An Adventure in Microphone Design

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THE IMPROVEMENTS in loudspeakers and complementary reproducing components in recent years have done much to point up the deficiencies in microphones. In the past, one of the most popular microphones has been the ribbon type because it can easily be adapted to unidirectional designs. But inefficient hf response, boominess in the high bass region caused by the proximity effect, and low sensitivity in spite of the large magnet size in the generating element have gradually tended to force into disrepute the use of this type of transducer.

In television work, ribbon transducers reveal high sensitivity to shock when employed on booms. The repeated failure of the fragile ribbon element suggests the need for a more rugged and lighter microphone. The wide range possible with FM audio presupposes a microphone with the best hf response obtainable, and also an extension of the bass range, provided that it is clean and free from boominess.

The ribbon microphone fails on almost every count. Considerable advantage would accrue if a microphone were available which weighed ounces instead of pounds, was small and unobtrusive, exceeded the ribbon microphone in sensitivity, attained much wider range, and was more rugged and less subject to shock and air noise.

A microphone that meets these requirements has recently become commercially available. This is the Model 655 "Slim-Trim" unit (Fig. 1). Operating as a pressure device, the pattern is mildly directional. Although a ribbon microphone of the unidirectional type has distinct advantages under high noise conditions, the flexibility of this new microphone and the ease with which it meets most of the difficult conditions of television offset the single advantage of the ribbon transducer to a large degree.

The design of the Model 655 presented many interesting problems, the solutions to which lay in the exploiting of four principal acoustical phenomena. These phenomena were susceptible to optimum use in a pressure microphone of the moving-coil type. In order to explain more easily the development of the Model 655 transducer, a digression is in order on the general theory of operation, assisted by a description of several mechanical, electrical, and acoustical analogies.

FIG. 1. Relative size and weight of the Model 655 and the ribbon-type microphone.

GENERAL THEORY OF THE MOVING-COIL PRESSURE-TYPE TRANSDUCER

One of the most basic concepts of a microphone, perhaps, is that of a coil of wire attached to a supported diaphragm operating in a magnetic field and enclosed by a cavity on one side (Fig. 2). The response of the microphone to wave motion in the air will assume the character of the curve shown. This is known as a *pressure* microphone, because it responds to the pressure of the air upon its surface, reflecting some, dissipating a small portion of the energy into heat, and translating a certain amount into motion. That portion which is used to cause motion we can employ after the manner of an electrical generator and thus feed an electrical system for various purposes, such as amplification, recording, and reproducing.

The virtues of this system are the extreme ruggedness, the relatively high output level for a given size and weight, and the fact that it adapts itself to the processes described later which promote practically flat response over the audible range.

The value of the generated voltage can be calculated from the simple formula for a moving-coil system:

$$E_0 = BL(F/G)$$

where E_0 = generated voltage in abvolts.
B = gap flux density in gauss.
L = length of conductor in centimeters.
F = force in dynes.
G = mechanical impedance in dynes per centimeter per second.

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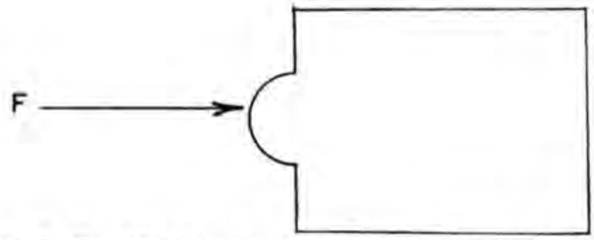

FIG. 2. $F = AP$, where F = force, A = area of the diaphragm, and P = pressure.

The gap flux density, B, and the length of the conductor, L, are independent of frequency. The response characteristic of the microphone will be obtained by evaluating the force, F, and the mechanical impedance, G, as a function of the frequency. Observe the diagram of Fig. 2. Where the diameter dimensions of the case are small compared to the wavelength, the force exerted on the diaphragm is equal to the area of the diaphragm, A, times the pressure, P. The effect of the case dimensions upon the shorter wavelengths will be explained later.

