CONDENSER MICROPHONES—A TUTORIAL

Neville Fletcher
Research School of Physical Sciences and Engineering
Australian National University
Canberra ACT 0200

ABSTRACT: This tutorial discusses the operation of several types of condenser microphone including standard omnidirectional measuring microphones, simple cardioid microphones, and studio microphones with adjustable response pattern. The physics underlying their operation is discussed, and the approach to a detailed analysis using electrical network analogs is outlined.

1. INTRODUCTION

Fifty years ago the number of microphone types in common use was very large. Dynamic microphones were the most common, and came in both omnidirectional and cardioid response patterns, but broadcasting and recording studios often used ribbon microphones, usually with figure-eight response patterns. Omnidirectional condenser microphones were in use for acoustic measurements, and were beginning to penetrate the recording and broadcasting fields. Today the situation is very different: nearly all microphones in common use are condenser types, from simple cheap microphones in telephones and other voice recorders, through studio microphones with variable response patterns, to sophisticated measuring microphones. It is the purpose of this tutorial paper to give a brief survey of these condenser microphone types and to explain their operating principles, particularly in relation to frequency response and directional pattern.

Because microphones are so fundamental to the practice of acoustics, most classic books on practical acoustics, such as those by Olson[1], Beranek[2], Kinsler et al.[3], and Rossing and Fletcher[4] have a chapter on various common microphone types and their operation. More recently there is a whole book devoted to microphones, edited by Michael Gayford[4], and a specialised book on condenser microphones of the measurement type edited by George Wong and Tony Embleton[5]. Despite this, it is not easy to find a treatment along the lines to be attempted here.

2. ELECTRIC NETWORK ANALOGS

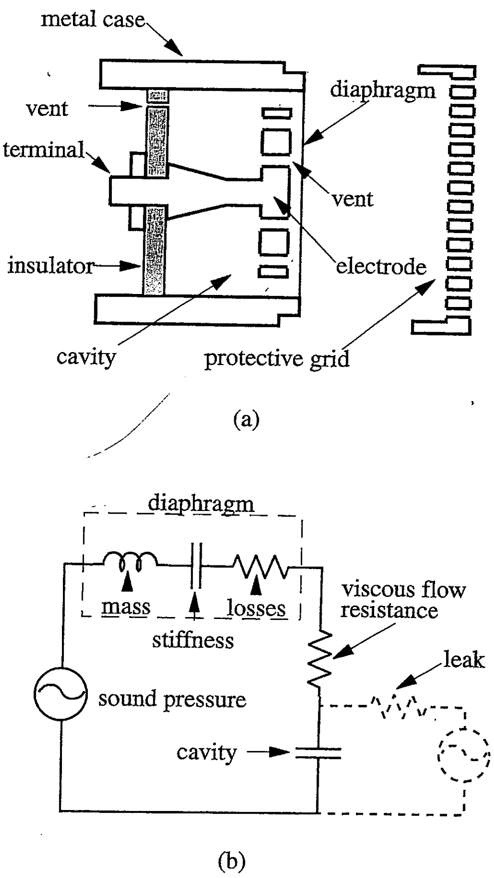
The behaviour of mechanically simple systems can usually be analysed by considering quite directly the motion of the mechanical elements when acted upon by an acoustic pressure signal. As the system becomes more complex, however, so does the analysis, and it has been found simplest to calculate this behaviour in terms of an electrical analog in which voltage V represents acoustic pressure p and electric current i represents acoustic volume flow U. (The same idea can be applied to mechanical systems by taking voltage to represent force rather than pressure, and current to represent velocity rather than volume flow, but it is simpler to use the acoustical analog from the beginning.) The one significant limitation of this approach is that it is essentially one-dimensional like the wires of an electrical circuit. More complex three-dimensional ideas have to be added later.

In this electric analog system an acoustic resistance, such as a layer of felt, becomes an electrical resistance, and Ohm's law $V=iR$ becomes the acoustic flow law $p=RU$. Similarly, a mass m that presents an area S to the acoustic pressure is represented by an electrical inductance $L=m/S^2$ and a mechanical spring by a capacitance C proportional to the compliance of the spring. A sealed cavity of volume V is represented by a capacitance of magnitude $C=V/\rho c^2$, where ρ is the density of air and c the velocity of sound in air, these relations being derived by considering the physics of the resulting motion or air flow. All the standard techniques of electrical circuit analysis can then be applied to work out the behaviour of the acoustic system being studied. In what follows we shall sometimes use these techniques, but also try to explain in physical terms what is going on.

