A CAPACITOR MICROPHONE SYSTEM

USING SEMI-CONDUCTOR DEVICES

Elimination of the vacuum tube in capacitor-microphone construction offers some advantages and simplifies the work. The unit described should be sufficiently simple for any advanced experimenter to undertake as an interesting and rewarding project.

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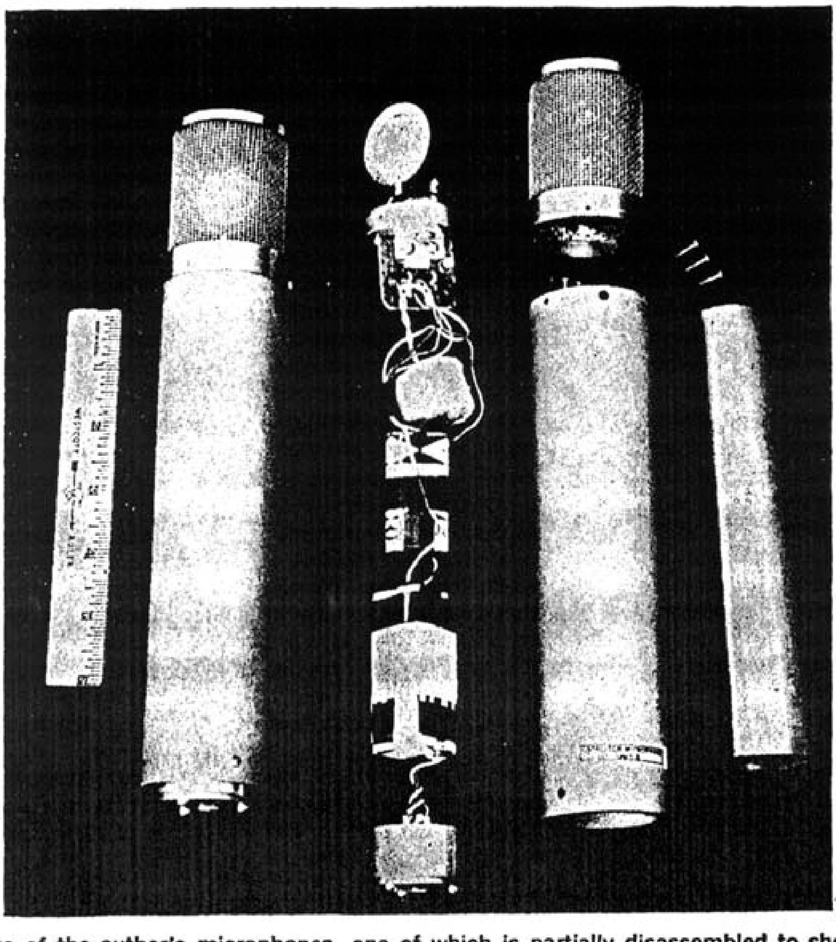

Two of the author's microphones, one of which is partially disassembled to show its internal layout.

As a result of R. Williamson's article "A Professional Condenser Microphone" in the July, 1963, edition of AUDIO, this Audio experimenter developed an interest in the construction of quality capacitor microphone systems. Since that time, several microphone systems have been constructed and tested, including that designed by Mr. Williamson. Within the past year, however, favorable results have been obtained using a field-effect transistor in the microphone impedance-matching circuit, and a complete microphone system has been developed and tested. Generally, the system consists of a capacitor pickup, similar in construction to that of Mr. Williamson, a single FET impedance-matching stage, and a low-impedance emitter-follower transistor output stage. The system developed offers several practical advantages over the conventional tube type, transformer-output, d-c polarized microphone scheme. As a result of the use of semiconductor devices, self-contained battery operation is practical, and by virtue of an unbalanced low-impedance output stage, conventional 2-conductor shielded cable can be employed using one conductor and

