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# Electrodynamic Vibration Standard with a Ceramic Moving Element

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This paper describes a new rectilinear vibration exciter specifically developed for accurate calibration of piezoelectric accelerometers. It is an electrodynamic shaker, using a permanet magnet with a ceramic moving element guided by an air-bearing system. The moving element has a simple circular cross section and the driving coil is wound directly onto it. Its first axial resonance is near 25 000 Hz. The working range of the shaker extends from 5000 to less than 5 Hz. The moving element includes a means of mounting an internal accelerometer that can be used as a secondary standard. Alternatively, the moving element/accelerometer assembly can be calibrated by a reciprocity method and used as an absolute standard. The results of measurements of transverse motion and harmonic distortion are presented, as well as an exmple of pickup calibration.

## INTRODUCTION

As described in a previous paper,[1] the modification made in a commercial electrodynamic exciter, in which the flexural plates were replaced with air bearings, eliminates or reduces many of the transverse motions. The moving element—consisting of table, connecting shaft, and driving coil—was not significantly changed. In this moving element, Fig. 1(a), there are several materials with different moduli of elasticity. Troublesome resonances are present not only in the long aluminum shaft but also in the other parts: the velocity coil wound on thin Bakelite, and the driving coil wound on four studs and held together with coil varnish and a large supporting ring. It is unlikely that the transverse motions of this exciter can be reduced more or the useful range of frequency increased without changing the geometry of the moving element.

Exciters of this type have been calibrated by a reciprocity method and used for calibration of vibration pickups at the National Bureau of Standards.[2] The output of the pickup mounted on the table for calibration is compared with the output of the velocity coil. The range of calibration is between 10–2000 Hz, but many frequencies in this range have to be avoided because of the distorted motion of the vibration table caused by the shortcomings described above. More-detailed discussions of the principles of operation and limitations of the electrodynamic vibration standard are given in the first three Refs. 1–3.

The present paper describes a new electrodynamic exciter developed at the National Bureau of Standards for calibration of small piezoelectric vibration pickups. The moving element has a simple uniform cross section and maximum axial and transverse stiffness. The characteristics of the exciter are listed in Table III.

## I. CONSTRUCTION

Considering the moving element as two masses connected by a spring, where one mass represents the table, the second mass the driving coil, and the spring the material between, the fundamental axial resonance

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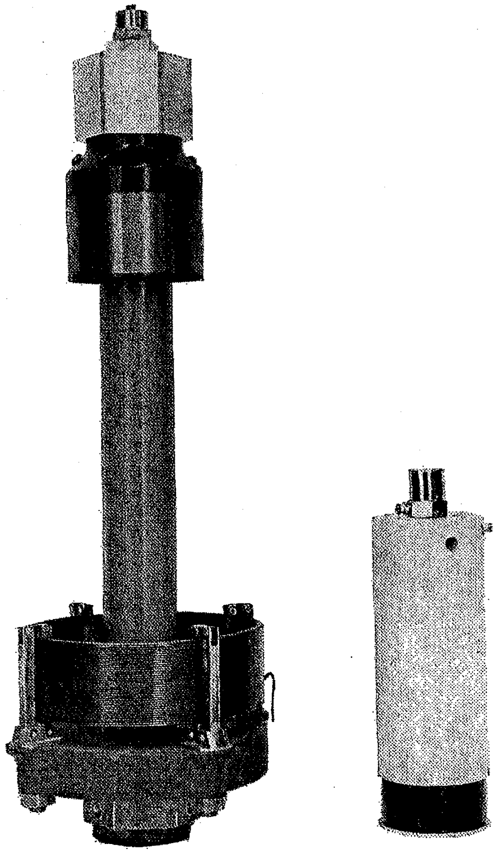
[1] T. Dimoff and B. F. Payne, "Application of Air Bearings to an Electrodynamic Vibration Standard,." J. Res. Natl. Bur. Std. (U. S.) **67c**, 327–333 (1963).

