Vibration Sensitivity Measurements on Subminiature Condenser Microphones*

MEAD C. KILLION

Industrial Research Products, Inc., a Knowles Company, Elk Grove Village, Ill. 60007

A recently introduced series of subminiature electret-condenser microphones has brought to light an interesting problem: Their vibration sensitivity is so low that an accurate measurement becomes difficult. Not only must the microphone be isolated from the sound pressure generated by the vibration driver, but simply vibrating the microphone creates a "radiation pressure" which must be taken into account. Measurement techniques are described which permit the accurate measurement of vibration sensitivity even when the vibration sensitivity of the microphone is extremely low.

INTRODUCTION: To a first approximation, the vibration sensitivity of a condenser microphone will be directly proportional to the mass of the diaphragm: the lighter the diaphragm, the lower the vibration sensitivity. It can be readily calculated, for example, that a condenser microphone using a 0.001-inch (0.025-mm) thick fluorocarbon diaphragm (typical of recent electret-condenser microphone designs) will have an "acceleration pressure" on the diaphragm of 5.4 dyn/cm^2 at 1 *g* of vibration, equivalent to a sound pressure level of 89 dB re 0.0002 microbar.[1]

If the diaphragm is made light enough, however, the mass of the air on both sides of the diaphragm can add a noticeable component to the apparent "diaphragm mass" undergoing vibration. This added inertial load can be conveniently divided into two components: the one due to the air contained *inside* the microphone case, and the other due to the air *outside* the microphone case. The effect of the air contained inside the microphone is an integral part of the original microphone design and need not be considered here (although it can be easily calculated as will be shown later). The acceleration of the air outside the microphone, however, must be taken into account even before a definition of what is meant by the vibration sensitivity of the microphone is possible.

DEFINITION OF VIBRATION SENSITIVITY

Although several definitions of vibration sensitivity could be made, we have found the following definitions useful. We use the term "gross free-field vibration sensitivity" to describe the electrical output of the unencumbered microphone when it is vibrated freely in space. This condition can be approached (but never fully realized) if the driving force is applied to the microphone through a slender rod (or rods) whose cross section is small compared to that of the microphone. We use the term "intrinsic vibration sensitivity" to describe that component of the total vibration sensitivity which is attributable solely to the material inside the microphone case. The remaining component, that due to the acceleration of the air outside the microphone, we have loosely labeled the "radiation pressure" component. Thus the gross free-field vibration sensitivity of any microphone will be the (vector) sum of its intrinsic vibration sensitivity plus the effect of any "radiation pressure" acting at the microphone inlet.

An example illustrates the distinction. Consider the condenser microphone of Figs. 1 and 2 [5]. The intrinsic vibration sensitivity of that microphone at 1 kHz and 1 *g* of vibration in its most sensitive plane is equivalent to a sound pressure level of 75 dB in the following sense: Subjecting the microphone to a 1-kHz sound field of 1.1 dyn/cm^2 (75 dB sound pressure level) would produce the same electrical output as subjecting it to a 1-kHz vibration of 1 *g* if no external sound pressure were generated at the microphone inlet by the vibration. The gross free-field vibration sensitivity of the microphone, on the other hand, is approximately equivalent to a 77-dB sound pressure level.

---

[1] Interestingly enough, one obtains almost exactly the same answer for the laboratory standard 640AA condenser microphone, which uses a 0.0003-inch (0.0076-mm) stainless steel diaphragm [1].

---

* Presented September 10, 1974, at the 49th Convention of the Audio Engineering Society, New York.

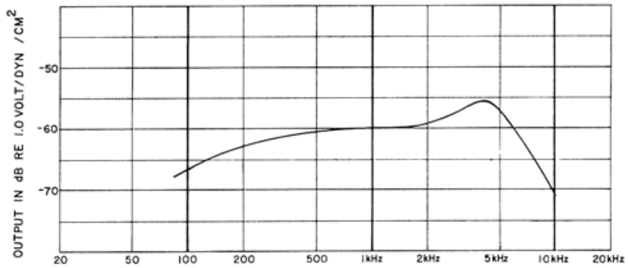

Fig. 1. Typical frequency response of BT-1750 and BT-1751 condenser microphones.