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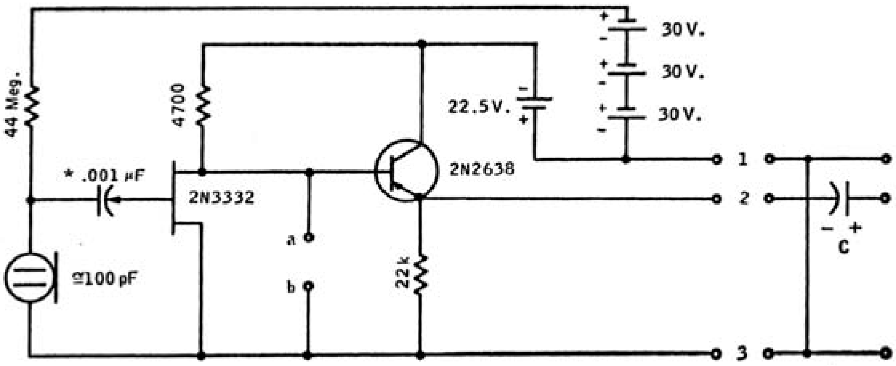


*POLYSTYRENE OR MYLAR FOR LOW D.C.LEAKAGE

Fig. 1. The complete schematic for the author's microphone. The .001-μF capacitor marked with * should be polystyrene or Mylar® for low d.c. leakage.

ground in conjunction with cable connectors as an on-off switch.

Semiconductor Capacitor Microphone Systems

When considering the use of semiconductor devices in capacitor microphone circuits, one generally encounters three approaches to the problem. The first and oldest is a d.c. bias scheme which relies on the relation between voltage (V) and charge (Q) on a capacitor i.e. $Q = CV$. If the capacitor transducer is polarized through a resistor (R), the voltage across the capacitor will obey the previous equation for capacitance variation above the frequency $f = 1/2\pi RC$ at which point it is 3 dB down from its high-frequency limit. If 30 Hz is considered a practical low-frequency cutoff point, and a typical C of 100pF is used, the necessary R is about 50 megohms. If this voltage is to be amplified, severe restrictions are placed on the low-frequency input impedance of the amplifying device. This is the primary reason that vacuum tubes, as opposed to bipolar transistors have been used with such schemes until the recent availability of field-effect devices.

A second possible approach is to use the capacitor pickup in a radio-frequency scheme, whereby an AM, FM, or phase modulated signal is generated and detected. One such system constructed and tested by the author was that proposed by P. J. Baxandall.[1] This system consisted of a 1-MHz oscillator, which was amplitude modulated by the capacitor pickup in a balanced-bridge configuration, the output of which was detected by a phase-sensitive detector and filter. Even though Mr. Baxandall's experimental results indicated his system to be of professional quality, the author's experimental system suffered from a slight signal-to-noise-ratio problem. As a result of this experimental problem, I would not advise construction of such systems except to individuals skilled in the techniques of r.f. circuitry and having extreme patience in regard to small problems affecting signal-to-noise ratio. For the interested experimenter, however, additional references are given in regard to r.f. schemes at the end of this article.[2,3]

The third approach is that of a permanently polarized capacitor, in which a Mylar diaphragm, serving as the variable capacitor plate, is polarized by heating and cooling in a high electric field. Such a system has been developed by G. M. Sessler and J. E. West of The Bell Telephone Laboratories[4,5], and offers certain advantages over the other schemes described. Due to the fact that the transducer is permanently polarized, a much smaller electrode spacing can be used than conventional d.c. bias or r.f. schemes, and hence high sensitivity and high source capacitance result. By virtue of the increased source capacitance, conventional transistors can be employed in an amplifying circuit. Even though such systems were not pursued by the author, due to the complexity of pickup construction and diaphragm polarization, they are certainly worthy of consideration by the interested experimenter.

A Capacitor Microphone System Using a FET

As previously pointed out, the field-effect transistor, by virtue of its high

[1] P. J. Baxandall. "New low-noise transistor circuit for electrostatic microphones." *Wireless World*, November and December, 1963.

[2] Edmond DeNiet. "Parametric amplifiers used in electrical acoustics and Condenser microphone amplifier with semi-conductor elements." *J.A.E.S.*, July, 1964, Vol. 12, No. 3.

[3] Hans Joachim Griese. "Circuits of transistorized r.f. condenser microphones." *J.A.E.S.*, January, 1965, Vol. 13, No. 1.

[4] G. M. Sessler. "Electrostatic microphones with electret foil." *J. Acous. Soc. Am.*, September, 1963, Vol. 33, No. 9.