3. MEASUREMENT MICROPHONES

An omnidirectional measuring microphone of standard design is shown schematically in Fig. 1(a). A strong thin metal diaphragm is stretched tightly over the entry to the microphone capsule and a plane insulated electrode is positioned about $20\mu m$ away from it. The capsule is sealed except for a fine capillary tube that provides a leak and prevents long-term build-up or deficit of pressure inside the capsule. The electrode is perforated by a number of holes for a reason that will become clear later.

When an oscillating acoustic pressure is applied to the outside of the diaphragm, this tends to move it towards the electrode, but the motion is resisted by the need to accelerate the mass of the diaphragm, by the diaphragm stiffness, and by the need to move air from between the diaphragm and the electrode through the vent holes and into the cavity behind the electrode. This back cavity itself has some acoustic elasticity, as noted above, and there is the vent to outside to be considered, but we ignore these for the moment. The microphone behaviour can therefore be analysed in terms of the analog circuit shown in Fig. 1(b), in which we want to calculate the current through the diaphragm impedance in terms of the applied pressure. The small extra stiffness from the air in the air enclosed in the cavity can be neglected in comparison with the diaphragm stiffness, which we do by assuming the analog cavity capacitance to be very large, and we also neglect the effect of the slow leak into the cavity, shown by the dashed-line part of the network. At low frequencies, diaphragm stiffness impedance $1/j\omega C$ is dominant over the diaphragm mass impedance $j\omega L$ and resistive losses R, and the diaphragm displacement is simply proportional to the acoustic pressure.



(a)

(b)

Figure 1. (a) Schematic diagram of an omnidirectional condenser measurement microphone. (b) Electrical analog network for the microphone in (a); the added effect of the slow leak is shown with dashed lines, since it is important only at very low frequencies.

In use, the microphone electrode is charged to a potential of perhaps 200 volts through a very large resistor (perhaps 1000 megohms). This charging may take several seconds, so that effectively the charge on the electrode is constant. The electrical capacitance C_E between the electrode and the diaphragm is $\varepsilon_0 S/d$ where S is the electrode area, d is its separation from the diaphragm, and ε_0 is the permittivity of free space. Since the charge on this electrical capacitor is fixed despite the rapid diaphragm motion, the voltage across it is inversely proportional to the capacitance C_E, and therefore proportional to the diaphragm spacing d, which follows the acoustic pressure with just a change in sign. The electrical signal will therefore be a faithful replica of the acoustic pressure signal.

At higher frequencies things get more complicated. The motion of the diaphragm must now be considered in terms of its mass, its stiffness, and the resistive losses provided by the viscosity of the air as it is forced to move between the diaphragm and the electrode. As shown in Fig. 1(b), these elements are all in series, as is plain when it is considered that each one is separately resisting the diaphragm motion, which is equivalent to the electrical current in the circuit. The circuit is that of a simple resonator with resonance frequency f^* given by $2\pi f^*=(1/LC)^{1/2}$, and quality factor $Q=mf^*/2\pi R$, where the acoustic analog values are used for L, C, and R. The existence of this resonance means that the diaphragm motion will be increased by a factor Q at the resonance frequency f^* , the width of this resonance being about f^*/Q. Above the resonance, the diaphragm response will decline by 12 dB/octave.

