NEW LOW-NOISE TRANSISTOR CIRCUIT FOR ELECTROSTATIC MICROPHONES

By P. J. BAXANDALL, B.Sc.(Eng.)

Amplitude-modulated R.F. Bridge Method with Many Advantages

THE conventional way of using an electrostatic (or condenser) microphone is shown, in its simplest form, in Fig. 1. The resistance R is made so large that, even at low audio frequencies, insufficient current can flow into or out of the microphone capacitance C, during one audio cycle, to cause a significant alteration in the stored charge Q. Since Q=CV, it follows that if Q is kept constant, the voltage V across the capacitance must vary when acoustic pressure causes C to vary. With the values shown, the response will be 3 dB down at about 30 c/s. From the point of view of signal-to-noise ratio, however, it is advantageous to use an even higher value of
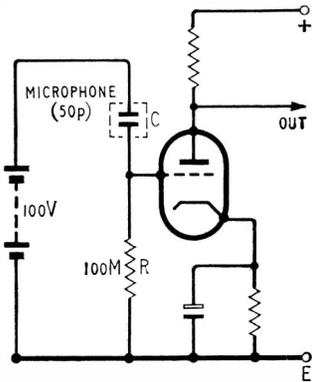

Fig. 1. Conventional electrostatic microphone circuit.

resistance than that dictated by the required low-frequency response.

When, in 1957, the writer first considered the problem of using an electrostatic microphone with purely transistor circuitry, it was quite obvious that the impedances involved in a circuit of the Fig. 1 type were far too high for it to be practicable simply to replace the valve by a transistor.*

However, by operating the electrostatic microphone element in a radio-frequency circuit, so that its capacitance variations are caused to modulate an r.f. carrier, the above-mentioned high impedances

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* It is interesting to reflect, however, that the notion of transistorizing the Fig. 1 circuit now seems to be much more nearly a satisfactory practical proposition than it did in 1957. This is because some types of silicon planar transistor are now available which will operate satisfactorily, in very high impedance circuits, at collector currents of a small fraction of a microamp.

Whilst the signal-to-noise ratio obtainable when using such a transistor in the Fig. 1 type of circuit would probably be rather inferior to that given by a valve, there are signs that other amplifying devices may in due course become available which will overcome this limitation. One such device is the insulated-gate field effect transistor (ref. 1) and another is the insulator valve (ref. 2).

are completely avoided and a very good performance can then be obtained with semiconductor circuits.

The general idea of using radio-frequency circuits for electrostatic microphones is, of course, quite old, and both frequency modulation and amplitude modulation have been employed.

F.m. systems have the disadvantage that random noise f.m. on the oscillator output inevitably gives rise to noise at the audio output terminals. Since the wanted f.m. is usually of quite small deviation, this noise f.m. can prevent the overall noise performance from being up to the highest professional standards.

In an a.m. system, however, by using a balanced bridge circuit, random noise modulation of the oscillator may be prevented from reaching the audio output terminals, and it was mainly for this reason that the author rejected f.m. systems right at the beginning and concentrated on a.m. bridge circuits—and if a bridge was to be used, then there was everything to be said for employing the transformer ratio arm principle first proposed by A. D. Blumlein.

R.F. Bridge Circuit

The broad outline of the system adopted is, then, to have a radio-frequency oscillator with a centre-tapped output winding, the microphone element and a capacitor of equal value being connected in series across this winding, forming a bridge network. An r.f. out-of-balance voltage is then obtained between the junction of the capacitances and the winding centre tap, of magnitude dependent on variations in the microphone capacitance with acoustic pressure. This amplitude-modulated r.f. voltage is subsequently demodulated to recover the wanted audio signal.

In the first experiments, the centre tap of the oscillator winding was earthed and the bridge output was tuned to parallel resonance by an inductor to earth from the junction of the capacitances. This output was fed straight to a diode detector, the bridge being set slightly out of balance to give some carrier output and thus ensure linear demodulation. Quite encouraging results were obtained, though it was found important to select the right type of diode if excessive detector-circuit noise was to be avoided. Ordinary point-contact diodes were hopelessly noisy, but G.E.C. EW78 silicon junction diodes (now obsolete) gave consistently good results (10 samples tried), the noise output then being only slightly above the thermal noise level.

It was soon realized, however, that by employing a proper phase-sensitive detector and operating the
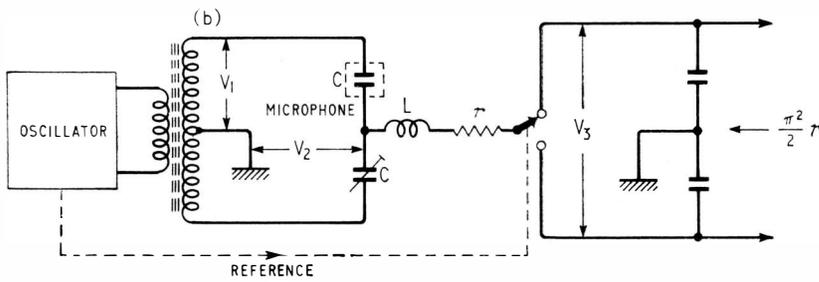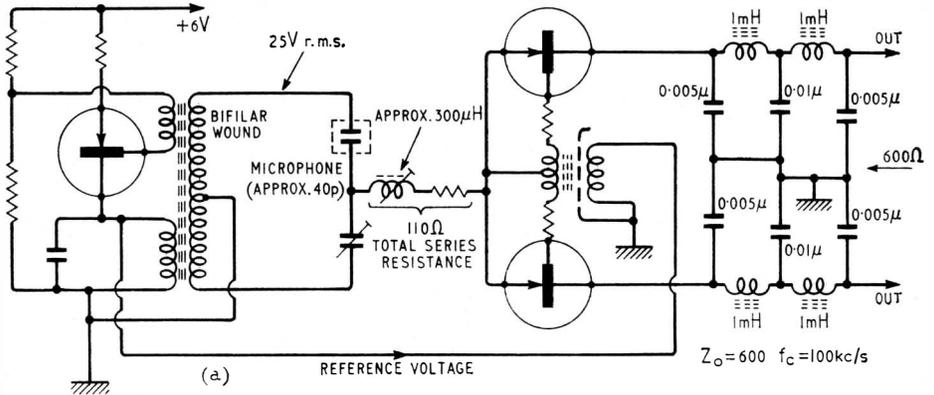
Fig. 2. The author's system:—(a) Complete experimental circuit. (b) Simplified diagram to show principle.

bridge in a nominally balanced state, larger long-term drifts in the bridge balance could be tolerated and the possibility of degradation of the noise performance by oscillator noise would be reduced.

