A Professional Condenser Microphone

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In 1957 the author decided to do what amateurs are not supposed to do—build a professional-quality condenser microphone. Here are his footsteps for the serious, and extremely careful, amateur to follow.

Few audio engineers would deny that for flexibility of use and superiority of fidelity one particular type of microphone reigns supreme above all others—the condenser (electrostatic or capacitor to the technical *avant garde*). Now in almost universal use where the highest quality is demanded, the modern condenser microphone has that often indefinable "something" that makes it the preferred type amongst discriminating professional engineers and audiofans alike. Unfortunately, along with its superiority of performance, all condenser microphones share one common denominator, that of high cost. It was this last factor which induced one impecunious audio enthusiast to undertake in 1957 a detailed study of the basic design features of all condenser microphones and, if at all practicable, to actually construct one. This article is intended as a broad survey of a venture that so far has proved highly successful and more fruitful than originally anticipated. The information herein may be of some help to any other enthusiast who is tempted to tackle a rather difficult construction project.

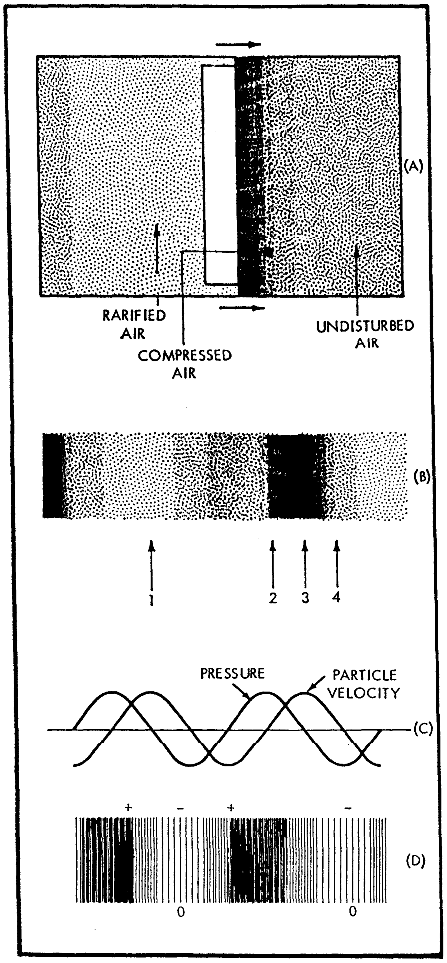


Fig. 1. (A) and (B) show generation of a plane sound wave by a vibrating body. (1) and (3) show node and anti-node of pressure component; (2) and (4) similarly show node and anti-node of velocity component. (C) and (D) show the same thing in graphical form.

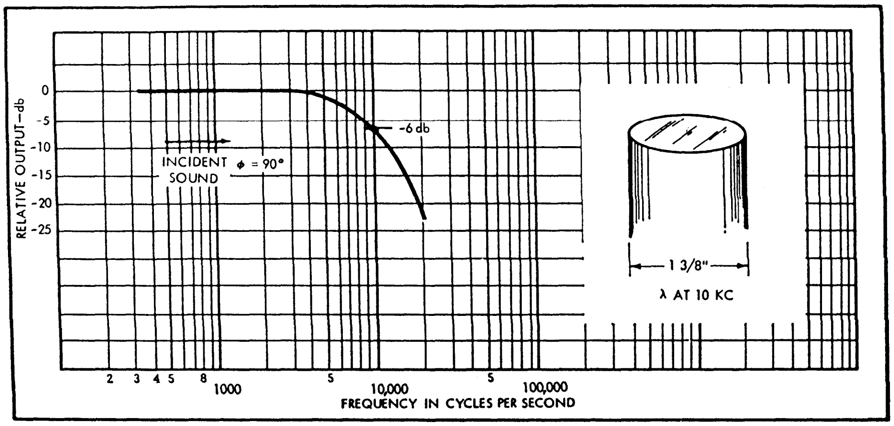


Fig. 2. Phase-loss effect.