[5] G. M. Sessler and J. E. West. "Condenser microphones with electret foil." *J.A.E.S.*, April, 1964, Vol. 12, No. 2.

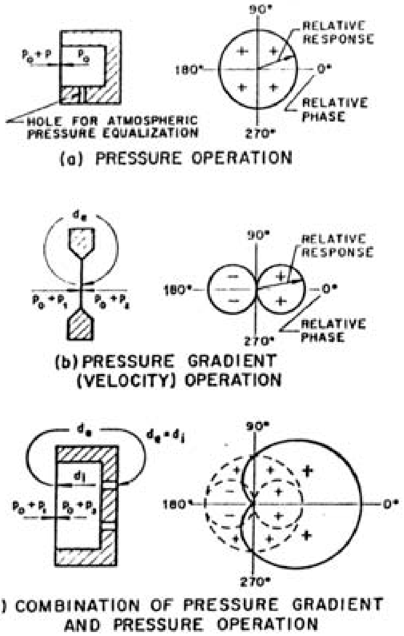


Fig. 2. Transducer directivity patterns: (A) in pressure operation; (B) in pressure-gradient (velocity) operation; and (C) in a combination of pressure-gradient and pressure operation.

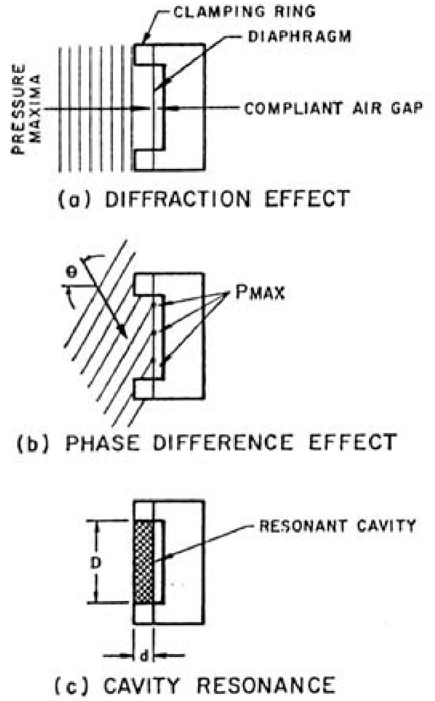


Fig. 3. Transducer dimensional effects: (A) diffraction effect; (B) Phase-difference effect; and (C), cavity resonance.

input impedance, is worthy of consideration in d.c. biased capacitor-microphone systems. One of the most important problems in any capacitor-microphone scheme is the signal-to-noise ratio of the circuitry, and this proved to be a genuine problem at the beginning of the author's experimentation. Part of the problem involved picking a low-noise device from published manufacturer specifications which are generally not in a form meaningful for this type of circuitry. After purchasing and trying numerous devices, two particular units (2N3332 or 2N2500 P-channel FET) were found most suitable for the final circuit. For those interested in considering other devices or future devices, the parameters shown in Table 1 may be of some help.

Using either of the suggested devices, the final microphone circuit is as shown in *Fig.* 1. In the circuit, the capacitor is polarized by the 90-V supply through 44 megohms, which corresponds to a low-frequency 3-dB cutoff of about 35 Hz. Separate battery supplies are used for polarizing and for biasing, since the current demands for polarizing are almost negligible in comparison to the drain for biasing. (i.e. Approx. 30 nA leakage through the polarized pickup and approx. 3 mA biasing.) Of particular importance for low-noise operation is the need to couple the output of the transducer to the FET with a low d.c.-leakage capacitor of the Mylar or polystyrene variety. As far as the rest of the circuit is concerned, the transistor used in the emitter follower should have a beta of about 200 at a collector current of 500 μa in order to produce an output impedance of about 150 ohms. Since the circuit has this low an output impedance, long unbalanced cables can be used without inducing objectionable hum or capacitive high-frequency loss. If the tape recorder or amplifier used with the microphone is not a.c. coupled, a coupling capacitor should be used as indicated at the amplifier end of the cable so as not to alter the biasing condition of the microphone circuit or possibly damage the output transistor by shorting the output to ground. For a given amplifier input impedance, the value of this capacitor can be determined from the expression $C \cong 1/49R_i$ where C is the coupling capacitance in farads and R_i the amplifier input impedance in ohms.

