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Electronic Sound Absorber

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The electronic sound absorber is so named because it absorbs sound or reduces the sound level by means of an electronic transducing system, as contrasted to conventional sound absorption by direct conversion from acoustical to heat energy. The electronic sound absorber consists of a microphone, amplifier, and loudspeaker connected so that, for an incident sound, wave and sound pressure at the microphone is reduced. Thus it will be seen that the electronic sound absorber is a feedback system which operates to reduce the sound pressure in the vicinity of the microphone. The sound pressure in the neighborhood of the microphone can be reduced 10 to 25 decibels over a frequency range of three octaves in the low-frequency portion of the audio-range. The electronic sound absorber may be used to reduce the noise over a small volume, that is, spot type noise reducer or it may be used with an acoustical resistance to obtain a high order of sound absorption in the low-frequency range.

INTRODUCTION

WHEN sound energy impinges upon a surface, it may be tacitly assumed that the energy is divided into three portions, namely, the incident, reflected, and absorbed energy. Furthermore, it may also be assumed that the fraction of absorbed incident energy is a property of the physical characteristics of the surface exposed to the sound. It is upon these assumptions that the classical theories of sound absorption are based. From these theories evolved a quantity termed "the sound absorption coefficient of a material," which is the ratio of the absorbed sound energy to the incident sound energy. In general, the object is to obtain a large absorption coefficient over a wide frequency range with a practical material.

All conventional sound absorbing materials are made of some sort of porous material. The absorption of sound is due to dissipation of energy incurred by viscosity as the sound passes through the narrow tortuous passages in the porous material. When this material is used as a surface sound absorber, the volume current is inversely proportional to the acoustical impedance of the material. The sound absorption is the product of the square of the volume current and the acoustical resistance. Since the acoustical impedance of all practical sound absorbing materials in conventional mounting arrangements is very high in the low-frequency range, the resultant volume current is small, and as a consequence, the sound absorbing efficiency is poor.

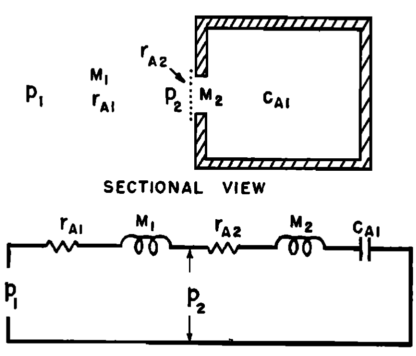

FIG. 1. Sectional view and acoustical network of a Helmholtz resonator sound absorber. p_1=sound pressure in free space. M_1=inertance of the air load. r_{A1}=acoustical resistance of the air load. M_2=inertance of the aperture. C_{A1}=acoustical capacitance of the volume. r_{A2}=acoustical resistance of the cloth over the opening of the resonator. p_2=sound pressure at the mouth.

There are many applications for a sound absorber which exhibits high absorption efficiency in the low-frequency range. Some of the applications are as follows: the reduction of noise in spot locations in the vicinity of machines, in airplanes, in automobiles, and in trains, a direct reduction in sound output of a machine by application of the absorber at the source of the noise and the absorption of sound by the use of the absorber similar to that of conventional materials.

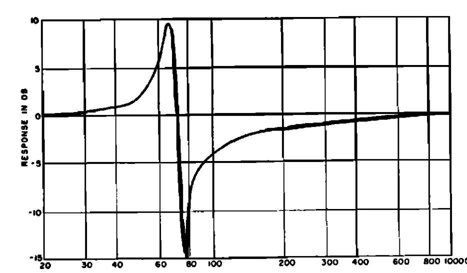

FIG. 2. Sound-pressure reduction frequency characteristic of a Helmholtz resonator having a volume of two cubic feet.

Conventional sound absorbing systems with high efficiency in the low-frequency range are extremely bulky. Therefore, conventional sound absorbing systems are unsuitable because the above-mentioned applications require a compact high-efficiency sound absorbing system.

The efficiency of sound absorption can be increased by using a resonator with the absorbing material. In effect, this improves the coupling between the medium and the absorbing material. However, the frequency range of high sound absorption obtained by the use of a resonator is confined to a fraction of an octave.

Furthermore, the resonator must be of considerable size to obtain high absorption. These two factors make the range of usefulness of the resonator somewhat limited because several resonators are needed to obtain absorption over one or two octaves. Such a system is too bulky for most applications.

