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DEVELOPMENT OF AN INDUCTANCE TYPE ACCELEROMETER FOR USE IN A FREQUENCY MODULATED RECORDING SYSTEM

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U. S. NAVAL ORDNANCE LABORATORY

WHITE OAK, MARYLAND

DEVELOPMENT OF AN INDUCTANCE TYPE ACCELEROMETER FOR USE IN A FREQUENCY MODULATED RECORDING SYSTEM

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ABSTRACT: The development, characteristics and calibration of a new inductance type accelerometer is described. The mechanical features of this accelerometer are characterized by a mass unit suspended by a double cantilever beam spring system. An excursion of this mass unit changes the gap spacing of a mu metal pad relative to an E coil. The resulting change in reluctance of the magnetic circuit produces an inductance change in an inductance coil which comprises the inductance element in the tank circuit of an FM oscillator. Thus an acceleration of the mass unit results in a frequency modulation of the carrier frequency of the FM system. Accelerometers were produced with the following characteristics:

Range	0.1g to 38g
Damping	0.5 to 0.7 critical
Frequency shift	+ 7.5% at full range
Accuracy	Better than 5%.

Calibration techniques described include the use of a tilt table, spin table, and shake table.

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White Oak, Maryland

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This report is part of a classified report issued as report NOLR-1167. The numbering system used in this report is accounted for by the fact that it is part of a more extensive report. The purpose of this report is to declassify and circulate on a wider basis certain parts of this more extensive report which deal with instrumentation development of general interest. It may be stated that a considerable number of the accelerometers herein described were successfully used on large scale explosion tests. The frequency modulated recording system used in conjunction with the accelerometers described in this report is reported in unclassified NAVORD 2713. This work was carried out by the Explosion Effects Division of the Explosives Research Department under Task NOL-187.

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By direction

CONTENTS

ILLUSTRATIONS

CHAPTER 4

ACCELEROMETER DEVELOPMENT, CALIBRATION AND INSTALLATION

4.1 ACCELEROMETER DEVELOPMENT

4.1.1 Introductory Remarks

In the early stages of planning for the test, it was established that accelerometer records were to be obtained by recording FM signals on magnetic tape. The gages were to be coupled to field oscillators located at the respective test stations and FM signals from the oscillators transmitted directly by cable to the recording units.

In determining the type of the accelerometers to be used, it was considered advisable to require a unit operating on a variable inductance or variable capacitance principle. Other types of accelerometers would have required a relatively complex oscillator design which had as yet been undeveloped. Time limitations were such as not to allow for such development work to be undertaken. A further consideration was the possibility that increased complexity of the oscillator circuit would result in reduced reliability.

An extensive survey was made through various commercial and government agencies of the availability of an accelerometer with suitable electrical and mechanical properties. Units with the frequency and high sensitivity characteristics required for a large number of gage stations could not be located. Further, those commercial units which would have been satisfactory for some of the stations could not be obtained in the time required.

An experimental and theoretical research program was therefore established at the Naval Ordnance Laboratory (NOL) which resulted in the development of the accelerometers used on the test. The final design was completed in cooperation with Schaevitz Engineering of Camden, N.J., where all of the units required for the test were manufactured. The instrument is now available commercially as the Schaevitz Accelerometer, Type B.

A comprehensive study of the general properties of the gage was conducted at NOL. A summary of the research and testing program is presented in the following section of this report. Individual topics are generally unrelated; however, an attempt has been made to offer some degree of continuity in the order of presentation.

4.1.2 Design Specifications

All efforts were directed toward producing an accelerometer operating on a variable inductance principle and capable of measuring linear accelerations.

The desired mechanical properties were:

(a) Vibratory system to have one degree of freedom with linear response characteristics

(b) Full-scale sensitivities from ± 0.1 g to ± 38 g for both vertical and horizontal units

(c) Resonant frequency as high as possible

(d) Damping between 0.5 and 0.7 of critical

(e) Variation of sensitivity due to temperature changes less that 2% between 32°F and 78°F

(f) Accuracy within 5% over the gage range

(g) Accelerations normal to the gage axis to introduce negligible effects

(h) Over-all dimensions not to exceed 3 in. in any direction

The necessary electrical properties as governed by the characteristics of the recording system were:

(a) Initial inductance approximately 130 mh at 4 kc to 10 kc

(b) Q of the coil greater than 10 at 4 kc to 10 kc

(c) Inductance variations of about 15% corresponding to full-scale accelerations

(d) Double stops to limit frequency range to a maximum of ± 10% of the center frequency.

4.1.3 Description of Gage

Based on the foregoing requirements, the accelerometer design evolved by NOL and Schaevitz Engineering had the basic features outlined schematically in Fig. 4.1. The instrument consists of a metal housing within which are mounted an inductor and two cantilever beams. The beams are located directly above one another with a mass centrally supported between them at their free ends. Fixed rigidly to one end of the mass is a Mu-metal pad having a high permeability. A sensitive magnetic circuit is formed by locating the Mu-metal pad in close proximity to the inductor. Alignment of the various elements of the instrument is such as to afford a single axis of sensitivity.

When subjected to an acceleration, the movable mass and Mu-metal pad undergo an excursion controlled by the bending of the cantilevers. The motion of the Mu-metal pad changes the gap spacing in the magnetic circuit, resulting in a change of magnetic reluctance. A measure of the reluctance change is the corresponding inductance variation of inductor E-coil. The gage is coupled to an inductance controlled oscillator whose frequency of oscillation is a function of the displacement of the Mu-metal pad from equilibrium.

To provide necessary damping, the instrument is filled with a non-corrosive damping oil. A neoprene gasket separating the fluid from a vented recess in the cover plate permits expansion and contraction of the fluid.

A double stop is provided limiting the frequency range as required to ± 10% of the center frequency. The purpose of the stop mechanism is essentially to prevent damage to mechanical parts due to excessive accelerations and to prevent the subcarrier frequency from going out of its band and interfering with other channels.

The final model weighs approximately 0.7 lbs, and has overall dimensions of 2.1 x 1.5 x 2 inches. A photograph of the instrument is shown in Fig. 4.2.

4.1.4 Spring-Mass System

Extensive information can be found in the literature[1-4] on

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[1] P.M. Morse, "Vibration and Sound", McGraw-Hill Book Co.

[2] S. Timoshenko, "Vibration problems in Engineering", D. Van Nostrand Co.

[3] R. J. Roark, "Formulas for Stress and Strain", McGraw-Hill Book Co.

[4] Gross & Lehr, "Die Federn", VDI Berlin.

the deflection and vibration properties of cantilever springs, generally classified as fixed-free beams. The response of a double cantilever system with simple mass load at the free ends, as used in the gage, closely resembles that of a single cantilever with both axial and lateral loads. The coupling of the free ends by the terminal mass restricts the freedom of rotation by introducing an axial force which is a function of the deflection of the springs and the relative spacing between them.

A double cantilever system was chosen because of its stability against torsional and rotational effects. This feature was highly desirable in order to minimize potential extraneous signals when the instrument is subjected to accelerations in random directions.

The various parameters of the spring-mass system were determined empirically. In general, it was necessary to vary only the spring thickness for different gage ratings. Because of its low temperature coefficient, Ni Span-C was used for the spring material. To insure uniform electrical sensitivity for various gage ranges, the displacement of the mass under peak rated accelerations was designed to be the same in each case, within reasonable tolerances. All displacements of the mass under operating conditions were small so that the linear stress-strain limits of the springs were not exceeded.

4.1.5 Magnetic Circuit

The inductor of the gage consists of an E-coil mounted in a metal housing and cemented in position by a potting compound. The E-coil is composed of a series of E-shaped Mu-metal laminations bound together by an electrical coil wound around the center arms.

To insure the required high permeability of the Mu-metal pad, a hydrofining process was necessary. The pads were heated in a furnace box to about 2,100°F. While the temperature was steadily increasing a stream of specially dried hydrogen was introduced. The units were then kept at 2,100°F for a period of 5 hours. Following this soaking treatment, the parts were then cooled in a similar stream of hydrogen. This entire process increased the permeability of the Mu-metal chiefly by removing impurities (mostly carbon) from the alloy.

The E-coil and Mu-metal pad of the gage comprise a magnetic circuit whose reluctance varies with gap spacing. A corresponding variation results in the inductance of the E-coil. Shown in Fig. 4.3 is a typical example of the relation between inductance L and gap spacing d. Fig. 4.4 shows how the Q of the gage coil varies with gap spacing, where Q is a measure of the energy loss in the magnetic circuit per cycle of AC current through the E-coil.

An experimental study was made of the sensitivity of inductance to transverse and rotational motions of the Mu-metal pad. The results of this study are summarized by the series of contours in Figs. 4.5, 4.6, and 4.7. On the basis of these results and other auxiliary tests, a gap spacing of 15 mils was chosen as most practical for the gage design, with the pad deflection to be 5 mils at an acceleration equal to the gage rating.

For the gage oscillator, a shunt-feed Hartley circuit was used to minimize any magnetic attractions that would result from DC current passing through the E-coil. In the case of the 0.1 g gage the magnetic effect proved to be serious when a series-feed circuit was first used.

4.1.6 Calibration techniques

Of the various methods available for calibration of accelerometers[5-7], three were applied in the present case. A spin table and tilt table permitted independent static calibrations and a shake table offered a means for dynamic calibration.

Due to the unavailability of a commercial unit within the required time limit, a spin table was designed and built at NOL. The unit was highly stable, well balanced and easily transportable for field use. Incorporated in the design was the use of a positive speed control which minimized drift and hunt and allowed for quick adjustments to exact speeds. A report[8] now in preparation describes in detail the construction and operation of the spin table. A photograph of the unit is shown in Fig. 4.8. In principle, an accelerometer is mounted on an arm which is pivoted at its center and rotated in a horizontal plane at a constant angular velocity. The acceleration applied to the gage

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5 Armour Research Foundation, "Study of Methods of Calibration of Accelerometer, Velocimeters and Displacement Gages", Proj. 90-534, Oct. 1947.

6 S. Levy, A. E. McPherson & E. V. Hobbs, "Calibration of Accelerometers", BuStds Res. Paper 1930, Vol. 41, Nov. 1948.

7 Statham Laboratories, "Calibration and Test of Accelerometers", Instrument Notes No. 6, Dec. 1948.

8 R. G. Quick, "Spin Table for Calibrating Accelerometers", NavOrd Rpt. 2301.

is $a = r\omega^2$, where r is the distance of the instrument from the center of the arm and ω is 2π times the frequency of rotation. By means of a tachometer generator geared to the drive shaft of the arm, an accurate measure of the speed of rotation of the arm was available. Balancing of the arm was accomplished by an adjustable counterweight. Accelerometers could be mounted at a distance of either 9 in. or 11 in. from the center of the arm. The speed limits were 17 to 430 rpm, so that the over-all acceleration range was about 0.08 g to 55 g.

