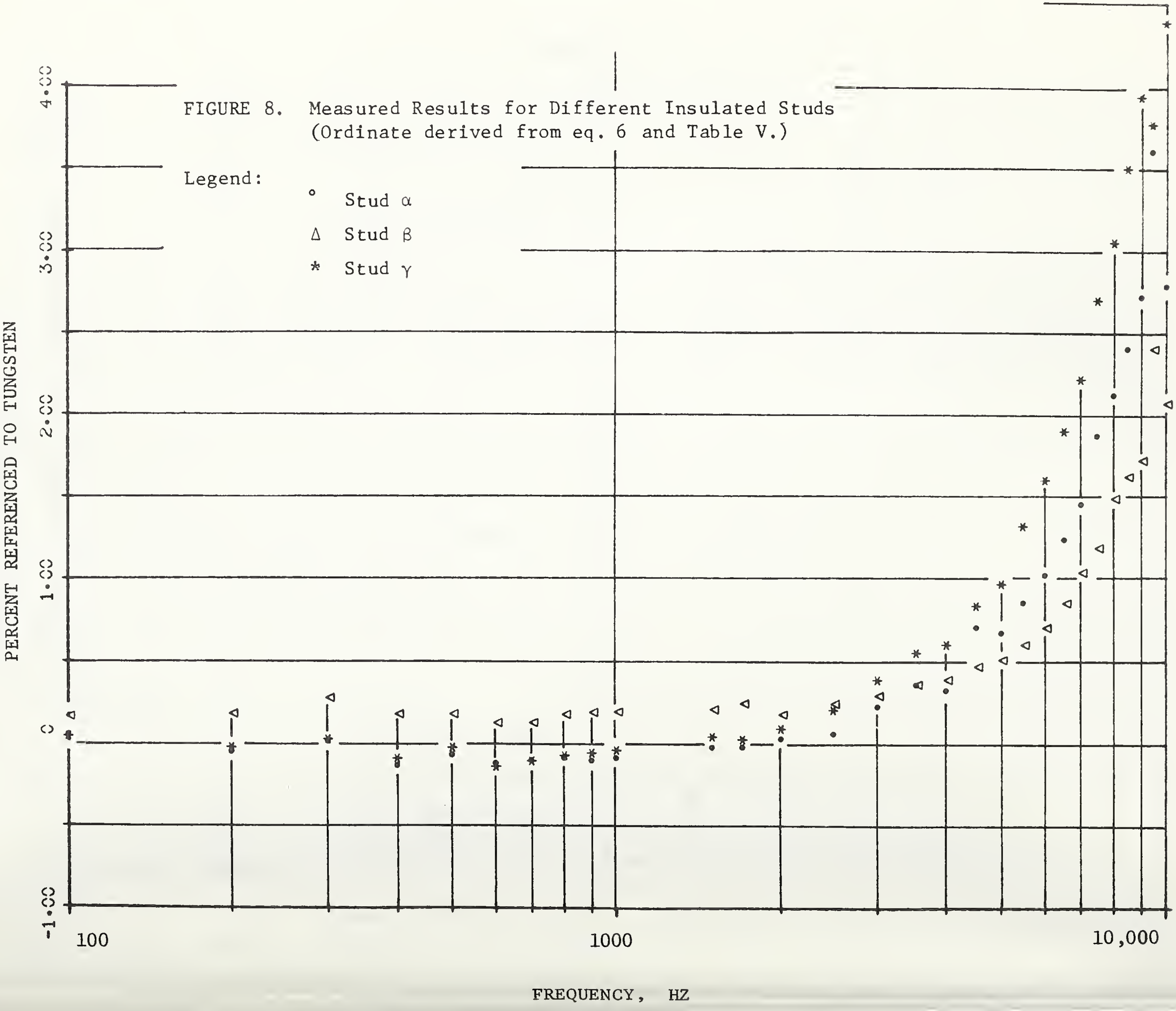


FIGURE 8. Measured Results for Different Insulated Studs (Ordinate derived from eq. 6 and Table V.)

FIGURE 9. Standard Deviations for Data on Different Insulated Studs (Ordinate derived from eq. 7 and Table V.)