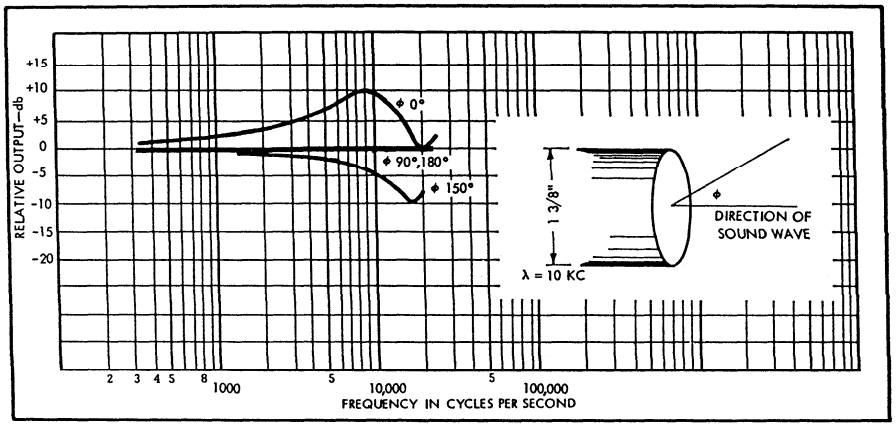


Fig. 3. Diffraction by cylinder.

To understand fully the construction of a modern condenser microphone, it is vital to familiarize oneself with the basic design features first. Otherwise it is quite easy to make what seems to be an insignificant alteration to a particular constructional detail, with subsequent adverse effects on the performance of the finished microphone.

All microphones are electroacoustical transducers; that is, they convert acoustics energy into electrical energy. All microphones have a diaphragm coupled to an electrical generator and, in common with ribbon microphones, the diaphragm of a condenser shares both functions. Essentially, it is a variable capacitor with one fixed element and one (the diaphragm) free to move in sympathy

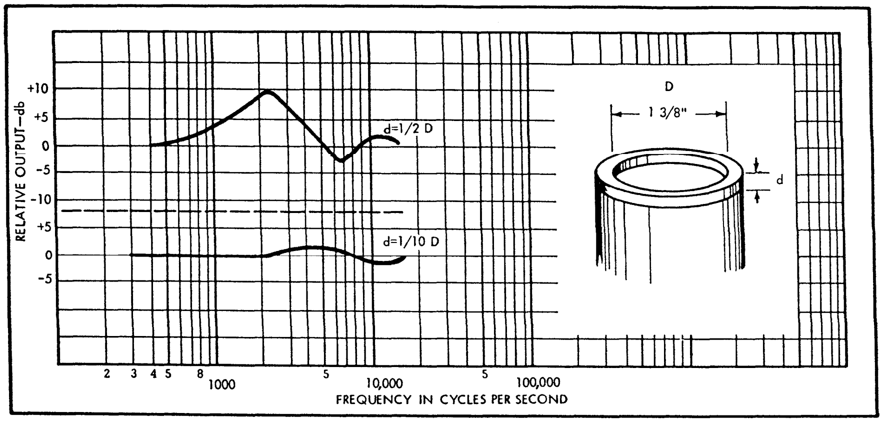


Fig. 4. Effects of clamping ring (cavity resonance).

with sound vibrations impinging upon it. Dependent upon the type of microphone, the diaphragm will respond to either the pressure or the velocity component in a sound wave, ignoring for the moment the types which respond to both (*Fig.* 1). A velocity-sensitive diaphragm will respond only to the pressure difference between the two sides, so such a diaphragm is open to the sound field on both surfaces. A typical example is the ribbon, and it is well known that all such velocity microphones are bi-directional and have maximum sensitivity to sound sources at right angles to the plane of each side of the diaphragm. Since, too, the forces which operate on each side of the diaphragm are 180 deg. out of phase, the electrical output will also be 180 deg. out of phase for sounds on each side of the microphone. Pressure-operated mircophones, on the other hand, respond only to the pressure component in a sound wave and only one side of the diaphragm is exposed to the sound field; the other side is completely enclosed and internal pressure is constant. Since the pressure component in a sound wave is also constant, irrespective of directionality of source, a pressure-operated microphone is omnidirectional, that is, gives constant electrical output whatever the direction of the sound source. Into this latter category came the earliest condenser microphones.