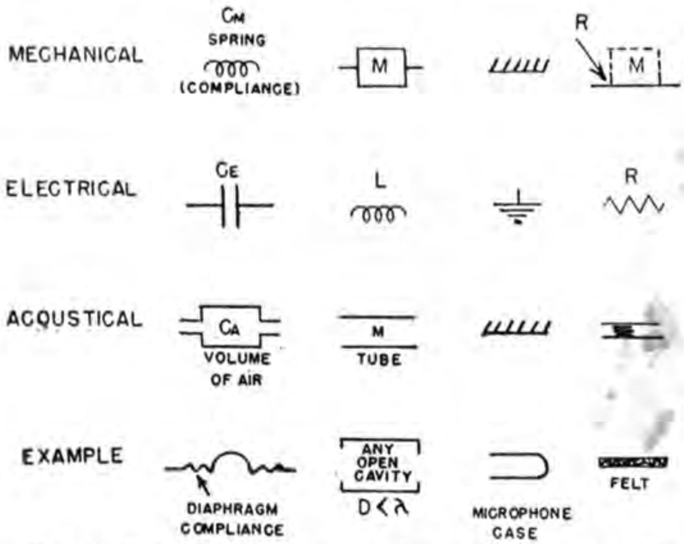

FIG. 3. Mechanical, electrical, and acoustical analogies. In a mechanical or acoustical system, C must have one side grounded.

MECHANICAL, ELECTRICAL, AND ACOUSTICAL ANALOGIES

Figure 3 presents a useful tool for the solution of acoustical problems. These analogies permit the various factors involved in the design of acoustical or mechanical systems to be translated into electrical equivalents. In most of the explanations that follow, a combination of mechanical and acoustical symbols is used to make the text clear by comparing their use in the equivalent electrical circuit. Several explanations listed below will assist in the interpretation of the symbols shown in the figure.

Mass is the mechanical element which opposes a change in velocity.

Inductance is the electrical element which opposes a change in current.

Resistance is the electrical dissipative element.

Friction is the mechanical dissipative element.

Capacitance is the electrical element which opposes a change in the applied force.

Compliance is the mechanical element which opposes a change in the applied force.

It should be noted that in a mechanical or acoustical system the capacitive element always must have one side grounded.

PRESSURE MICROPHONE OPERATION

Figure 4 shows the operation of a simple pressure-operated microphone of the moving-coil type. The electrical equivalent circuit of the mechanical system shown at the top of the drawing reveals that the compliance of the volume, C_v, the mass of the diaphragm, M_d, and compliance of the diaphragm, C_d, form a resonant circuit, the response-frequency characteristic of which is shown in the graph. The height of the peak and the broadness of the base are directly dependent on the Q of the circuit. A simple pressure microphone of this type produces a highly sensitive unit, but with violently peaked response somewhere in the region between 500 and 1,000 cps. Starting with this simple system, we shall now expose the methods by which a virtually flat pressure-operated microphone of the moving-coil type may be designed.