There is another sound absorbing system which can be developed to exhibit high absorption over many octaves in the low-frequency range, namely, an electronic sound absorbing system. It is the object of this paper to describe a sound absorbing system employing all electronic components. However, the first consideration will be a resonator absorber which will illustrate the problems of high-order sound absorption in the low-frequency range.

RESONATOR SOUND ABSORBER

The resonator sound absorber[1] consists of a simple resonant acoustical system. One type consists of a Helmholtz resonator with some absorbing material located in the cavity of the resonator, or with a cloth over the mouth to provide additional acoustical resistance. The acoustical performance is practically the same for all types of simple resonators. Therefore, a consideration of the performance of the Helmholtz type will indicate the characteristics of resonant sound absorbers.

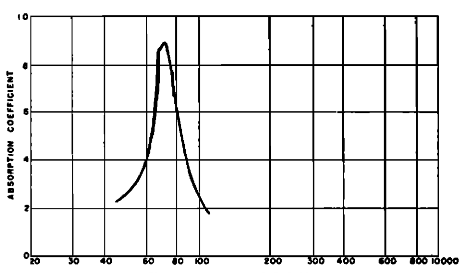

FIG. 3. Sound-absorption coefficient frequency characteristic of a Helmholtz resonator.

A sectional view and acoustical network of a Helmholtz resonator are shown in Fig. 1. The performance of the system can be determined from the acoustical network and the constants of the system. In one application, the problem is to reduce the sound pressure over a small volume. Under these conditions, the acoustical resistance r_{A2} should be made as small as possible. A typical measured sound-pressure frequency characteristic at the mouth of the resonator is shown in Fig. 2. The characteristic shows that there is a reduction in sound pressure in the frequency range above 72 cycles and an increase in sound pressure in the frequency range below 72 cycles. Since there is an increase of pressure over a certain portion of the frequency range, it is obvious that the simple resonator is not suitable for a free-field, spot-type sound reducer.

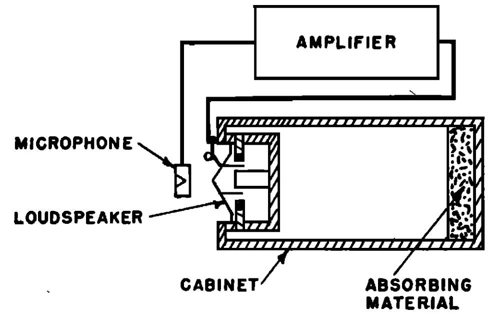

FIG. 4. The elements of an electronic sound absorber. A sectional view of the loudspeaker and cabinet and a schematic view of the microphone and amplifier.

When the resonator is used as a sound absorber, the action is somewhat different. In order to obtain the maximum sound absorption, the acoustical resistance r_{A1} should be equal to the acoustical resistance r_{A2}. This can be accomplished by selecting the proper value of the acoustical resistance r_{A2} provided by the cloth over the opening of the resonator. If a bank of resonators is used, so that the ultimate acoustical resistance r_{A1} is obtained, the maximum efficiency of sound absorption will be obtained. A typical sound-absorption frequency characteristic of a Helmholtz resonator is shown in Fig. 3. An examination shows that a high value of sound absorption is obtained over only a very narrow frequency range. At least twenty resonators would be required to cover the frequency range from 30 to 200 cycles with tolerably good absorption. Since the average cubical content of each resonator is two cubic feet, the total cubical content would be 40 cubic feet. Since a bank of resonators is required for each frequency, the entire assembly becomes an arrangement of tremendous bulk.

ELECTRONIC SOUND ABSORBER

The electronic sound absorber absorbs or reduces sound by means of an electronic transducing system, as contrasted to conventional absorption by direct conversion from acoustical energy to heat energy. Specifically, the electronic sound absorber consists of a micro-

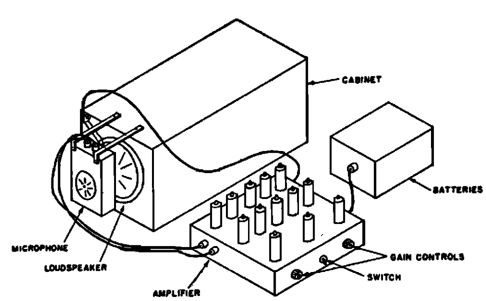

FIG. 5. A perspective view of the elements of the electronic sound absorber.