It was further realized that by using series instead of shunt tuning of the bridge output, and by employing transistors as low-impedance switches in the phase-sensitive rectifier, the output impedance could be made low (e.g., 600 ohms), and balanced, without the need for an audio transformer in the microphone. Also it was expected that the noise performance would be excellent. For these reasons experiments on circuits using diode detectors were discontinued.

Fig. 2(a) shows the essential features of the circuit finally adopted. This circuit was first successfully demonstrated in July, 1959, and is the subject of British Patent Application No. 6118/61.

Starting at the left-hand side, there is a single-transistor 1-Mc/s oscillator. This circuit was chosen as being the simplest that would do the job. It takes about 5 mA at 6 volts, and operates in class B. By using class C operation, the efficiency could have been improved, but an extra capacitor would have been required in the emitter circuit—and one of the considerations is that every component saved is a help when it comes to building the circuit inside a small microphone casing.

The output winding of the oscillator is bifilar, so as to obtain very tight coupling between the two halves and thus to ensure that the voltages at the two ends will be very accurately in antiphase. The two halves of this winding form two arms of a bridge, the microphone and an air-dielectric trimmer forming the other two arms.

If the bridge is slightly unbalanced, owing to a change in microphone capacitance, a small 1 Mc/s sine-wave voltage will appear at the junction of the capacitances, and will have a magnitude proportional to the change in microphone capacitance. The phase of the voltage will change by 180° as the bridge swings through the balanced condition. Thus, assuming the bridge to be perfectly balanced initially, the output waveform will be that of a suppressed carrier radio transmission when the microphone is acted upon by sound waves.

A very important point is that, looking back into the bridge output, the above modulated r.f. waveform comes from a source of quite low internal impedance, i.e., the reactance of the two capacitances in parallel, which is about 1,500 ohms—very different from the values of many megohms associated with conventional circuits.

Advantages of Tuning the Bridge Output:—By series tuning the bridge output by means of the inductor shown, the impedance seen looking into the right-hand terminal of the inductor is made even lower—Q times lower, in fact—but the bridge output e.m.f. is the same as before. Now, for a given e.m.f., the lower the internal impedance of the source of the e.m.f., the greater is the available power. The fact that in this system the tuned bridge, regarded as a source of modulated r.f. output signal, has such a low internal impedance, is the main reason for the excellent signal-to-noise ratio obtainable.

Of course, if there were no resistive losses, that is if the Q were infinite, the internal impedance of the tuned bridge would become zero, and infinite signal power would theoretically be available, at least for very slow changes in microphone capacitance.

In a practical microphone system the Q of the

series tuned circuit must not be made too high, otherwise the response of the system at high audio frequencies will be reduced, owing to sideband cutting, just as in a radio receiver. The resistor shown in series with the tuning inductor limits the Q to an appropriate value, in the region of 15.[*]

The rest of the circuit is concerned with the demodulating process, which is carried out by a simple phase-sensitive rectifier employing two junction transistors.

These transistors are used simply as on-off switches, which are operated by a reference voltage derived from the oscillator and fed in between their bases and emitters through the transformer shown. When a transistor is driven "on" at its base, it becomes capable of passing current in either direction between emitter and collector, or, in other words, it can function as a *bidirectional switch*. This is a great advantage possessed by transistors, as compared with valves.

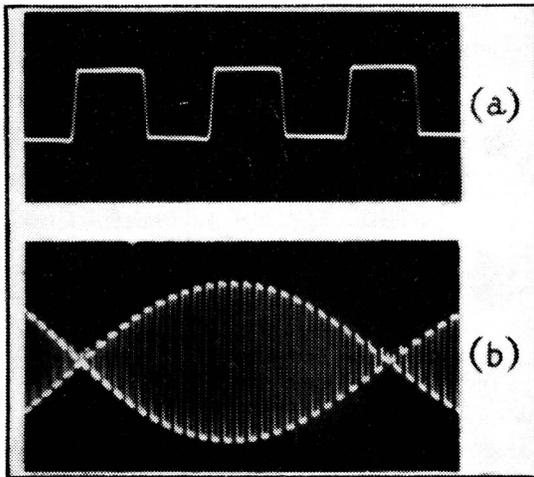Thus the two transistors, driven alternately into conduction by the 1 Mc/s reference voltage, per-

Fig. 3. Phase-sensitive-rectifier emitter-voltage waveforms:—(a) 1.5 V d.c. applied to output terminals. (b) 20 kc/s sine-wave voltage applied to output terminals.

form the same function as the two-way switch shown in the simplified diagram of Fig. 2(b).

Consider one instant of time at which current is flowing from left to right in the inductor of Fig. 2(b), the switch being supposed, at this instant, to be in the position shown. Then, while this condition holds, the tendency will be for the top plate of the top reservoir capacitor to be charged positively. During the next half cycle current will be flowing from right to left, but the switch will have changed over to the lower contact, so that the tendency will now be to charge the lower plate of the lower reservoir capacitor negatively, and so on.

* If the microphone amplifier input impedance is high compared with the output impedance of the microphone, then the resistor may be omitted without loss of h.f. response and with an improvement in signal-to-noise ratio. The d.c. input resistance of the amplifier is likely to be almost zero, however, owing to the input transformer, and if the damping resistor is omitted, a very small amount of unbalance of the bridge will give a large rectified current. For this reason it is considered better to retain the damping resistor even if an amplifier with a high a.c. input impedance is used.