The tilt table used was a standard universal dividing head with sensitive leveling adjustment and a vernier scale for reading angle of rotation. Accelerometers were mounted on the flat plate of the head and rotated to an angle such that a fractional component of the earth's gravitational field acted along the sensitive axis of the gage. (See Fig. 4.9). Because of its range limitations, the tilt table was used for gages with ratings of 1.0 g or lower. Excellent resolution was available for calibrating 0.1 g gages.

The auxiliary electronic equipment required for static calibration consisted of the gage oscillator, an oscilloscope, and a variable reference oscillator. The gage oscillator was coupled to one set of plates of the oscilloscope and the reference oscillator to the other set. By means of Lissajous patterns, the frequency changes of the gage circuit were easily determined. A similar technique was used to determine the speed of rotation of the spin table, where the output of the tachometer generator replaced that of the gage oscillator.

The accelerometers were calibrated dynamically using an MB Model C31 Shake Table (see Fig. 4.10). Rigidly fixed to the table head, the gage was subjected to a forced sinusoidal motion of various amplitudes and frequencies. Automatic control of this motion was possible such that the acceleration was constant over a continuum of frequencies. A measure of the excitation of the gage was gained by means of a velocity meter which formed an integral part of the vibratory system of the table. The gage oscillator was coupled to an FM discriminator whose output voltage signals were used for analysis of the gage characteristics.

In the early use of the shake table, a problem of correct interpretation of the output data developed because of the non-linear transfer characteristics of the gage. However, further investigation showed that the peak to peak output signal of the gage was linearly proportional to the input acceleration within 2 to 3% over an entire gage range. Thereafter, a vacuum tube voltmeter reading peak to peak voltages was used for recording gage output signals. All frequency response studies were based on this peak to peak data.

A typical normalized response curve is shown in Fig. 4.11 for a 10 g gage subjected to a uniform 10 g input acceleration over a range of applied frequencies. The same response curve was found for constant inputs of 5 g to 7.5 g. For comparison, a theoretical curve is shown in Fig. 4.11 by the solid line, corresponding to the response of a one-degree-of-freedom system with pure viscous damping. The theoretical curve was calculated to coincide with the experimental curve at $\omega/\omega_o = 1$. The good agreement between the two curves indicates that the gage response to sinusoidal excitation may be analyzed by simple linear theory.

In the design of the accelerometer, it was necessary that the damping factor β be limited to values of between 0.5 and 0.7 of critical. On the basis of the foregoing agreement between theory and experiment, the β for any particular gage could be evaluated by determining the ratio between the gage output signals at $\omega/\omega_o = 1$ and $\omega/\omega_o \ll 1$. According to theory, this ratio is equal to $1/2\beta$. In general, good results were obtained by this method. However, some problems were encountered at low frequencies because of distortion in the vibration of the shake table.

A phase comparison for determining β was devised which gave good agreement with the foregoing method. After the natural frequency was found, this technique permitted all measurements to be made at a single excitation frequency chosen in a range outside of any singular difficulties associated with the shake table. A report[9] on

[9] E. J. Culling, "A Phase Comparison Technique for Determining Damping Coefficients of Accelerometers", Navord Rpt. 2342.

this method is now in preparation. The method in essence may be described as follows. Considering peak to peak output, the accelerometer responds like a system of one degree of freedom with pure viscous damping. An electrical equivalent of the accelerometer by means of a passive L, C, R circuit can easily be devised. It has been shown in the literature[10] that for minimum-phase networks, one of which is the equivalent accelerometer circuit, there is only one possible phase vs frequency function for a specific amplitude vs frequency dependence. This leads to the possibility of comparing the accelerometer phase with the phase of an equivalent electrical simulating circuit. In this respect, the non-linear transfer characteristics of the gage do not influence its phase response and therefore a direct comparison may be made between the gage and simulating circuit. Common reference for the comparison was the signal from the velocity meter of the shake table. A nul technique by means of Lissajous patterns was applied to find the required simulating circuit having the same phase relation to the velocity signal as the gage output. A simple relation between the L, C, R parameters of the equivalent circuit determined the desired damping factor of the gage.

4.1.7 Damping

Early models of the accelerometer showed evidence of non-linear damping properties. It appeared that the damping factor β was a function of both the initial gap spacing in the magnetic circuit and the amplitude of displacement of the pad under motion. A study of the problem indicated that this effect could be eliminated by having the pole faces of the E-coil extend 50 mils above the level of the potting compound. Records for a series of free-fall drop tests taken with an early and final model of the gage are shown in Fig. 4.12, indicating the results of this change in the design of the E-coil. The patterns yielded by the final model are independent of the gap spacing. It might be noted that there is an excessive curvature in the respective signals. This was due to a characteristic angular motion of the recording pen over its range of motion.

The damping fluid used in all of the studies and final design was Dow Corning DC-200 Silicone Oil. Extensive measurements were

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10 H. W. Bode, "Network Analysis and Feedback Amplifier Design", Bell Telephone Laboratories.

made to determine the proper viscosity required for each individual gage range. A group of similar gages, with the same viscosity fluid, was found to have a variation in β of about 20%. These differences are possibly due to tolerances in the clearance between the mass and its channel of travel.

The variation of β with temperature was investigated to obtain information for expected field test conditions. For pure viscous damping, β is linearly proportional to the viscosity of the damping fluid. Therefore the temperature variation of viscosity for DC-200 fluids given in commercial literature also determines the corresponding variation of β. A study of viscosities from 20 to 1000 centistokes indicated that a single normalized curve η/η_o vs T could represent the entire group over a temperature range of about 7°C to 50°C, with a maximum error of only 5%. The normalization factor η_o is the rated viscosity at 25°C. A plot of this curve, designated as β/β_o vs T because of the linear relation, is shown in Fig. 4.13. With the aid of this plot, estimates of β expected under operating conditions are easily found from values of β measured accurately at convenient laboratory temperatures.

Oil leakage from a gage may at times be serious, depending on where resulting air bubbles become trapped. An experiment with one unit indicated there was little effect even when 25% of the damping fluid was lacking. (The total volume of fluid contained in a gage is 15 cc). This test consisted of determining a frequency response curve and a characteristic damping coefficient as compared to the data acquired when the unit was full. In general, even though possible effects may be small, extreme precautions were taken in the oil filling technique to eliminate any air bubbles, and the body of the gage was coated externally with a clear lacquer to minimize potential oil leakage.

4.1.8 Resonant Frequency

A prime requirement for an accelerometer is that its resonant frequency be several times greater than the component frequencies of the acceleration to be measured. Therefore careful consideration of this property was necessary in establishing the design criteria.

Harmonic motion of a simple vibratory system is governed by the relation $a = 4\pi^2 f^2 d$, where a is the peak acceleration, f the frequency of vibration, and d the peak displacement of the mass of the system. For free undamped motion f represents the natural frequency of the system. As mentioned earlier, the parameter d for the accelerometers was specified to be 5 mils at an acceleration equal to the gage rating. Therefore the spring-mass system in itself has the property that $f^2 \cong 2000$ a, where f is in cycles per second and a is in gravity units.

It was evident that this relation would not hold true for the accelerometer because of the presence of the damping fluid. The instrument was designed with all of the internal parts completely immersed in the fluid. Two effects were to be expected, namely buoyancy and loss of energy due to motion of the fluid. This latter effect would appear as if a virtual mass had been added to the mass of the vibrating system. The resonant frequencies of various gages measured experimentally were found to closely follow the relation $f^2 \cong 1000$ a. A plot of the data is given in Fig. 4.14. Since f^2 is proportional to 1/m, it is seen that the virtual mass added by the presence of the fluid was equal to the original mass of the system.

The resonant frequency of the accelerometers was determined by means of the shake table, and was defined as that frequency at which a gage output signal was in phase with the velocity signal of the table head. According to linear theory this frequency corresponds to the natural undamped frequency of the system. Therefore, for the case where the mass is immersed in a fluid, it may be classified as the "virtual undamped" resonant frequency. Taking into account the effect of viscous damping, the resonant frequency is decreased according to the relation $f = f_o\sqrt{1 - \beta^2}$ for free oscillations and $f = f_o\sqrt{1-2\beta^2}$ for steady state excitation, f_o being the "virtual undamped" frequency and β the damping factor.

4.1.9 Transfer Characteristic

The accelerometer is an electromechanical transducer. Its transfer characteristic is the relation between the mechanical effects being measured and the electrical signals produced.

From electrical theory, the frequency of the gage oscillator varies as $\frac{1}{\sqrt{L}}$, where L is the inductance of the E-coil for any particular position of the Mu-metal pad. Denoting the initial values by f_o and L_o, it is seen that as the inductance varies due to the motion of the pad, the frequency will vary according to the relation $\frac{f}{f_o} = \sqrt{\frac{L_o}{L}}$. Since the mechanical properties of the spring-mass system are linear, the pad displacement is directly proportioned to the applied acceleration in the case of static calibrations. Using the L vs d plot in Fig. 4.3, a corresponding $\frac{f-f_o}{f_o}$ vs $\frac{a}{a_R}$ curve was determined, where a_R is the acceleration rating of the gage corresponding to a 7.5% decrease in frequency. This curve, shown in Fig. 4.15, is the transfer characteristic of the unit, and it is essentially non-linear. For $\frac{a}{a_R} = +1$ and -1, it is seen that $\frac{f-f_o}{f_o} = -7.5\%$ and $+5.5\%$ respectively. Therefore, when analyzing gage records where the amplitudes are proportional to the frequency changes, it is necessary to use a calibration curve of the type shown in Fig. 4.15 for conversion to equivalent accelerations.

Because of the limited time available for the development of the accelerometer, no effort could be made to eliminate this non-linearity. To do so would have required designing a magnetic circuit such that the inductance varied as $\frac{1}{d^2}$ over the region of operation. Coupled with the property that f varies as $\frac{1}{\sqrt{L}}$, the net result would have been a linear transfer characteristic.

