April 23, 1940. B. BAUMZWEIGER 2,198,424

MICROPHONE APPARATUS

Filed Nov. 4, 1937

Fig. 4.

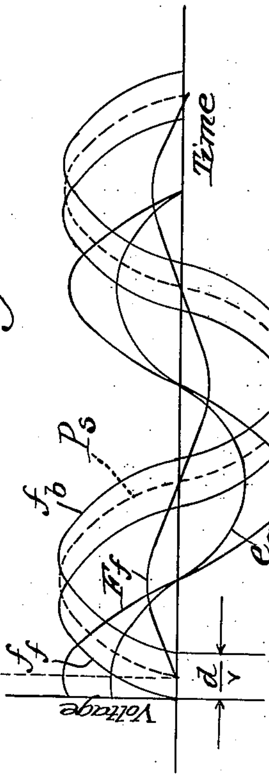


Fig. 1.

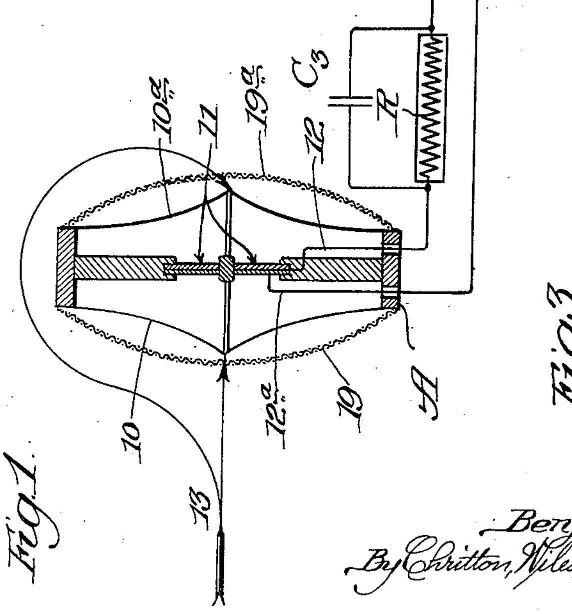


Fig. 2.

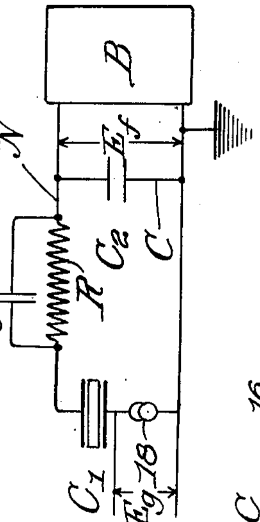


Fig. 3.

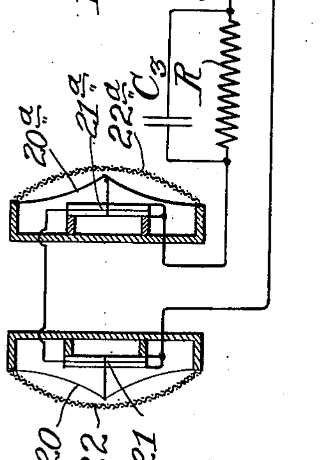
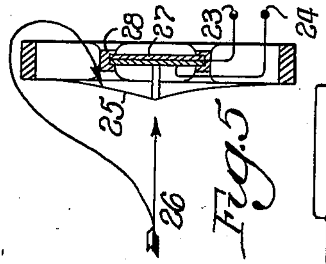


Fig. 5.



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Patented Apr. 23, 1940 **2,198,424**

UNITED STATES PATENT OFFICE

2,198,424

MICROPHONE APPARATUS

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Application November 4, 1937, Serial No. 172,840

5 Claims. (Cl. 179—1)

This invention relates to microphone apparatus and relates more particularly to a microphone device which employs a stiffness-controlled acoustical-electrical transducer and is sensitive to sound approaching from specific directions.