We can now consider the operation of a simple condenser microphone system consisting basically of a stretched diaphragm and a totally enclosed fixed electrode. The capacitance between them will vary as the diaphragm responds to sound vibrations and if a polarizing potential is applied across the diaphragm and fixed electrode through a very high resistance, the charge will be held constant. Since $V = Q/C$ the voltage across the condenser will vary inversely with its capacitance. The diaphragm of early condenser microphones was usually aluminum or one of its alloys, and a fraction of 0.001-in. thick. It was stretched so that when the compliance reactance equalled the mass reactance, the resultant resonance occurred at the upper end of the audio band. Below this frequency the diaphragm compliance determined the velocity of movement for a given sound pressure. As the reactance of the compliance varies inversely with frequency (compliance being analagous to capacitance) the velocity will also vary inversely with frequency. Thus the amplitude of movement will remain constant with frequency, but rising near the diaphragm resonance. The designer then contrives to introduce narrow channels and cavities in the space between the diaphragm and the fixed electrode, heavily damping the diaphragm resonance. This is roughly similar to resistance being introduced into a resonant electrical circuit to lower the "Q." Unfortunately, the "upper end" of the audio band has been moving steadily upwards over the past 30 years (and judging by some of our hi-fi amplifier specifications, is currently in the region of a megacycle!). Since sensitivity was inversely proportional to the frequency of this first fundamental resonance, plus the difficulty of stretching the fragile metal used as a diaphragm, the early microphones often had resonances as low as 8000–10,000 cps. Whilst this resonance was usually well damped, it did introduce coloration into the sound and it has been suggested that it was a contributory factor to the "steely" string tone of our early LP's. Superior diaphragm material came along with the rapid evolution of modern plastics—first polyvinyl chloride and now polyester film is in almost universal usage. Metal is rarely used, except where exceptional stability of characteristics is desired, such as accurate sound field measurement. Plastic diaphragms are rendered electrically conductive by an extremely thin film of metal, usually gold, silver, or aluminum vaporized in a vacuum and allowed to condense on the surface of the diaphragm. Only one surface is coated, that which is away from the fixed electrode. This provides a safety measure against accidental contact between diaphragm and fixed electrode, thus permitting a rather smaller gap than previously possible with metal diaphragms. The lower mass of these modern plastic foils has made it possible for the microphone designer to push the resonance to a much higher frequency, certainly well out of nuisance range and is determined almost entirely by the compliance of the air film in the cavity between the fixed electrode and diaphragm.

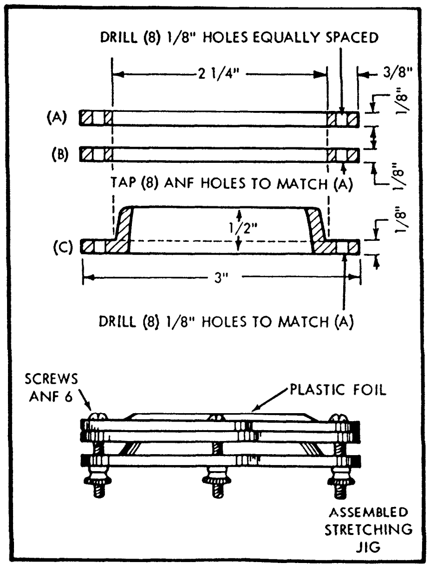


Fig. 5. Diaphragm mounting jig. Assemble by alternating ¼-in. long screws with ¾-in. long ones. Knurled nuts are screwed on the ¾-in. screws, and are used to stretch the membrane by forcing the boss on ring "C" into the plastic.

So far we have considered the function of the diaphragm and its influence on the main criterion of fidelity, frequency response, and bandwidth. There are, however, other important factors which influence the performance of a microphone —its shape and size. Ideally, the best microphone is one not there at all. This is not as nonsensical as it sounds and it is not entirely out of aesthetic consideration that modern microphones, particularly those used on TV are becoming more and more inconspicuous. A microphone literally stands in its own sound shadow, and its very presence will influence its frequency response and directional characteristics. These effects become significant when the wavelength of sound is a substantial fraction of the actual physical dimensions of the microphone. The net effect is usually to make the microphone more sensitive to the incident sound and less sensitive to reflected sound. In other words, there is a deviation from true omnidirectional characteristics and with increasing frequency to some degree of directionality. This may or may not be an advantage, dependent upon the designer's intention. With microphones designed for accurate sound field measurement, such an effect is usually undesirable and it can be

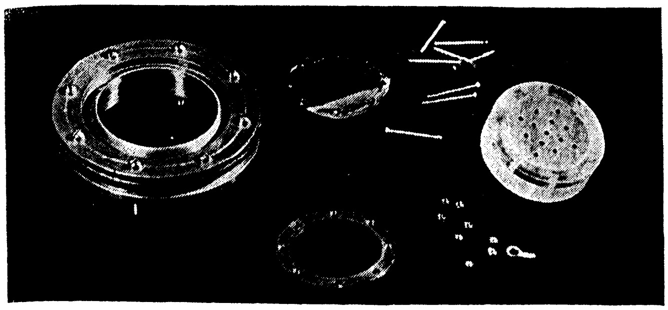


Fig. 6. A dismantled capsule with a discarded diaphragm. Assembly on left is diaphragm mounting jig.