It is often desirable to integrate acceleration records to find velocities and displacements associated with the phenomena being studied. However, because of the asymmetric form of the transfer characteristic about the equilibrium position, the integration errors from positive and negative phases would be cumulative. Where a gage record consists of a series of positive and negative signals, it is advisable to linearize the record by either electrical or mechanical means before integrating.

As mentioned earlier, a property of the accelerometer was that peak to peak signals were linearly proportional to acceleration. Fig. 4.16 shows a plot of $\frac{f_+ - f_-}{f_o}$ vs $\frac{a}{a_R}$ corresponding to the data of Fig. 4.15. It was assumed that sinusoidal accelerations of various magnitudes were applied to the gage, and the resultant maximum oscillator frequencies f_+ and f_- were determined by the transfer characteristic. The divergence from absolute linearity is seen in Fig. 4.16 to be very slight and definitely within practical limits for studying steady state response properties.

4.1.10 Selectivity Factor

The ability of an accelerometer to resolve only components of acceleration directed along its sensitive axis may be called its selectivity factor. Tests were conducted using the shake table to vibrate gages successively in three mutually perpendicular directions. Results indicated that the instruments recorded on an average about 3% of the accelerations when transverse to the sensitive axes, the maximum for the group tested being 6%. The selectivity factor is completely independent of the errors introduced by improper alignment of an accelerometer in a test position. Potential errors of this type are related to the angle of misalignment by simple sine and cosine functions.

Another measure of the selectivity factor was found when calibrating the 0.1 g vertical gages with the tilt table. For maximum gage rating of 0.1 g it was necessary to rotate the unit through an angle of 26°. At this angle, the component of acceleration normal to the gage axes was $\sin 26^{\circ}$ or 0.44 g. The contribution of this transverse effect was 3%, or 0.13 g, therefore resulting in an error of 13% in the gage reading. A simple method for compensating for this effect was found by rotating the gage clockwise and counterclockwise and averaging the calibration data. For these opposite directions of rotation, the transverse component acting on the spring-mass system is reversed, in one case being additive and in the other subtractive, thus essentially cancelling when averaged.

4.1.11 Temperature Dependence

As mentioned earlier in this report, there is an increase in damping coefficient with decreasing temperature. A question arose as to whether any other calibration factors were in some way temperature dependent.

A group of 42 gages consisting of 3 horizontal and 3 vertical units of each of seven acceleration ranges were checked for a possible variation in sensitivity with temperature. The test consisted of determining a_R and φ_R at room temperature (about $27^{\circ}C$) and at $2^{\circ}C$. The symbol a_R refers again to the gage acceleration rating and φ_R corresponds to the percent frequency change that occurs when an acceleration equal to $-a_R$ is applied to the gage. The test data showed random differences in variation of $\frac{\Delta a_R}{a_R}$ and $\frac{\Delta \varphi_R}{\varphi_R}$, where the reference values were those taken at room temperature. The mean deviations for the 42 gages were 2.46% and 3.04% for a_R and φ_R respectively, and the standard deviations were 3.33% and 4.16%. These random effects are in all probability due to an irregular combination of the various coefficients of volume expansion.

A definite temperature effect was noted by a shift of the center frequency with no applied accelerations. In 41 cases of the group tested, the center frequency of 3.9 kc was increased by an average of + 0.5%. In an attempt to locate the source of this shift, a group of five individual E-coils was checked over the same temperature range. The increase in center frequency of 3.9 kc was 13, 14, 14, 15 and 15 cycles, which was an average of about + 0.36%. No experiments have been conducted to establish the cause for this characteristic in the E-coil. In general, the effects of this property were not significant in the accuracy of an accelerometer, provided the center frequency was accurately determined for each particular test.

4.1.12 Accuracy

A number of potential sources of error have been described in the various sections of this report. It is believed that in general the instrument can be used to yield accuracies of 5% and better. This accuracy is naturally subject to the use of the instrument in the frequency ranges considered satisfactory for accelerometers.

Over a period of several months, a search was made for possible aging effects in the gage. No evidence of such effects were found. Small random differences in some of the calibration factors were noted, but these were within the limits of the accuracy of measurement. Pending tests over a longer period of time, an assumption that the shelf life of the accelerometer is indefinite appears reasonable, in view of its general design features.

4.1.13 Recommendations For Further Development

Because of a critical time element a number of features were incorporated in the design of the instrument without being fully explored. In the event further research is possible, several directions for improvement worth considering are as follows:

(a) Modification of the damping system such that the mass of the vibratory system is not immersed in the damping fluid. (Eliminating the virtual mass effect would tend to increase the resonant frequency by possibly 40%.)

(b) Design of a magnetic circuit such that the inductance of the E-coil varies inversely as the square of the gap spacing over the region of operation. (This property would insure a linear transfer characteristic.)

(c) Exploring the possibilities of decreasing the peak displacement of the Mu-metal pad corresponding to the gage acceleration rating. (A decrease from 5 mils to 3 mils would result in a resonant frequency greater by about 30%.)

(d) Determination of the optimum weight and geometry of the mass of the system to minimize the virtual mass effect of the fluid. (Higher resonant frequencies would be available for values of $\frac{m_f}{m_o}$ less than unity, as found in the present design.)

(e) Investigation of the effects of greater beam thickness for the cantilever springs in order to minimize the selectivity factor.

The foregoing fields of study are recommended as possible methods whereby the design of the accelerometer may be improved. The instrument in its existing form was found to be quite satisfactory for the purpose intended and should prove to be likewise for any similar test program requiring a variable inductance accelerometer.