In many acoustical applications, it is useful to have a microphone which is sensitive to sound waves incident upon it from specific directions and which will become notably less sensitive to sound waves incident upon it from other directions. Such a result may be accomplished by providing an acoustical-electrical transducer which is actuated by the difference of pressures existing at two regions in space.

If two points in space are in line with the direction of motion of the sound wave, the pressures at these points will in general be unequal because of the variations of pressure along the line of propagation of a sound wave, and the difference in these pressures may be converted into differences in electrical potential by a suitable transducer. However, if the sound wave is made to strike such a transducer from one side (perpendicular to a line between the points above referred to), the pressures at each of the points are the same at all times and their difference is zero. In the case of sound waves approaching from directions between the two extremes above mentioned, the pressure differences will vary as the cosine of the angle of incidence. It may be noted that sound waves approaching from the front or rear sides of the microphone will be effective while those approaching from either side will not.

It is well known in the art that the ribbon type transducer having a mass-controlled movable element may be employed for such bi-directional use. It is also known that the stiffness-controlled transducer such as the piezo-electric or crystal type may be actuated through the difference in pressure between two points and is, therefore, under these conditions, bi-directional. But especially in the use of the crystal type of transducer, there is a notable discrimination in favor of the higher frequencies. It will be shown later that, over a wide range of frequency, the pressure difference increases with increase of frequency of a constant-pressure sound wave. This variation of pressure difference due to change in frequency has made the use of the crystal transducer in the bi-directional microphone heretofore impracticable.

In the past, some attempts have been made to use a bi-directional microphone having a crystal transducer in combination with an amplifier system which system in itself discriminates in favor of the lower frequencies. This compensating means requires special amplifying equipment and therefore limits the use of the microphone to purposes where such equipment is available.

In my invention simple and adequate means are provided for elimination of discrimination in favor of the higher frequencies encountered in pressure-difference operated stiffness-controlled transducers. Thus the microphone of my invention employing stiffness-controlled elements is capable of being used with the standard amplifying equipment in common use. A more specific object is to provide a microphone which employs an electrical network for rendering the electrical output of the transducer free from discrimination.

Another object is to provide a relatively large directional transducer which would have a relatively high sensitivity, while retaining good frequency response. Such increase in sensitivity makes it unnecessary to provide extremely high gain in associated amplifying equipment. In most directional microphones previously known to the art the transducing element has had at least one important dimension small in size compared with the shortest wave-length to be received in order to achieve a sufficiently uniform frequency response, resulting in undesirably low sensitivity.

Still another object is to provide a transducer substantially pressure-operated at frequencies for which the wave-length of sound is of the same magnitude, or smaller than twice the distance between the pressure-difference elements, yet capable of retaining its directional properties.

Yet another object is to provide simple means which will correct for the excessive pressure-gradient common to low frequency spherical sound-waves.

A further object is to provide a stiffness-controlled microphone which will deliver an effective voltage which is substantially in phase with sound-pressures at the transducer. In stiffness-controlled microphones which are actuated by pressure-difference, the generated voltage is out of phase with the pressure of the sound-wave, and means is desired which will correct for this phase shift over a substantial part of the audible-frequency spectrum.

Still another object is to provide means for reducing the effect upon the delivered voltage of changes in the internal impedance of the transducer due to changes in its ambient temperature. Other specific objects will become apparent as the specification proceeds.

An embodiment of my invention is illustrated in the accompanying drawing in which—

Figure 1 is a diagrammatic view showing a transducer in cross section and indicating the electrical circuit; Fig. 2, a diagram of the equivalent electrical circuit; Fig 3, a diagrammatic view of a modification; Fig. 4, a graphical representation of phase relations; and Fig. 5, a diagrammatic view showing the form of transducer illustrated in Fig. 1 but employing a single diaphragm.

As illustrated in Fig. 1, A designates an acoustical-electrical transducer; B, receiving apparatus to which the effective voltage of the microphone is delivered; and N, an electrical network associated with the transducer, the purpose of which will be apparent as the specification proceeds.