shown that the dimensions of such a microphone should be of the order of $5/8$-in. diameter or less. However, for reasons it would take too long to go into, it has been found that complete omnidirectional characteristics are rarely desirable with, for example, orchestral music, and some degree of directionality is an advantage—say, above 5000 cps. Dimensions of 1 to $1\frac{3}{8}$-in. are common, and the attendant non-linearity can be minimized by the actual shape of the microphone. A sphere is the ideal, but does introduce construction problems, particularly for the amateur. There is also little point in designing a small microphone element unless the casing in which it is mounted has comparable dimensions. As we will see later, the casing of our prototype condenser microphone has to contain rather more than just the microphone element and as the writer has discovered, this was not amongst the least of the problems involved. A cylinder is the next favoured shape and is a satisfactory compromise, giving a reasonable performance commensurate with constructional difficulties. *Figures* 2 and 3 show the deviation from frequency linearity resulting from the two main effects know as "diffraction" and "phase loss." Graphic illustration of these effects has assumed a perfect plane wave, that is, one in which the entire wavefront is at a right angle to the direction of propagation. Such perfect plane waves in free air are rare, although the condition is approached for spherical waves at a considerable distance from the source. Also, sound never strikes a microphone from a precise angle (except in an anechoic room) but is diffused by surrounding objects, e.g. walls and so on. So it is perhaps fortunate for all microphone designers that the subjective performance of a microphone is usually far superior to that predicted in theory, otherwise an embarrassingly large proportion of the world's microphones would have been thrown out by their owners long ago!

One final consideration remains—the avoidance of cavity resonance. Any cavities in close proximity to the microphone, having dimensions comparable to wavelengths within the audio spectrum, can resonate and so modify the sound field pattern. A simple experiment can show this effect by speaking with a can held against the mouth. The hollow sound that results is caused by the absorbtion of a narrow band of frequencies within the audio spectrum. Obviously, the microphone casing itself is a possible cause of a pronounced cavity resonance and precautions must be taken against this. Effective sealing of the main body of the microphone casing against excitation by the sound field is the only method of prevention. A less obvious resonant cavity is the actual diaphragm-clamping assembly. A shallow cavity is formed of the diaphragm clamping ring, thickness (d) and its diameter (D). *Figure* 4 shows the effects of such a resonance and clearly demonstrates that for it to have negligible effect, the depth of the cavity, and thus the thickness of the clamping, ring, should not be greater than 1/10 the diameter.

Construction

We have now reached the point where the actual construction details of the prototype microphone can be examined. Whilst many of the design parameters could have been worked out mathematically beforehand, it was decided that the empirical approach would be tried first. At least, if preliminary tests proved encouraging it would be some indication whether the project was worth pursuing. (It must be admitted that the original intention was some practical demonstration to silence the "doubting Thomases" amongst the writer's fellow audiofans. All had declared the whole project harebrained—amateurs just don't *make* microphones.) A number of test microphone capsules were constructed of varying diameter, in which provision was made for adjustment of the gap depth behind the diaphragm and the size and depth of the damping holes. A series of tests were made to show the influence of any variation in these factors upon the sensitivity and frequency response. The two basic tests were free field measurement and direct excitation of the diaphragm with an electrostatic disc. These early experiments revealed that a surprising degree of latitude was permissible in actual construction details, so from the data obtained a prototype capsule was made. The diaphragm material used was polyethylene terephthalate, a polyester film of British origin, marketed under the trade name "Melinex." It can be obtained in $6\ \mu$ thickness and coated with a thin film of aluminum. (No doubt "Mylar" of similar thickness would be