Thus, all the time, the action of the circuit will be to tend to make the top output terminal positive with respect to the bottom one. It is easy to see that, if the bridge is unbalanced in the opposite direction, giving 180° difference in the phasing of the inductor current with respect to the operation of the switch, then the opposite polarity of d.c. output is produced.

Some Practical Points:—During most of the experimental work the circuit was exactly as shown in Fig. 2(a). No special arrangements were made for adjusting the phasing of the signal and reference in the phase-sensitive rectifier, though a slight phase adjustment is available by slightly detuning the series tuned circuit.

Later on, to improve the linearity of the demodulation process, the drive voltage to the base of each of the switching transistors was increased by about a factor of two, up to 3.5V r.m.s. This exceeds the base-to-emitter voltage rating of the transistors used, so two miniature point-contact diodes were added to prevent driving the bases too far positive. Small capacitors were shunted across the base resistors, now 4.7kΩ, to give a small reference-phase correction, thus allowing the series tuned circuit to be set exactly at series resonance. These measures improved the linearity at the expense of a small loss of signal-to-noise ratio. The measured results given later in this article were obtained with these modifications present, but the simpler arrangement is thought more appropriate for general use.

It may well be asked why the oscillator frequency was made 1 Mc/s, and several considerations were, in fact, involved. The frequency must be high enough to give a good noise performance and a conveniently low output impedance. A high frequency also makes r.f. filtering easier—the filter must have negligible attenuation at the highest audio frequency and 100 dB or so at the carrier frequency. On the other hand, the higher the carrier frequency the more difficult it becomes to get a really clean performance from the switching transistors. One has a natural bias towards round numbers and 1 Mc/s seems about as good a choice as can be made.

The procedure adopted for setting the circuit up correctly is the following. A 0-1 mA meter is connected across the phase-sensitive rectifier output, and the bridge is set slightly unbalanced to give a small reading on this meter. The slug of the tuning inductor is then adjusted for a maximum milliammeter reading. Finally the bridge is balanced for zero reading.

Sensitivity of Microphone Circuit:—With reference to Fig. 2(b), the no-load r.f. output voltage of the bridge is given by:—

$$\hat{V}_2 = \frac{\hat{V}_1}{2} \times \frac{\delta C}{C} \quad \ldots \qquad \ldots \qquad \ldots \qquad (1)$$

where δC is the amount by which the microphone capacitance departs from its balanced value.

With no audio load on the final output terminals, no power can be supplied to the input of the phase-sensitive rectifier, since there is nowhere for it to go. Consequently V_3 must be such that the peak value of the fundamental component of the square wave on the switch is equal to $\hat{V}_2$, thus giving zero

current in L and r. This leads to the result:—

$$V_3 = \frac{V_1 \pi}{4} \times \frac{\delta C}{C} \dots \qquad \dots \qquad \dots \qquad (2)$$

In this equation V_3 may be regarded as the peak audio output e.m.f., δC being the peak value of the capacitance variation.

Audio Output Impedance:—It is interesting to consider what will be the audio output impedance seen looking back into the output terminals of the phase-sensitive rectifier. All we need to do is to determine how much direct current flows in the output leads as a result of applying a direct voltage, V_{dc}, to the output terminals. The ratio of the voltage to the current will be the output impedance, at low audio frequencies at least.

With V_{dc} between the two switch contacts (Fig. 2(b)), the waveform on the moving contact of the switch will be a square wave of peak-to-peak value V_{dc}. Owing to the selectivity of the r.f. tuned circuit, only the fundamental component of this square wave will be significant in causing r.f. current to flow in the tuned circuit, and the peak value of the fundamental component of a square wave is $4/\pi$ times the peak value of the square wave itself.

Thus we can calculate the current flowing in the series tuned circuit, and the power dissipated by it in the series loss resistance. This power must be supplied by the d.c. source connected to the output terminals, and there is nowhere else where the power supplied can be dissipated. Thus, by equating $V_{dc} I_{dc}$ to the power dissipated in the series loss resistance of the tuned circuit, we may find I_{dc} and hence the output impedance. Doing this in detail gives the result:—

$$\left[Z_{out} \right]_{LF} = \frac{\pi^2}{2} r \dots \qquad \dots \qquad \dots \qquad (3)$$

where $[Z_{out}]_{LF}$ is the output impedance at low audio frequencies and r is the total series loss resistance of the tuned circuit.

At higher audio frequencies things are more complicated, because the sidebands are then well separated from the frequency to which the tuned circuit is tuned (1 Mc/s), and the current in the tuned circuit is affected by its reactance as well as by the series loss resistance. Allowing for this, the total output impedance looks like a resistance of $\frac{1}{2} \pi^2 r$ in series with an inductance; the reactance of this inductance is equal to the resistance at an audio frequency equal to half the bandwidth of the tuned circuit. The inductive component is fairly

negligible, even at 15 kc/s, in the design adopted, owing to the low Q of the tuned circuit.

Provided sufficiently fast transistors are used in the phase-sensitive rectifier, the measured sensitivity and output impedance agree quite closely with the calculated values. Semiconductors Ltd. surface-barrier transistors, type SB240, were chosen. OC44s were used in the earliest experiments, and whereas these did produce results, the waveforms were far from the simple theoretical ones which would be produced by an ideal switch, and the output impedance was considerably lower than the calculated value.

The photographed waveforms shown in Fig. 3 show that quite fast switching action occurs. For these waveforms the tuned circuit was disconnected from the input terminal of the phase-sensitive rectifier and a high-speed oscilloscope was connected to this input point. The top waveform, a 1 Mc/s square wave, was obtained with a 1.5 V dry cell connected to the output terminals of the phase-sensitive rectifier. For the lower waveform, the dry cell was replaced by a 20kc/s sine wave from an oscillator.