I prefer to use an acoustical-electrical transducer A of the piezo-electric type. As here shown, two diaphragms **10** and **10**^{a} are employed, one at the front side and the other at the back side of the transducer. Each of diaphragms **10** and **10**^{a} is mechanically connected at its driving point to the piezo-electric crystal **11** and is adapted to exert varying stresses upon the crystal upon movement back and forth, thus generating a voltage Eg, due to strain in the crystal. Conductors **12** and **12**^{a} connect the crystal **11** with the rest of the associated electrical elements, thus allowing the voltage E_g to establish electrical current in the combined electrical circuit.

The diaphragms **10** and **10**^{a} are shown associated with acoustical networks **19** and **19**^{a}. These networks are provided for the purpose of nclosing cavities, damping resonances, and otherwise affecting the volume-velocity of the sound-wave at different points of the frequency spectrum, and can be made in addition to serve as a protecting element for the internal mechanism of the transducer. These networks may be located at any suitable position relative to the transducer.

From inspection of Fig. 1 it is seen that forces due to positive sound-pressure upon the diaphragms are in such a direction that their effects upon the crystal **11** are subtractive. Instead of acting subtractively together upon one crystal, it is possible to allow each diaphragm to act upon its own crystal, and to subtract the voltages generated in the individual crystals.

It is evident that such a transducer is not operative when the total force, due to the sound-pressure upon diaphragm **10**, is equal in magnitude and phase to the force due to sound-pressure on diaphragm **10**^{a}, such as is the case for sound waves traveling in a direction parallel with a plane perpendicular to and bisecting the line joining the acoustic centers of the diaphragms. This plane is herein defined as the "plane of symmetry" of the transducer, and is the plane of minimum sensitivity.

Thus a sound-wave approaching the transducer in a direction parallel with the plane of symmetry will act upon the diaphragms **10** and **10**^{a} in an exactly similar manner because for every element of force due to the action of the sound pressure upon an elementary area of the diaphragm **10** there will be at the same time an exactly equal element of force on the corresponding elementary area of the diaphragm **10**^{a}, and therefore the total stress upon the crystal **11** will be zero. On the other hand, a sound wave moving in the direction of arrows **13** will reach the diaphragm **10** earlier than it will reach the diaphragm **10**^{a} by a time equal to that required for the sound-wave to travel an effective acoustical distance, hereinafter known as d, between the diaphragms. Thus only waves having components perpendicular to the plane of symmetry of the diaphragm are effective in generating a voltage in the crystal **11**. It should be observed here that use is made of two diaphragms to promote acoustical symmetry, and in many cases one of the diaphragms could be entirely dispensed with; if such were the case, the distance d would be considered the effective acoustical path from the front to the back of the single remaining diaphragm. Such a transducer is illustrated in Fig. 5 which is similar to Fig. 1 except that it has only one diaphragm **25**. The sound wave **26** has access to both sides of the diaphragm, the total effective force being proportional to the difference of pressure at the two sides of the single diaphragm. This effective force is applied to the piezoelectric crystal **27** in a manner similar to that used in connection with the piezoelectric crystal **11** in Fig. 1, and output leads **23** and **24** are used instead of the leads **12** and **12**^{a}.

The resultant force produced by a sound-wave whose pressure is held constant and whose frequency is varied, increases with the frequency of the sound-wave up to a frequency whose corresponding wave-length is at least twice the distance d, which in a preferred form of my invention will occur at several thousands cycles per second. This can easily be shown in terms of mathematics.