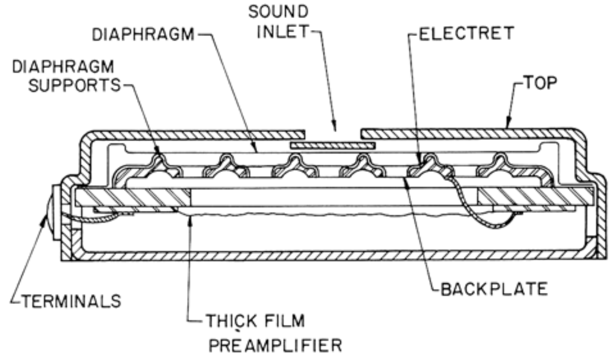

Fig. 2. Cross section of BT-1750 condenser microphone. Length—0.312 inch (7.9 mm); width—0.218 inch (5.6 mm); height—0.09 inch (2.3 mm).

The difference between the intrinsic vibration sensitivity and the free-field vibration sensitivity is due to the pressure generated by accelerating the air in front of the microphone. Simply put, a microphone vibrating freely in space acts as a small loudspeaker, generating oppositely phased sound pressure on the two faces of the unit. For such a small microphone this "radiation pressure" component is nearly independent of frequency over the audio band[2] and amounts to approximately 0.3 dyn/cm² at the center of the face of the unit, when the unit is driven with a constant 1 *g* acceleration. Since the sound inlet on the microphone is a small hole located at the center face of the unit (and directly over the diaphragm), this acoustic pressure adds directly to the intrinsic acceleration pressure. At a vibration level of 1 *g*, therefore, the total pressure acting on the diaphragm is equivalent to 1.4 dyn/cm² or about 77-dB sound pressure level.

MEASUREMENT PROBLEM

Assume that an attempt is made to measure the vibration sensitivity of the condenser microphone of Fig. 2 by mounting it to the surface of a typical vibration driver having a total vibrating area of several square inches. Ones ears warn that the vibration driver is also a loudspeaker. A quick check by holding the microphone slightly off the surface of the driver will confirm that the radiation pressure developed at the vibrating surface far exceeds the acceleration pressure we are trying to measure. A typical vibration driver will produce sound pressure levels of 80 to 90 dB at the vibrating surface when driven to a vibration level of 1 *g*. The electrical output of the microphone placed on such a surface would obviously give the experimenter little clue to the true vibration sensitivity of the microphone.

The first solution that comes to mind is to close off the microphone inlet, making the microphone insensitive to any externally generated sound fields. Unfortunately, this tends to immobilize the diaphragm due to the stiffening effect of the air trapped between the diaphragm and the microphone inlet. Thus a measurement uncontaminated by external sound fields can be made, but it does not represent the true vibration sensitivity of the microphone.

MEASURING VIBRATION SENSITIVITY

In this section, some of the experimental techniques we have used to measure vibration sensitivity will be discussed. The task of verifying experimentally what has been calculated theoretically is made easier if the same basic microphone is available in several different configurations. The basic microphone case, for example, is essentially a rectangular box approximately 0.3 inch long by 0.2 inch wide by 0.1 inch thick (7.6 by 5.8 by 2.5 mm). The 0.2 by 0.3-inch (5.8 by 7.6 mm) surface is normally called the "top" of the microphone, and the plane of the diaphragm is parallel with this surface as shown in the cross-sectional view of Fig. 2. The sound inlet is in the center of the top.

Another version of this microphone is identical in construction except for the position of the sound inlet, which is a tube centered on the edge of the case in what is informally called the "end fire" configuration (Fig. 3). This configuration is useful for several reasons. First of all, the sound inlet remains at the same location in space whether the unit is mounted right side up or upside down. Since inverting the unit reverses the phase of the vibration response but leaves the phase of the acoustic response unchanged, this provides a ready check for the contribution of any external acoustic field. If the two vibration curves are different, this indicates the presence of an external sound field at the microphone inlet, since such an external sound would tend to add to the vibration response in one case and subtract from the response in the other case. (The only exception would occur in the unlikely event that the acoustic and vibration stimuli were exactly 90° out of phase.)

By turning the unit 90° while leaving the inlet tube in the same position in space, moreover, a direct measurement of the acoustic field can often be made. With the unit turned 90° to the axis of its maximum vibration response, its vibration sensitivity will typically be 20 to 40 dB below that at 0°.