[2] S. Levy and R. R. Bouche, "Calibration of Vibtation Pickups by the Reciprocity Method,." J. Res. Natl. Bur. Std. (U. S.) 57, 227–243 (1956).

[3] Anon., "Calibration of Shock and Vibration Pickups," ASA S2.2-1959 (Feb. 1959).



(a) (b)

FIG. 1. (a) Moving element with velocity coil. (b) Ceramic moving element.

frequency of this system is given by

$$f=\frac{1}{2\pi}[K(M_1+M_2)/M_1M_2]^{\frac{1}{2}}, \tag{1}$$

where $K$ is the spring constant, and $M_1$ and $M_2$ are the two masses. It can be seen from this equation that, to obtain a high resonance frequency, the spring constant should be as large as possible and the masses as small as possible. In addition to the resonances of the mass–spring system of the moving element, we have the resonances of the suspension system and the magnet assembly. In order to have each of these major resonances at the highest possible frequency within the limitation of size and form of the moving element, sintered aluminum oxide [alumina ($Al_2O_3$)] was selected as the material for the moving element.[4]

TABLE I. Some physical properties of alumina ceramic contrasted with those of steel and aluminum.

| Material | Modulus of elasticity (psi) | Specific gravity | Thermal expansion (in./in. °C) |
|---|---|---|---|
| Alumina ($Al_2O_3$) | $54\times10^6$ | 3.7 | $7.8\times10^{-6}$ |
| Steel | $30\times10^6$ | 7–8 | $18\times10^{-6}$ |
| Aluminum | $10\times10^6$ | 2.5–2.8 | $24\times10^{-6}$ |

The relevant properties of this material are contrasted with those of steel and aluminum in Table I. In addition, alumina is an excellent electrical insulator.

For the magnetic field, a permanent magnet was selected instead of the usual electromagnet. The magnetic field in an exciter with an electromagnet is produced by a field coil that generates unwanted heat, complicates the mechanical structure, and present some danger of an ac ripple in the dc field current. Such perturbations cannot be tolerated if calibrations of high accuracy are to be attained. The new types of permanen magnets are stable and provide enough magnetic field strength to produce the necessary force output.

To minimize transverse motion due to the suspension system of the moving element, the moving element was supported in the lateral direction and guided by air bearings. The air bearing permits free axial motion and prevents or reduces lateral motions.

### A. Ceramic Moving Element

The vibration exciter with the ceramic moving element and the airbearing suspension is shown in Figs. 2 and 3. The moving element is a $5\frac{1}{4}$-in.-long tube of alumina ceramic with an integral closure at one end. The outside diameter is 1.8770 in. and the inside diameter is 1.4920 in. The closed end is the mounting table. It is $\frac{3}{4}$ in. thick and has a center hole with a 10–32 thread. The standard pickup and the pickup to be calibrated are mounted along the center axis of the moving element on opposite sides of the $\frac{3}{4}$-in.-thick mounting table, as shown in Fig. 2; the table surfaces are flat and parallel. The standard builtin pickup, in conjunction with the driving coil,[5] can be calibrated absolutely by the reciprocity method or as a secondary standard by comparison. The hole at one side of the mounting table is for the lead of the builtin pickup. The three threaded radial holes are for an auxiliary radial suspension, which consists of three pieces of rubber tubing $\frac{1}{4}$ in. in diameter. It provides an elastic vertical support for the moving element and it can be adjusted to maintain the position of the driving coil with respect to the permanent magnet. These pieces of rubber tubing are attached to the bearing by Teflon® studs. The

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[4] E. Jones, "Use of High-Strength Ceramics in Vibration Transducers," J. Acoust. Soc. Am. 36, 1615–1616 (1964).

[5] R. R. Bouche and L. C. Ensor, "Use of Reciprocity Calibrated Accelerometer Standards for Performing Routine Laboratory Comparison Calibration," Shock & Vibration Bull. 34, No 4 (Dec. 1964).