Assuming that the sound-wave pressure due to a simple harmonic wave perpendicular to the plane of symmetry is, at the plane of symmetry, given by the equation:

$$P_s = \sin \quad P \sin (2 \pi ft) \qquad \text{(I)}$$

where

p_s is the instantaneous pressure at the plane of symmetry of the transducer
P is the maximum value of the sound pressure
π is the constant 3.14159 . . .
f is the frequency of sound in cycles per sec.
t is the time in seconds

then the sound-wave coming from the direction **13** will reach the front diaphragm **10**, $d/2v$ seconds earlier, and will reach the diaphragm **10**^{a} $d/2v$ seconds later, than it will reach the plane of symmetry. Hence the forces exerted upon the front and back diaphragms will be

$$f_f = P\ A \sin 2\pi f(t + d/2v \qquad \text{(II)}$$

$$f_b = P\ A \sin 2\pi f(t - d/2v \qquad \text{(III)}$$

in which all terms have the same meaning as before and in addition:

f_f is the instantaneous force exerted upon the front diaphragm
f_b is the instantaneous force exerted upon the back diaphragm
d is the effective acoustic path between the diaphragms
v is the velocity of sound
A is the effective area of the diaphragms affected by sound-wave pressure.

Since the transducer is arranged so that the effects of the front and back force are subtractive, the net resultant force available at the driving points of the diaphragms will be given by the expression

$$f_r = f_f - f_b = 2PA(\cos 2\pi ft)(\sin \pi fd/v) \qquad \text{(IV)}$$

f_r is the instantaneous resultant force available for generation of voltage

In a stiffness-controlled piezo-electric transducer, and more generally in most stiffness controlled transducers, the voltage generated is proportional to the resultant force applied on the transducer element. Hence it can be written:

$$e_g = 2E(\cos 2\pi ft)\ (\sin \pi fd/v) \qquad \text{(V)}$$

where all terms have the same meaning as before and in addition:

e_g is the instantaneous voltage generated in the transducer

E is the value of the voltage generated at the tranducer upon application of the force PA upon the transducer element

For convenience in electrical analysis, the Equation V can be rewritten in vector form, thus:

$$E_g = j2E \sin (\pi f d/v) \quad \text{(VI)}$$

where E_g is the root-mean-square voltage generated

j is the imaginary unit $\sqrt{-1}$ used in the vector sense

For sound approaching in directions other than that indicated by the arrows 13 in Fig. 1, the generated voltage would be multiplied by the terms $\cos \theta$, where θ is the angle of departure from the direction of arrow 13. This implies that the directivity characteristic would be in a form of figure 8 with maximum receptivity in the directions perpendicular to the plane of symmetry of the transducer, and the minimum receptivity in the directions parallel with the plane of symmetry.

Upon an examination of the Equation VI, it is seen that the generated voltage E_g is a sine-function of the frequency of the incident sound wave for a given pressure. For frequencies at which the distance d is considerably smaller than a half wave-length, the voltage is closely proportional to frequency. As the frequency becomes equal to half the length of the sound-wave, the condition for maximum pressure difference occurs. This maximum pressure difference as can be seen from Equation IV, is equal to twice the sound pressure in free space. The lowest frequency at which such pressure first occurs will be subsequently referred to as the "critical frequency". It should not be inferred that when the frequency exceeds the critical frequency value, the difference of pressure decreases following the sine function, because due to the baffle effect common to an object of dimension large compared with the wave-length, there is a doubling of sound-pressure at the front of the microphone, and a very substantial reduction of sound-pressure at the back of the microphone. Therefore, at frequencies much above the critical frequency the transducer will become a pressure-operated device, retaining to a very large extent the directional characteristics common to the pressure-difference type, and generating a voltage proportional to the pressure of the sound, and substantially independent of the sound-frequency except as modified by the acoustic networks 19 and 19^a. One of the important objects of my invention is to provide means in conjunction with a stiffness-controlled transducer which will compensate for the dependence of the generated voltage of the transducer upon frequency below the critical frequency, and which will also maintain the independence of the generated voltage from frequency effects above the critical frequency.