One of the most attractive features of the "end fire" configuration, however, is that its gross free-field vibration sensitivity is equal to its intrinsic vibration sensitivity. This comes about as follows: Recall that a disc vibrating in free space acts as an acoustic dipole producing sound of opposite phase on the two faces. At the edges of the disc, therefore, one finds a velocity maximum and a pressure null; in effect, the two sound waves cancel at the edges. Since the sound inlet tube on the "end fire" microphone is centered on the edge of the unit, the radiation pressure component at the inlet will thus be zero when the unit is vibrated perpendicular to the plane of the diaphragm.

Thus the "end fire" microphone was chosen for the initial set of vibration measurement experiments.

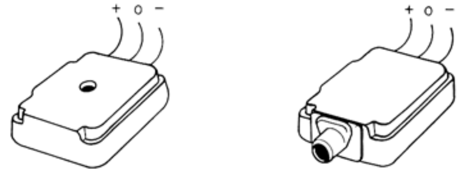

Fig. 3. **a.** BT-1750 "Top fire" microphone. **b.** BT-1751 "End fire" microphone.

---

[2] The radiation pressure is due almost entirely to the mass reactance portion of the radiation impedance in this frequency region. See, for example, [2].

CLOSED CAVITY MEASUREMENT OF INTRINSIC VIBRATION SENSITIVITY

The first experiment was conducted by placing the unit in the center of a closed cavity which was mounted to the surface of the vibration driver. Fig. 4 shows a cross section of the cavity. Note that the unit is mounted along its edges to two tines of a rotatable plug. Fig. 5 shows the vibration response of a unit measured in this cavity as it is oriented at 0° (top up) and at 180° (top down). The cavity was purposely designed so that the position of the microphone inlet remains unchanged as the mounting plug is rotated. Thus the close agreement between the 0° and 180° curves indicates that any external sound field at the microphone inlet is unimportant. The lack of the external sound field at the microphone inlet is confirmed by the response obtained with the unit turned 90° (the dashed curve in Fig. 5) which is nearly everywhere at least 20 dB below the first two curves. Thus it seems safe to conclude that Fig. 5 shows the true intrinsic vibration sensitivity of the "end fire" microphone.

It should be noted that the success of the closed-cavity technique for obtaining the intrinsic vibration sensitivity of the microphone depends on the microphone inlet being placed in the exact center of the cavity. A moment's reflection reveals the reason. Visualize a simple box sitting on the vibration driver. If the walls of the box are vertical, it makes little difference whether they move up and down or not, since only a vanishingly small amount of energy can be transferred into a gas by shear. Thus assume that only the top and bottom of the box move in unison with the vibrating force. During the half-cycle when the acceleration is upward, a pressure increase will occur at the bottom of the box and a rarefaction will occur at the top of the box. As long as the dimensions of the box are small compared to a wavelength, a pressure null will occur halfway between the top and the bottom of the box.[3] Similar reasoning can be applied to any symmetrical cavity, such as the one in the first experiment.

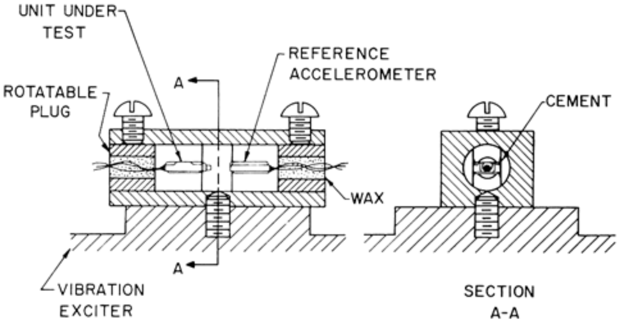

Fig. 4. Closed cavity setup for measuring intrinsic vibration sensitivity.

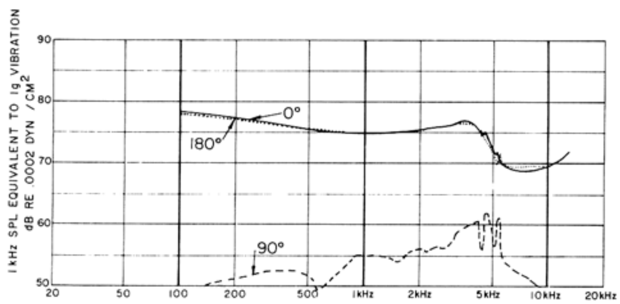

Fig. 5. Intrinsic vibration sensitivity of BT-1751 microphone measured in closed cavity setup of Fig. 4.

