LB-845

COMPOUND DIRECT RADIATOR LOUDSPEAKER

RADIO CORPORATION OF AMERICA

RCA LABORATORIES DIVISION

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Approved

Stuart W. Seeley

Introduction

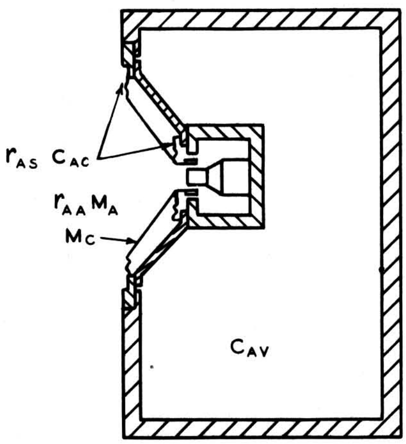
The completely closed cabinet as a mounting arrangement for a direct radiator loudspeaker mechanism is generally accepted as superior in performance to that of the open back cabinet. The open back cabinet of conventional dimensions exhibits a serious resonance which accentuates the response at a relatively high frequency in the low frequency range. In addition, the low frequency response is highly attenuated below the resonant frequency. On the other hand, the response at the resonant frequency of a completely closed cabinet of conventional dimensions is not as severely accentuated as in the open back cabinet. In addition, the resonant frequency occurs at a lower frequency than the corresponding open back cabinet. It is for these reasons that the closed cabinet with or without a port has become the standard for high quality sound reproduction in the home, monitoring in broadcasting, television and recording studios, and in other small scale sound reproducing applications.

One of the objections to the closed loudspeaker cabinet with or without a port is the large size required to maintain the response in the low frequency range. There are many applications requiring high fidelity sound reproducing systems in which the cabinet space allocated to the loudspeaker is limited, as for example, combination instruments including television, radio and phonograph in a single integrated unit, built-in custom installations, monitoring loudspeakers in some locations in broadcasting and television applications, etc. As a consequence it is impossible to obtain wide frequency range, high quality sound reproduction for these applications.

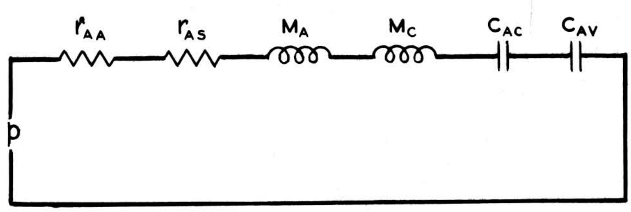
In order to obtain adequate low frequency response in a small completely enclosed cabinet some means must be provided for increasing the effective volume of the cabinet. The effective volume of a cabinet may be increased by decreasing the stiffness presented to the radiating loudspeaker mechanism by the cabinet in the low frequency range. It is possible to reduce the effective stiffness of the cabinet by the use of an auxiliary loudspeaker mechanism which drives the radiating loudspeaker mechanism. This system has been termed a compound direct radiator loudspeaker. It is the purpose of this bulletin to describe a compound direct radiator loudspeaker.

Direct Radiator Loudspeaker Mechanism Mounted in a Closed Cabinet

The first consideration will be the relation between the dimensions of the loudspeaker and cabinet and the low-frequency response of a direct radiator loudspeaker mechanism operating in a completely enclosed cabinet. This analysis will show the limitations of the system from the standpoint of the volume of the cabinet and the characteristics of the loudspeaker mechanism.



SECTIONAL VIEW



ACOUSTICAL CIRCUIT

Fig. 1 - Sectional view and acoustical circuit of a direct radiator loudspeaker mechanism mounted in a closed cabinet. In the acoustical circuit: p = driving pressure. r_{AA} = acoustical radiation resistance. r_{AS} = acoustical resistance of the suspension system. M_A = inertance of the air load. M_C = inertance of the cone and coil. C_{AC} = acoustical capacitance of the suspension system. C_{AV} = acoustical capacitance of the cabinet.

A sectional view and the acoustical circuit of a direct radiator loudspeaker mechanism mounted in an enclosed cabinet are shown in Fig. 1. The voice coil electrical circuits of the loudspeaker of Fig. 1 are shown in Fig. 2. A photograph of a 12-inch direct radiator loudspeaker mechanism mounted in a closed cabinet having a volume of two cubic feet is shown in Fig. 3. The total acoustical impedance z_{AT}, in acoustical ohms, of the vibrating system of Fig. 1 is given by

$$z_{AT} = r_{AA} + r_{AS} + j\omega M_A + j\omega M_C - j/\omega C_{AC} - j/\omega C_{AV} \qquad (1)$$

where r_{AA} = acoustical resistance due to air load, in acoustical ohms,

r_{AS} = acoustical resistance of the suspension system, in acoustical ohms,

M_A = inertance of the air load upon the cone, in grams per (centimeter)^4,

M_C = m_C/A^2 = inertance of the cone and coil, in grams per (centimeter)^4,

A = Area of the cone, in square centimeters,

m_C = mass of the cone and coil, in grams,

C_{AC} = acoustical capacitance of the suspension system, in (centimeter)^5 per dyne,

C_{AV} = $V/\rho c^2$ = acoustical capacitance of the volume of the cabinet, in (centimeter)^5 per dyne,

ρ = density of air, in grams per cubic centimeter,

c = velocity of sound, in centimeters per second,

V = volume of the cabinet, in cubic centimeters,

The volume current $\dot{X}$, in cubic centimeters per second, in the system is given by

$$\dot{X} = \frac{p}{z_{AT}} = \frac{p}{r_{AA} + r_{AS} + j\omega M_A + j\omega M_C - j/\omega C_{AC} - j/\omega C_{AV}} \qquad (2)$$

where p = f_M/A = pressure developed by the voice coil, in dynes per square centimeter,