Legend:

° Stud α

Δ Stud β

* Stud γ

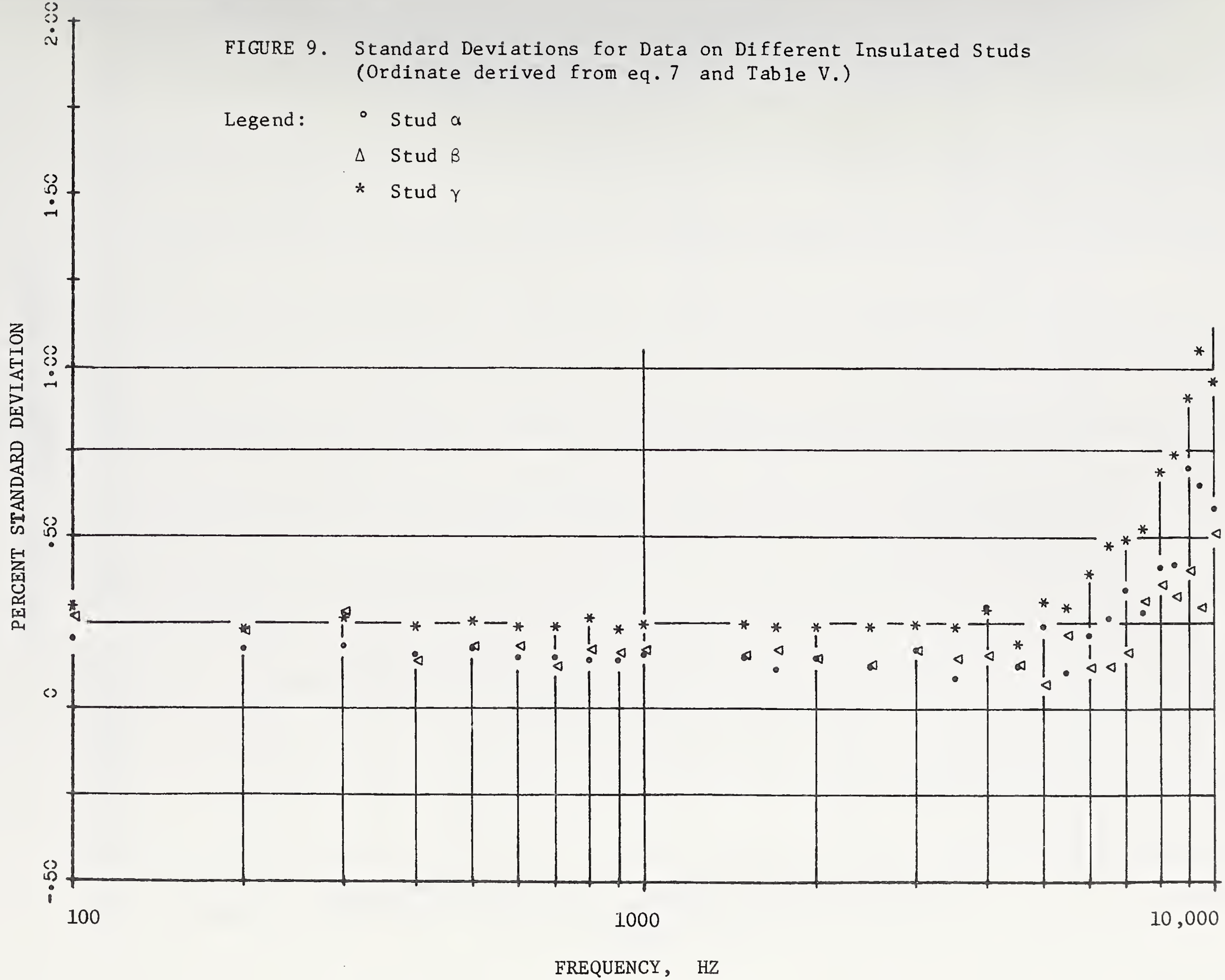


FIGURE 10. Measurement Results for Different Thread Size Adaptors (Ordinate derived from eq. 9 and Table VI.)