Low-pass Filter:—Referring to Fig. 2(a) again, it will be seen that a low-pass filter is included between the phase-sensitive rectifier and the outgoing microphone line. This is to prevent r.f. currents getting out onto the microphone cable, and to prevent r.f. signals from elsewhere, picked up by the cable for example, getting back into the microphone circuits. This filter is very necessary, as otherwise objectionable heterodyne whistles could be generated under some conditions. The design of the filter is, however, very uncritical—it must have little effect on the audio-frequency response, but must have a very large attenuation at 1 Mc/s and above. The cut-off frequency has been made 100 kc/s, and no close-tolerance components are required. The attenuation at 1 Mc/s is about 100 dB, which is comfortably sufficient. The inductors were wound on $\frac{1}{2}$ in outside diameter ferrite toroids, and have so few turns that they can be quickly wound by hand, whilst the capacitors are small metallized paper ones, the maximum value being 0.01 μF.

Constructional Aspects

For the experimental work on this system, the circuit was built in the manner shown in the accompanying photographs, no attempt being made to produce a compact layout. All the components
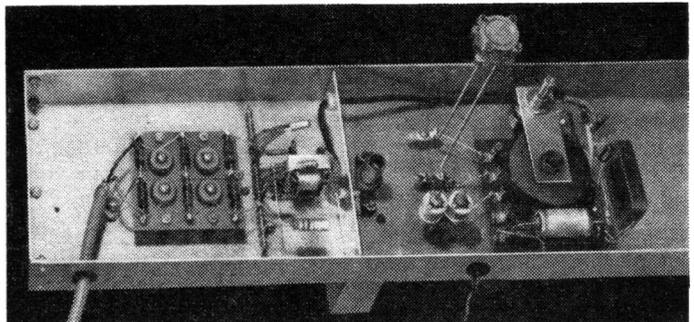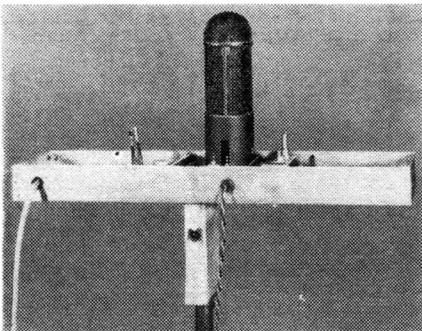
Two views of the microphone with its associated oscillator, phase-sensitive rectifier and r.f. filter.
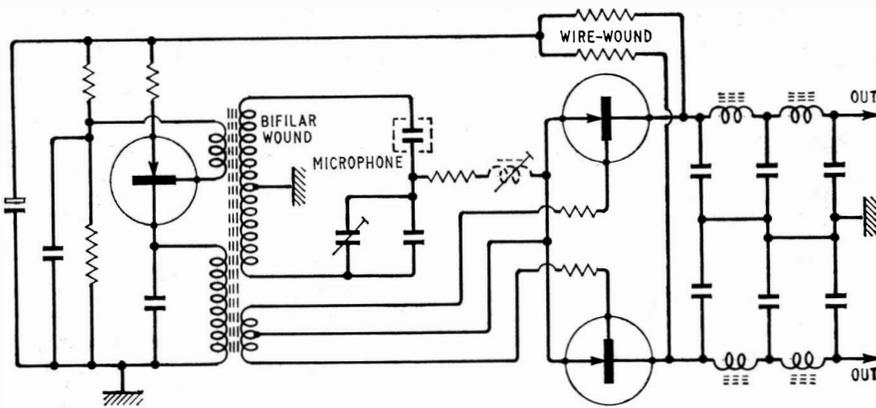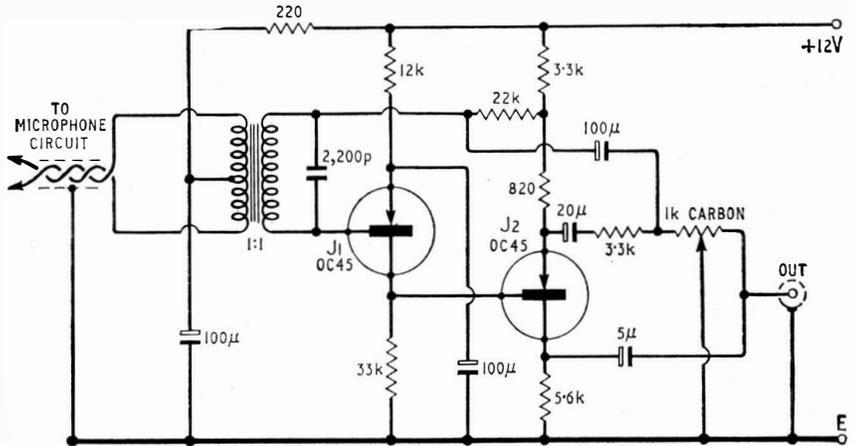
Fig. 4. Final microphone circuit.

Fig. 5. Microphone amplifier.

employed can be of very small physical size, however, thus permitting the final version to be built inside a microphone casing $\frac{3}{4}$ in diameter and 6 in long. The smallest size of Mullard "red series" Vinkor is very satisfactory for the oscillator coil.

D. C. Supply via Signal Cable:—In the early stages of the work, the d.c. supply for the oscillator was fed in along a separate pair of wires from those used for conveying the audio-frequency output—the wires may be seen in the photographs. More recently, however, the d.c. supply has been fed in along the audio frequency cable, the necessary arrangements for doing this being shown in Figs. 4 and 5, for the microphone circuit and the microphone amplifier circuit respectively. The amplifier is that described in reference (3), suitably modified to apply the required d.c. voltage to the incoming line. The amplifier will give an output of 10 mV r.m.s. for any input between 0.15 mV r.m.s. and 150 mV r.m.s., the harmonic distortion being under 0.2% throughout the whole of this 60 dB range.

With this scheme the only microphone cable required is an ordinary twisted and screened pair, such as might be used, say, with a moving-coil microphone—and it may be made up to at least 100 yards long if required with no appreciable difference in performance.

It will also be seen, in the Fig. 4 circuit, that the

separate transformer originally used for feeding the reference voltage to the phase-sensitive rectifier has been eliminated, an appropriate centre-tapped winding being added to the oscillator transformer.