To make a microphone with a good flat frequency response therefore requires a high resonance frequency f^*, and sufficient damping that the response peak near f^* is not too prominent. Measurement microphones have strong metal diaphragms that can be tensioned so as to give resonance frequencies in the range 15 to 50 kHz, the higher frequencies applying to microphones of smaller diameter. The damping can be adjusted by changing the diaphragm spacing and also the diameter and spacing of the holes in the electrode so that the resonance peak is nearly eliminated, but too much damping will also reduce the response at frequencies a little below the resonance

There are a few other things to be considered in design of this simple type of microphone. The vent hole in the capsule has already been mentioned, and the addition this makes to the network is shown dotted in Fig. 1(b). If the vent has an acoustic flow resistance R_V, then the time constant for pressure equalisation within the capsule by flow through the vent is $R_V C$ where C is the acoustic analog capacitance of the cavity volume. The vent resistance is normally adjusted so that this lower cut-off frequency is about 10–20 Hz, since that is below the range of human hearing, and this prevents the microphone from being too sensitive to pressure changes from shutting doors or other influences.

The second thing is that the one-dimensional model is too simple sound can reach the microphone from different directions and this can have an effect. If the sound incidence direction is along the axis of the microphone and normal to the diaphragm, then there is no problem at low frequencies, and the microphone diaphragm samples the pressure in the acoustic wave. If, however, the diaphragm diameter were to be very large, then the wave would be reflected from it, and the pressure on the diaphragm would be doubled, an increase of 6 dB. This increase occurs when the sound wave frequency is high enough that the sound wavelength is less than the diameter of the diaphragm. At this same sort of frequency, the microphone response also becomes increasingly directional, favouring signals arriving normally from along its axis. The reason for this can be seen by examining a signal arriving at right angles to the axis and thus tangential to the diaphragm. If the wavelength is about equal to the diaphragm diameter, then half of the diaphragm will feel a positive acoustic pressure and half a negative pressure, nearly cancelling.

All these things have to be taken into account in the design of a microphone, particularly if it is to be used for precise measurements for which accuracy better than 1 dB is required over the whole frequency range. For this reason these microphones are divided into sub-classes designed for measuring either free fields or else simply acoustic pressure, which is more suitable for randomly incident sound.

4. SIMPLE MICROPHONES

A variant of the design discussed above is used in many practical microphones. The main difference is that the diaphragm is made from polymer material about 10–20 μm in thickness, and has an evaporated gold film over its central portion to make it electrically conducting. The electrode then becomes part of the microphone case, which is held at ground potential, and there is a separate connection to the metallised part of the diaphragm. The main difference that this design change makes is that, because the plastic diaphragm cannot support a large tension, its resonance frequency is only about 1–3 kHz, depending upon the diameter of the microphone. To obtain adequate frequency response it is therefore necessary to make use of the added elastic stiffness provided by the air enclosed behind the diaphragm to raise the effective resonance frequency to 15–20 kHz. In the case of measurement microphones, the diaphragm tension was so high that this extra contribution to stiffness could be neglected.

The electric analog circuit for this case is identical with that in Fig. 1(b). The difference is that the cavity stiffness can no longer be neglected and is, indeed, now much larger than the diaphragm stiffness. The circuit arrangement can be justified by the consideration that air flow caused by displacement of the diaphragm, which activates its mechanical stiffness, flows equally into the cavity, as does the electric current in the analog circuit. Analysis of the resonance behaviour is similar to that for a measurement microphone.

Use of a plastic diaphragm rather than a metallic one has another consequence. When the electrical potential is applied to activate the microphone, this imposes a mechanical stress on the diaphragm attracting it towards the electrode. In the case of a measuring microphone with a metallic diaphragm this causes very little displacement because the diaphragm tension is so high, but for a plastic diaphragm the normal displacement is perhaps as great as 5–10μm. It can further be shown that, if this displacement exceeds about one fifth of the total separation between diaphragm and electrode, then the diaphragm will collapse against the electrode and the microphone will become inoperative. For this reason, the electrical polarising voltage used in a microphone of this type is generally much less than in a measurement microphone, and the initial diaphragm separation is larger, which decreases the sensitivity.

One further feature used in some of these microphones is to do away with the external polarising voltage altogether and use instead an electret film deposited on the surface of the electrode, or sometimes built into the diaphragm itself. The great advantage of not requiring an external power supply makes electret microphones ideal for portable apparatus and also reduces the overall cost. The only disadvantage is that the polarisation of the electret material gradually changes with time, so that the microphone sensitivity is less stable than for an externally powered design.