[1] C. M. Harris, and C. T. Malloy, J. Acoust. Soc. Am. 24, 1 (1952). This paper contains references to the publications of other investigators on the subject of resonator sound absorbers.

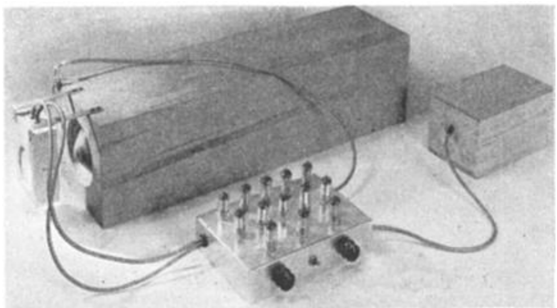

FIG. 6. Electronic sound absorber.

phone, amplifier, and loudspeaker, shown schematically in Fig. 4. A perspective view of the microphone, amplifier, loudspeaker, and battery supply is shown in Fig. 5. A photograph of the system is shown in Fig. 6. The system is connected so that for an incident sound wave, the sound pressure at the microphone is reduced. Thus it will be seen that the electronic sound absorber is a feedback system which operates to reduce the sound pressure in the vicinity of the microphone. In order to achieve this type of operation, special precautions in the choice and design of the elements used in the electronic sound absorber are necessary. The sections which follow will describe the elements and the performance characteristics of these elements.

Microphone

The microphone which seems to be particularly suitable for this application is the electronic microphone[2] in which the impinging sound vibrations directly control the electron stream in a vacuum tube. The advantages of the electronic microphone for this application are as follows: the response in the low-frequency range is independent of the frequency, the output impedance is a constant electrical resistance, the phase relation between the sound pressure and the voltage output is a constant in the low-frequency range, and the sensitivity is relatively high. A sectional view of the electronic microphone is shown in Fig. 7. The microphone consists of a diaphragm connected to a mechano-electronic transducer. The voltage output of the mechano-electronic transducer is proportional to the amplitude of the anode rod. In the frequency region in which the vibrating system is stiffness-controlled, the ratio of the electrical output to the impinging sound pressure is independent of the frequency. The response frequency characteristic of the microphone is shown in Fig. 8. The resonant frequency of the electronic microphone is about 5000 cycles. The response is very smooth below 1000 cycles. Furthermore, uniform response extends down to zero cycles or dc sound pressure. Under these conditions, the variation in phase angle between the actuating sound pressure and the voltage output is less than two degrees from 20 to 400 cycles. Since the electrical impedance of the microphone is an electrical resistance of about 10 000 ohms, the problems of maintaining uniform phase and response in coupling an amplifier to the microphone are simplified.

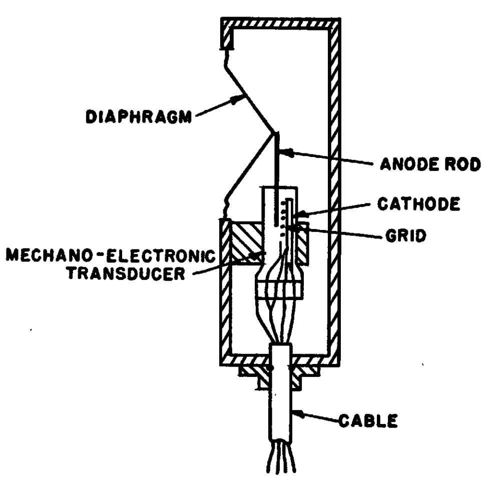

FIG. 7. Sectional view of the electronic microphone used in the electronic sound absorber.

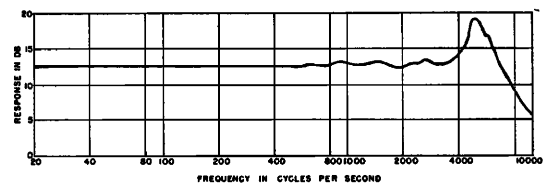

FIG. 8. Response frequency characteristic of the electronic microphone shown in Fig. 7.