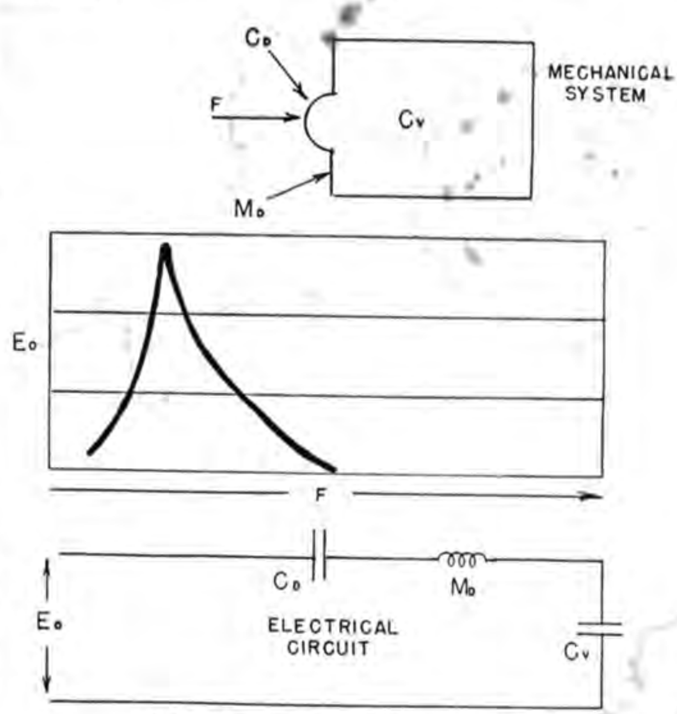

FIG. 4. Pressure microphone operation.

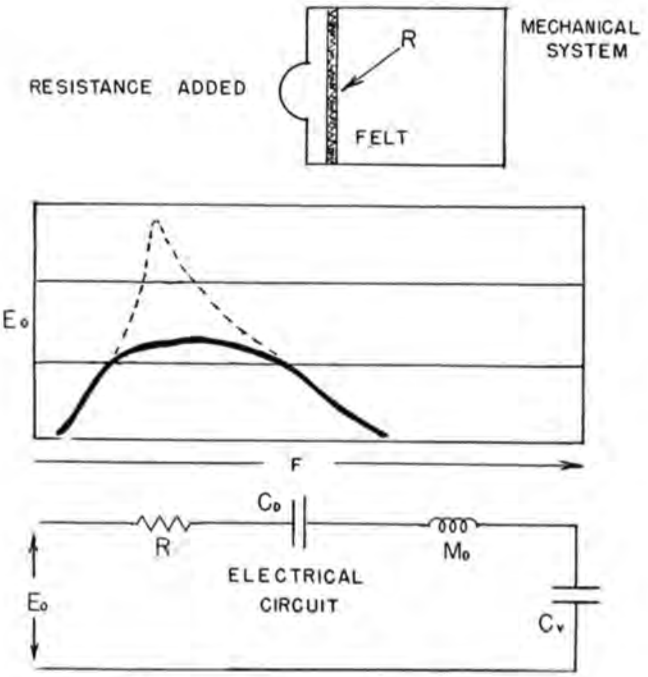

FIG. 5. *Step 1:* Extending the range.

EXTENDING THE RANGE

Step. 1. In electrical terms, the resistance added to the equivalent circuit, shown in Fig. 5, will lower the Q of the system and eliminate the previously experienced violent peak in the response-frequency characteristic. Referring to the table of analogies, we find that in the acoustical system this resistance can take the form of a piece of felt, and such an acoustical means is quite frequently used to provide the necessary damping for smooth response. All things considered, we now have a thoroughly usable microphone with reasonably good range, similar to that acceptable for public address work. The lf range still leaves something to be desired, and the sensitivity in the high end of the spectrum is not considered the ultimate.

IMPROVING THE BASS RANGE—USE OF BASS REFLEX

Step 2. Better lf response can be obtained from the system if we now introduce a mass, M_t, in the design (Fig. 6). This element is in parallel with the resonant circuit formed by the resistance of the microphone introduced by the felt, R, the compliance of the diaphragm, C_d, and the mass of the diaphragm, M_d. The tube is connected from the outside of the case to the enclosed volume, C_v. Once the mass and compliance of the diaphragm itself are fixed, the lf range will be determined by the values assigned to the case volume and the air mass of the tube. If the case compliance, C_v, is made too low, it will not be possible to improve the bass range, regardless of the tube dimensions chosen. In general, for the optimum size of this microphone, the case volume has been determined to be no less than 4 in.^{3}. It is interesting to note that the bass reflex loudspeaker cabinets derived their operation from the original employment some years ago of the principle just discussed in the design of microphones. Observe one phenomenon caused by the introduction of this bass reflex principle: Although we have improved the bass response efficiency to an extent, beyond a certain point we have caused a much more rapid attenuation of the bass range. Originally our attenuation slope was 6 db per octave, whereas now we find that the "doublet" effect introduced by the tube opening results in a slope of 12 db per octave. There is nothing more that we can do, practically, to extend the bass range and efficiency past this point. By careful adjustment of the acoustic resistance of the felt material used to introduce damping, the mechanical impedance, G, can be made substantially constant with respect to frequency. We now have a microphone with good bass response, but the deficiency of hf response results in a displeasing quality.