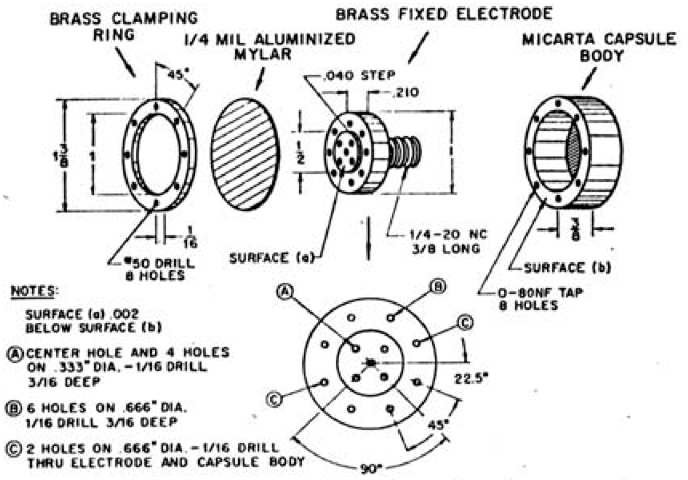


Fig. 4. Details of the author's capacitor microphone capsule.

The Capacitor Pickup

Once the impedance-matching circuitry had been developed, specific attention was given the capacitor pickup. During the initial experimentation, the pickup used was modeled after that designed by Mr. Williamson, however, the present pickup design is somewhat different. In redesigning the capacitor pickup, three basic problems were considered, viz. directionality, frequency response, and sensitivity.

Directionality: The important factors which affect the directionality of a capacitor pickup, or for that matter, any microphone, can be seen in *Fig.* 2. Here it is demonstrated how pressure and pressure-gradient (velocity) diaphragm operation can be combined to achieve various directionality patterns from an ideal* single-diaphragm transducer. *Figure* 2a depicts a pickup which has only one side of its diaphragm exposed to the sound field and consequently its response is independent of the direction of incident sound waves. In *Fig.* 2b, a pressure-gradient or velocity-operated diaphragm is shown where it is noted that both sides of the diaphragm are exposed to the incident sound field, resulting in a figure-eight directionality pattern. This directionality pattern can be inferred by noting that a wave front incident at right angles to the diaphragm will cause the diaphragm to experience a net pressure p_1-p_2 due to the phase shift in p_2 referred to p_1 as the wave front traverses the distance d_e, whereas a wave front incident parallel to the diaphragm will result in zero net pressure since p_1 will equal p_2. Finally, in *Fig.* 2c, pressure-gradient may be combined with pressure operation by creating small sound passages in the back of the pressure-operated diaphragm of *Fig.* 2a. The accompanying directivity plot indicates graphically how a proper mixture can result in a cardioid directivity pattern.

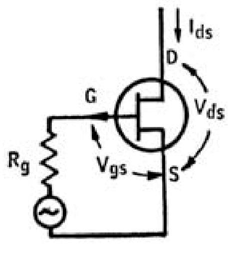
Frequency Response: In general, most capacitor microphones (including the one constructed by the author) rely on the fundamental diaphragm resonance being above the audio-frequency band. Under such conditions,

*By this I mean a pickup whose largest dimension is small compared with the shortest wavelength considered.

TABLE 1

PARAMETER	TEST CONDITIONS	DESIRABLE VALUE
g_m	$V_{ds}=-10$ $V_{gs}=0$ f = 1000 Hz	≥ 2200 μmhos
I^*_{ds}	$V_{ds}=-10$ $V_{gs}=0$	≤ 2.5 mA
SPOT NOISE FIGURE (NF)	$V_{ds}=-5$ f = 1000 Hz $I_{ds}=-1$ mA $R_g=1$ Meg	≤ 1 dB