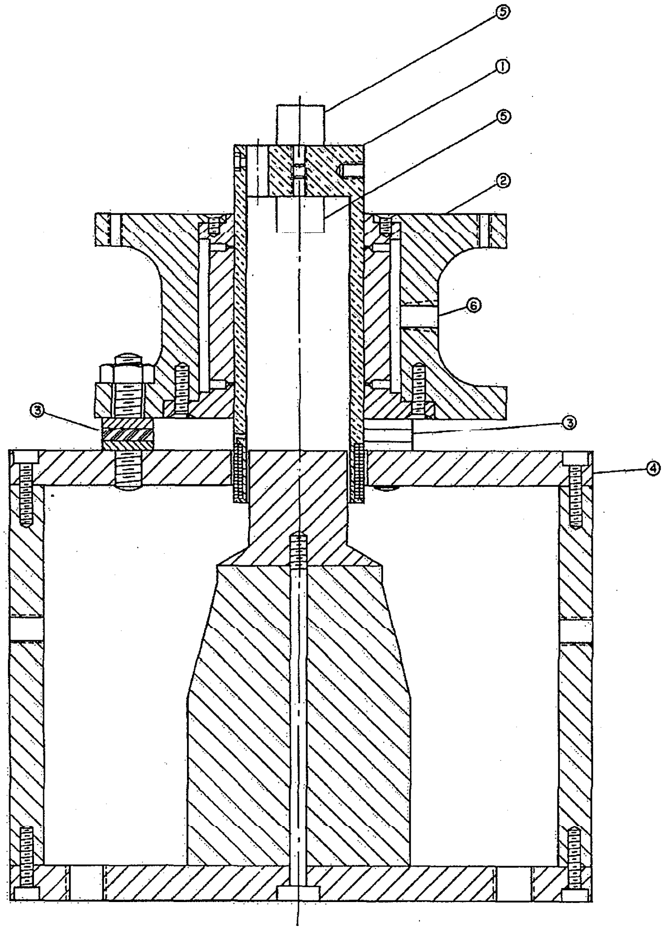

FIG. 2. Electrodynamic vibration exciter uipped with ceramic moving element 1 and bearing 2, vibration absorber 3, permanent gnet 4, vibration pickup 5, and air inlet 6.

vertical suspension stiffness can be adjusted easily by tensioning the rubber tubing (Fig. 4). The vertical suspension can be accomplished also by passing a dc current through the coil simultaneously with the ac current and the rubber tubing can be eliminated completely.[6]

The driving coil is wound on the reduced-diameter portion of the moving element, directly on the ceramic. Thus, as shown on Fig. 1(b), a separate housing for the coil is eliminated. Each layer of copper wire is impregnated with high-strength epoxy cement. The constant flow of cool air (60°F) keeps the mounting table cool. Having the lead of the driving coil coming to the top of the shaft permits the moving element to be easily removable (Fig. 5). Armatures with different configurations or different standard pickups can be inserted and removed conveniently when required.

### B. Air Bearing

The air bearing, shown in Figs. 2 and 3, is of the external pressure or hydrostatic type. It is 1.8772 in. in diameter and 3 in. long. The material is 303 stainless steel. There are two rows of six orifices each, 2 in. apart. The orifices of 0.02 in. diam are drilled through the inner sleeve. The surface of the bearing and the journal have a surface finish of approximately 8 $\mu$in. and this permits a bearing–journal radial clearance of 0.0001 in.

The compressed air used is the building supply, filtered twice. The air is transmitted to the bearing by means of flexible tubing with an inside diameter of $\frac{1}{8}$ in. The pressure is kept at 50 psi, and no oscillatory effect due to the air flow is observed.

### C. Magnet

The permanent magnet, shown in Figs. 2 and 3, consists of a soft steel outer part, a center piece of

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[6] B. Reznek, "Elimination of Static Shaker Deflection by D. C. Armature Biasing," Proc. Inst. Environ. Sci. 1963, 425–432 (1963).