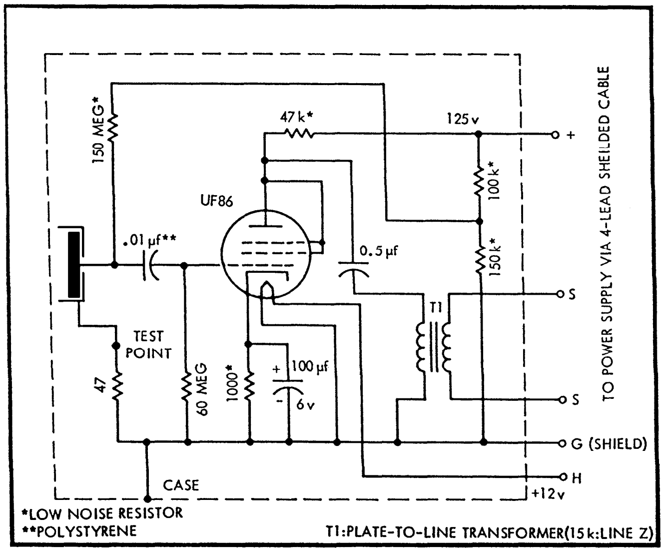
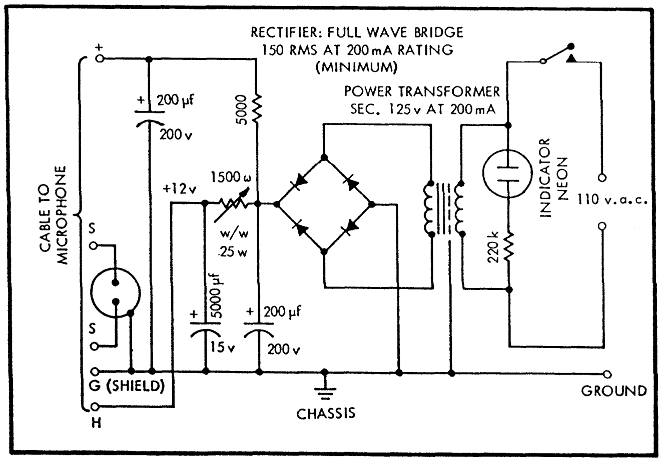


Fig. 7 (left). Schematic of microphone. Fig. 8 (below). Schematic of power supply.



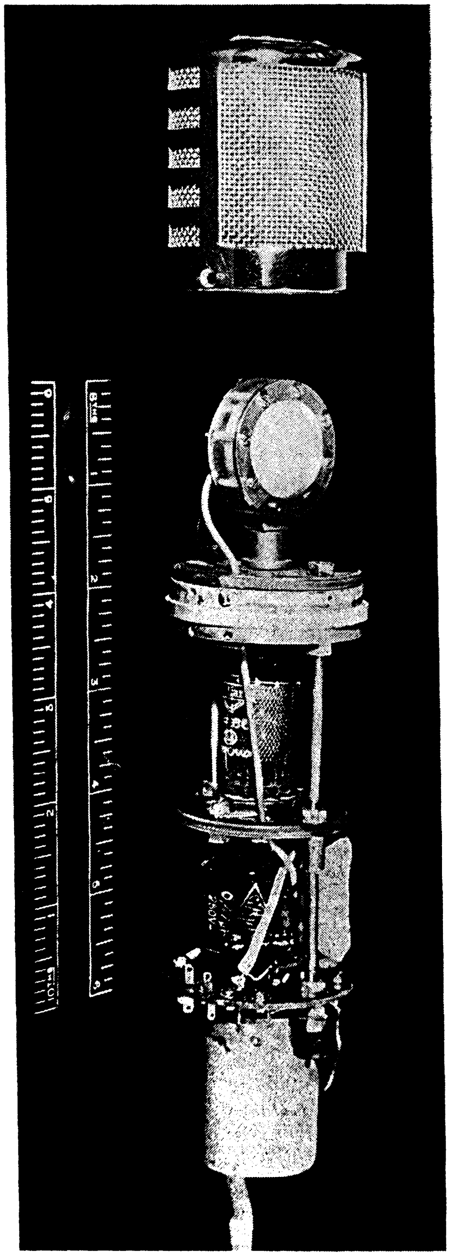


Fig. 9. Internal construction of one of the microphones. The plate-to-line transformer (balanced 30–50 ohms) is at the lower end. Note that the 2-in. diameter metal case and bottom cap are not shown.