For this purpose, I provide an electrical network coordinated with the transducer, the transmission characteristic of said network being inversely proportional to the frequency up to the critical frequency, and above the critical frequency becoming independent of frequency. This action of the network, in conjunction with the opposite frequency characteristic of the generated voltage effectively renders the output voltage of the microphone substantially independent of frequency. Although a network with the required transmission characteristic can be made in a variety of ways, I have discovered that an extremely simple type of network is entirely satisfactory under the common condition of receiving apparatus of relatively high impedance. Fig. 1 shows a preferred form of such a network N which comprises a parallel combination of a resistor R and a condenser C_3, connected to conductor 12, and a capacitance C_2 in series relation with the parallel combination of R and C_3, and in electrical connection with the conductor 12^a of the transducer. The voltage receiving apparatus B is connected across the capacitance C_2.

I have found that the inherent shunt capacitance of a suitable cable leading to the receiving apparatus can be made to comprise the network capacity C_2. The conductors 16 and 17 may be considered the cable and the capacitance C_2, indicated by dotted lines between them, the shunt capacitance. In the absence of sufficient capacitance due to the conducting line, condenser of sufficient value may be added.

The action of the network N can be best understood by reference to Fig. 2. The condenser C_2 is chosen so that its reactance is numerically equal to the resistance R at some low frequency, such as 100 cycles per second. The condenser C_3 is chosen so that its reactance is numerically equal to the resistance R at a high frequency, approximating the critical frequency, which, in the preferred form of my invention, occurs at several thousands cycles per second depending upon the size of the diaphragms. I have found that by using for the transducer element a piezo-electric crystal whose internal capacity lies between 500 and 5,000 micro-micro farads, good results are obtained with a network having the following values: Condenser C_2, between 200 and 2,000 micro-micro farads; condenser C_3 between 10 and 100 micro-micro farads and resistance R between 5 and 0.5 megohms. Although in a preferred form of my invention, the critical frequency occurs at approximately 2,000 cycles per second, the critical frequency may have any desired value and still come within the scope of my invention.

Since the numerical value of the impedances of the condenser C_3 and resistance R are equal at approximately the critical frequency, the parallel branch formed by R and C_3 becomes predominantly resistive below the critical frequency and predominantly capacitive above the critical frequency. In either case, at frequencies of the order of 100 cycles and above this parallel branch forms the greater part of the total series impedance of the network, and hence its characteristics determine the amount of current flowing in the circuit.

The output voltage E_f is the product of the current i and reactance of condenser C_2. The generated voltage E_g is increased with the frequency, at frequencies below the critical, as shown by Equation VI and since the controlling impedance is preponderately resistive below the critical frequency, the current i will also be increasing. However, the reactance of the condenser C_2 decreases with frequency, hence the produce of these two quantities or the output voltage remains constant.

Now, considering the action of the transducer at frequencies considerably above the critical frequency, that is when the generated voltage is independent of the frequency of a constant-pressure wave, the capacitance C_3 may be considered as the sole element of the parallel combination of C_3 and R, and the network thus practically reduces to a capacitive voltage divider, consisting of the two condensers C_3 and C_2. Thus the voltage E_f will be related to the voltage E_g by a constant factor, and therefore E_f will be independent of frequency.

The action of the transducer in the vicinity of the critical frequency is an intermediate one. Thus upon transition from a frequency below the critical to a frequency above the critical, the transducer slowly changes from a pressure-difference device to a pressure-operated device. At the same time, the impedance of the parallel combination of R and C_3 changes slowly from resistive to capacitive predominance. Therefore the output voltage remains essentially independent of frequency during the transition period also. Thus the network described, when used with a stiffness-controlled transducer, pressure-difference operated throughout at least a part of the audio-frequency range, renders the output voltage substantially independent of frequency of the impressed sound-wave, thus enabling the microphone to be used with standard amplifying equipment for high-quality sound reproduction.

It should be noted that if the critical frequency is placed at or near the maximum frequency to be transmitted, condenser C_3 may be eliminated without impairing the corrective action of the network for frequencies below the critical.