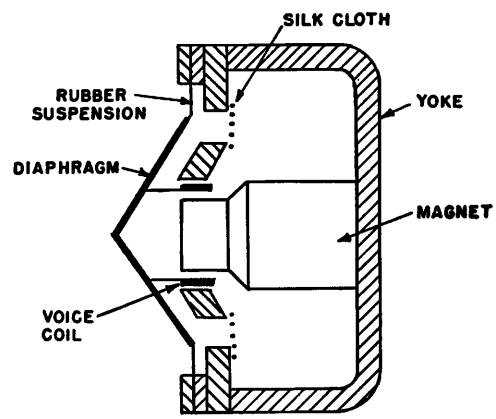

FIG. 9. Sectional view of the loudspeaker mechanism used in the electronic sound absorber.

Loudspeaker

Coupling transformers between a vacuum tube and a loudspeaker introduce considerable phase shift in the low-frequency range. Therefore, in this system it

[2] H. F. Olson, J. Acoust. Soc. Am. 19, 307 (1947).

appeared that the logical solution was the elimination of the transformer by the use of a high-impedance voice coil which could be coupled directly to a vacuum tube. Accordingly, the voice coil was wound with wire which gave an electrical resistance of 200 ohms.

In this feedback system, the loudspeaker should be a zero-order radiator, which means that the back of the loudspeaker mechanism must be enclosed. In order to obtain an enclosure of reasonable size, the loudspeaker diaphragm must be relatively small. For a cone diameter of three inches, the required cabinet volume is about one-half cubic foot. This is a cabinet of tolerable size.

The resonant frequency of the loudspeaker mechanism alone should be about 30 cycles in order to keep the resonant frequency in the cabinet to around 45 cycles. A limp suspension is required to obtain a resonant frequency of 30 cycles with the small vibrating mass of the cone and voice coil. The suspension arrangement developed for this loudspeaker is shown in Fig. 9. Placement of the outer suspension near the plane of the voice coil makes a center suspension unnecessary. The suspension was made of sheet rubber in order to obtain a sufficiently low value of stiffness.

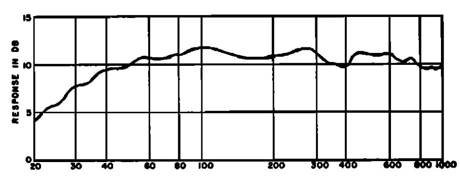

FIG. 10. Response frequency characteristic of the loudspeaker mechanism of Fig. 9 operating in a cabinet of one-half cubic foot.

The response of the loudspeaker in the cabinet indicated that some damping was required. The damping is provided by an acoustical resistance in the form of silk cloth covering the holes in the top plate of the magnetic structure which completely encloses the back of the diaphragm.

The response frequency characteristic of the loudspeaker is shown in Fig. 10. It will be seen that the performance is remarkably good for a loudspeaker of such a small size.

Amplifier

The schematic diagram for the amplifier of the electronic sound absorber is shown in Fig. 11. A battery powered amplifier was selected so the sound absorber could be tested in locations remote from power lines. Separate filament batteries were used on each stage, and separate plate supplies were used on the voltage and power stages to reduce amplifier regeneration difficulties. Ten 3S4 vacuum tubes in parallel were connected directly to the 200-ohm voice coil. The plate resistor, combines with the relatively low electrical impedance of the loudspeaker, to reduce the amount of power that can be obtained from this combination as contrasted to

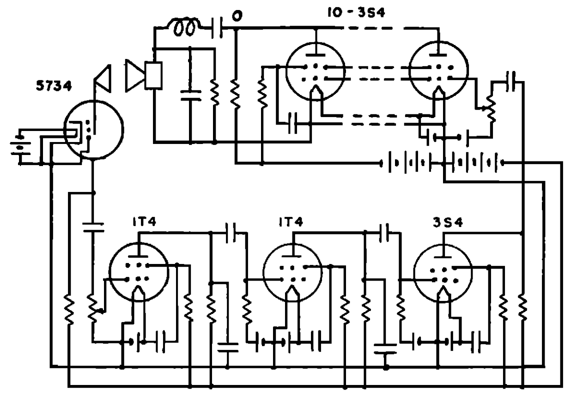

FIG. 11. Circuit diagram of the amplifier used in the electronic sound absorber.

that which could be obtained under optimum operating conditions. Nevertheless, the maximum undistorted power output to the loudspeaker is 0.5 watt. This is more than adequate for this application.