* OF PRACTICAL IMPORTANCE FOR BATTERY OPERATION



the diaphragm is said to be compliance controlled, in that the mechanical impedance of the pickup is primarily that of a compliant element within the audio-frequency band. Thus:

$$Z_m = \frac{F}{U} = \frac{PA}{U} \cong \frac{1}{C_d s}$$

Where:
Z_m = Mechanical impedance
F = Force on diaphragm
U = Velocity of diaphragm
P = Pressure
A = Diaphragm area
C_d = Effective diaphragm compliance

For a constant applied pressure independent of frequency we can then write:

$$\frac{PA}{X_s} = \frac{1}{C_d s}, \text{ or } X = C_d PA$$

This is a desirable result indicating the diaphragm displacement — and hence capacitance variation—to be independent of frequency. Generally, this is not the case except for diaphragms of infinitesimal size and consequently the dimensions of the transducer must be considered. *Figure* 3 demonstrates three of the basic effects which tend to cause the pressure on any finite size diaphragm to deviate from that of the unperturbed sound field at the point of the microphone. The first effect, known as diffraction, results when the reflected component of the sound wave front incident upon the diaphragm causes a sufficient standing wave to produce pressure doubling or tripling. This effect generally occurs for wavelengths comparable to the diaphragm diameter. A second form of difficulty is known as the phase-difference effect and again becomes important for wave lengths comparable to the diameter of the diaphragm. This effect occurs when the incident wave front strikes the diaphragm at an angle ϕ causing the pressure to vary considerably over the face of the diaphragm and hence not accurately represent the true sound pressure at the point of the microphone. As a final point of consideration, attention must be given to the cavity created by the clamping ring used to maintain the stretched diaphragm. This cavity will become resonant at a wave length comparable to its inside circumference and will cause an increase in sound pressure in proportion to the ratio of d/D. In summary of these effects, it is generally felt that for audio entertainment applications the effect of diffraction can be adequately minimized by a diaphragm diameter less than 2 in., the effect of phase difference by a diameter of 1 in. or less, and cavity resonance minimized by a ratio of d/D less than 1/10.[6]

Sensitivity: For the case of the circular-parallel-plate capacitor transducer, the open-circuit output voltage is approximately $V\Delta C/C$ where V is the applied d.c. bias and ΔC is the change in the unexcited capacitance C. In an attempt to increase the sensitivity of a given pickup, one might try to increase the polarizing voltage, but would soon learn that the diaphragm would collapse or be biased into a position of unstable equilibrium due to the electrostatic attraction of the capacitor plates. For such diaphragms having a diameter of about 1 in., bias voltages much over 100 volts are impractical for this reason. A similar argument also applies when one decreases the capacitor spacing in an attempt to increase the ratio $\Delta C/C$ for a specific polarizing voltage. One method commonly used to increase sensitivity is based on the fact that most of the ΔC results from the displacement of the center of the diaphragm and not its edges since a clamped diaphragm does not move as a piston. By making the fixed-back electrode smaller than the vibrating diaphragm, this effect may be taken advantage of to improve sensitivity. This method of optimization, as well as that of varying the magnitude of the bias voltage across the surface of the back electrode, is considered by K. Teer.[7]

[6] A. E. Robertson. "*Microphones,*" Hayden Book Co., New York, 1963.

[7] K. Teer. "On the optimization for a condenser microphone." *Acustica*, Vol. 15, 1965.

The Author's Pickup

As previously mentioned, the author's initial work was done with a pickup modeled after that of R. Williamson. Serious diaphragm mounting problems were, however, encountered using his recommended 1-mil air gap, 90-volt bias, and ¼-mil. aluminized Mylar. The problem experienced was that of diaphragm collapse and is believed by the author to be a result of an unstable bias voltage for the indicated spacing. Much more reliable results were achieved using a 2-mil air gap. Also, the sensitivity was improved by reducing the diameter of the back electrode as indicated in *Fig.* 4, where the final pickup is shown. For those interested in constructing such a pickup, the machining techniques and diaphragm mounting procedures discussed in Mr. Williamson's paper have proven to be quite satisfactory.