5. DIRECTIONAL MICROPHONES

The simplest sort of directional microphone is the pressure-gradient design. Suppose that sound is allowed equal access to both sides of the diaphragm and that the entry ports to the two sides are a distance d apart. Then if a sound wave of amplitude p and frequency f is incident at an angle θ to the axis of the microphone, the pressure tending to move the diaphragm is $p_1 - p_2$ where

$$p_1 = p\exp(jkd/2); \quad p_2 = p\exp(-jkd/2) \qquad (1)$$

with $k = 2\pi f/c$ and $j = \sqrt{(-1)}$. If the separation between the two ports is much less than the sound wavelength, then $p_1 - p_2 \approx jpkd$. If we extend this model to sound coming in at an angle θ to the microphone axis, then the effective distance between the two ports is not d but rather $d\cos\theta$, and the amplitude of diaphragm motion is proportional to $pkd\cos\theta$, so that the microphone has a figure eight or $\cos^2\theta$ directional response. Such a microphone thus responds to the component of the acoustic pressure gradient parallel to its axis, and has a response proportional to f and thus rising with frequency at 6 dB/octave unless some other design feature enters. We shall see later what this is.

There is another feature of ideal pressure-gradient microphones that should be noted. Since a spreading spherical pressure wave has a form like $p(r) = (1/r)\, e^{j(\omega t - kr)}$, differentiating this to find the gradient inserts a factor $[1 + (kr)^{-1}]$ relative to a plane wave and so gives a strong bass boost if $kr < 1$, which means within about $\lambda/2\pi$ of the source. This boost must be corrected for, or at least recognised.

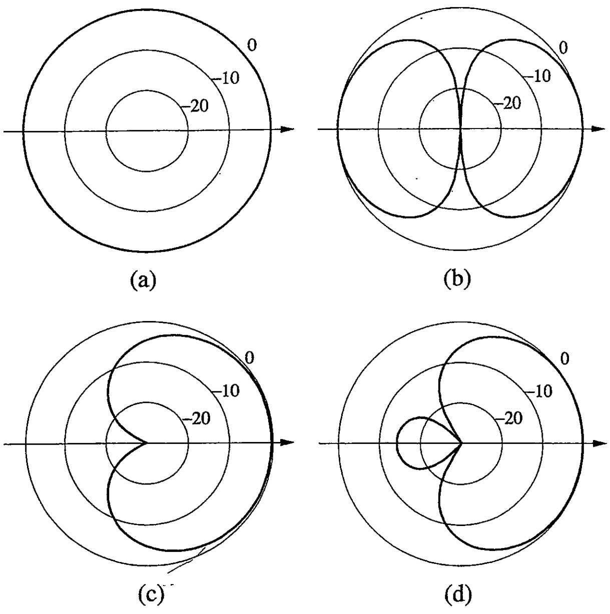
6. CARDIOID MICROPHONES

A figure-eight directional response is sometimes useful, but more often the requirement is for a response concentrated in the forward direction along the microphone axis. If some way could be found to combine the response pattern of a pressure-gradient microphone with that of a simple pressure microphone, then the result would be

$$p(A + B\cos\theta) \qquad (2)$$

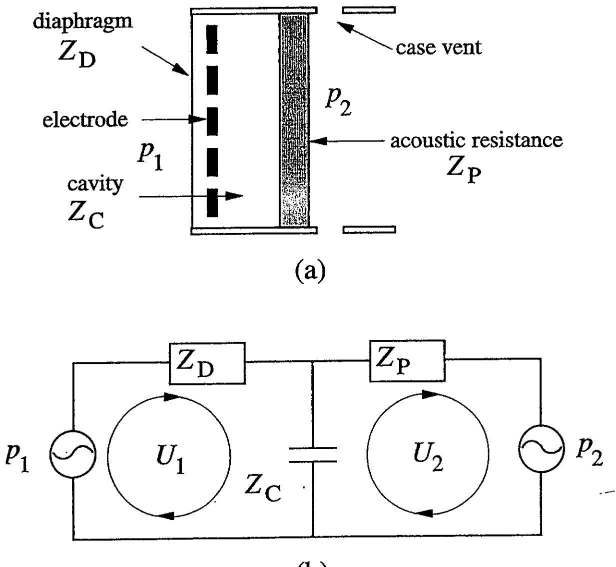
where A and B are constants. If the value of B/A could be varied, then a variety of directional patterns could be achieved, ranging from omnidirectional for $B = 0$ to figure-eight for $A = 0$ and with a particular cardioid (heart-shaped) pattern for $B = A$. These possibilities, plotted on a polar decibel scale, are shown in Fig. 2. The one remaining problem is the frequency dependence of the gradient response, which would cause the pattern to be omnidirectional at low frequencies and gradient-like at high frequencies because the pressure gradient at a given pressure amplitude increases with increasing frequency as shown by (1).