(*To be continued*)

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"Wireless World Diary"

THE answers to 1,001 technical and general questions (from addresses of U.K. and overseas organizations to television standards and from u.h.f. television frequencies to valve and transistor connections) will be found in the 80-page reference section of the 1964 "*Wireless World* Diary". Now in its 46th year of publication the Diary —giving a week to an opening—is published by T. J. & J. Smith Ltd., and is available from newsagents and booksellers or direct from this office. It costs 5s 6d in rexine or 7s 6d in morocco leather, including purchase tax. Overseas prices are 4s 8d and 6s 5d and postage is 4d.

NEW LOW-NOISE TRANSISTOR CIRCUIT FOR ELECTROSTATIC MICROPHONES

Measurements of Frequency Response, Linearity, Noise and Sensitivity

　　　　By P. J. BAXANDALL, B.Sc.(Eng.)

IT is important to distinguish between the frequency response of the microphone element itself, and the frequency response of the associated circuit.

To measure the circuit frequency response, one wants, in effect, to cause one of the two capacitances in the r.f. bridge to vary, at audio frequency, uniformly throughout the audio band. This, fortunately, is quite easy to do, by exploiting the fact that the capacitance of a back-biased junction diode is voltage dependent.

The circuit arrangement employed is shown in Fig. 6. The two 0.5pF capacitors and the diode form a capacitive potential divider network which feeds an additional reactive current to the bridge output point, the magnitude of this current being varied at audio frequency by the changing diode capacitance. The effect is just the same as if one of the normal bridge capacitances was varied at audio frequency.

The frequency response obtained in this manner was well within $\pm$ 1 dB over the whole audio spectrum, up to 15 kc/s, on open circuit, on short circuit or on a 600-ohm resistive load.

It was interesting to observe that, when using a valve amplifier with a 1:10 input transformer, unloaded on the secondary side, the response was about 0.5 dB up at 10 kc/s but had returned to its low-frequency level again at 15 kc/s, whereas this same amplifier when fed from a resistive 600 ohm source showed no rise and was 0.5 dB down at 15 kc/s. This is due to the effect of the series inductive component of the output impedance of the microphone circuit in association with the shunt capacitance of the transformer. If desired the microphone output impedance could be rendered more purely resistive by the addition of a suitable series combination of C and R across the output terminals.

The frequency response of the complete system, including the microphone element, for a constant alternating pressure on the diaphragm, may be obtained in the manner shown in Fig. 7.

The centre tap of the bridge transformer, instead of being directly earthed, is here earthed at r.f. only, via a capacitor. A d.c. polarizing voltage, from a battery, is applied, and on this is superimposed an
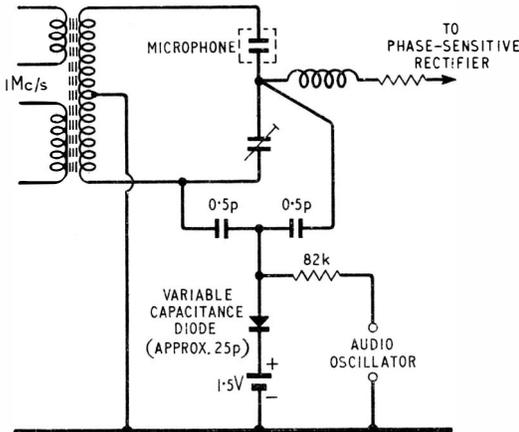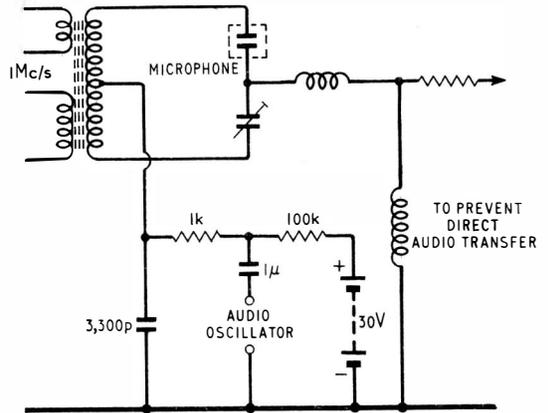

Fig. 7. Set-up for overall frequency-response measurement.

audio voltage from an oscillator. The d.c. polarizing voltage causes a force of attraction between the diaphragm and the back electrode, and the effect of the very much smaller audio voltage is to cause this force to vary almost perfectly sinusoidally at the oscillator frequency. This results in an audio output from the microphone circuit just as if the diaphragm were actuated by a constant acoustic alternating pressure.

In practice it was found desirable, however, to take one precaution, which was to add, temporarily, a small choke (about 100 μH) to earth at the phase-sensitive rectifier input, as shown in Fig. 7. Without this, there was significant direct transfer of audio frequency signals at high audio frequencies, which gave misleading results.

Fig. 8 shows the frequency response obtained

Fig. 6. Set-up for circuit frequency-response measurement.

using the Fig. 7 set-up. This is, of course, a rather poor frequency response for a microphone, but the reader will not be surprised at this on hearing that the microphone element used for these experiments is of pre-war vintage!

Microphone Characteristics

It is interesting to consider the main features of the Fig. 8 response curve. The main resonance occurs at 7.3 kc/s, and is very underdamped. There is also evidence of a higher-frequency resonant mode at just over 10 kc/s. The gradual change in response at lower frequencies is thought to be probably due to a changeover from isothermal to adiabatic operation of the air behind the diaphragm with rising frequency. Most of the diaphragm stiffness in this design appears to be provided by the air behind the diaphragm rather than by the diaphragm tension, so that one would expect the stiffness at low audio frequencies to be less than that at higher frequencies by a factor equal to the ratio of the specific heat of air at constant pressure to that at constant volume. This ratio is 1.4, and would give a change in response of approximately 3 dB, which is, in fact, about what is observed.