Performance

Of the quantities commonly specified for high-quality condenser microphones, the following were measured

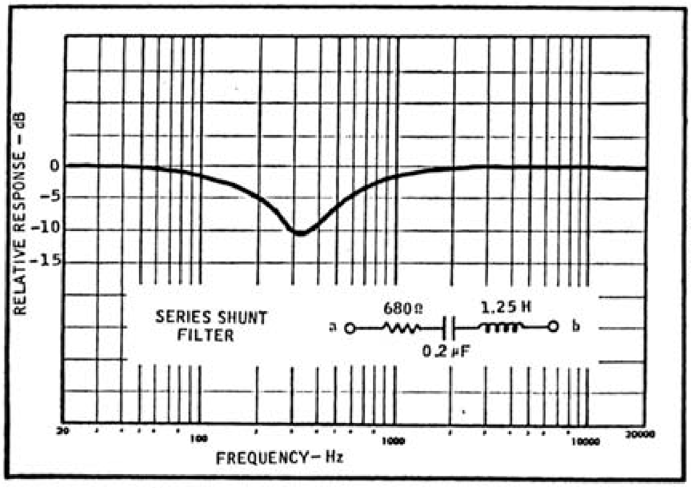


Fig. 5. Octave-band response of completed condenser microphone to pink noise.

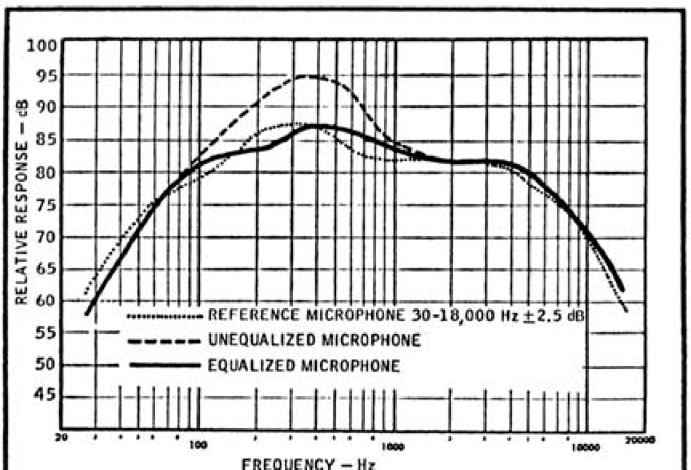


Fig. 6. Shunt-applied series RLC filter, and its insertion characteristic.

by the author:

Sensitivity: Using a pink-noise generator (constant power per octave), and a calibrated General Radio condenser microphone, the two microphones constructed had measured sensitivities of approx. —49 dB re 1 volt/μbar.

Noise: The unweighted noise-open-circuit voltage as measured over an 80-/ to 10,000-Hz bandwidth in a quiet room was ≃ 6 μV.

Output Impedance: Using a 2 μF output coupling capacitor, the output impedance at 1000 Hz was 150 ohms.

Frequency Response: Frequency response was inferred from a pink-noise source and an octave band analyzer and compared to that of a high-quality commercially available capacitor microphone whose calibrated response was known. The results of these measurements are shown in *Fig.* 5 where a 6-dB peak is indicated at about 300 Hz. As a result of this peak, listening test gave the impression of a lack of high-frequency response. The problem was, however, conveniently corrected by the insertion of a series RLC filter within the microphone between points a and b in *Fig.* 1. This filter and its insertion characteristics are shown in *Fig.* 6, and the resulting microphone response characteristics in *Fig.* 5. The basis for this problem is felt to lie in the diameter and length of the two phase-delay tubes coupling the back side of the diaphragm with the sound field, with respect to the acoustic compliance of the air mass behind the diaphragm. While it would be desirable to correct this problem in the pickup itself, the fact that the desired net results can be easily obtained through filtering is worthy of merit. It must also be realized that the proper modification of the capsule to correct the problem will most likely result in a loss in sensitivity which may be intolerable with the marginal noise characteristics of reasonably priced FET's currently available. The author is, however, considering the problem, but is presently limited by the lack of accurate measuring instruments and a good mechanical analog of the present pickup. Two microphones constructed by the author are shown in the illustration at the beginning of this article, one of which has been disassembled to show the component layout. As a final note, I would like to make it quite clear that the design of capacitor microphone systems is not as straightforward as some portions of this article might imply, but requires a detailed knowledge of accoustical and electrostatic effects, accurate testing equipment, and much time and patience.