EXTENSION OF THE MID-HIGH RANGE

Step 3. The shape of the microphone has a decided bearing on the hf range response. For years there has been considerable academic discussion on the diffraction of a sound field by an obstacle. Lord Rayleigh[1] met with some practical success in the derivation of a theoretical expression for diffraction in the case of a spherical object. But it

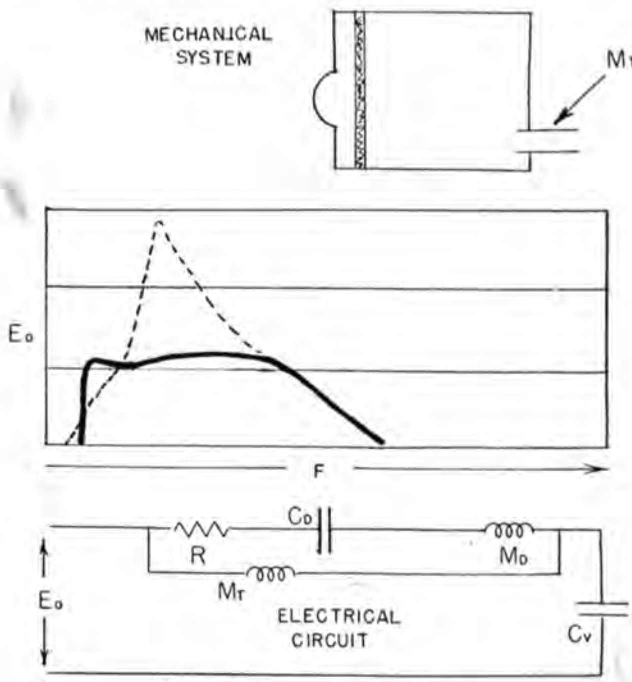

FIG. 6. *Step 2:* Use of bass reflex.

[1] Rayleigh, *Theory of Sound,* Vol. 2, p. 2, paper No. 287; Vol. 5, p. 112, paper No. 229; Vol. 5, p. 149.

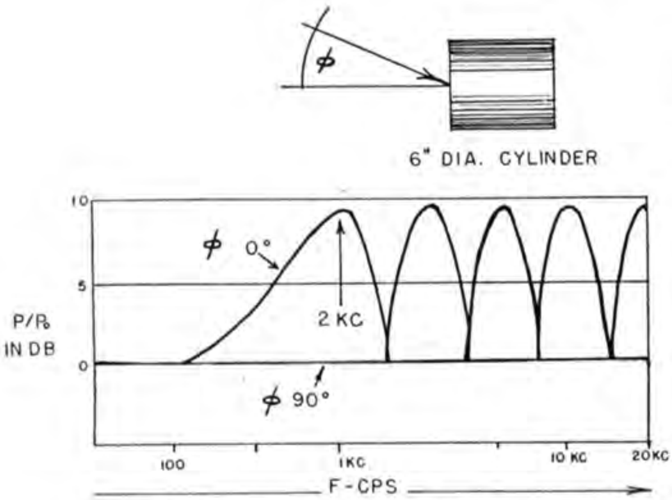

FIG. 7. Effect predicted by Muller, Black, and Davis.