The response curve of Fig. 8 may be taken, with slight reservations, to be the response curve of the microphone as normally used. The reservations are concerned with the fact that the method of measurement does not take into account diffraction effects at high frequencies (ref. 4), where the dimensions of the microphone element are not negligible compared with a wavelength, nor does it take into account the possibility of acoustical or mechanical resonances in the microphone casing. However, in view of the very small size of the omnidirectional element here used, and the unobstructive nature of the wire-mesh casing, these effects would be expected to be small.

To improve the sound quality obtainable, an equalizer circuit was added to the microphone amplifier to compensate for both the resonant peak and the smooth change in level at lower frequencies. The overall response is then level, within ± 2 dB, up to 12 kc/s.

Audibly, the main effect of adding the equalizer is to remove the excessive sibilants on speech, leaving the reproduction smooth and pleasant—not lacking top, but without its previous artificial rustle and glitter. Various recordings which have been made with the equalized microphone, of piano, harpsichord, organ, brass band and choir, have led to the belief that, for an omnidirectional microphone, the performance leaves little if anything to be desired.

Linearity Measurements

The amplitude linearity may be investigated in a very simple manner, because this microphone system has a response extending down to zero frequency. All one has to do is to change the capacitance on one side of the bridge circuit by small known amounts and measure the d.c. output by means of a meter across the output terminals.

The result of such a measurement, with a 600-ohm load on the output, is shown in Fig. 9. An equally good characteristic was obtained with the microphone on open circuit, but on measuring the output current with almost zero load resistance, a slight trace of non-linearity was observable at the extreme limits of the curve.
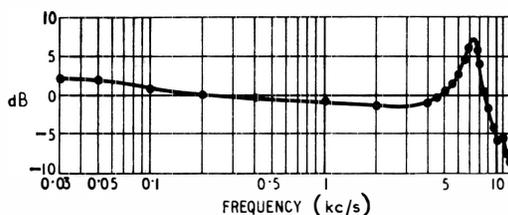

Fig. 8. Overall frequency response of microphone system, without equalization.

It should be emphasized that under almost all conditions of use only an extremely small part of the Fig. 9 characteristic is traversed. Ordinary conversational speech at a foot or two corresponds to about 1 dyne/cm^2 alternating pressure, and this causes, with a typical modern electrostatic microphone element, a capacitance change in the region of 0.001 pF. Such a small capacitance change is virtually invisible on the scale to which Fig. 9 is plotted.

The small capacitance changes required for determining the Fig. 9 characteristic were obtained by means of a small Philips concentric ("milkcan") trimmer. A fine pencil mark was made on the rotor of this, a series of such marks being made on the stator. The capacitance with the rotor mark opposite each stator mark was then determined on a capacitance bridge; the capacitor, thus calibrated, was returned to the microphone circuit.

Noise Measurements

The results of some measurements made to determine the noise performance of the microphone circuit are shown in Fig. 10. For these measurements the microphone element was replaced by a trimmer, so as to avoid acoustically picked up noise and mechanical thermal noise generated within the element. The noise (unweighted) was measured using a low-noise valve amplifier, thermocouple and galvanometer, over a bandwidth (determined by sharp-cutting filters) extending from approximately 400 c/s to 15 kc/s.

From the top curves in Fig. 10 it will be seen that the noise is very dependent on the degree of unbalance of the bridge circuit, particularly when the oscillator is operated with the transistor not bottoming. This is quite reasonable, because the effect of allowing the collector to bottom is to clamp the tuned circuit voltage to a well-determined amplitude once per cycle. When there is no bottoming, the amplitude is free to wander about in a random manner, under the influence of transistor and thermal noise, giving rise to greatly increased "a.m. noise".

Curve B in Fig. 10 (a) has been plotted, it will be seen, on a decibel scale, 0dB representing the noise output which would be produced if the only source of noise were Johnson noise in the 600-ohm resistive component of the microphone output impedance

In Fig. 10 (b), the same curve has been replotted on a different basis—the vertical quantity here is really the extra noise *voltage* resulting from unbalancing the bridge. This discloses the true nature of the effect; all that is happening is that, as the bridge is more and more unbalanced, more and

more noise from the oscillator is let through, in direct proportion to the degree of unbalance.

Phase-sensitive Rectifier Noise:—It will be seen from Fig. 10 that, *with the bridge perfectly balanced,* there is more noise when the oscillator is bottoming than when it is not bottoming.

Now the absence of bottoming, achieved by suitably increasing the oscillator emitter resistance, is accompanied by a reduction in the oscillator output voltage and hence in the reference voltage fed to the phase-sensitive rectifier. It seems, therefore, that some of the observed noise is generated by the phase-sensitive rectifier transistors and that this noise is reduced if the reference voltage is reduced.

An independent test, in which the reference voltage was varied by other means, also showed a reduction in noise output for a decrease in reference voltage.

At first sight, since a reduction in reference voltage will make the switching operation slower, i.e., less nearly ideal, one might well expect a poorer, rather than a better, noise performance.

In an entirely separate experiment, a 600-ohm resistor was connected across the primary of the input transformer of a low-noise audio-frequency valve amplifier. The emitter and collector of an SB240 transistor (as used in the phase-sensitive rectifier) were also connected across this circuit, provision being made for varying the d.c. bias voltage applied, via a 4.7kΩ series resistor, between the base and emitter.