A solution to all these problems is given by the design in Fig. 3(a). Here we see the cavity behind the perforated electrode of a simple microphone vented to the surroundings through some sort of partition with an acoustic impedance Z_P. If Z_D is the acoustic impedance of the diaphragm and Z_C that of the cavity, both of which we have discussed before, then the whole microphone can be represented by the network analog shown in Fig. 3(b). The topology of the network can be understood by considering the paths by which acoustic volume moves from one component to anotherif the same flow moves through each, then they must be in series, while if the flows



(a) (b) (c) (d)

Figure 2. Response patterns obtainable by varying the constant A in equation (2): (a) omnidirectional when $B = 0$; (b) figure-eight when $B/A >> 1$; cardioid when $B/A = 1$; (c) a form of hypercardioid when $B/A = 1.5$. Relative levels are in decibels in all cases.



(a)

(b)

Figure 3. (a) Design of a simple cardioid microphone.
(b) Analog network circuit for this microphone.

combine then they must be in parallel. Solution of this network is simple, and the calculated value of the acoustic volume flow through the diaphragm, caused by its movement, is

$$U = [Z_P p_1 + Z_C(p_1 - p_2)]\,[Z_P Z_D + Z_P Z_C + Z_C Z_D]^{-1} \qquad (3)$$

where p_1 and p_2 have the form given in (1). If the impedance Z_P of the partition is made a simple resistance R, then the numerator of this expression, which is the only part containing the angular factor $\cos\theta$, takes the simple form $R + d\cos\theta/cC$, where C is the analog capacitance of the cavity. This is of just the form in equation (2), and the response can be made cardioid in form by arranging that $R = d/cC$, the frequency dependence of this part of (2) cancelling out. The denominator of (3) is nearly inversely proportional to frequency over most of the operating range, so that U is nearly proportional to frequency and the diaphragm displacement is nearly independent of frequency, as it should be for a flat response. Because it is not possible to vary the various impedances once the microphone has been built, its directional characteristic, generally either cardioid or hypercardioid, is fixed at the design stage.

Looked at physically, what happens is that, if the partition is simply resistive, then the pressure acting on the inside of the diaphragm for a given sound wave amplitude varies inversely with frequency above the value of $1/RC$ for the cavity, and this cancels out the frequency-dependent rise in the magnitude of the pressure gradient, giving a constant response amplitude and pattern. This no longer holds for frequencies below $1/RC$, when the internal pressure approaches the external pressure and the response declines.

7. STUDIO MICROPHONES

The final type of microphone to be discussed is the studio microphone, which generally has a response characteristic that can be varied between all the patterns shown in Fig. 3. The general idea, developed more than thirty years ago, is essentially to mount two condenser microphones back-to-back with some sort of acoustic coupling between them, and then to control the directional response by varying the voltages applied to the two diaphragms.

Figure 4(a) shows the design of a traditional studio microphone. The electrodes are made of thick metal with cavities to provide acoustic stiffness to the plastic diaphragm, and about half of these cavities lead through small holes to the thin central space which provides a resistive coupling between the two microphone elements. We can identify two basic modes for this microphone. In the first the two diaphragms move inwards together so that there is no flow through the central space, and the response is essentially to the pressure signal at the mid-point of the microphone axis. In the second mode, one diaphragm moves in while the other moves out, and the main impedance to the motion is the resistance of the central space through which the acoustic current must flow. The response in this case is to the difference between the pressures on the two diaphragms, and thus to the gradient of the acoustic wave pressure. If the diaphragm tension is low, so that the impedance to motion is largely that of air flow through the central resistance, then the diaphragm velocities will be proportional to the pressure gradient and their displacements will have a $(\text{frequency})^{-1}$ factor that cancels out the frequency factor in the gradient, thus giving a flat response for the figure-eight pattern.