equally satisfactory). The body of the capsule was fabricated on a lathe from one of the methacrylate plastics, "Perspex." (Again, "Plexiglas" would probably do just as well.) The clamping ring and center electrode are of brass. The construction of the capsule demands reasonable proficiency in lathe work and the simple technique adopted to provide the accurate gap between the fixed electrode, and diaphragm should be of interest. Both electrode and body are made slightly over thick, with the electrode a snug fit inside the body. A shim of 1-mil thickness is fitted behind the electrode and firmly clamped by the retaining screw into the plastic body. The face of the entire assembly is then turned down carefully in the lathe to the required dimension. Tool marks should be as little as possible, although a high polish is neither necessary or desirable. Both body and electrode are then given a minute "key" mark at the edge with a scriber and the electrode removed. With the shim discarded, the electrode is thoroughly cleaned and replaced, the "key" marks being used to ensure an identical position in the plastic body. The uniformity of the 1-mil gap can be checked visually by a steel ruler held edgewise against the surface of the plastic surround and examined whilst held up to the light. If all is well, the holes can now be drilled, again with great care, all burrs and metal particles being thoroughly cleaned away on completion. The actual diaphragm mounting technique was a minor problem and was eventually solved with a simple mounting jig (*Fig.* 5 and 6). There was some toying with the idea of a self-stretching clamping ring, but such a ring always effectively increased the diameter of the capsule. As mentioned earlier, this was undesirable and so was rejected. The plastic is clamped between the two rings, coated side upwards. The third ring with the stretching boss is carefully fitted over the four long, alternately spaced clamping screws, and the plastic very gently stretched by tightening the four knurled nuts. Stretching should be only *just* enough to remove the natural wrinkles in the plastic (which, incidentally, should be examined carefully for any minute flaws before being selected for use). It cannot be emphasized too strongly that the whole mounting process must be carried out in conditions absolutely clean and free from dust. It is admittedly difficult to create in the average amateur's workroom conditions akin to a factory "white" area, but the writer can confirm from bitter experience that the slightest particle trapped between diaphragm and electrode will eventually cause failure of the capsule and usually at the most inconvenient moment. The body of the capsule should now be held against the uncoated side of the stretched plastic and by breathing on the coated side the position of the screw holes for the clamping ring will become visible. At the same time, the surface of the diaphragm should be examined to ensure that no particles of dust or grit are trapped behind the diaphragm. If during the entire mounting procedure there is any indication of this, then the whole process *must* begin again. It is permissible to clean the surface of the electrode with a lintless cloth moistened with carbon tetrachloride, but cleaning of the plastic should be kept to a minimum, no more than a very gentle brushing with a soft sable brush.

If at this stage all is well, the diaphragm is very gently pierced with a

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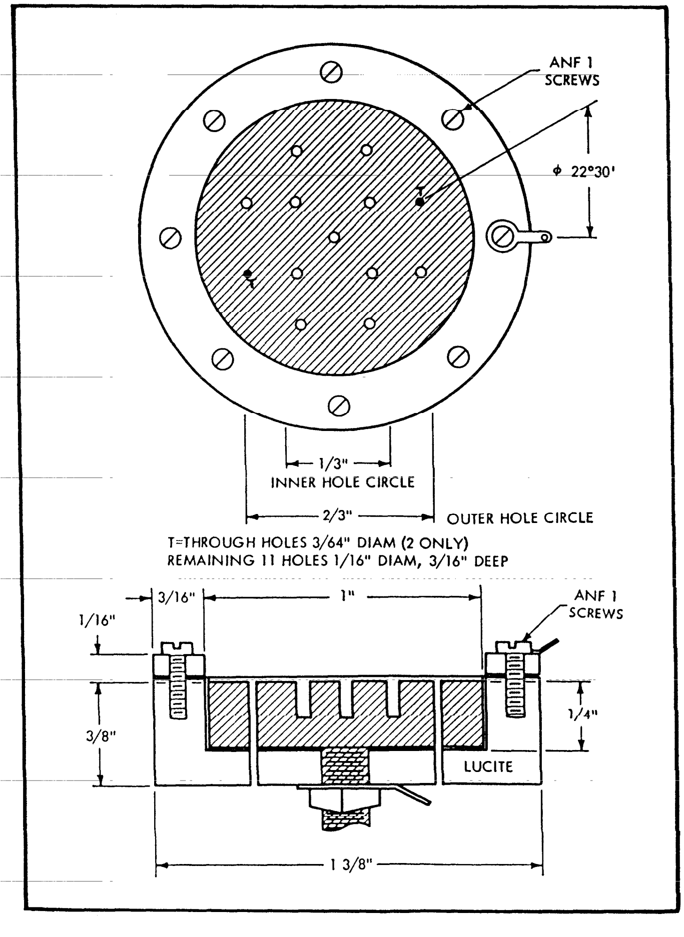

Fig. 10. Dimensions of the capsule.