The effects of the network upon the phase position of the output voltage E_f can be understood from inspection of Fig. 4 which is drawn in reference to Equations I to V inclusive. Thus curves marked p_s, f_f, and f_b represent the instantaneous pressure at the plane of symmetry of the transducer, and the forces upon the front and back diaphragm, respectively, in their proper phase position. The resultant force f_r is shown as a result of subtracting f_b from f_f, and hence is leading p_s by 90°, and the generated voltage e_g is also shown in phase with p_r. Upon being impressed on the series combination of R and C_2, the output voltage E_f developed across C_2 is shifted approximately 90° out of phase with E_g because of the quadrature relation of the impedance of C_2 and R for frequencies below the critical. Hence the network used in conjunction with the pressure-difference operated piezo-electric transducer is effective in compensating for the phase shift of the voltage generated as referred to pressure at the plane of symmetry of the transducer.

With increase in the temperature of the crystal above the Curie point (70° F.), the internal capacity of a Rochelle Salt piezo-electric transducer is known to change, and such variation ordinarily changes the output of a crystal microphone. However, with the network described, such variation of output is so diminished as to be unimportant. Referring to Fig. 2, it will be seen that the presence of a relatively large resistance in the circuit renders unimportant changes in the value of capacitance C_1 so far as the value of the effective voltage E_f is concerned.

When the microphone is used for close-talking purposes, the response at low frequencies, say below 100 cycles per second, becomes unduly exaggerated due to the increase of pressure gradient associated with sphericity of the sound waves. My improved apparatus is effective also in correcting for this tendency to distortion. It will be observed from Equation V that below the critical frequency, the generated voltage E_g tends to decrease with decrease in the frequency of sound, and this tendency is compensated for, in my invention, by the use of the associated electrical network. By adjusting the elements of the network so that the compensating network becomes substantially inoperative at frequencies below say 100 cycles per second, the effective or resultant voltage delivered will be more nearly free from frequency discrimination than if the voltage were corrected for frequency distortion throughout the whole audible range of frequencies. For this reason I prefer to provide a resistor R which has a resistance value numerically equal to the capacitive reactance of the circuit at a frequency somewhat above the lowest audible frequency. I have referred to the frequency of 100 cycles per second only as an example, and by varying the value of R relative to C_1 and C_2 the compensating effect of the network may begin at any other audible frequency that may be desired.

In Fig, 3 of the drawing is illustrated a modified form of the invention in which two transducers are used. Here the two pressure-operated transducers X and Y are to be supported in spaced relation so that their respective diaphragms **20** and **20**^{a} are actuated by a sound wave in a way similar to that described in connection with diaphragms **10** and **10**^{a}. Preferably adjacent to the diaphragms **20** and **20**^{a} are the acoustical networks **22** and **22**^{a} similar to the networks **19** and **19**^{a} described in connection with the first-described embodiment. The crystals **21** and **21**^{a} of these transducers are electrically connected so that the voltages developed by them subtract and so that the generated voltage of their combination is the difference of the voltages developed by each. This is another type of dual-directional microphone which constitutes an embodiment of my invention.

It is understood that in cases where the conducting line leading to the receiving apparatus is very short, or otherwise has a very low internal capacity, a condenser may be connected across the line to supply adequate capacitance in the network.

It is understood that the corrective network herein described may be employed in connection with pressure-gradient operated transducers of types other than the piezo-electric variety. Any stiffness-controlled pressure-gradient operated transducer in which the generated voltage is inherently a function of the displacement of the diaphragm or voltage-producing element, might be used. For example, the carbon type transducer may be effectively used in connection with a corrective network and I have found it effective to employ a parallel combination of an inductance and a resistance constituting the controlling impedance, and a resistance in series arrangement in the output circuit across which the output voltage is developed. The amplifier input transformer may be used to reflect the proper value of resistance for the output branch of the network.

The foregoing detailed description has been given for clearness of understanding only and no unnecessary limitations should be understood therefrom, but the appended claims should be construed as broadly as permissible, in view of the prior art.