In the accompanying electric preamplifier, the two diaphragms are connected to a differential input. If, therefore, the polarising voltages on the two diaphragms are equal, the response to a simple pressure signal will be zero, but the response to a gradient signal will be a maximum. Conversely,

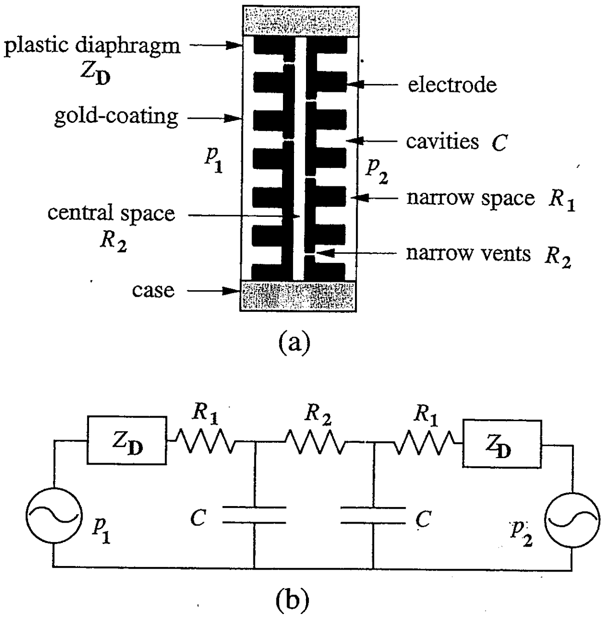


Figure 4. (a) Design of a simple studio microphone.
(b) The analog circuit

if the polarising voltages are equal and opposite, then the gradient response will be zero and the pressure response will be at a maximum. Somewhere in between, perhaps with one voltage nearly equal to zero, the response will have a cardioid pattern.

Fig. 4(b) shows the analog circuit for this microphone from which the motion of the two diaphragms under the influence of a signal at angle θ to the microphone axis can be calculated, and the design parameters varied to give the desired frequency response and directional pattern. Solution of the network equations is straightforward but algebraically a little complicated, since there are three separate meshes to the network, implying three equations, and each is complex so is really two separate equations. Nevertheless these equations were solved long ago and microphone designs with excellent frequency response and directional characteristics were produced. Some of these designs, with improved manufacturing and the use of transistor rather than valve preamplifiers, are now widely sought after in the recording industry. The microphone capsule, of course, is mounted within a metal mesh enclosure, both to provide mechanical protection and also to reduce breath noise.

8. CONCLUSION

There has been space in this review to consider only the basic types of microphone design, and even within this limited field there is an immense amount of technical variation, from large studio microphones with double capsules up to 30 mm in diameter to tiny microphones for in-ear hearing aids with diameter less than 2 mm. Diaphragms of thin taut metal and of much softer plastic have been mentioned, but some microphones now use diaphragms etched out of crystals of silicon so that they can be in close proximity to components of the electronic circuit. With sight and hearing providing the primary sensory links between humans and the environment, the development of new microphone types is bound to continue.

REFERENCES

1. H.C.F. Olson, *Acoustical Engineering*, (Van Nostrand, Princeton NJ 1947).
2. L.L. Beranek, *Acoustics*, (McGraw-Hill, New York 1954, reprinted by the Acoustical Society of America, New York 1986).
3. L.E. Kinsler, A.R. Frey, A.B. Coppens and J.V. Sanders *Fundamentals of Acoustics*, third edition (Wiley, New York 1982).
4. T.D. Rossing and N.H. Fletcher, *Principles of Vibration and Sound*, second edition, (Springer-Verlag, New York, in press for 2003)
5. M. Gayford (editor) *Microphone Engineering Handbook*, (Focal Press, Butterworth-Heinemann, Oxford 1994).
6. G.S.K. Wong and T.F.W. Embleton (editors), *AIP Handbook of Condenser Microphones*, (American Institute of Physics, New York 1995).