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(*From page 20*)

needle over two holes on opposite sides of the capsule body. The clamping ring is then placed over the coated surface of the plastic; two screws are inserted through the holes in the ring and the plastic and carefully screwed into the body. This procedure is followed with the remaining six, inserting each screw on opposite sides of the ring. When all are fitted, each is tightened with equal firmness. The whole capsule can now be removed by cutting away from the mounting jig and trimming off the surplus plastic. At no time during this process should either surface of the plastic be touched with the fingers.

The final step is heat treatment of the mounted diaphragm. This has the effect of further shrinkage of the plastic and stabilizes the diaphragm against extremes of temperature change. A hot blast of air from a hair dryer held close to the capsule for 3 or 4 minutes is the recommended method.

Having now completed the "heart" of the microphone, attention can be given to catering to its electrical requirements. A condenser capsule of this type is almost pure capacitance and a typical value is in the region of 100 pf rising a little when the polarizing potential is applied. This is caused by electrostatic attraction between diaphragm and fixed electrode, so reducing the nominal gap. It will be appreciated that one cannot connect the capsule by ordinary cable to the terminal equipment with which it is being used. Even using coax, a substantial part of the signal can be lost due to the shunt capacitance of the cable itself. So the usual practice is a "head amplifier" in close proximity to the capsule and within the body of the microphone casing itself. Actually, the term "head amplifier" is something of a misnomer, since its prime function is to match the very high source impedance of the capsule down to a more manageable low impedance usually the familiar 30 or 600 ohms. *Figures* 7 and 8 indicate the line adopted by the writer, but should not be regarded as definitive. Although a tube of European origin was used since it was ideally suited for this particular application, there are probably a number of American alternatives. A triode with a plate resistance between 10,000 and 20,000 ohms designed for low-noise work should fit the basic requirements, and one section of a 12AY7, or its "preferred" equivalent 6072 would seem a satisfactory substitute. In this particular application, the most important factor to aim at is low noise so that, due to the high impedance in the grid circuit, d.c. "heating" is absolutely essential. It will be noted in the writer's power supply that a common B + and heater supply is used with the unwanted voltage being dropped down to the required 12 volts at 100 mA by a large preset resistor. This may seem a wasteful way of going about it and there are more conventional methods, but it does use less components than a separate heater supply, and a suitable transformer happened to be available. There is one advantage—the heater supply is from a virtually constant current source and the microphone cable can be extended at will from a short to a very long length without appreciable losses in the cable itself. With the more orthodox low-voltage heater supply, there may be fluctuations in the heater voltage due to variations in cable resistance if the length is altered. The actual polarizing voltage was determined experimentally and is in the region of 80 volts for the capsule shown. Higher potentials have little advantage; the sensitivity does not increase appreciably above a certain voltage level and there is the risk of collapse of the diaphragm from excessive electrostatic force. The choice of values for the polarizing and grid resistors warrant some mention. The recommended value for the polarizing resistor is 150 megohms and it must be a high-stability type, as indeed should all the resistors in the head amplifier. The choice of value for the grid resistor is mildly controversial. First of all, both polarizing and grid resistors are effectively in parallel with the capsule. Since the source impedance is pure capacitance at a certain low frequency, when the source impedance equals the two resistors in parallel, output will fall 3 db and thereafter at 6 db per octave. It is preferable that the polarizing resistor be as high as practicable to minimize accidental leakage currents, therefore the value of the grid resistor can ultimately determine the low-frequency response of the microphone. One school of thought suggests that, aside from low-frequency considerations, the value of the grid resistor should also be as high as practicable, on the grounds that theoretically a low noise figure results. Contrary to this, it has been found even more desirable to use the grid resistor in combination with the capacitance of the capsule as a high-pass filter and to proportion values to attenuate everything below 30 cps. The response of the capsule extends well down into the subsonic region and it is contended that nothing below 30 cps has any musical value. In fact, there is adequate proof that it can be a positive nuisance and any such sounds might even overload the amplifier in extreme cases. The capsule shown has a source capacitance of 120 pf when polarized, so a grid resistor of 60 megohms was chosen. The over-all bandwidth of the completed microphone can be checked by inserting a low value of resistor in the "ground" side of the capsule and injecting an audio signal via a relatively high resistance.