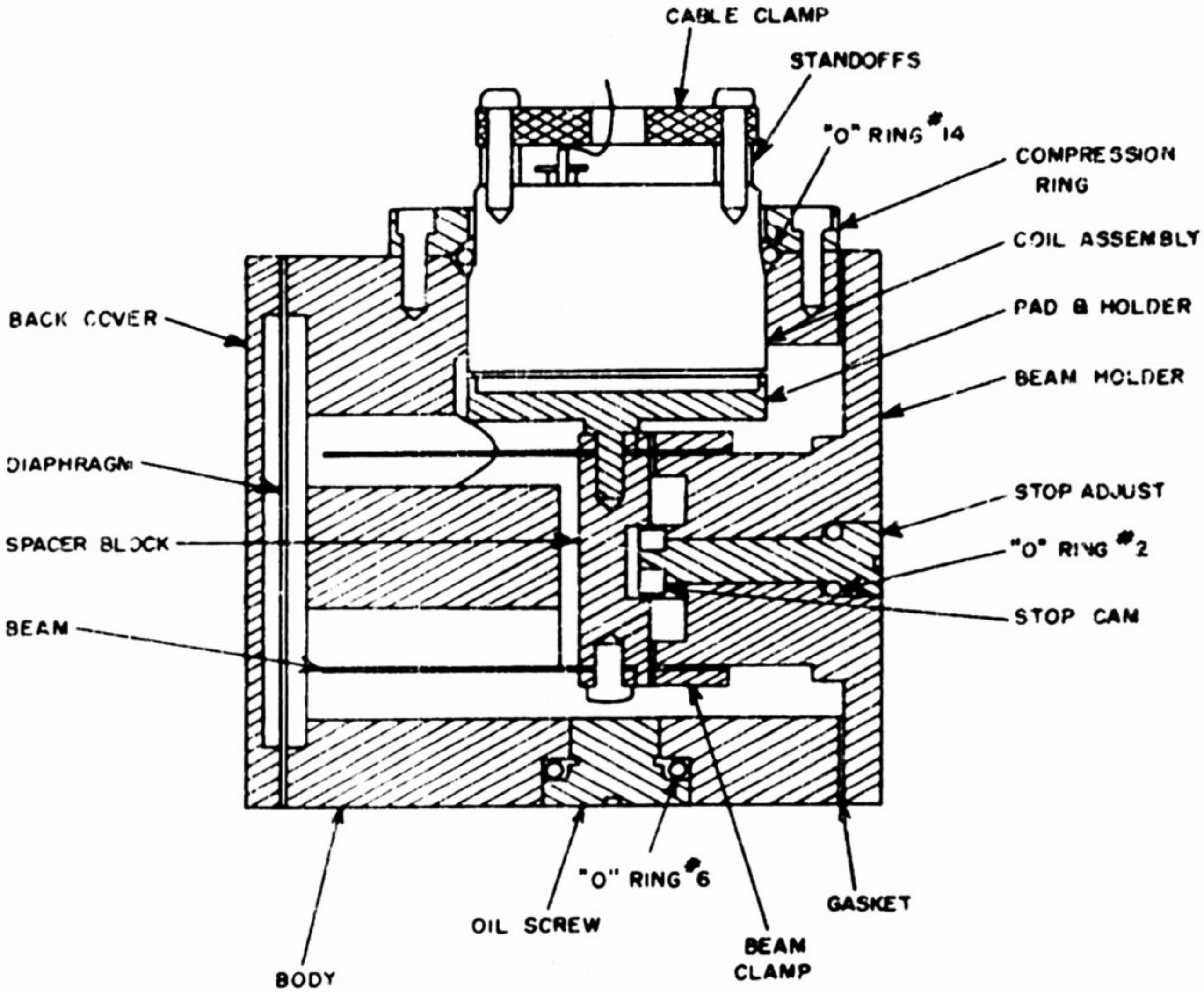

Fig. 4.1 Sectional Diagram of Gage Construction

Fig. 4.2 Schaevitz Type B Accelerometer

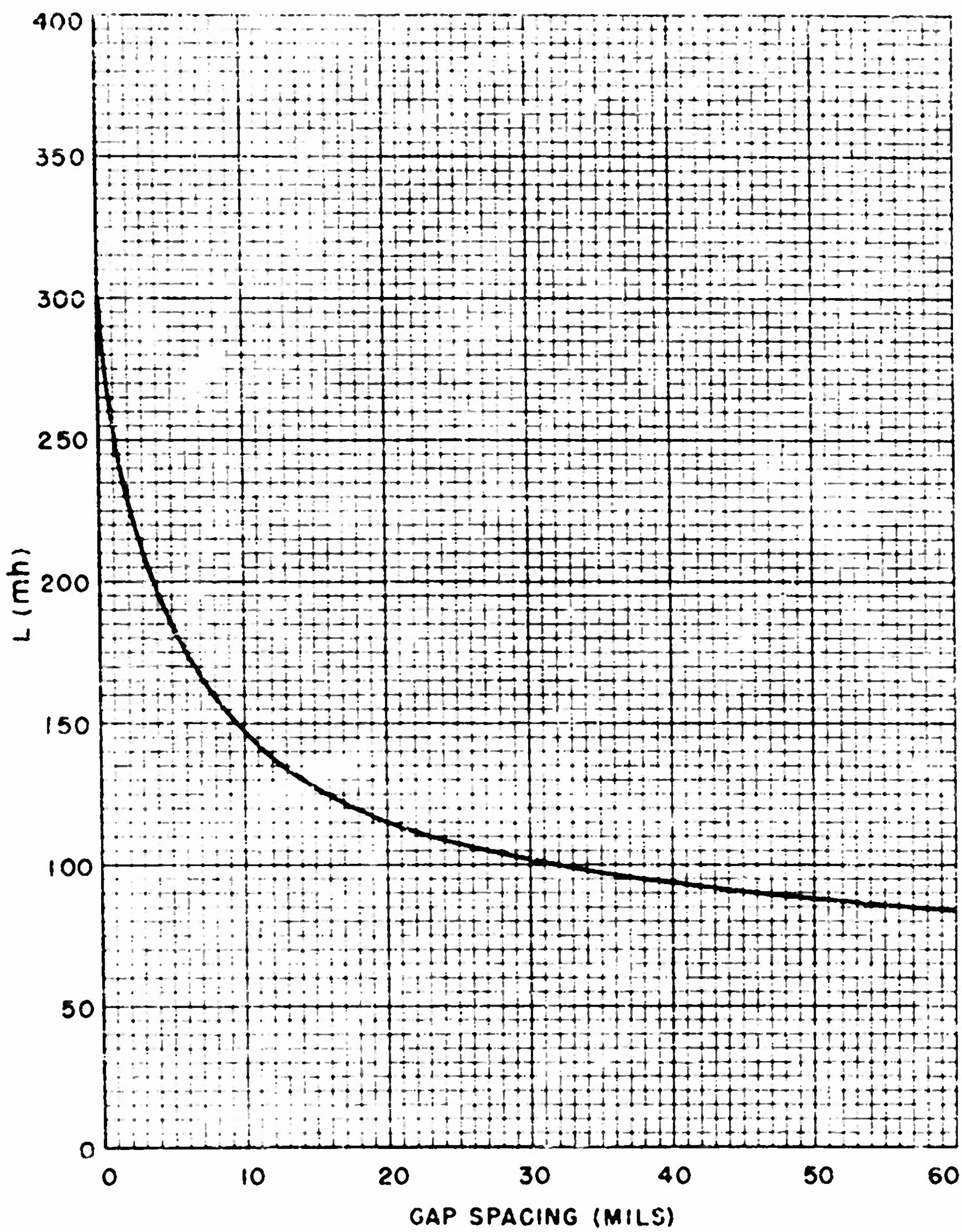

Fig. 4.3 Inductance of Coil vs Gap Spacing

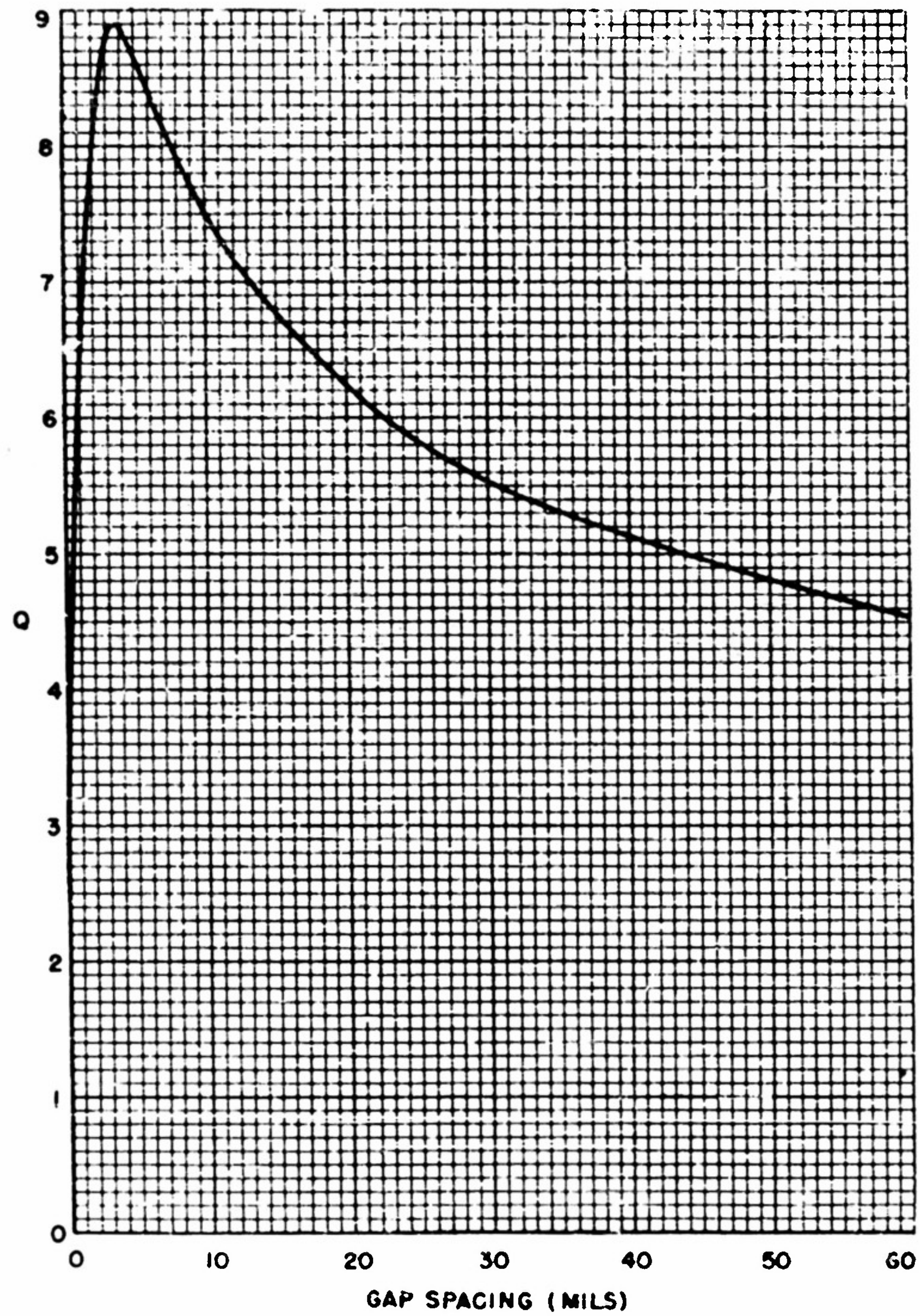

Fig. 4.4 Q of Coil vs Gap Spacing

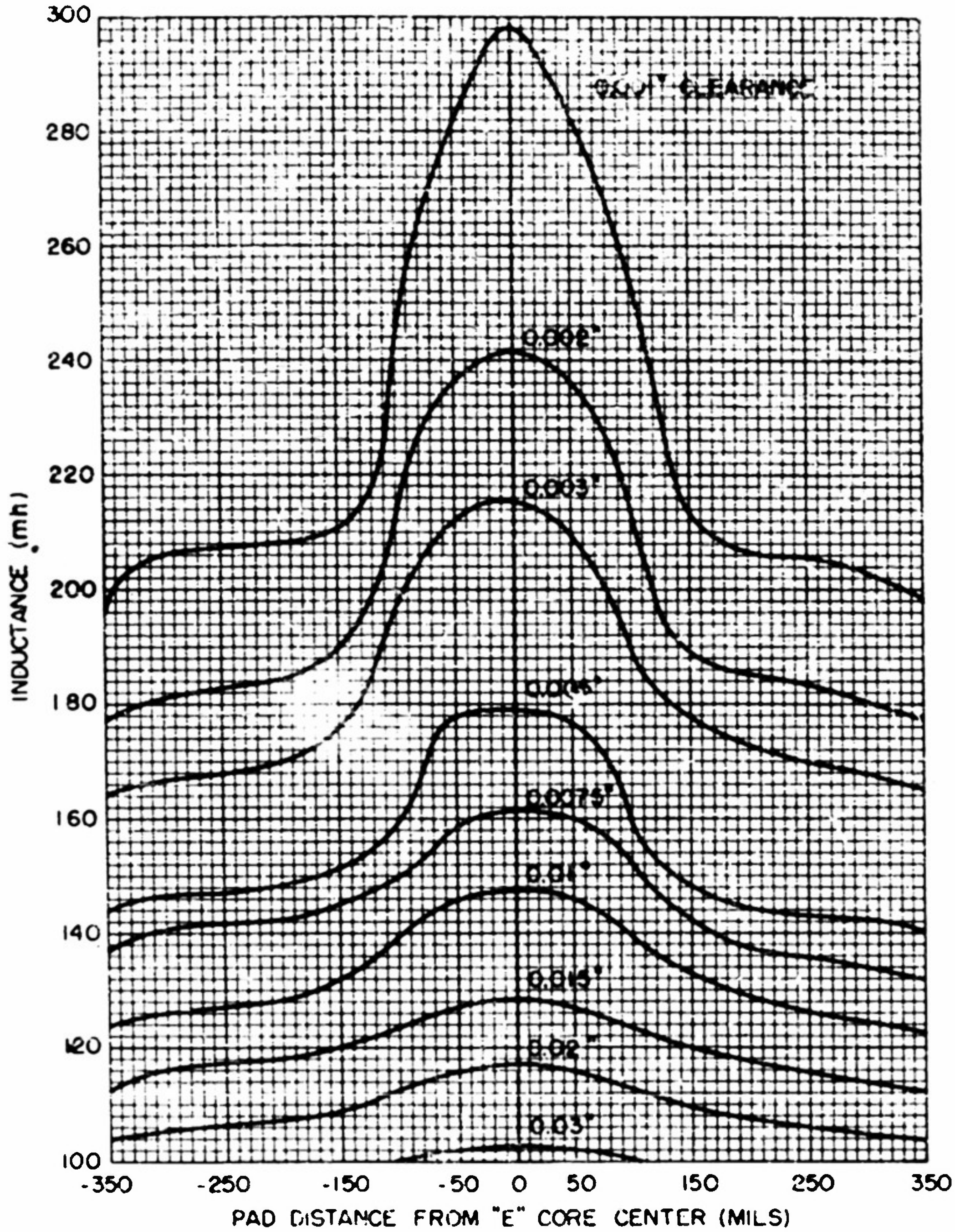

Fig. 4.5 Variation of Inductance Due to Lateral Displacement of Pad Along Line of Pole Faces