The response frequency characteristic of the amplifier from the input to the grid of the first tube to the point 0 of Fig. 11 is shown in Fig. 12. The reduction in output with frequency range is introduced to reduce noise and positive feedback in the high-frequency range. Further reduction in high-frequency response is obtained from the inductance-capacitance network between the amplifier and loudspeaker.

Operation

A sectional view, schematic electrical diagram, and acoustical circuit of the electronic sound absorber are shown in Fig. 13. The system is connected and equalized for frequency response and phase so that the sound pressure is reduced at the microphone. The driving pressure p_2 is given by

$$p_2=\frac{Bli}{S},$$

where B = flux density in the air gap of the loudspeaker, l = length of the conductor of the voice coil, i = current in the voice coil, and S = area of the cone.

The amplitude and phase relations between the sound pressures p_1 and p_2 are such as to make the sound pressure p_3 as small as possible over a wide frequency range. Under these conditions of operation the system

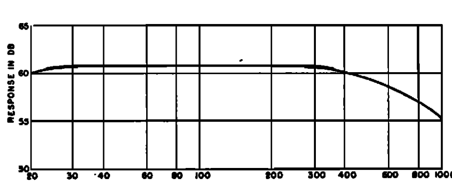

FIG. 12. Response frequency characteristic of the amplifier of Fig. 11.

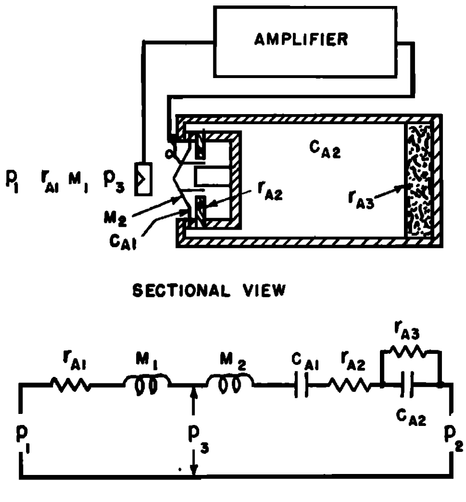

FIG. 13. Sectional view, schematic electrical diagram, and acoustical network of an electronic sound absorber. p_1=sound pressure in free space. M_1=inertance of the air load. r_{A1}=acoustical resistance of the air load. M_2=inertance of the cone and voice coil of the loudspeaker. C_{A1}=acoustical capacitance of the suspension system of the cone. r_{A2}=acoustical resistance of the cloth over the apertures in the back plate. C_{A2}=acoustical capacitance of the volume of the cabinet. r_{A3}=acoustical resistance of the sound absorbing material in the cabinet. p_2=driving sound pressure in the loudspeaker. p_3= sound pressure at the microphone.

is a sound pressure reducer. The system can also be designed so it will absorb sound. This can be done by designing the system so the proper phase relations are

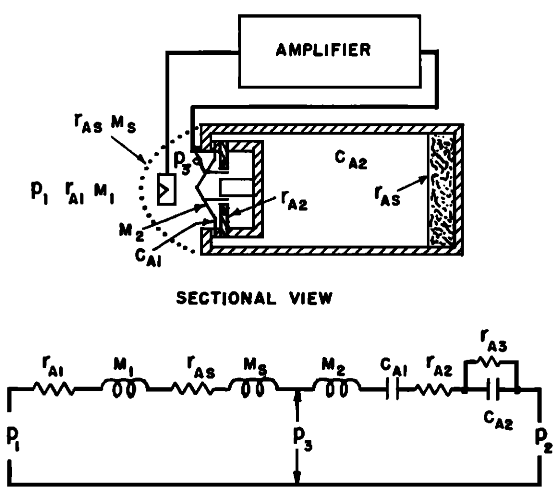

FIG. 14. Sectional view, schematic electrical diagram and acoustical network of an electronic sound absorber. p_1=sound pressure in free space. M_1=inertance of the air load. r_{A1}= acoustical resistance of the air load. M_2=inertance of the cone and voice coil of the loudspeaker. r_{AS}=acoustical resistance of the screen covering the microphone and cone. M_S=inertance of the screen. C_{A1}=acoustical capacitance of the suspension system of the cone. r_{A2}=acoustical resistance of the cloth over the apertures in the back plate. C_{A2}=acoustical capacitance of the volume of the cabinet. r_{A3}=acoustical resistance of the sound absorbing material in the cabinet. p_2=driving sound pressure in the loudspeaker. p_3=sound pressure at the microphone.