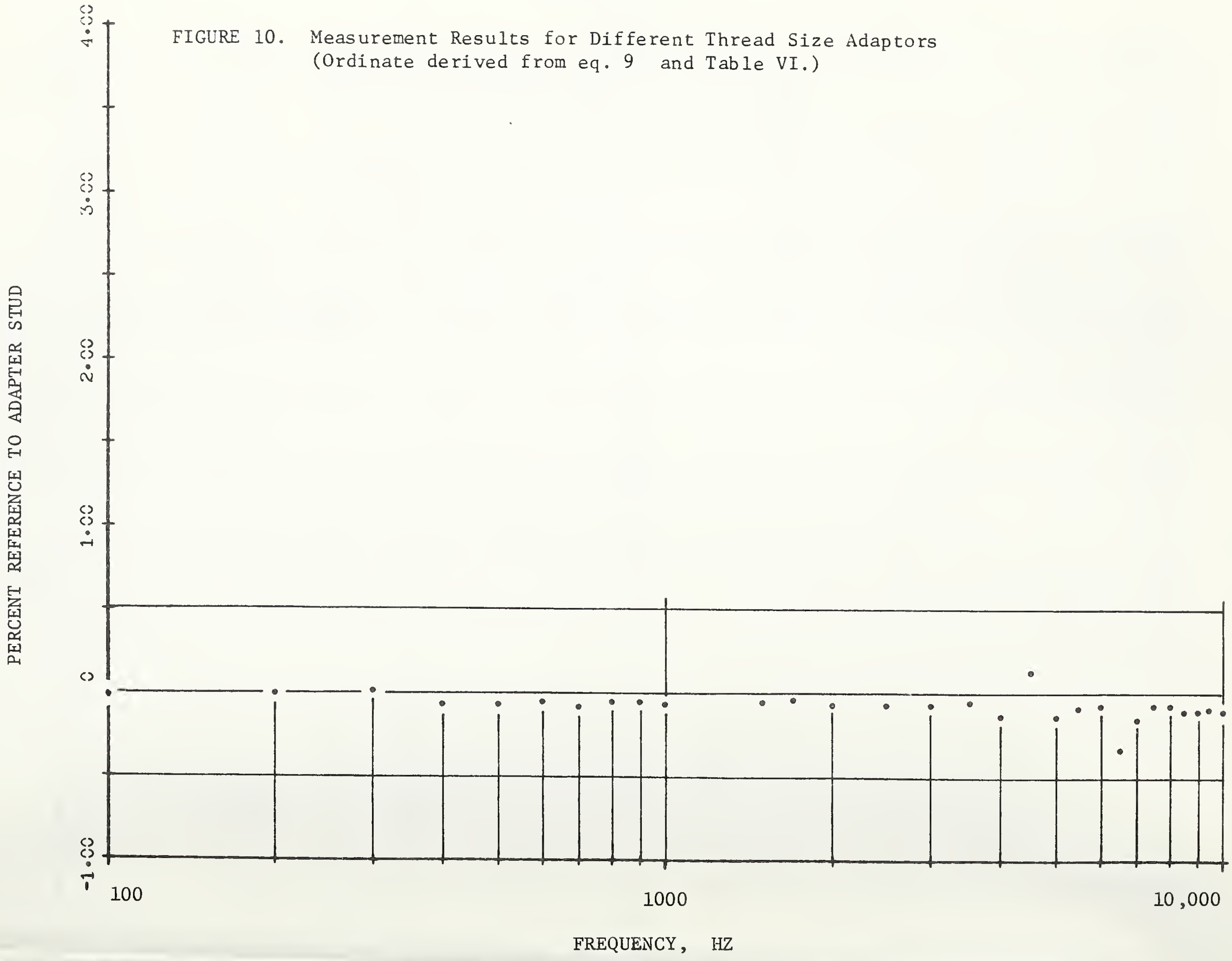
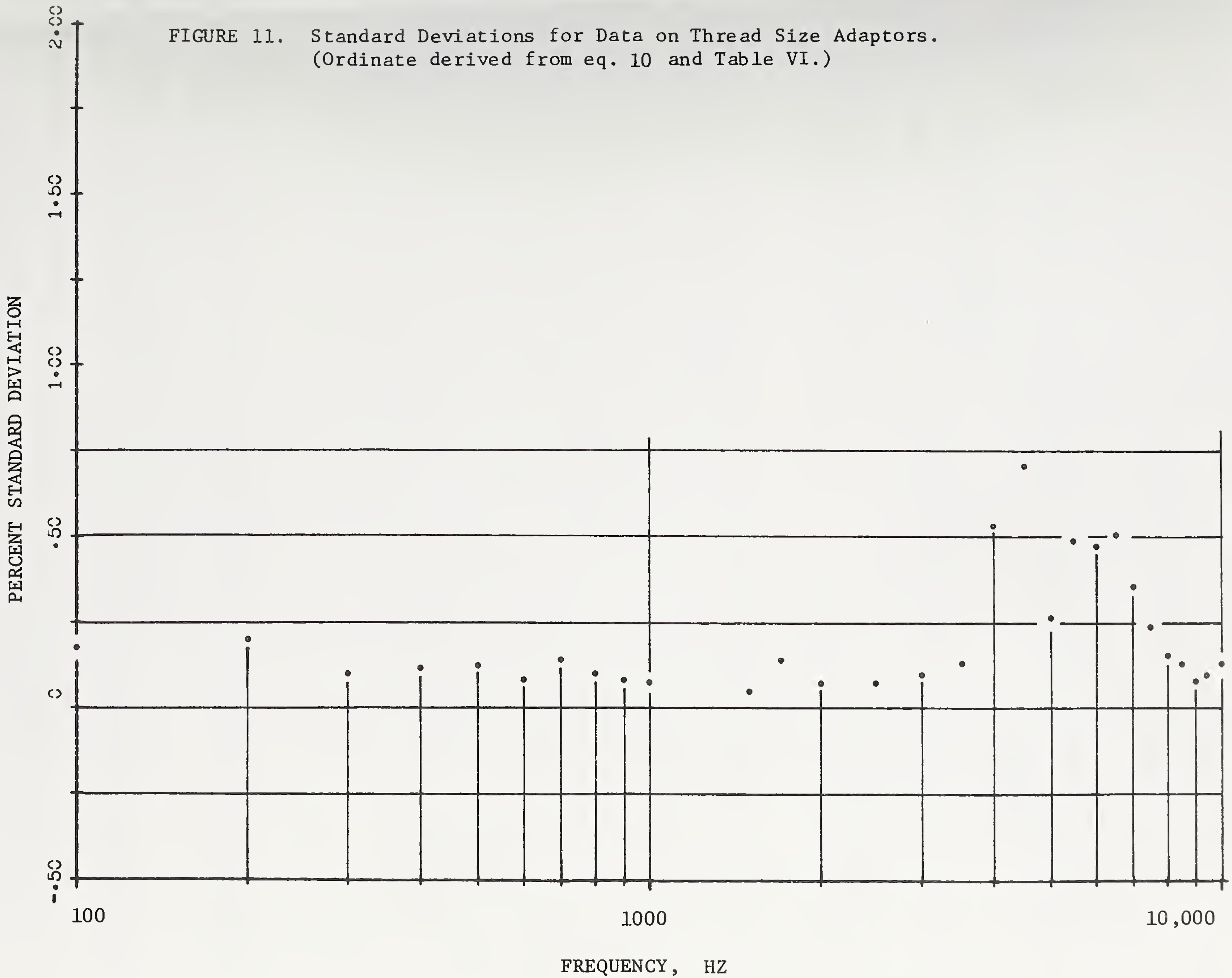