It is easy to calculate the internal pressure which will be developed at the bottom (or top) of a small vibrating box, incidentally. If the dimensions of the box are small compared to a wavelength, the air everywhere in the box will be moving with essentially the same velocity; the total mass of the air in the box is accelerated uniformly, with the top and bottom surfaces each contributing half of the required accelerating force. Thus the pressure developed at the bottom (or top) surface of a rectangular box will be given by

$$P = \frac{a\rho V}{2A} = a\rho \frac{h}{2} \tag{1}$$

where h is the height of the box, ρ is the density of the enclosed gas, and a is the acceleration of the box.

For air, $\rho = 0.0012$ g/cm^3. At a vibration level of 1 g = 980 cm/s^2, therefore, this reduces to

$$P = 1.18 \frac{h}{2} \tag{2}$$

where P is in dyn/cm^2 and h in cm, as long as the box is small compared to a wavelength.

The effect of placing the microphone inlet slightly above or below center can be readily estimated since the pressure falls off linearly from a maximum at the bottom (or top) to a null at the center. Placing the microphone inlet 0.08 inch (2 mm) off center, therefore, would subject it to a pressure of roughly 0.12 dyn/cm^2 (55 dB sound pressure level). Note that this result is independent of the size of the box itself, as long as it is small.

It is interesting to note that placing an "acoustic shield" over a unit mounted on a vibrating surface amounts to the same thing as putting the unit at the bottom of a vibrating box; very little reduction in the acoustic pressure seen by the microphone inlet may result.

END-OF-ROD MEASUREMENT OF GROSS VIBRATION SENSITIVITY

The second set of experiments were performed at the end of an 8-inch (203-mm) long aluminum rod, 5/16 inch (7.9 mm) in diameter, with the last half inch (10 mm) of the rod tapered to the same cross section as the unit under test, i.e., a rectangle 0.312 by 0.218 inch (7.9 by 5.6 mm). The use of a long rod makes it possible to separate the unit far enough from the vibration driver to allow the sound generated by the vibration driver to be contained inside a double-walled isolation enclosure built around the vibration driver. A small hole in the top of the enclosure allows the rod to pass through. If the hole is made only slightly larger than the diameter of the rod, only a negligible amount of sound leaks out through the gap.

The radiation pressure developed at the end of such a vibrating rod can be easily calculated. (Formulas are given in any acoustics text, see, for example, Beranek [3] or Rocard [4].) Moreover, a direct measurement of the radiation pressure developed at the end of the rod can be made using an "end fire" microphone as a probe microphone by simply holding it off the vibrating surface slightly. (The small 0.055-inch (1.4-mm) diameter of the microphone inlet, combined with the small cross section of the unit when it is held edgewise, provides a nearly ideal "point pickup" probe microphone.[4]) The measured sound field developed at the end of

---

[3] The volume of the box should be large compared to the (equivalent acoustical) volume of the microphone, however, to avoid stiffening the diaphragm due to the trapped air.

[4] A microphone with a flat frequency response is sometimes more convenient for use as a probe microphone. (The frequency response of the BT-1751 "end fire" microphone has been tailored specifically for hearing-aid usage and is not flat). One candidate is the BL-1685 ceramic microphone, which is identical in external dimensions but has a frequency response which is relatively flat from about 20 Hz to 8 kHz.

the rod at 1 *g* vibration is shown as a dashed curve in Fig. 6. As would be expected from theoretical considerations, the sound pressure developed at the center of the end of a long rod is higher than that at the center of a thin disc having the same dimensions, amounting to approximately 0.4 dyn/cm^2 in this case compared to the 0.3 dyn/cm^2 mentioned earlier for the unit vibrating as a free disc. (The perturbation of the sound field shown in Fig. 6 in the 500- to 700-Hz region was caused by a resonance in the double-walled enclosure built around the vibration driver.)

The second experiment was thus performed by mounting a "top fire" microphone on the end of a rod as shown in Fig. 7. The acceleration provided at the tip of the rod was measured using a special vibration pickup which had mass and dimensions identical to the "top fire" microphone, but no sound inlet. This was calibrated initially by placing it next to a known accelerometer on the main surface of the vibration driver. It was then attached to the end of the rod as a permanent reference and the unit under test placed on the top.