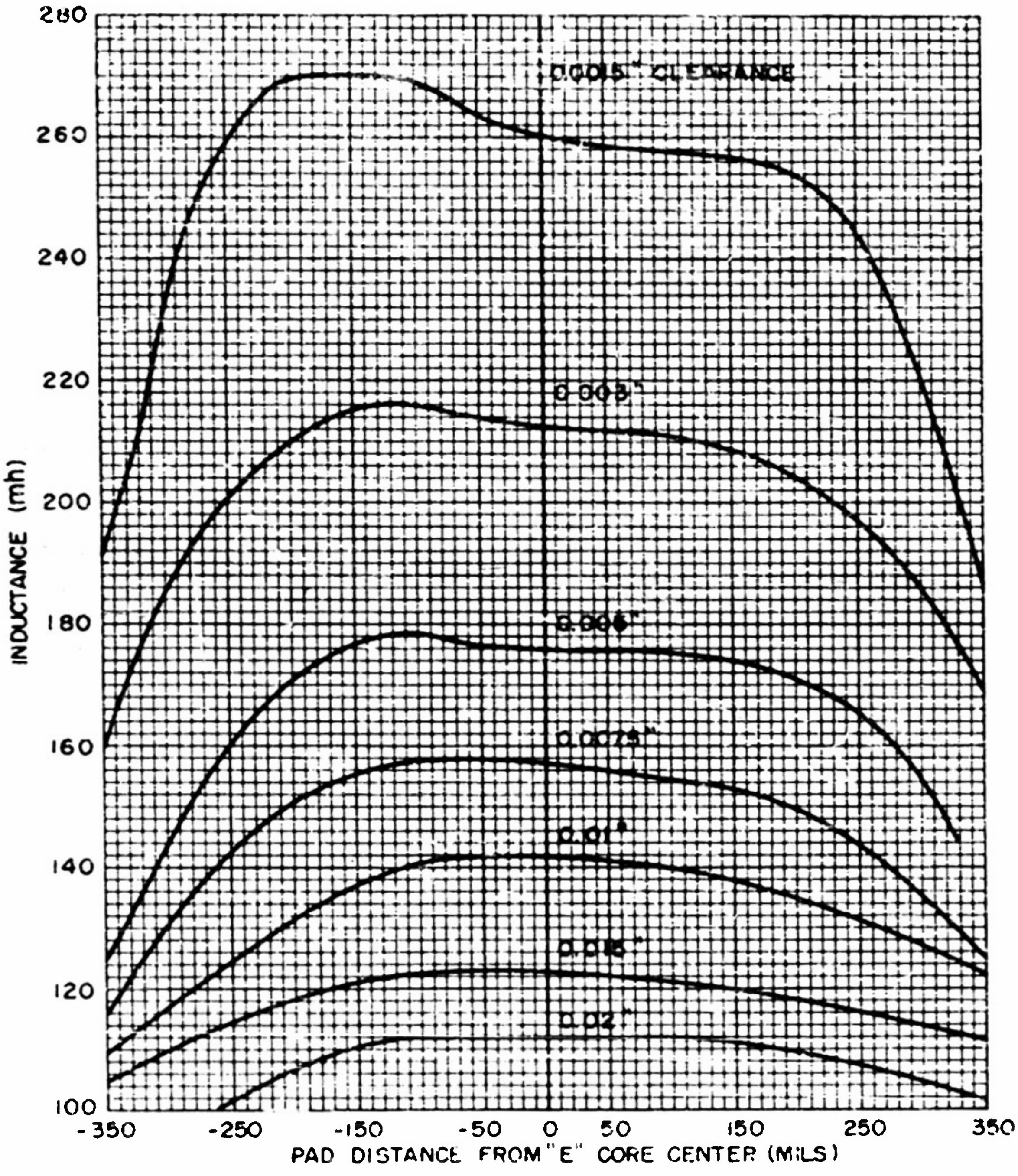

Fig. 4.6 Variation of Inductance Due to Lateral Displacement of Pad in a Direction Normal to the Line of Pole Faces