FIGURE 11. Standard Deviations for Data on Thread Size Adaptors. (Ordinate derived from eq. 10 and Table VI.)



U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET	1. PUBLICATION OR REPORT NO. NBSIR 73-291	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE "A SYSTEMATIC STUDY OF VIBRATION TRANSFER STANDARDS - MOUNTING EFFECTS"			5. Publication Date September 1973
			6. Performing Organization Code
7. AUTHOR(S) Robert S. Koyanagi James D. Pollard John D. Ramboz			8. Performing Organ. Report No. NBS IR 73-291
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 2130426
			11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address (*Street, City, State, ZIP*) Department of Defense Calibration Coordination Group			13. Type of Report & Period Covered Final
			14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

The purpose of this study was to determine the extent of the sensitivity change of laboratory quality piezoelectric accelerometers for various mounting conditions. The mounting variables included the material upon which the accelerometer was mounted, geometry, the use of commercial insulated studs, and the use of mounting stud thread size adaptors. For the stated test conditions, the effect of different materials and geometry was insignificant below about 3000 Hz. For stainless steel, beryllium, alumina, and tungsten, the deviations were less than 0.5 percent up to 10,000 Hz. The aluminum alloy base showed an increase of about 2 percent at 10,000 Hz. The effect of insulated studs showed deviations beginning at about 3,000 Hz. No significant deviation was found between the different stud thread size adaptors.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Acceleration calibration, mounting variable, vibration.

18. AVAILABILITY	19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
☐ Unlimited ☒ For Official Distribution. Do Not Release to NTIS	UNCLASSIFIED	28
☐ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 ☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price