The total vibration sensitivity of the "top fire" microphone measured on the end of this rod is shown as the solid curve in Fig. 6. Measured in this manner, it has a gross vibration sensitivity at 1 kHz equivalent to a 1-kHz sound pressure level of 77.5 dB, or 1.5 dyn/cm^2. As expected, the radiation pressure added directly to the intrinsic vibration sensitivity. As illustrated in Fig. 7, the intrinsic vibration sensitivity of 1.1 dyn/cm^2 plus the radiation pressure component of 0.4 dyn/cm^2 gave the expected total of 1.5 dyn/cm at 1 kHz. It should be noted that the radiation pressure contribution to the total vibration sensitivity is dependent on frequency because of the tailored frequency response of the microphone (see Fig. 1).

SLOTTED-ROD MEASUREMENT OF INTRINSIC VIBRATION SENSITIVITY

In a third set of experiments we were able to obtain results essentially identical to those obtained in the closed cavity by use of a 0.312-inch (7.9-mm) diameter by 10-inch (254-mm) long rod in which a 0.220-inch wide by 2-inch long (5.6 by 25.4-mm) slot had been milled starting 3/16 inch (4.8 mm) down from the top. The special vibration pickup mentioned earlier (with mass and dimensions identical to the "top fire" microphone but with no sound inlet) was placed midway up the slot in order to calibrate the system. The vibration pickup was then replaced with the microphone under test and a measurement made of the latter's vibration sensitivity. Direct measurement of the acoustic pressure developed at the position occupied by the "end fire" microphone inlet indicated a sound field which was nearly everywhere at least 26 dB below the equivalent sound pressure level of the unit's vibration sensitivity.[5] Fig. 8 shows the typical gross free-field vibration sensitivity measured on several "end fire" microphones in the slotted rod. Also shown for comparison is the theoretically calculated vibration sensitivity of the microphone based on its electrical analog.

Two units were carefully measured both in the slotted rod and in the closed cavity setup. In both cases the measurements agreed within 0.2 dB, confirming experimentally that the intrinsic and gross free-field vibration sensitivity of the "end fire" microphone are indeed the same.

TWO MISCELLANEOUS OBSERVATIONS

While the subminiature cases of the condenser microphones are normally considered quite sturdy, we have observed that a variety of peculiar vibration response curves can be obtained if the vibrating force is applied so as to cause flexure of the case walls. We have found that this can be avoided by applying the driving force along the edges of the unit or uniformly over the entire face of the unit.

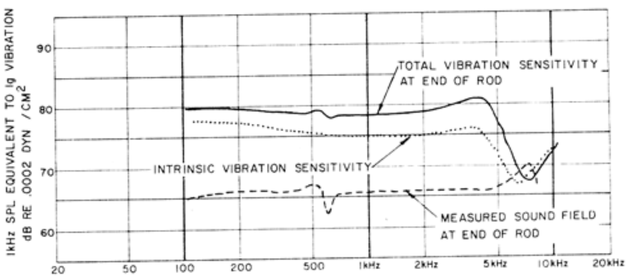

Fig. 6. Vibration sensitivity of BT-1750 microphone measured at end of rod.

	dyn /cm^2	dB SPL
APPARENT SOUND PRESSURE SENSED BY MICROPHONE	1.5	77.5
ACTUAL SOUND PRESSURE AT MICROPHONE	0.4	66.0
APPARENT SOUND PRESSURE DUE TO THE VIBRATION SENSITIVITY	1.1	75.0

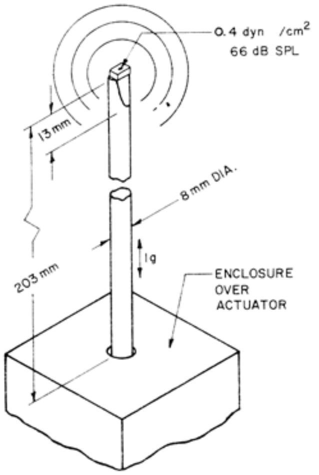

Fig. 7. End-of-rod measurement.

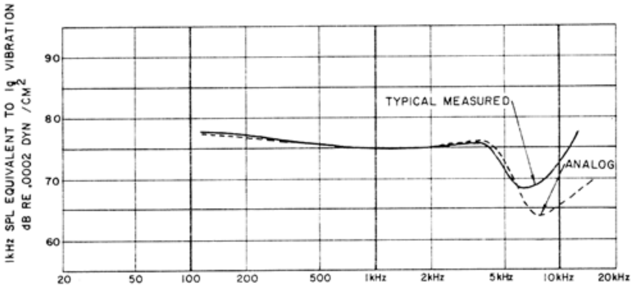

Fig. 8. Comparison between gross free-field vibration sensitivity of typical BT-1751 microphone and theoretical sensitivity based on complete electrical analog.