So much for the construction of the prototype microphone. *Figures* 9 and 10 show the basic construction technique adopted by the writer, with the whole assembly built turret-fashion on two threaded-metal pillars. Tube base and line transformer are mounted on circular plastic discs, suitably dimensioned to a comfortable fit in the tubular metal body. These discs are drilled and fitted withrivetted soldering lugs and, as shown, the components are wired between the two discs. The rest is dependent upon the constructor's skill at metal work and there are, no doubt, other ways of solving the construction problems involved. The important factors are avoidance of any open cavities in the microphone structure, negligible sound obstruction around the capsule and above all, very thoroughly shielding because of the exceptionally high impedance of the grid circuit at hum frequencies.

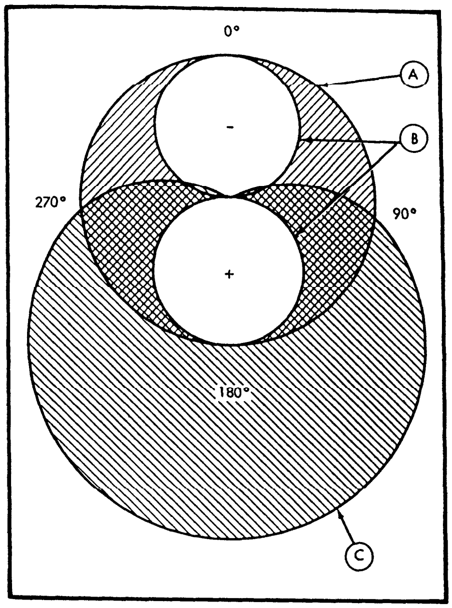

Fig. 11. Various microphone patterns: (A) circular (omnidirectional); (B) cosine (bidirectional); (C) cardioid (unidirectional), or (A) + (B).

Different Patterns

So far the microphone discussed has been of the omnidirectional type, and when the preliminary field trials confirmed its obvious superiority in fidelity over the others in the writer's microphone armory, it was frequently tempting to use it where its omnidirectional characteristics were wholly unsuitable. So back to theory and experiments with the test capsules. As shown earlier, a plane sound wave has a velocity and a pressure component and the diagram shows that each is displaced in phase from the other by 90 deg. It can be demonstrated that when the output from a pressure-sensitive microphone (e.g., a dynamic) is combined with that of a velocity sensitive microphone (e.g., a ribbon) a cardioid pattern results, assuming both outputs are equal (*Fig.* 11). (This can be proven experimentally with two microphones and a mixer; the two microphones should be very close together.) This is one way of obtaining a cardioid pattern electrically and is, in fact, the basis of at least one commercial design. With condenser microphones, the mixing is carried out acoustically and, in the single-diaphragm type, sound from the back of the capsule is allowed to reach the diaphragm via phase delay networks. These take the form of long, narrow channels through the body of the capsule. With careful proportioning of the length and diameter of the channels, the phase of the velocity component cancels the pressure force for sounds from the rear of the capsule. Thus a cardioid response results. In the capsule illustrated (*Fig.* 10) these "velocity conversion" tubes are shown and unblocked, the capsule has an excellent cardioid response. If on occasion an omnidirectional response is required, it is a simple matter to block these holes with small metal plugs. In the extensive tests since 1960 this basic design has acquitted itself admirably and in fact, quite a number have been constructed successfully. It has been tempting to continue work on the more sophisticated capsules such as the twin-diaphragm, multi-pattern types. However, experimental work is under way to try to solve some of the considerable construction difficulties of a single-diaphragm velocity capsule first. It may be possible to give details of this at a later date.

It might be asked, how does this microphone measure out by the usual objective tests? Anechoic chambers are not for the amateur, so free-field measurements have been conducted in the open air, using as a sound source the most linear tone source available—a full-range electrostatic loudspeaker. Since an accurate calibrated reference microphone was not available, results of this test cannot be regarded as highly accurate because the amplitude nonlinearity of the speaker was included. Nevertheless, the frequency response can be regarded with confidence as substantially flat from 30 cps to 16,000 cps. Total harmonic distortion measured at 200 cps was less than 1 per cent up to an extremely high volume level—in fact, the limit that could be handled by the test speaker. In the cardioid mode, the back to front discrimination was 18 db at 1000 cps and holds to this figure, or better, over a substantial part of the audio band. Finally, since most microphones are used to record music, how does it sound? In one word—superb—and more than worth the considerable work it has entailed.

In conclusion, an apology. If, in describing some of the highly complex design features of microphones generally, the writer has been guilty of over-simplification, this has been solely in the interest of brevity. Any reader wishing to pursue a more detailed (and possibly accurate!) analysis, is referred to the numerous textbooks on the subject of electroacoustics. Æ