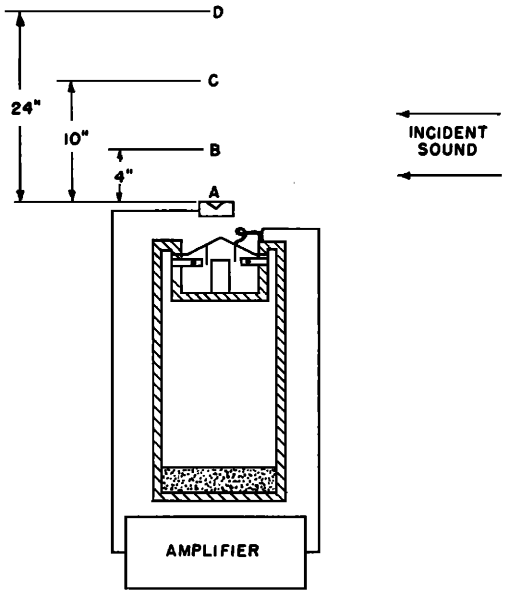

FIG. 15. Test arrangement for the electronic sound absorber. A, B, C, and D are test locations. A. At the face of the microphone. B. Four inches from the face of the microphone. C. Ten inches from the face of the microphone. D. Twenty-four inches from the face of the microphone.

obtained. However, for this application, the system shown in Fig. 14 is somewhat simpler in operation.

The problem in low-frequency sound absorption is to provide an acoustical impedance of a relatively small value so that the volume current which introduces the sound absorption will not be limited by a high acoustical impedance. The electronic sound absorber provides a low acoustical impedance for terminating a dissipative acoustical impedance. The dissipative acoustical impedance is provided by the screen r_{AS}, M_S in Fig. 14. If a bank of electronic sound absorbers is used so that the ultimate acoustical resistance of r_{A1} is obtained, then the inertance M_1 becomes practically zero. Under these conditions, the acoustical impedance of the screen should be an acoustical resistance equal to r_{A1}. Then, if the sound pressure p_3 is zero, 100 percent absorption is obtained.

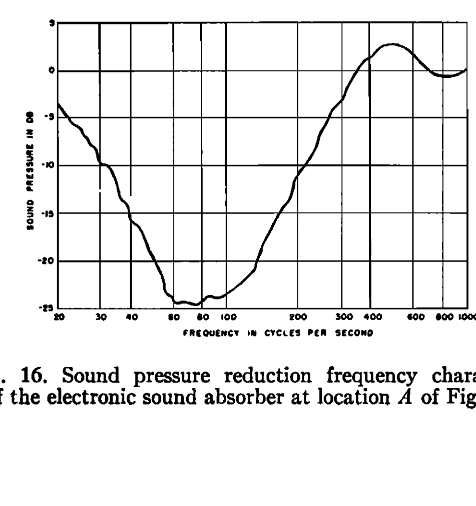

FIG. 16. Sound pressure reduction frequency characteristic of the electronic sound absorber at location A of Fig. 15.

Performance

The electronic sound absorber was placed in a plane-wave sound field as shown in Fig. 15. The pressure response frequency characteristics at point A at the face of the microphone were obtained with the amplifier turned on and off. The difference between these two characteristics gives the reduction in sound pressure due to the electronic sound absorber. The sound pressure reduction frequency characteristic at point A is shown in Fig. 16. It will be seen that a very high order of sound

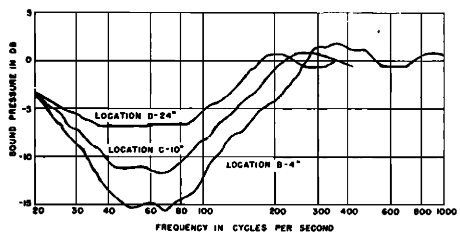

FIG. 17. Sound pressure reduction frequency characteristics of the electronic sound absorber at locations B, C, and D of Fig. 15.

reduction is obtained over a frequency range of more than three octaves. It would be practically impossible to obtain this order of sound reduction with a resonator over even a very small fraction of an octave. The pressure reduction frequency characteristics at various distances from the electronic sound absorber are shown in Fig. 17. It will be seen that a high value of sound reduction is obtained at a considerable distance.