I claim:

1. In a microphone, a transducer element comprising a vibratory body having pressure-sensitive surfaces adapted to move substantially in accordance with the pressure-difference due to a sound-wave at its press-sensitive surfaces at frequencies below the critical, and to move substantially in accordance with the pressure of said sound-wave at frequencies above the critical frequency, means of changing the vibrations of said body into corresponding electrical variations and a network whose transmission characteristic is substantially inversely proportional to frequency below the critical frequency, and whose transmission characterisic is substantially constant at frequencies above the critical frequency, the input of the network being connected to the transducing element, and the output of the network being connected to the terminals of the microphone.

2. In a microphone, a piezoelectric transducer element comprising a vibratory piezoelectric body having pressure-sensitive surfaces and being arranged to move substantially in accordance with the pressure difference at its pressure-sensitive surfaces due to a sound-wave at frequencies below the critical frequency, and to move substantially in accordance with the pressure of the sound-wave at frequencies above the critical frequency generating a voltage proportional to the amplitude of said motions, and means including a network consisting of a parallel combination of a resistance and a condenser, said parallel combination in series with a larger condenser, the reactance of the smaller condenser being approximately equal to resistance at critical frequency, and the reactance of the larger condenser being equal to the resistance at a frequency in the vicinity of 100 cycles per second, the output terminals of the microphone being connected across the larger capacitance.

3. In a microphone, an electroacoustic transducing element consisting of a diaphragm, means for supporting said diaphragm, means for establishing an acoustic path from the front to back of said diaphragm substantially greater than half the wavelength of the highest frequency to be received, means for coupling the diaphragm to a piezoelectric body adapted for generation of a potential proportional to the difference of pressures at the faces of said diaphragm, and a network consisting of a parallel combination of a resistance and a condenser, said parallel combination in series with a larger condenser, the network being connected across the leads of the transducing element, the output terminals of the microphone being connected across the larger condenser, the components of said network being so proportioned that the capacitive reactance of the smaller condenser is approximately numerically equal to the resistance at the critical frequency, and the capacitive reactance of the larger condenser is approximately numerically equal to the resistance at a relatively low audible frequency.

4. A microphone composed of a transducing element consisting of two enclosures each one of which is provided with a diaphragm operating upon a piezoelectric crystal adapted to generate a voltage proportional to the pressure of sound falling upon it, said enclosures being so spaced from each other that the equivalent effective acoustical path between their pressure-sensitive sides is substantially larger than half the wavelength of the highest frequency to be received, a network composed of a parallel combination of a resistance and a condenser, said parallel combination being in series with a larger condenser, the values of said network elements being so adjusted that the reactance of the smaller condenser equals the resistance at approximately the critical frequency and the reactance of the larger condenser equals the resistance at some low audible frequency, said network being connected across the transducing element, the output voltage of the microphone being taken across the larger condenser.

5. In a microphone, a transducing element operated by the difference of pressures at two regions in a sound wave at frequencies below the critical frequency, and operated substantially by the pressure of the sound wave at one of said regions above said critical frequency, said transducing element having means for changing the effect of said pressures into corresponding electrical variations, and a network associated therewith whose transmission characteristic is substantially inversely proportional to frequency below the critical frequency and substantially constant at frequencies above the critical frequency, the input of the network being connected to the transducing element and the output of the network being connected to the terminals of the microphone.

BENJAMIN BAUMZWEIGER.

CERTIFICATE OF CORRECTION.

Patent No. 2,198,424. April 23, 1940.

BENJAMIN BAUMZWEIGER.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows: Page 2, first column, line 26, for "nclosing" read --inclosing--; and second column, lines 45 and 46, insert a right hand parenthesis mark at the end of each equation; page 5, first column, line 6, claim 1, for "press-sensitive" read --pressure-sensitive--; line 43-44, claim 3, for "establising" read --establishing--; and that the said Letters Patent should be read with this correction therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 24th day of September, A. D. 1940.

Henry Van Arsdale,
Acting Commissioner of Patents.

(Seal)