The noise input to the amplifier with the transistor biased off on its base was found to be virtually just the Johnson noise from the 600-ohm resistor. As the transistor was slowly turned on by bringing the base negative to the emitter, the noise

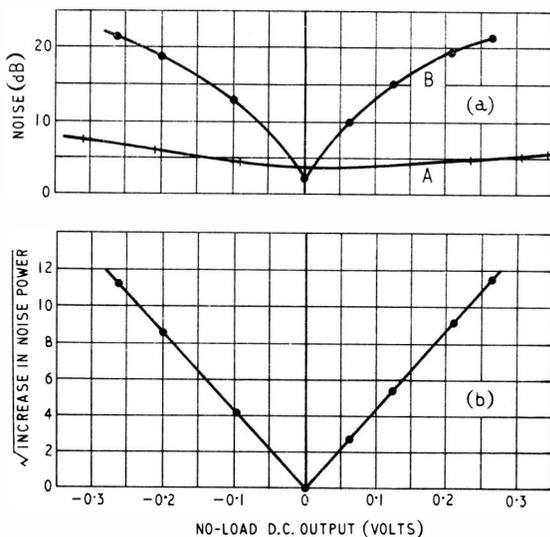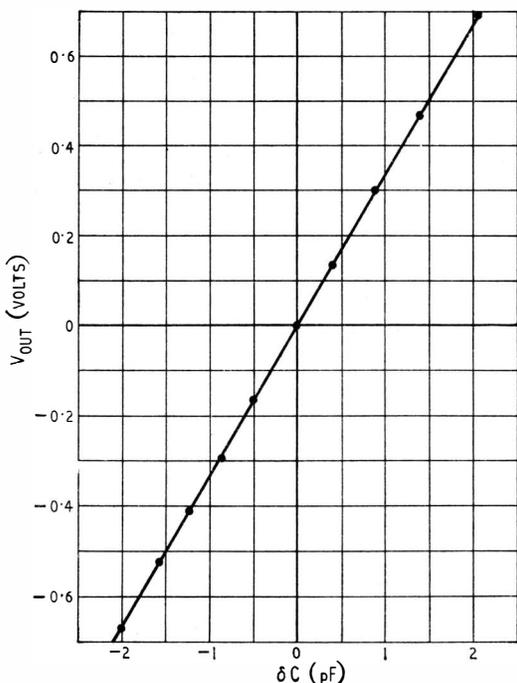*Fig. 9. $V_{out}/\delta C$ characteristic for microphone circuit, with 600Ω load.*

Fig. 10. Variation of noise output with bridge unbalance. Zero dB in (a) is equivalent to 600Ω Johnson noise.

output fell smoothly until, by the time a small fraction of a milliamp of base current was flowing, the noise input to the amplifier corresponded to the Johnson noise from a resistance of well under 100 ohms.

It would thus seem that the mechanism of noise generation within the phase-sensitive rectifier cannot be explained on a simple low-frequency basis and that it evidently operates only when the switching is done at radio frequency.

A possible clue lies in the further experimental observation that if a small d.c. e.m.f. is introduced in series with the collector lead in the above experiment, tending to make the collector negative, then the noise reaches many times the Johnson noise level if the base is sufficiently negative to make the transistor conduct but insufficiently negative to bottom it—under these conditions the transistor is simply functioning as an amplifier. It could well be that, in the phase-sensitive rectifier, when allowance is made for the effect of hole-storage delay time, a condition may be established, during a small part of the cycle of operations, in which the transistor is in an active amplifying state, with enough negative voltage between collector and base to make it give amplified noise output.

A good deal of further investigation would be necessary, however, to gain a full understanding of the mechanism involved.

Overall Noise Performance:—Even though the noise introduced by the phase-sensitive rectifier is not, in its present state, completely negligible, it must, nevertheless, be emphasized that the overall noise performance of the system is extremely good—indeed it is potentially much better than can be achieved using the conventional valve technique. Some relevant points are:—

(a) The unweighted noise output of the present system, over the frequency band 400 c/s to 15,000 c/s, corresponds to a sound pressure about 23dB above 0.0002 dynes/cm². (Expressed in less scientific terms, the sound of the author's wrist watch ticking, under sufficiently

quiet ambient conditions, can be picked up at five feet from the microphone, using the transistor microphone amplifier of Fig. 5!)

(b) The microphone element used in these experiments is of lower sensitivity than some more modern ones. The capacitance between the diaphragm and the back electrode constitutes only about half the total capacitance, and the latter varies by less than 1 in 10^5 per dyne/cm^2. A capacitance change in 3 parts in 10^5 per dyne/cm^2 is probably more typical of modern electrostatic microphones, and the circuit noise when using one of these elements in the present circuit would be in the region of 13dB above 0.0002 dynes/cm^2.

(c) The pressure equivalent of the circuit noise may be reduced by a further 12dB or so, so that it becomes about equal to 0.0002 dynes/cm^2, by raising the bridge voltage from its present value of about 25 V r.m.s. to 100 V r.m.s. However, by this time, it is evident from reference (5) that most of the noise output from the system would no longer be that generated by the electrical circuit, but would come from the thermal agitation of the air particles behind the diaphragm. No significant further improvement in noise performance is then possible except by modification of the mechanical design of the microphone element. The only beneficial modifications which are possible are either to reduce the viscous damping resistance acting on the diaphragm or to increase the area of the diaphragm. Reduction of damping can only be effected without introducing a peaky response if the diaphragm mass is correspondingly reduced.

(d) A further reduction in the pressure equivalent of the circuit noise can in theory be achieved by raising the oscillator frequency. If the frequency is doubled, the bridge reactances are halved and the tuned circuit series resistance may be divided by four for the same bandwidth. Thus we obtain the same signal voltage from a quarter of the impedance and have an improvement of 6dB in signal-to-noise ratio. In practice, unless better transistors are used, the noise performance of the phase-sensitive rectifier may well fall off with increasing frequency, which will offset some of the improvement otherwise gained. Since better and better transistors are tending to become available at lower and lower prices, however, this is not a serious problem in the long run.

(e) If, by the above means, the noise output caused by mechanical thermal agitation is made well above the Johnson noise level in the microphone amplifier input circuit, then the noise contribution from the amplifier will be negligible even though the amplifier may not have a particularly good noise factor. This is a very attractive feature of the system.

Electroacoustical Sensitivity

To express the noise level of the microphone as an equivalent acoustical noise pressure acting on the diaphragm, as has been done above, it is necessary to determine the sensitivity of the microphone in mV/dyne/cm^2.