Applications

There are many applications for a sound absorber which exhibits high sound reduction or high sound absorption efficiency in the low-frequency range because conventional sound absorbing materials exhibit very low absorption in this range. The sound absorption coefficients of a typical acoustical material as a function of the frequency are shown in Table I. It will be seen

TABLE I. Absorption coefficient of a typical sound absorbing material, 1¼ inch in thickness, cemented to a wall.

Frequency	64	128	256	512	1024	2048	4096
Coefficient	0.08	0.14	0.42	0.99	0.74	0.60	0.50

that the absorption coefficient is very small in the low-frequency range. Therefore, the sound reduction which can be obtained in the low-frequency range is only one or two decibels. It is in this range that the electronic sound absorber is very efficient. It is conceivable that the cost could be brought to a point where the electronic sound absorber could be used as a wall treatment for a room to provide absorption in the low-frequency range. The other application for the system is that of a spot-type sound reducer, that is, for reducing the sound level over a limited space.

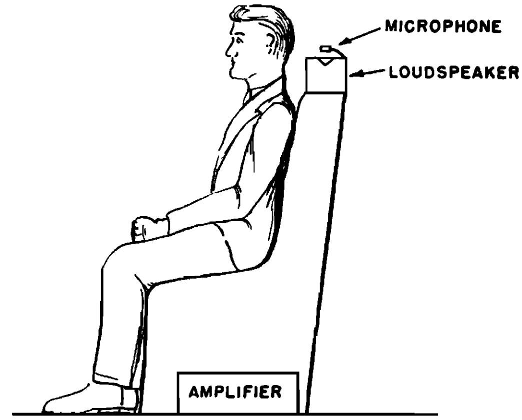

FIG. 18. Electronic sound absorber used in an airplane or automobile to reduce the noise in the vicinity of the occupant's head.

One application for the electronic sound absorber is in the form of a sound reducer in airplanes and automobiles where the noise level is very high in the low-frequency region. As pointed out above, the conventional sound absorbing material will not reduce the noise level in this frequency region to any appreciable degree. The electronic sound absorber can be installed on the back of a seat as shown in Fig. 18. In this way a sound reduction of 10 to 20 decibels can be obtained in the low-frequency range at the ears of the passenger. There are many other applications for a spot-type low-frequency noise reducer in factories, shops, and offices where the frequency noise level is high and the position of the person is fixed. For example, the application of

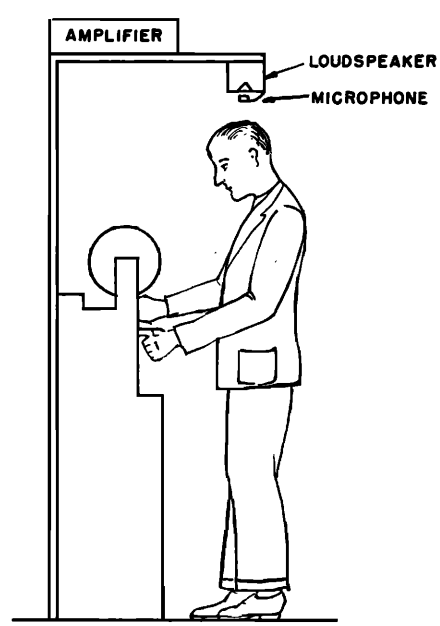

FIG. 19. Electronic sound absorber used to reduce the low-frequency machinery noise in the vicinity of the head of an operator.

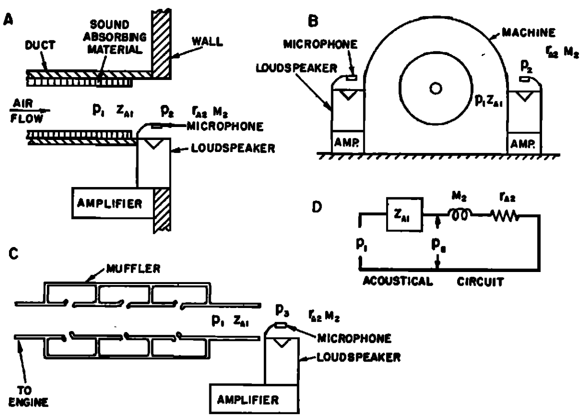

FIG. 20. Applications of electronic sound absorber for reducing the low-frequency sound output from different sound sources and the acoustical circuit depicting the performance of these systems. A. Sectional views of an air conditioner output. B. End view of a generalized machine. C. Sectional views of a muffler for an internal combustion engine. D. Acoustical circuit of systems in A, B, and C. p_1=driving sound pressure of the sound or noise source. z_{A1}=acoustical impedance of the source. r_{A2}=acoustical radiation resistance of the source. M_2=inertance of the source. p_2=radiation sound pressure.

an electronic sound absorber in a machine shop is shown in Fig. 19. Here the electronic sound reducer is located directly above the head of the operator.