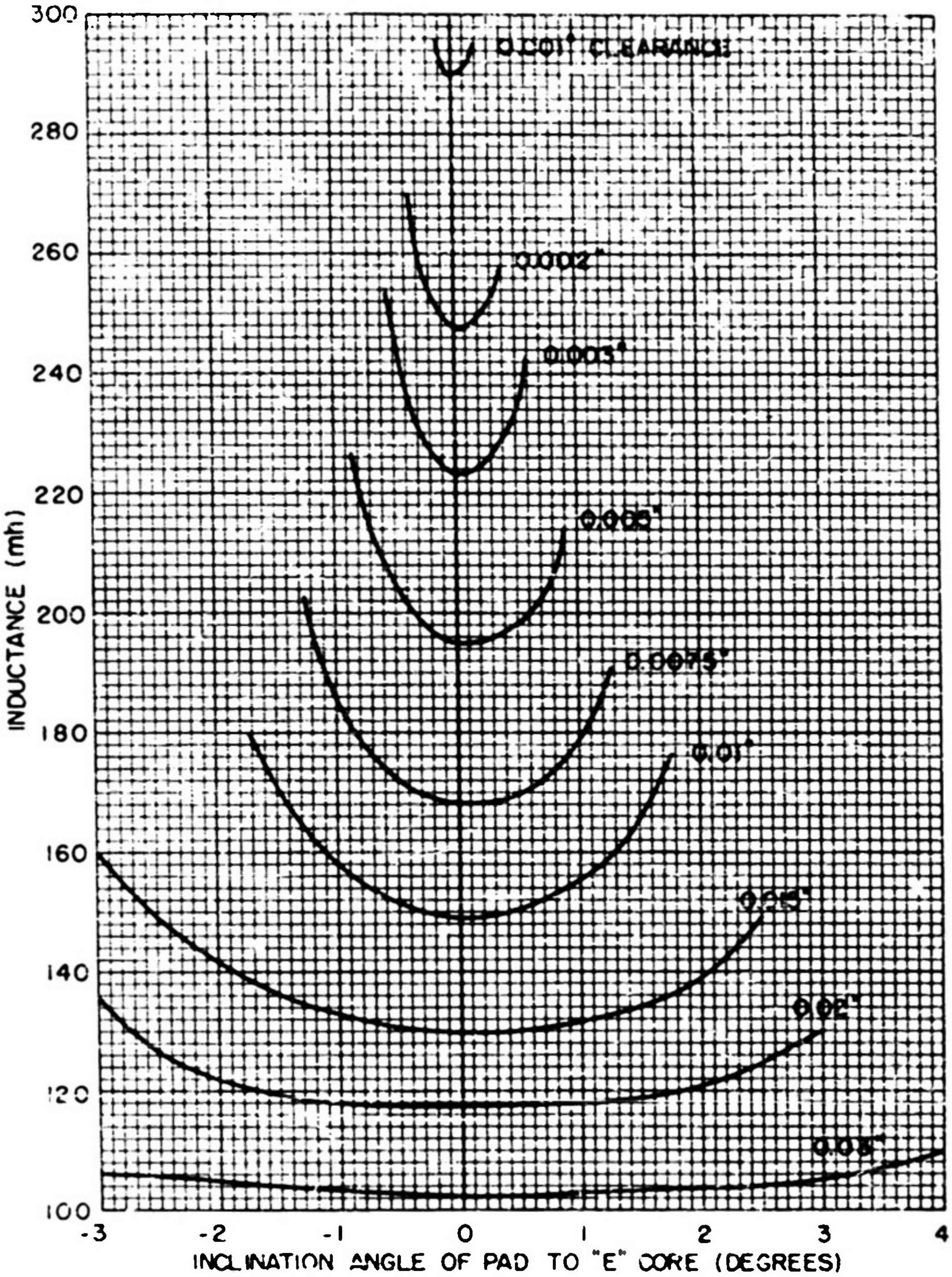

FIG. 4.7 VARIATION OF INDUCTANCE DUE TO ROTATION OF MU-METAL PAD

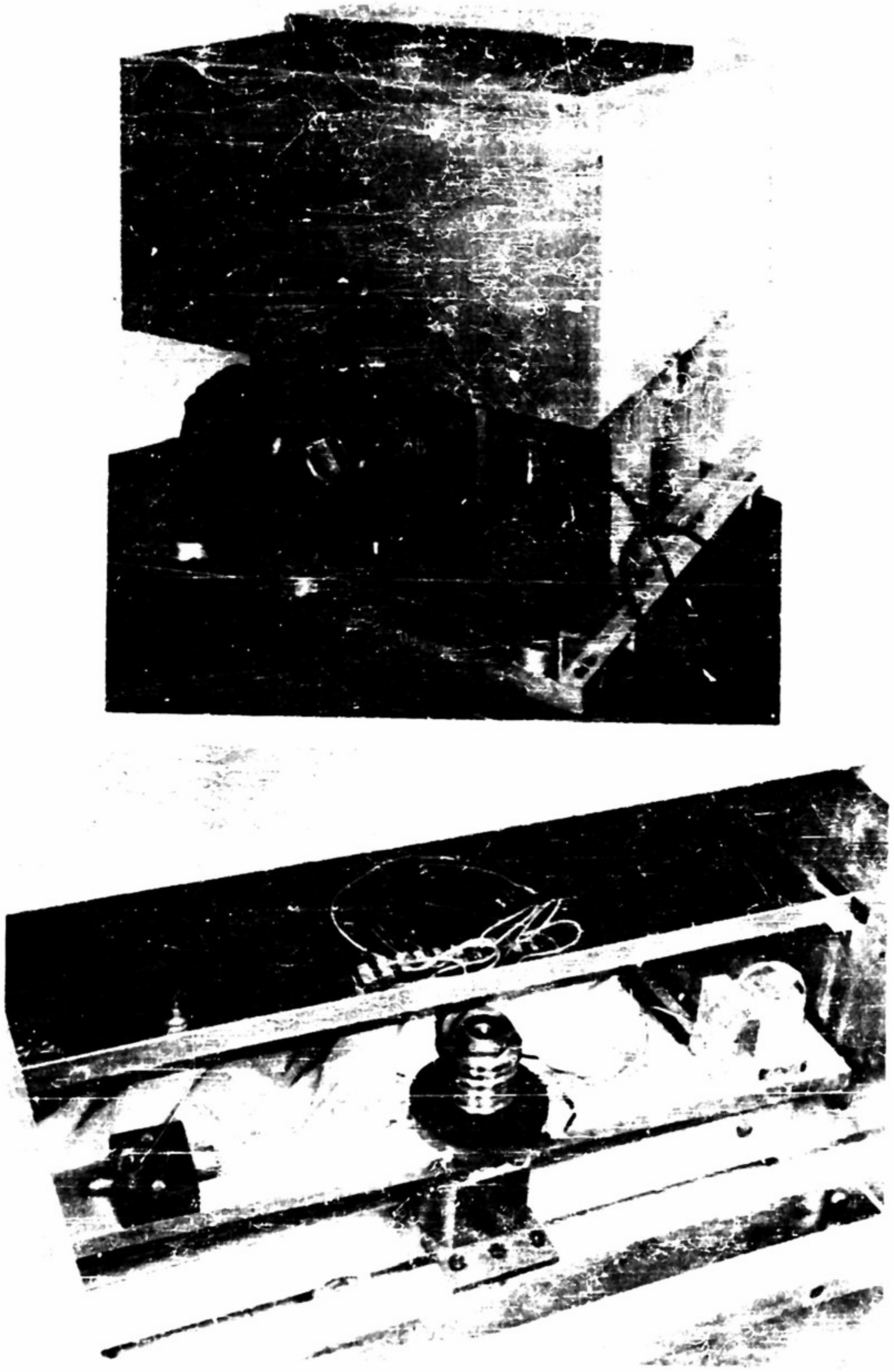

Fig. 4.8 NOL Spin Table Used for Static Calibration

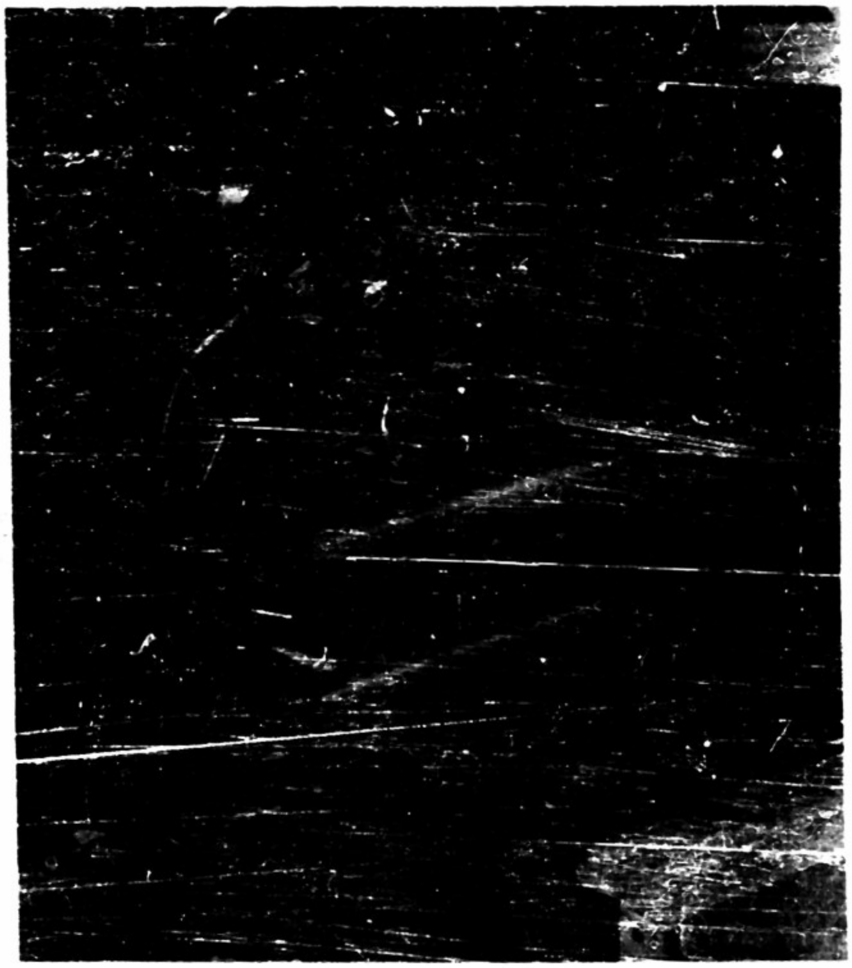

Fig. 4.9 Tilt Table Used for Static Calibration

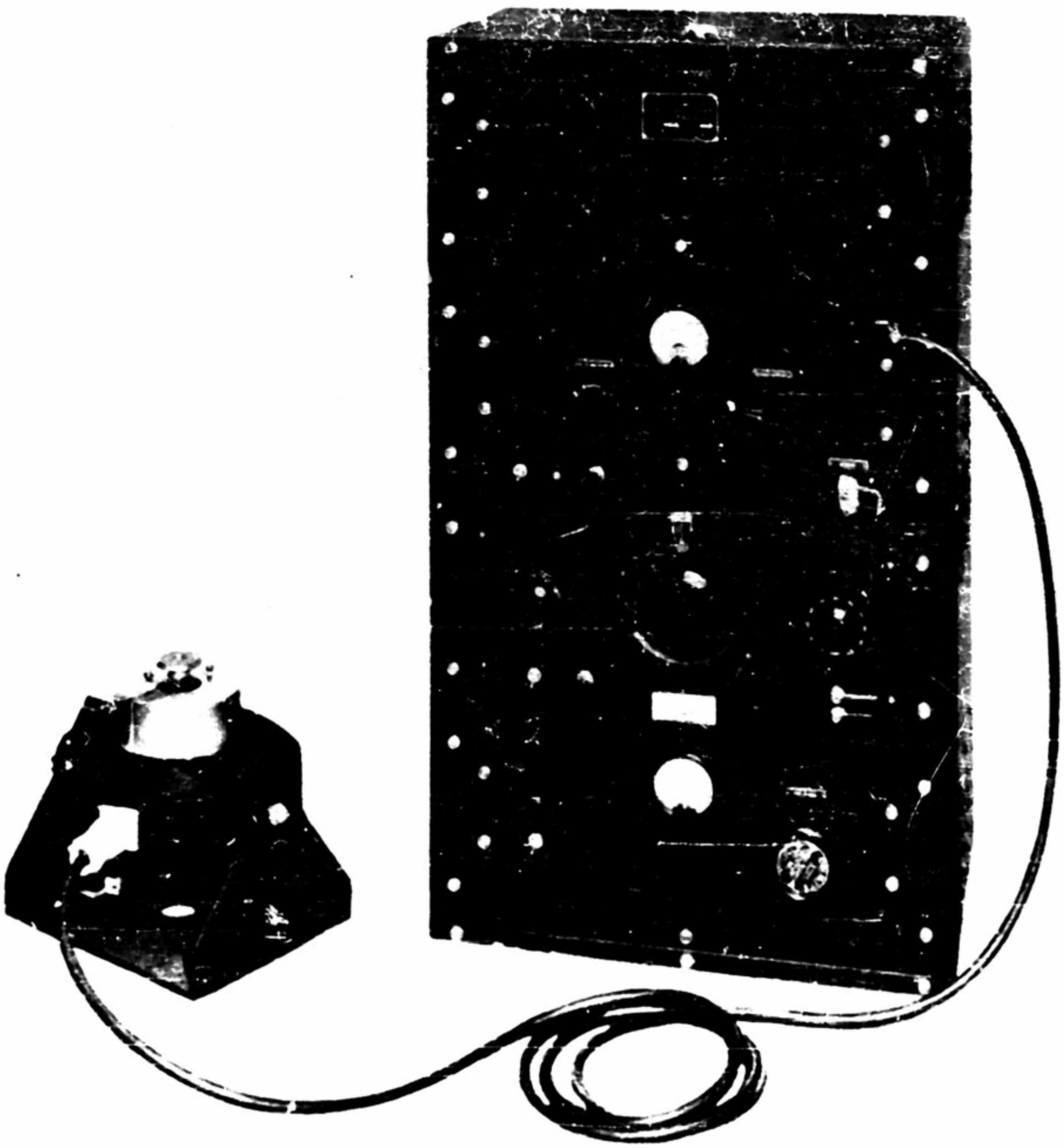