A similar problem can arise using commercial accelerometers. One can be tempted to mount a microphone (or transfer accelerometer) directly to the top of a commercial accelerometer. Many commercial accelerometers, however, use a compression spring between the top of the accelerometer and the vibration element to help hold the vibrating mass in place. Placing any mass on top of such an accelerometer can markedly change its calibration.

VIBRATION SENSITIVITY COMPARISON

Fig. 9 shows a normalized comparison of the vibration sensitivity of several commercially available subminiature microphones. This is similar to the graph shown in a previous paper [5], but has been revised slightly to reflect the refinements in measurement

---

[5] The same double-walled enclosure mentioned previously was used to contain the sound generated by the vibration driver, with the slotted rod protruding through a small hole as in the end-of-rod experiments.

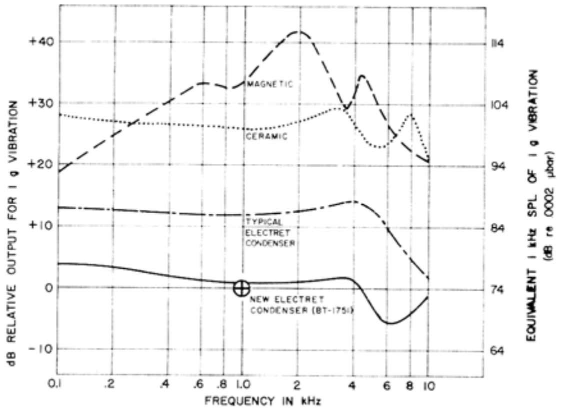

Fig. 9. Comparison of vibration sensitivities between magnetic, ceramic, and electret-condenser microphones. ⊕ —output for 1 μbar sound pressure.

techniques described in this paper. By way of reference, the laboratory standard W. E. 640AA condenser microphone has a vibration sensitivity which is about 4 dB higher than the curve labeled "typical electret-condenser."

SUMMARY

An accurate measurement of the vibration sensitivity of a microphone requires first of all a definition of what is meant by the term. Two definitions we have found useful have been given. Depending on what one wishes to measure, several techniques for avoiding some of the common measurement artifacts have been described, and their validity has been confirmed both theoretically and experimentally. Simply stated, the new techniques permit an honest measurement of the vibration sensitivity of a low-vibration-sensitivity microphone.

Although this paper has concerned itself primarily with the problem of *measuring* vibration sensitivity, these results have broader implications. The subminiature microphones discussed here are normally mounted in some sort of housing, whether it be a hearing aid or something else. This housing will, of necessity, be larger than the microphone cartridge itself. Because the intrinsic vibration sensitivity of these microphones is so low, the gross free-field vibration sensitivity of the finished package may be determined primarily by how the microphones are mounted. In other words, the radiation pressure produced by vibrating the entire package may be greater than the intrinsic acceleration pressure of the microphone unless some thought is given to how the microphone is mounted.

ACKNOWLEDGMENT

The author is indebted to Neil Herbert and Linda Schmidt for the painstaking experimental work required to make accurate vibration sensitivity measurements, and to Elmer Carlson for numerous helpful discussions on the subject.

REFERENCES

[1] M. S. Hawley, "The Condenser Microphone as an Acoustic Standard," *Bell Labs. Rec.*, pp. 6-10 (1955).

[2] H. S. Knowles, "Loudspeakers and Room Acoustics," in K. Henney, *Radio Engineering Handbook*, 5th ed. McGraw-Hill (1959) pp. *11*-1 to *11*-48.

[3] L. L. Beranek, *Acoustics* (McGraw-Hill, New York, 1954).

[4] Y. Rocard, *General Dynamics of Vibration*. Frederick Ungar, N.Y. (1960).

[5] M. C. Killion and E. V. Carlson, "A Subminiature Electret-Condenser Microphone of New Design," *J. Audio Eng. Soc.*, vol. 22, pp. 237-243 (May 1974).

Note: Mr. Killion's biography appeared in the May 1974 issue.