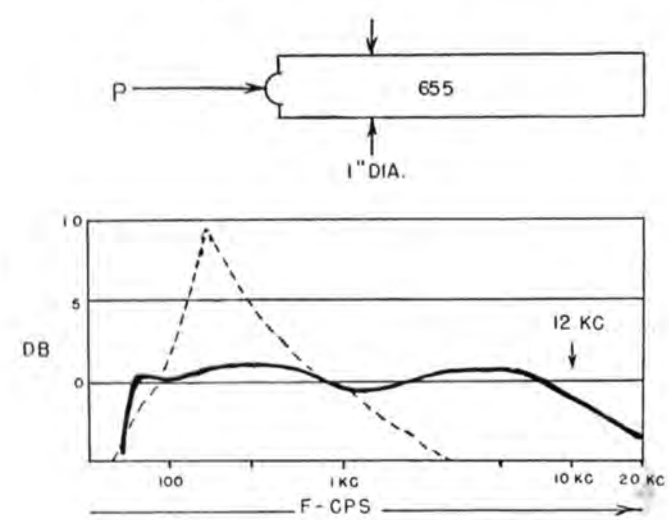

FIG. 8. *Step 3:* Increase of mid-highs.

was not until 1937 that Muller, Black, and Davis[2] derived practical theories applicable to semi-infinite planes, very long cylinders, and paraboloids of practical dimensions. The general solutions for diffraction caused by obstacles, particularly of spherical and tubular shapes, have been set forth by these authors. Briefly, what happens is this:

For a cylinder 6 in. in diameter and 6 in. in length, it has been determined that the response-frequency characteristic will assume closely the curve shown in Fig. 7. Observe that sound approaching on the axis is subject to reinforcement of approximately 10 db at 2 kc. For this cylindrical shape, there follows a series of reinforcements as the frequency increases.

In line with this principle, a series of experiments reveals that a reduction in diameter by one-half results in a first reinforcement peak at double the first frequency, or 4 kc.

A microphone 1 in. in diameter would seem to provide a happy solution to the requirement for small size, at least in one dimension. Accordingly, tests were conducted on a 1-in. cylinder, and the results of these tests conformed closely to those predicted by the original diffraction experiments. The requirement to include 4 in.[3] in the back cavity dictated a certain length to the cylinder which influenced the magnitude of the original size predictions. The extension of the mid-high range was satisfactory to the 12-kc point as shown in the curve on Fig. 8.

At this stage of development, the Model 655 compared most favorably with high-quality microphones available commercially. But in order to exceed the performance of existing microphones by a marked degree, further work was required. This will be evolved in step 4 to follow.

REINFORCEMENT OF THE VERY HIGH FREQUENCIES WITH A FRONTAL RESONATOR

Step 4. Observe in Fig. 8 that the attenuation rate past

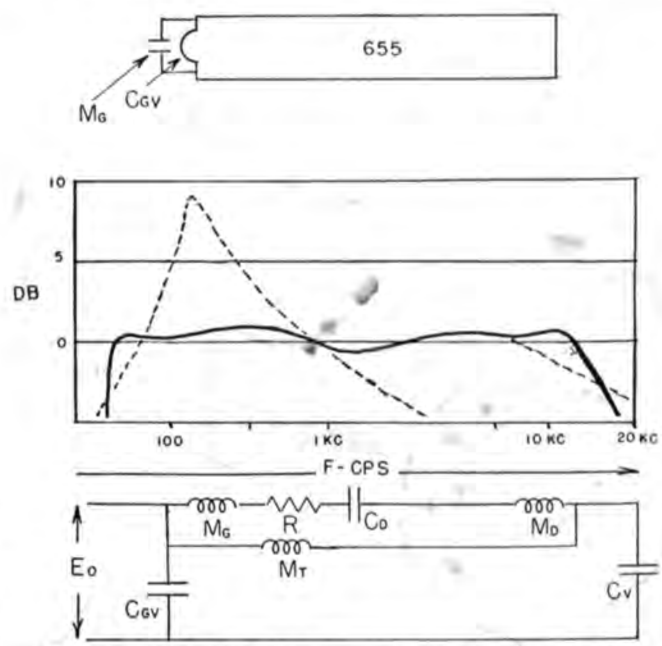

FIG. 9. *Step 4:* Vhf reinforcement with frontal resonator.