Alnico® 7 magnet, and a Permandur® pole piece. The air gap is $\frac{1}{4}$ in. and the magnetic-field strength in this gap is 8000 G ($8\times10^{7}$ T). The magnetic stray field or the table top is 13 G ($13\times10^{4}$ T).

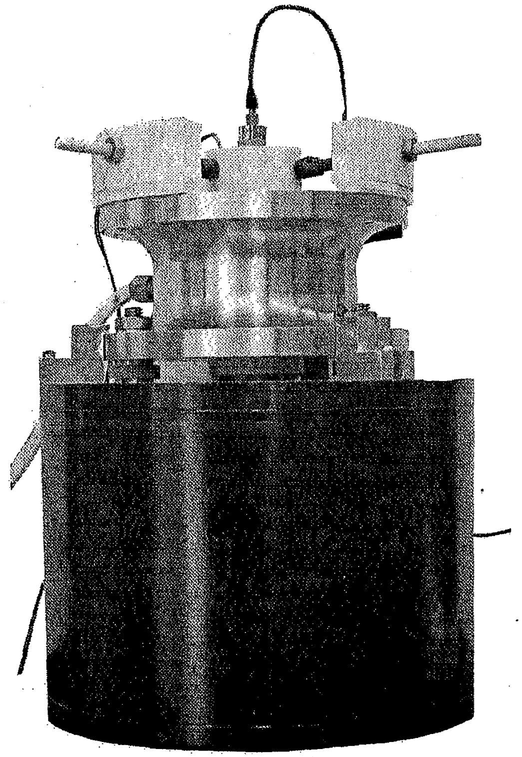

FIG. 3. Electrodynamic vibration exciter equipped with air bearing and ceramic moving element.

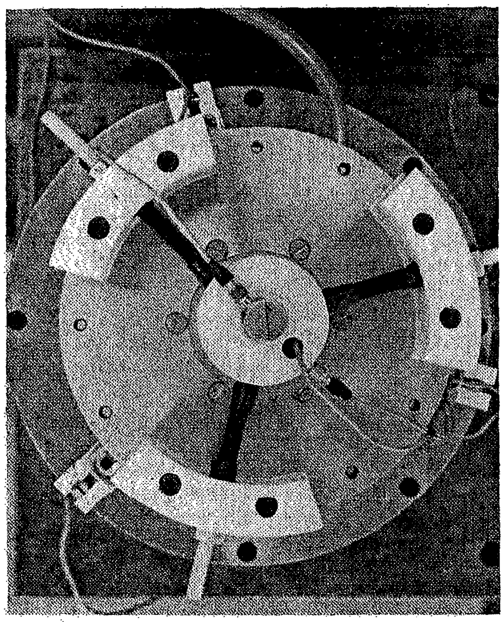

FIG. 4. Setup for calibration of a piezoelectric accelerometer.

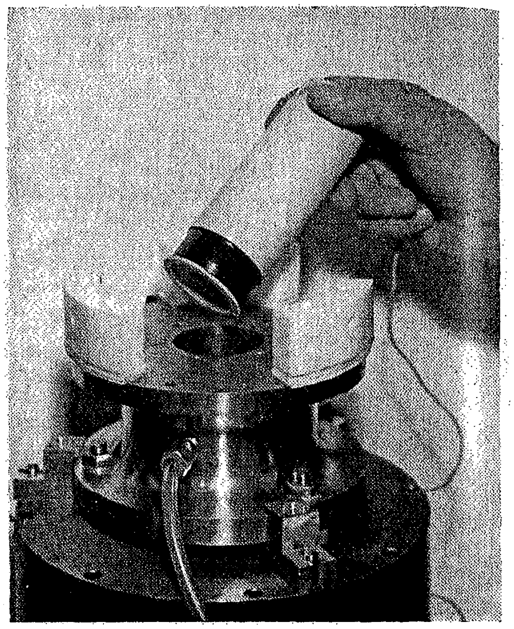

FIG. 5. Removable moving element.