The electronic sound absorber provides a system which reduces the sound pressure over a considerable space. This suggests applications for reducing the sound output of sound producing systems by acoustically short circuiting the acoustical generator. Three examples of this application of the acoustical sound absorber are shown in Fig. 20A, B, and C. The acoustical circuit which applies to all three systems is shown in Fig. 20D.

The arrangement in Fig. 20A depicts the outlet portion of an air conditioning duct. It is well known that the sound in mid- and high-frequency ranges can be absorbed with high efficiency by lining the duct with acoustical sound absorbing material. However, the sound in the low-frequency range is not absorbed with good efficiency. As a result, the sound output in the low-frequency range is above the tolerable point. The sound output in the low-frequency range can be reduced by the use of an electronic sound absorber as shown in Fig. 20A. The sound pressure p_2 at the microphone and in the vicinity of the microphone is reduced to a very low value. Under these conditions the sound output is reduced, as can be deduced from a consideration of the acoustical circuit of Fig. 20D. Measurements upon an air duct indicated a reduction in sound output from the duct approximately the same as the characteristic of Fig. 16.

The low-frequency sound output of internal combustion engines is very difficult to reduce by the means of mufflers. Here again the electronic sound absorber can be used to reduce the sound output in the low-frequency range as shown in Fig. 20B. As in the preceding example, the acoustical circuit of Fig. 20D illustrates the action.

The low-frequency output of many machines is very high and cannot be reduced to a tolerable value by the use of sound absorbing materials. The electronic sound absorber can be used to reduce the sound output as shown in Fig. 20C. As in the preceding example, the idea is to reduce the sound pressure at the sound generators. Since the wavelength is relatively long in the low-frequency range, the sound absorber exerts its influence to reduce the sound pressure over a large space. Experimental tests have indicated that a reduction similar to the characteristics of Figs. 16 and 17 can be obtained. The amount of sound reduction by a single unit depends upon the dimensions of the noise source. In the case of large sources, several electronic noise reducers may be used and thereby obtain the maximum reduction in noise.

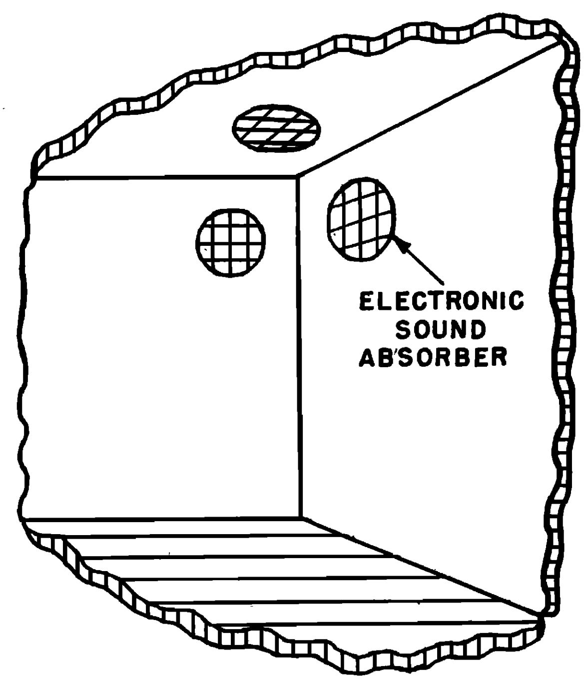

FIG. 21. Three electronic sound absorbers located in the corner of a room.

The electronic sound absorber can be used in the same manner as conventional wall materials for the absorption of sound in the low-frequency range by the use of the system shown in Fig. 14. In order to obtain a high acoustical resistance load the absorbers should be mounted in the corner at the intersection of three surfaces as shown in Fig. 21. As contrasted to the resonant absorber with a narrow frequency range of sound absorption, the electronic sound absorber exhibits high sound absorption over a wide frequency range.