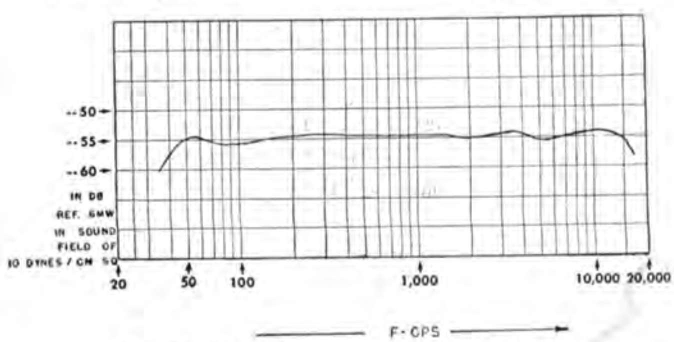

FIG. 10. Typical response of the Model 655.

[2] G. G. Muller, R. Black, and T. E. Davis, The Diffraction Produced by Cylindrical and Cubical Obstacles, and by Circular and Square Plates, *J. Acoust. Soc. Amer.*, **10**, 6ff (1938).

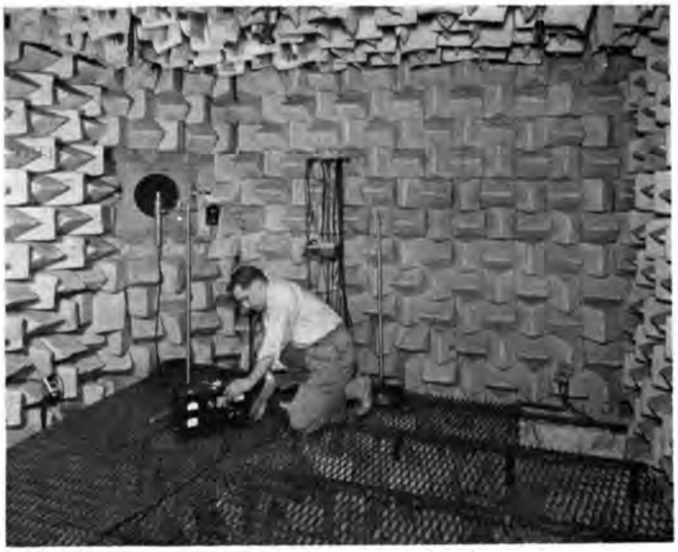

FIG. 11. Anechoic sound chamber.

12 kc appears to be about 6 db per octave. It is desirable to make the microphone flat to 15 kc and thus encompass the entire audible range in the hf direction. A cavity and tube on the front of the Model 655 diaphragm assembly, concealed in the grillwork, form the inductive and capacitive elements shown as C_{gv} and M_g in Fig. 9. These represent the cavity of the grill volume and the mass introduced by the grill configuration, respectively. Thus, a resonant circuit is formed which produces an increase in hf response which is essentially flat to 15 kc as shown. Past the 15-kc point, the attenuation is rather rapid, at a rate of approximately 18 db per octave.

The application of the four acoustic principles here described has resulted in the production of a microphone whose response is flat within 2 db from 40 to 15,000 cps, as presented in Fig. 10. It may be reasonably inferred that practically perfect response has been achieved in this unit. Response from 20 to 40 cps under usual conditions of operation is quite likely undesirable because of extraneous lf noise communicated through stage walls, electrical overloads due to closing large doors, and other low-end hf energy communicating little or no program material.