Fig. 4.10 MB Shake Table Used for Dynamic Calibrations

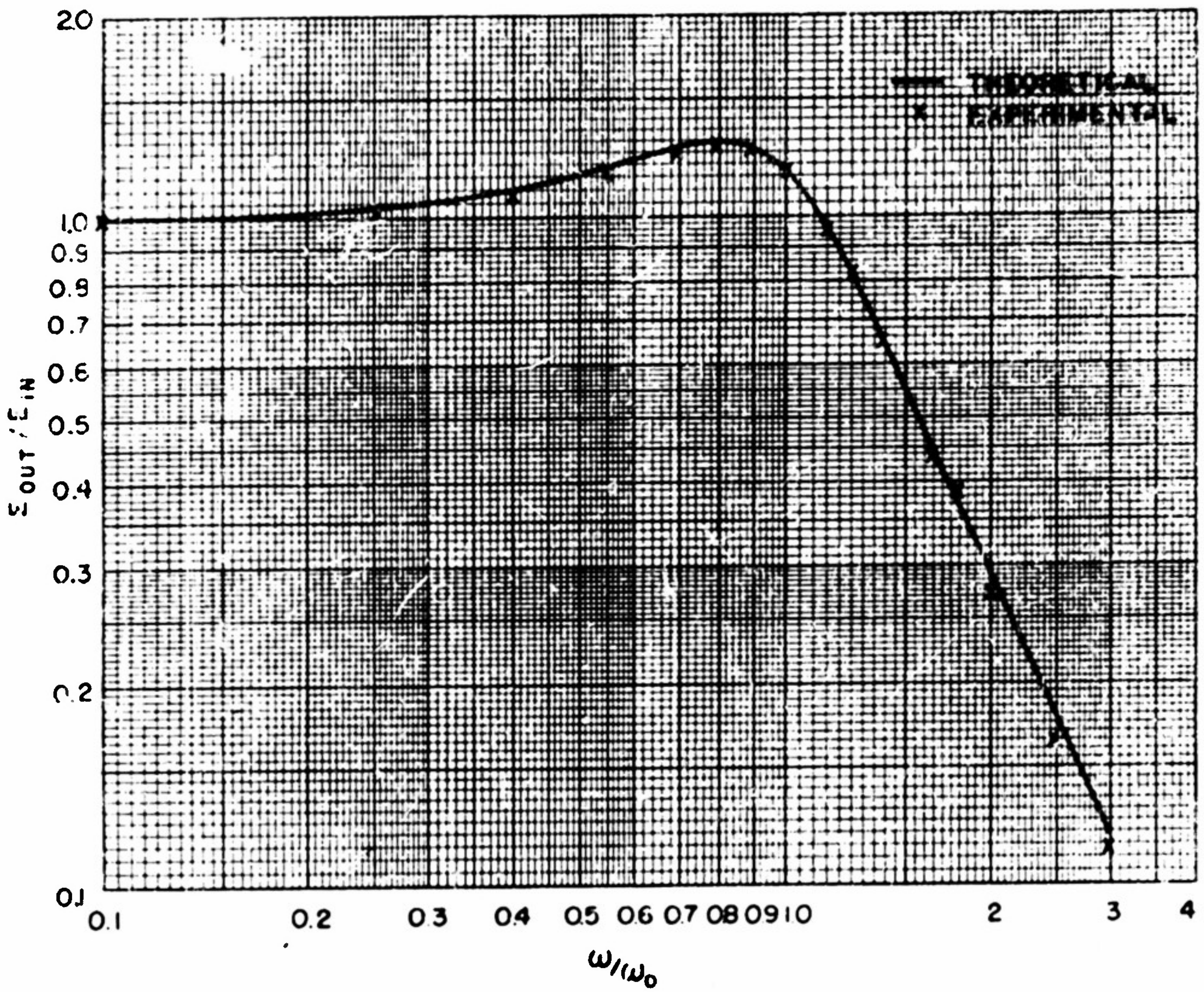

Fig. 4.11 Frequency Response to Sinusoidal Excitation

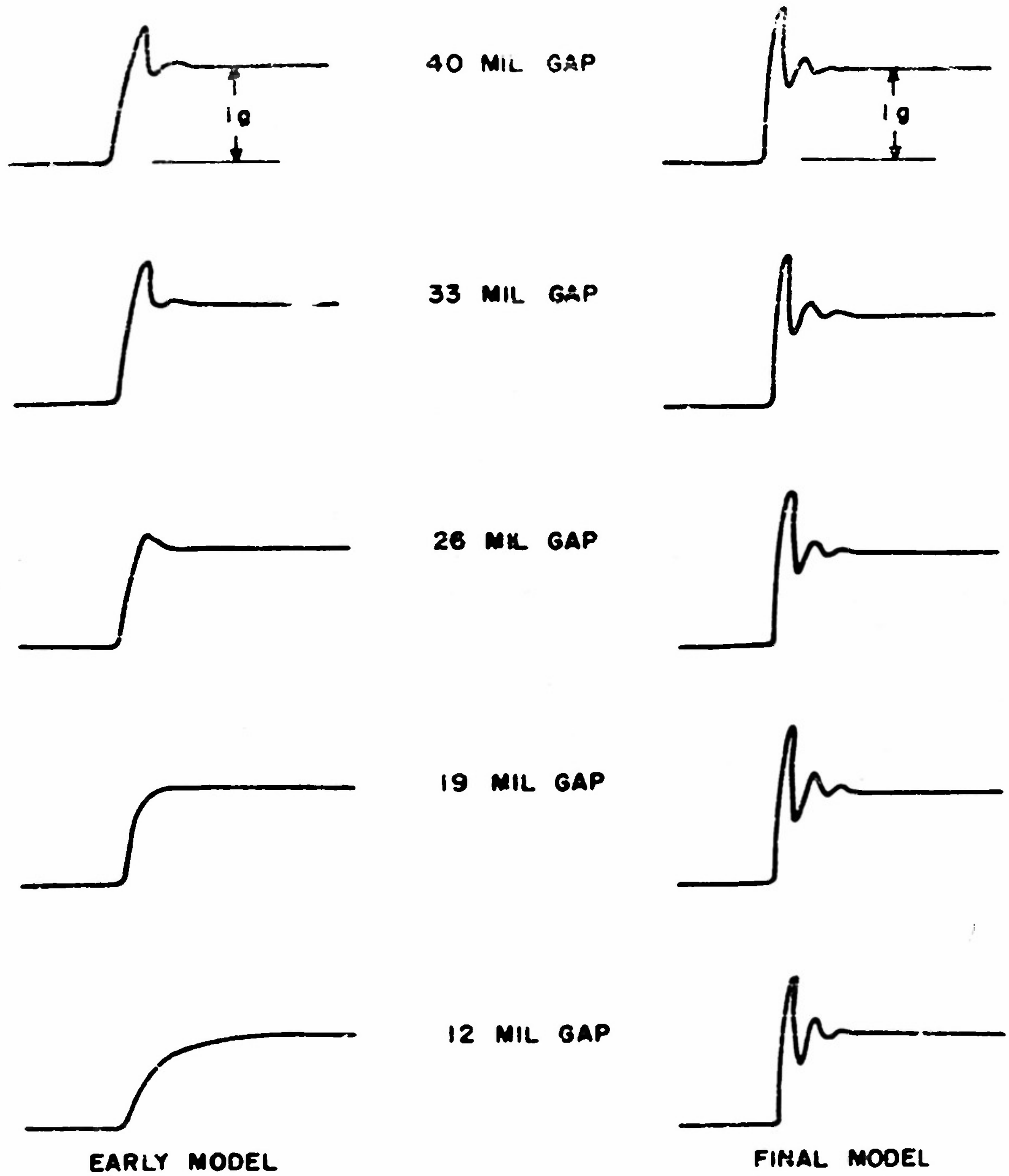

Fig. 4.12 Study of Damping Properties by Drop Tests

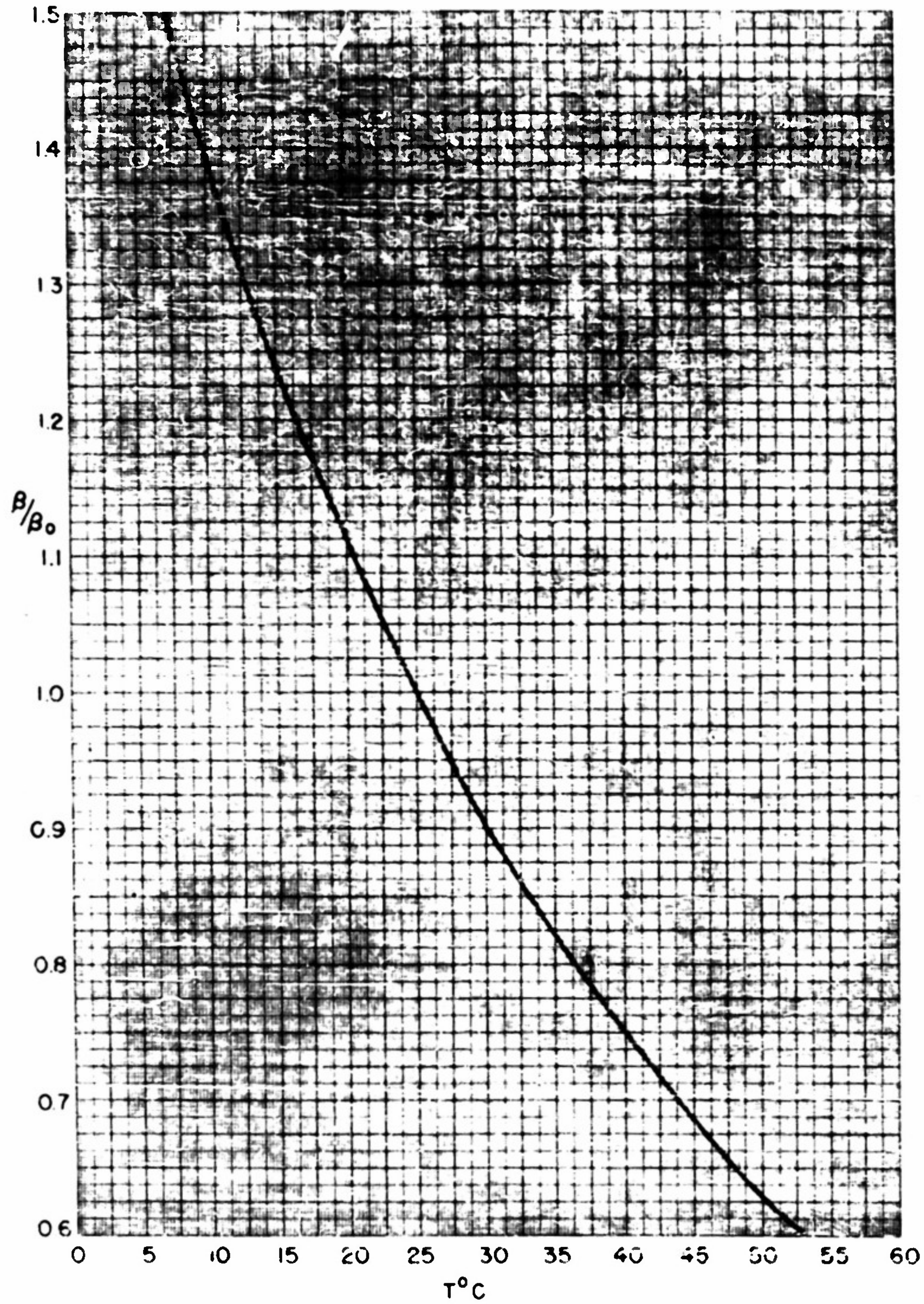

FIG. 4.13 NORMALIZED VARIATION OF DAMPING FACTOR WITH TEMPERATURE