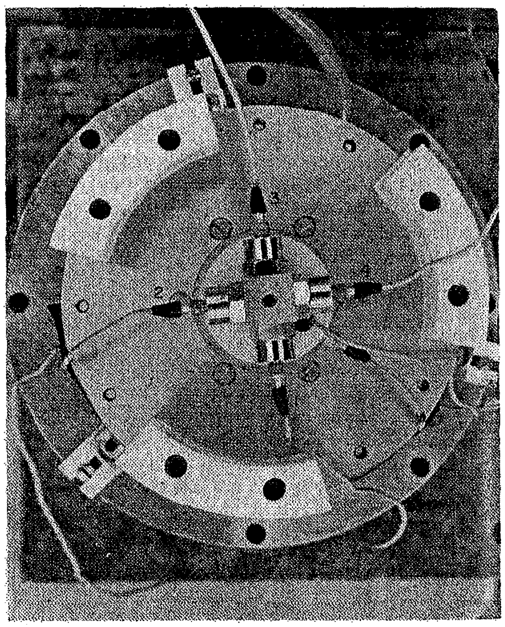

FIG. 6. Setup for measuring transverse accelerations.

If the bearing-table assembly were mounted rigidly the permanent magnet, many of the resonances enerated at the permanent magnet would be transitted to the bearing, and, consequently, to the mounting table. This would cause undersirable transverse otions superimposed on the required sinusoidal axial otion of the moving element. By mounting the bearingable assembly, as shown in Figs. 2 and 3, on three ubber vibration isolators, the troublesome resonances re isolated from the mounting table.

## I. TRANSVERSE-MOTION MEASUREMENTS

The ideal vibration exciter–calibrator should produce ure sinusoidal motion without any transverse motions. ransverse motions or accelerations of the mounting able were measured using two piezoelectric accelerometers mounted with their principal axes mutually erpendicular to each other and to the direction of otion. As shown in Fig. 6, the accelerometers were ounted in pairs to provide a symmetrical inertial oad on the moving element. No significant difference was observed between measurements made with individual members of any pair. Axial acceleration was measured with the builtin accelerometer. The equipment used for the measurements is listed in Table III.

Figure 7 shows the transverse acceleration of the exciter in percent of the axial acceleration. The transverse motions indicated by these devices should not be attributed entirely to the exciter, since no correction was made for the transverse sensitivity of these pickups.

According to the manufacturer's specification, they have 0.5% transverse sensitivity at low frequencies. The manufacturers' determination of the transverse sensitivity of an accelerometer is usually performed at a single low frequency. Thus, the indicated transverse acceleration at high frequencies in Fig. 7 may be owing to transverse response of the accelerometers or to transverse motion of the exciter or both. However, a number of different determinations provide assurance that the transverse acceleration is no worse than the 1½% in Fig. 7.

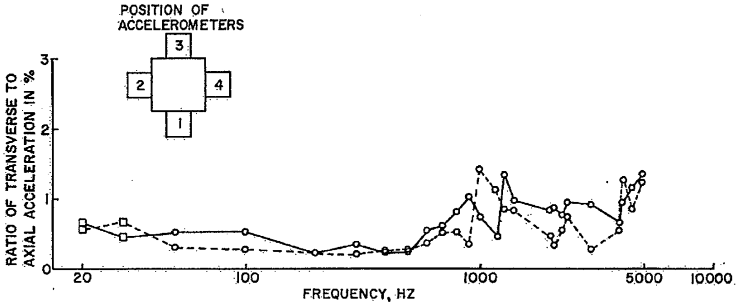

FIG. 7. Measured transverse accelerations due to transverse motions. o: Horizontal No. 2. ---o: Vertical No. 1. o: 10 g. □: 5 g.