RUGGEDNESS AND RELIABILITY

Of special importance in the design of the Model 655 is its extreme ruggedness. Its unusual ability to withstand shock and rough handling is due principally to the use of a nonhygroscopic specially treated, cast plastic of high tensile strength. Tangential compliances are formed in the mold to effect a complete control over the compliance characteristic with a minimum of space. This diaphragm material is commercially termed Acoustalloy and has very high tensile strength. The manufacturing process used in the forming of the diaphragm is carefully controlled, and the tolerances on thickness are kept within one ten-thousandth of an inch. Nominal thickness is 1.3 thousandths in order to present the most favorable mechanical compliance for this element, in conjunction with the other elements of the system, to produce the best bass range. The microphone can be dropped on the floor without damage and completely submerged in water without impairing subsequent operation.

The high resonant frequency employed in the moving system of about 500 cps makes the microphone resistant to lf microphonic effects, thus eliminating in practical use the need for shock mounts.

QUALITY CONTROL IN PRODUCTION

During the development of Model 655, an anechoic sound chamber, shown in Fig. 11, was employed for frequent tests. A standard calibrated Model 640-AA microphone, shown in the illustration, was used for frequent calibration of the test electrical system.

An unusual test procedure for production can be observed in Fig. 12. The equipment pictured consists of a somewhat smaller anechoic chamber than that used for laboratory work. A standard Model 655 is used in conjunction with the production unit inside the chamber, and a comparative decibel meter reads the log of the difference between the standard and the unit under test. Tolerances of ½ db are allowed on production. The microphones are also given an actual voice test, at which time cable connections and mechanical rattles are screened.

SUBJECTIVE LISTENING TESTS

A model recording studio in which microphone developments are conducted allows studies under actual field conditions. A monitor room with an eight-position console

FIG. 12. Test procedure for the Model 655.

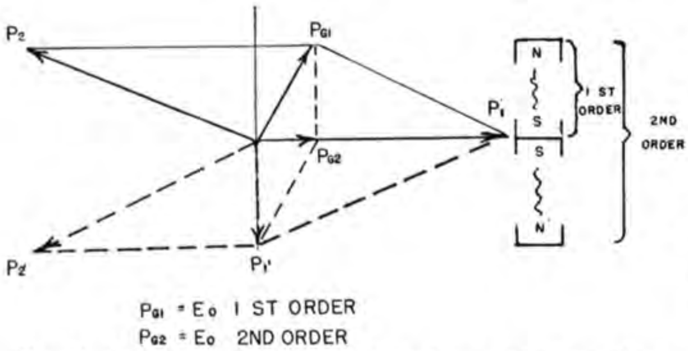

FIG. 13. Pressure gradient and higher-order gradient operation.

will simulate actual conditions of use and permit the development engineers to record their tests and play them back at will for careful analysis.

In conclusion, it may be pointed out that the test of the success of any design is in the public acceptance achieved.

TREND OF MICROPHONE DEVELOPMENT IN THE FUTURE

The direction for future microphone developments is indicated by the need for microphones similar in characteristics to the Model 655 but with the addition of the unidirectional feature.

These future microphones will probably work on the pressure gradient of the first order and on higher-order gradients. With reference to the upper half of Fig. 13 for the vector diagram of first-order gradient operation, P_1 is the pressure on the front of the element, and P_2 the pressure, different in phase, on the rear of the element. The resultant pressure on the element is shown as P_{g1}. Any sound whose wavelength is greater than the length of path from the front to back openings will be differentiated. Since the attenuation is proportional to wavelength, discrimination takes place at the rate of 6 db per octave. Therefore, to achieve complete discrimination, the microphone must be designed to cut off frequencies shorter than this critical wavelength.

Since the ability to discriminate direction is the criterion of good unidirectional design, a more effective microphone of this type is achieved with differentiation of 12 db per octave by juxtaposition of a second element as shown. The dotted lower half of the vector diagram indicates the effect of this addition. The second-order differentiation is the lower pressure P_{g2}. It is obvious that gradients of still higher order will permit smaller elements and provide increasingly effective discrimination at higher frequencies.

Considerable work is now being conducted along these lines, and a more flexible transducer for industry will be produced in the near future.