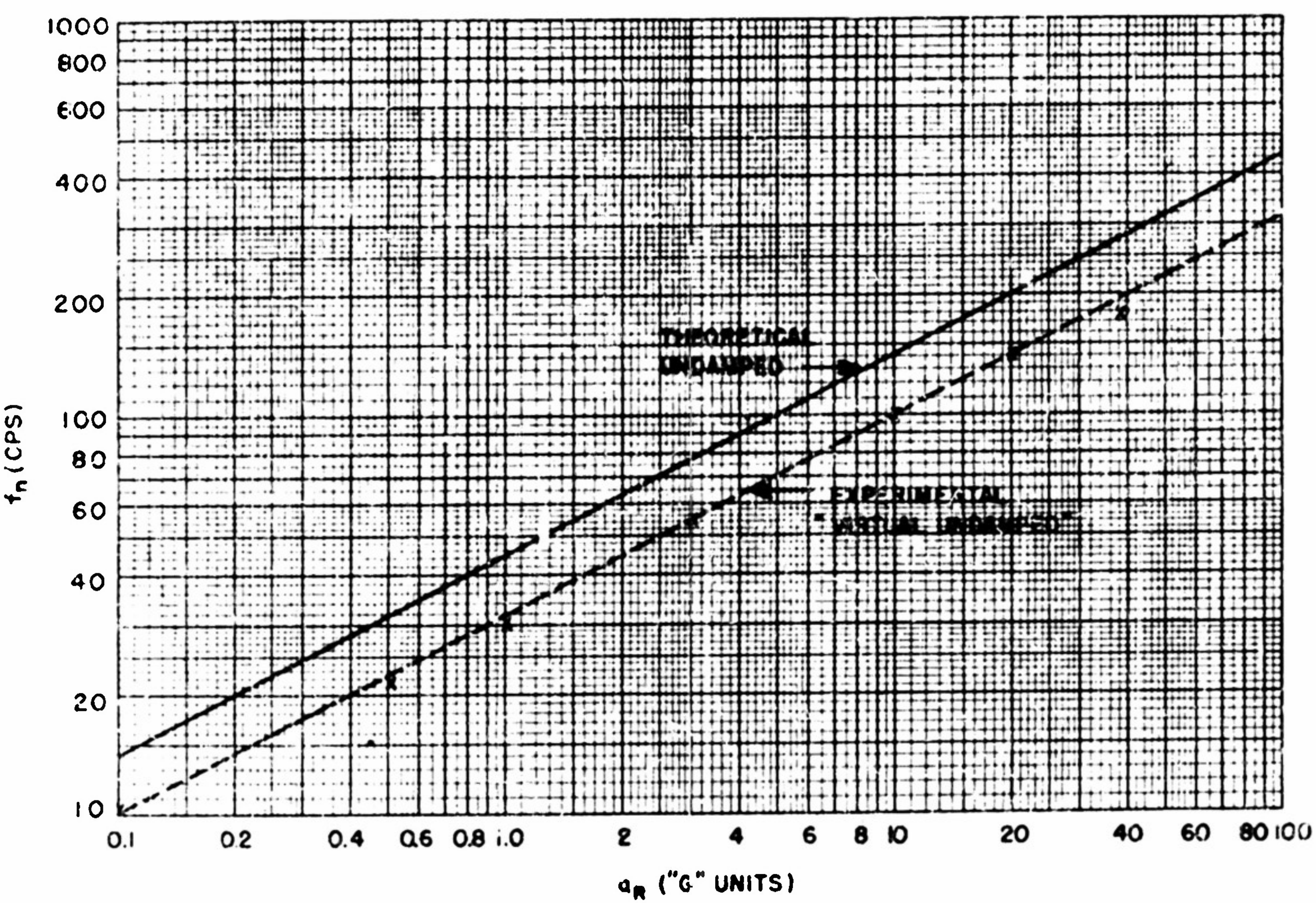

Fig. 4.14 Natural Frequency vs Gage Rating

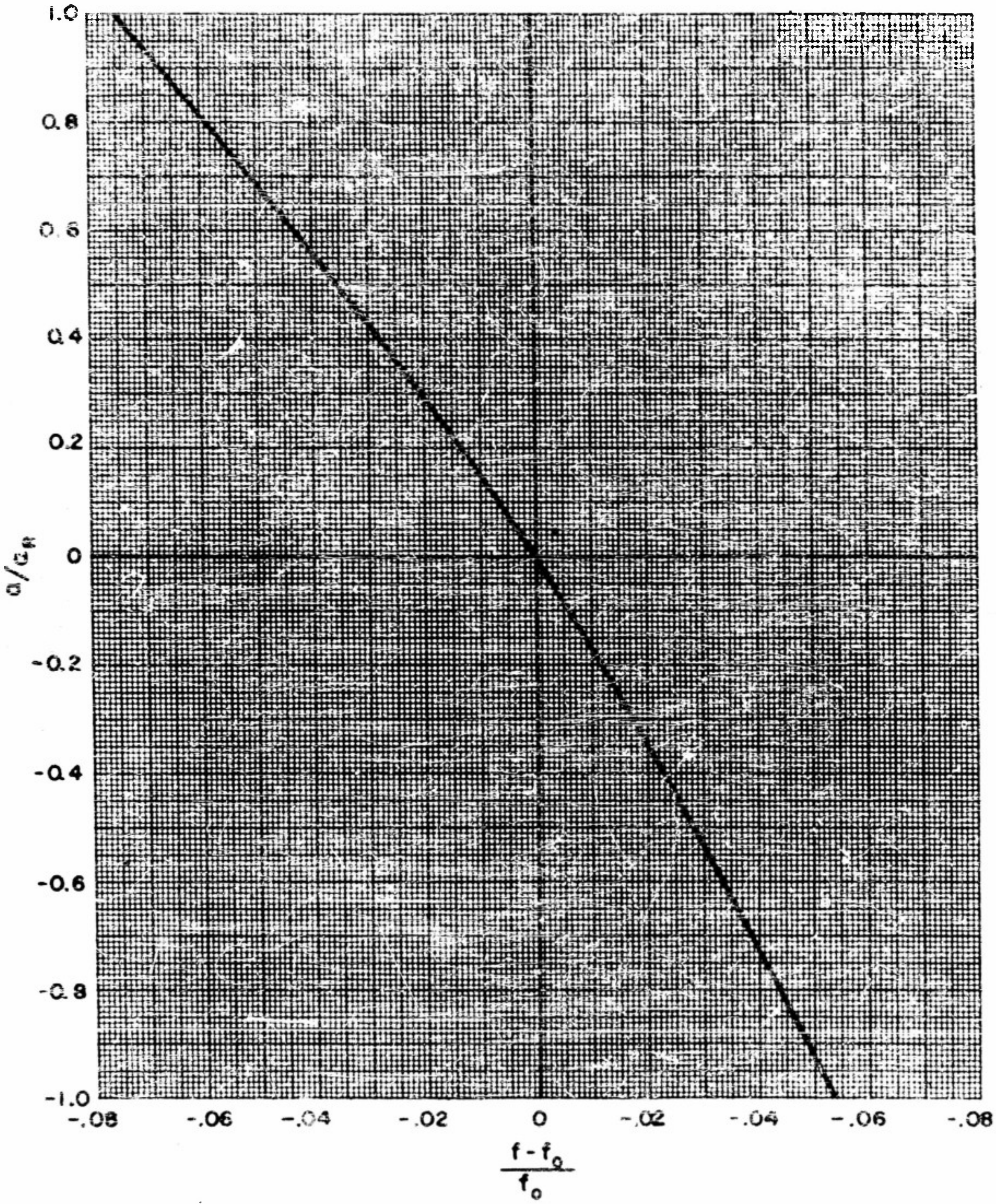

Fig. 4.15 Gage Transfer Characteristic

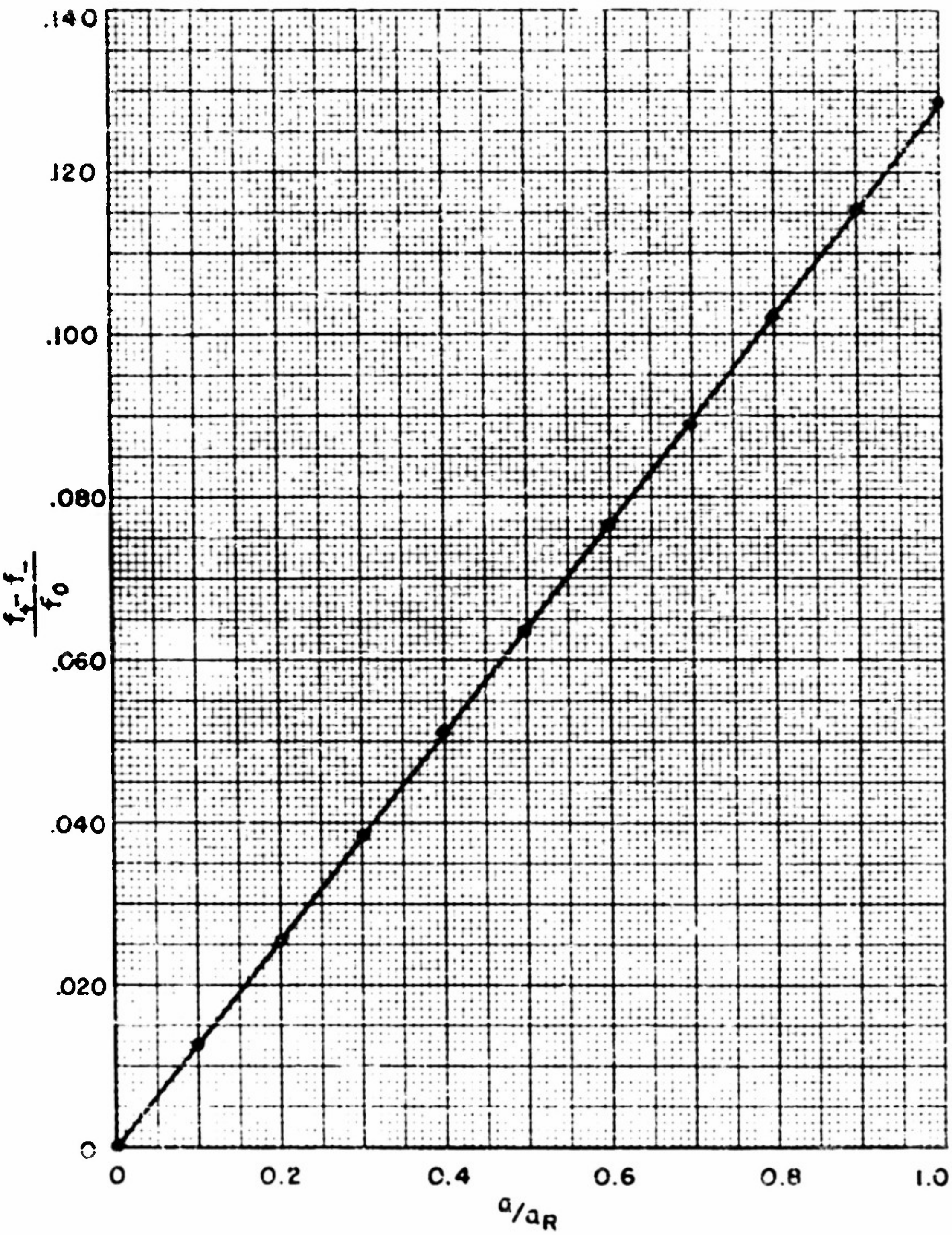

Fig. 4.16 Peak to Peak Response to Sinusoidal Excitation

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