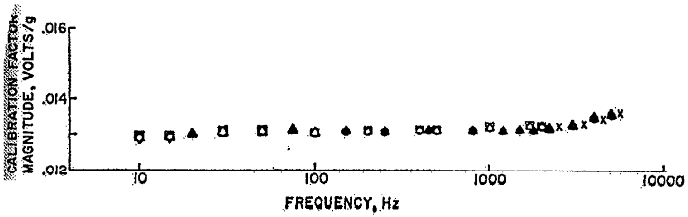

FIG. 8. Calibration factors of a piezoelectric acceleration pickup. *Air-bearing exciter*—●: 10 g. ▲: 5 g. ■: 2 g. *Vibration Standard*—○: 10 g. □: 5 g. △: 2 g. ▽: 1 g. *Piezoelectric exciter*—X: 4 $\mu$ in.

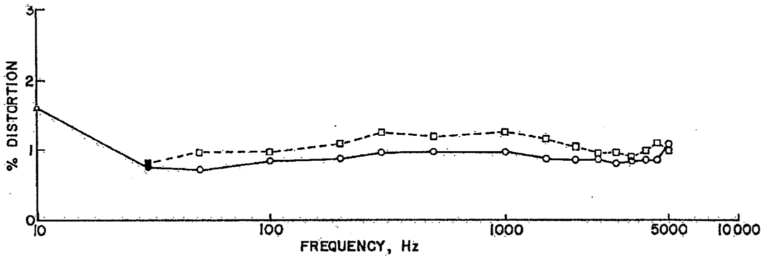

FIG. 9. Indicated distortion vs requency. —○: 0.06-lb payload. --□: 0.285-lb payload. ○: 10 g. □: 0 g. ●: 5 g. ■: 5 g. △: 2 g.

TABLE II. Performance data for air-bearing exciter.

| | |
|---|---|
| Weight of moving element | 1 lb |
| Force rating | 15 lb |
| Maximum table excursion | 0.7 in. |
| Frequency of major resonance | 25 000 Hz |
| Driver-coil resistance | 3.3 Ω |
| Stray magnetic field at table level | 13 G ($13\times10^{4}$ T) |

TABLE III. Equipment used.[a]

1. Standard built in accelerometer, Kistler, model 808K1.
2. Accelerometers for measurements of transverse motions, Endevco, model 2224C.
3. Oscillator, Hewlett–Packard, model 202CR.
4. Amplifier, optimation model P. A. 250.
5. Distortion analyzer, Hewlett–Packard, model 331A.

[a] Certain commercial materials and equipment are identified in this paper in order to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

## III. CALIBRATION OF PICKUP

The setup for calibration of a piezoelectric accelerometer is shown in Fig. 4. Figure 8 shows the calibration factors of a piezoelectric accelerometer obtained by 3 independent calibrations.

The first set of symbols represents the results of calibration by the comparison method using the air bearing exciter. The second set of symbols represents the results of calibration using a vibration standard of the conventional design that has a velocity-sensing coil calibrated by the reciprocity method. The third set of symbols represents the results obtained by measuring the amplitude of vibration by photometric interferometry on a piezoelectric exciter.

## IV. DISCUSSION

The tests performed on the new exciter indicate that the goal for which it was designed has been attained. The performance data of the exciter are given in Table I. In the frequency range below 5000 Hz, the exciter meets present requirements for accurate calibration of piezoelectric accelerometers weighing less than 0.5 lb. For such loads, a level of 10 g can b generated throughout the frequency range with transverse acceleration due to transverse motion everywhere less than 1½% and with distortion less than 1% (see Fig. 9).

If care is taken to avoid a few narrow frequency ranges, good motion can be obtained at frequencies up to 20 kHz.

## ACKNOWLEDGMENTS

The objectives of this project as shown by the performance described in the body of this paper depended on the skilled work of G. E. Crowther and R. H. Harwell, in machining the bearing and supporting assembly.

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