The set-up of Fig. 7 enables the sensitivity to be determined in a very straightforward manner, provided the value of the capacitance between the microphone diaphragm and the back electrode is known and provided the construction is such that the electrode covers substantially the whole of the diaphragm area. This latter requirement was satisfied with the element used, and it was also possible to slide the electrode block inside the outer casing, after slackening four screws, thus withdrawing it from the diaphragm. Quite a small movement reduced the capacitance between diaphragm and electrode to a fairly negligible value and thus enabled the remaining, inactive, part of the total microphone capacitance to be determined approximately by measurement. By subtracting this inactive capacitance from the total measured under normal conditions, the capacitance between the electrode and the diaphragm, with normal spacing, was deduced to be approximately 22 pF.

Referring to Fig. 7, it may be shown that:—

$$P_{ac} = V_{ac} \times \frac{V_{pol}C^2}{A^2} \times \frac{4 \times 0.9}{10^5} \quad \ldots \quad (4)$$

where: P_{ac} = a.c. pressure on diaphragm (dynes/cm^2.)

$\quad V_{ac}$ = a.c. audio-frequency voltage applied (P_{ac} will be r.m.s. if V_{ac} is r.m.s.)

$\quad$ C = capacitance between diaphragm and electrode in pF.

$\quad$ A = electrode area in cm^2.

$\quad P_{pol}$ = polarizing potential in volts.

As an alternative to determining the active capacitance, it would be possible to determine dP/dV_{pol} for constant "d.c." output voltage from the microphone circuit, a small known steady air pressure being applied to the diaphragm by means of a close-fitting cup. This method should be capable of good accuracy, and does not assume that the fixed electrode covers the whole diaphragm area.

Advantages and Disadvantages of the New Microphone System

The system described in this article has the following advantages:—

(a) Relative insensitivity to damp. With the conventional valve circuit, as originally supplied with the microphone element used in these experiments, the effect of breathing heavily into the inside of the microphone casing was quite drastic—a succession of loud crackles and wheezing sounds occurred for many seconds afterwards. On subjecting the transistor system to the same treatment, however, there is almost no trace of such effects.

(b) Superior signal-to-noise ratio.

(c) Very low magnetic hum pick-up, since there is no audio transformer in the microphone; a balanced output is provided, however.

(d) Uses ordinary twin-core screened microphone cable.

(e) The microphone and its amplifier may be operated from a single, typically 12-volt, dry battery.

(f) The possibility of noises caused by valve microphony is eliminated.

There are, however, certain disadvantages, which it is important not to overlook:—

(a) The system is more complex to build and to adjust correctly.

(b) It is desirable, to avoid degradation of signal-to-noise ratio, that the two capacitances in the bridge should remain equal to within about 1% under all ambient conditions and preferably throughout many years of hard use; whereas in the conventional valve system capacitance stability is of little consequence.

For professional applications, a temperature range of, say, 0°C to 80°C may have to be coped with. The low temperature might apply if the microphone had been out in a cold van in winter time immediately before use, and the high temperature if it came accidentally into the beam of a television spot-light.

The requirement is for a temperature coefficient of the capacitance on one side of the bridge with respect to that on the other not exceeding about 120 parts in 10^6 per degree Centigrade. This is a conservative estimate and one might be able to allow up to 200 parts in $10^6/°C$ in practice. It is not a particularly stringent requirement, but must be faced up to. A cardioid microphone element would probably present the greatest difficulty in this respect, since it must employ quite low diaphragm tension. One is helped out, however, by the fact that quite a low r.f. polarizing voltage can be used, giving only a small electrostatic deformation of the diaphragm and consequently only a small capacitance change. A bi-directional (figure-of-eight) element presents less of a problem, since its two capacitances would be connected on opposite sides of the bridge, giving a large measure of cancellation of the effects of unwanted capacitance changes.

(c) The insulation in the element should be of low loss *at radio frequency*, otherwise the bridge output will contain an appreciable quadrature component when set as near as possible to balance. Too large a quadrature component will degrade the performance and make the setting-up adjustments much more difficult to carry out properly. There would appear to be no difficulty in satisfying this requirement, however.

(d) If a plastic diaphragm is used the conducting coating on the diaphragm must be reliably continuous since any tendency for some small area to become erratically detached electrically from the main area would give rise to crackling noises. This effect would not happen with the conventional method of use.

Other Work on Similar Lines

Whilst the system here described was developed quite independently of other work in the same field—indeed in regrettable ignorance of the fact that such work was going on—references (6) and (7) show that a very similar train of thought and activity has been pursued in Holland.

The paper by J. J. Zaalberg van Zelst describes an r.f. amplitude-modulation system using valve circuits and shows a detailed appreciation of the factors influencing the noise performance of such systems.

The much more recent paper by G. F. J. Arends describes a fully engineered system, in use in the Hilversum broadcasting studios, which has much in common with that described above, but which differs in the following details:—

(a) A two-diode peak-rectifying phase-sensitive rectifier is employed, with OA91 diodes. This gives an unbalanced output and a small audio transformer is normally included to convert this to a balanced signal for feeding the cable. The transformer also functions as an r.f. filter, the carrier frequency being 2 Mc/s.

(b) The bridge output circuit is untuned. With a given element and a given r.f. polarizing voltage, the noise performance of the circuit must, therefore, be considerably inferior to the author's. Nevertheless the overall noise performance of the microphone is evidently very satisfactory, and the elimination of the tuning adjustment is a convenient simplification.

(c) One side of the microphone element is earthed, the r.f. transformer centre tap being live at r.f. The present author preferred to keep the centre-tap earthed, thus preventing the transformer winding capacitances from affecting the conditions for bridge balance. It is admittedly convenient, mechanically, to have one side of the microphone element earthed, however.

Acknowledgements

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7. "Eine Kondensatormikrophonschaltung mit Halbleiter, Modell OV 442". Laboratory Report No. 396, Nederlandsche Radio Unie, Hilversum. (This is in German. The original Dutch article by G. F. J. Arends appears in the Nederlandsche Radio Unie journal "*Omroep-technische Mededelingen*" for Feb. 15th, 1961. Unfortunately no English version appears to be available).

8. "Acoustical Techniques and Transducers", book by M. L. Gayford (S.T.C.), published by Macdonald & Evans Ltd. This useful book gives much information on electrostatic microphones, including numerous references.