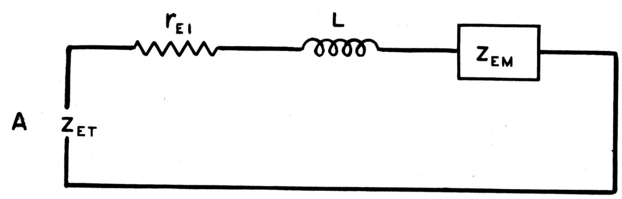
f_M = Bli = force developed in the voice coil, in dynes,

B = flux density in the air gap, in gausses,

l = length of the voice coil conductor in centimeters,

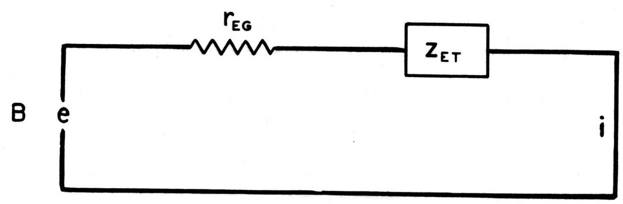
i = current in the voice coil, in abamperes,

A = area of the cone, in square centimeters



ELECTRICIAL CIRCUIT

Fig. 2 (A) – Electrical circuit of the voice coil of the mechanism of Fig. 1. z_{ET} = total electrical impedance of the voice coil. r_{E1} = electrical resistance of the voice coil. L_1 = inductance of the voice coil. z_{EM1} = motional electrical impedance of the voice coil.



ELECTRICIAL CIRCUIT

Fig. 2 (B) – Electrical circuit of the generator and voice coil. e = open circuit voltage of the generator. r_{EG} = electrical resistance of the generator. i = current in the circuit.

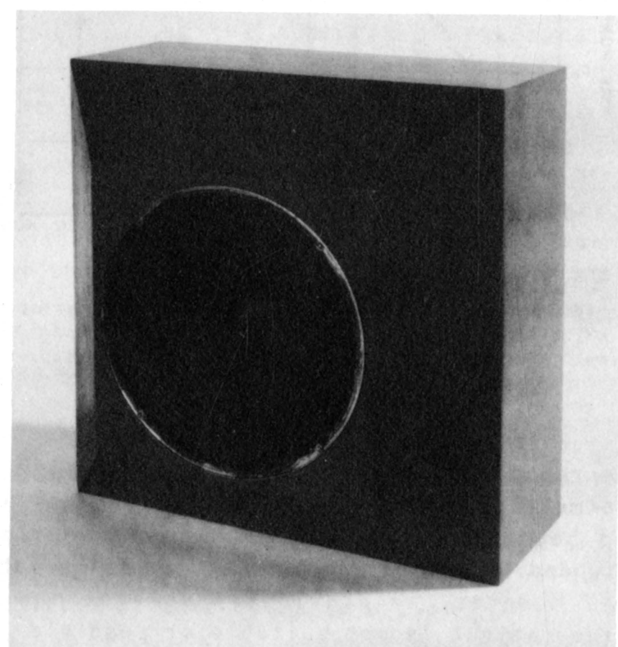


Fig. 3 – Photograph of a twelve inch direct radiator loudspeaker mechanism mounted in a closed cabinet having a volume of two cubic feet.

The motional electrical impedance z_{EM1}, in abohms, of the voice coil is given by

$$z_{EM1} = \frac{(Bl)^2}{z_{AT}A^2} \qquad (3)$$

The electrical circuit of the voice coil is shown in Fig. 2A. The total electrical impedance z_{ET}, in abohms, of the voice coil is given by

$$z_{ET} = r_{E1} + j\omega L_1 + z_{EM1} \qquad (4)$$

where r_{E1} = electrical resistance of the voice coil, abohms, and

L_1 = inductance of the voice coil in abhenries.

The electrical circuit of the voice coil and generator is shown in Fig. 2B. The electrical current i, in abamperes, is given by

$$i = \frac{e}{r_{EG} + z_{ET}} \qquad (5)$$

where e = open circuit voltage of the generator, in abvolts and

r_{EG} = electrical resistance of the generator, in abohms.

The acoustical power output P, in watts, is given by

$$P = r_{AA} \dot{X}^2 \cdot 10^{-7} \qquad (6)$$

The performance of a dynamic direct radiator loudspeaker mounted in a completely enclosed cabinet can be predicted from Eqs. 1 to 6 inclusive. To show the effect of the volume of the cabinet upon the response of a direct radiator dynamic loudspeaker mechanism the theoretical and experimental performance of a typical 12-inch loudspeaker mechanism mounted in an enclosed cabinet will be described. The specifications of the loudspeaker mechanism used in these tests are as follows: Effective diameter of the cone = 10.5 inches. Mass of the cone, voice coil and air load = 25.5 grams. Length of the voice coil conductor = 522 centimeters. Electrical resistance of the voice coil = 2.8×10^9 abohms. Inductance of the voice coil = 8.9×10^4 abhenries. Flux density in the air gap = 10,000 gausses. Resonant frequency of the mechanism = 70 cycles. The acoustical resistance of the suspension system = 0.003 acoustical ohms. The generator electrical resistance = 1.4 x 10^9 abohms. The acoustical radiation resistance of the air load upon the cone can be obtained from the conventional formulas[1] for these quantities. The performance may be predicted from the above data and the cabinet volume.

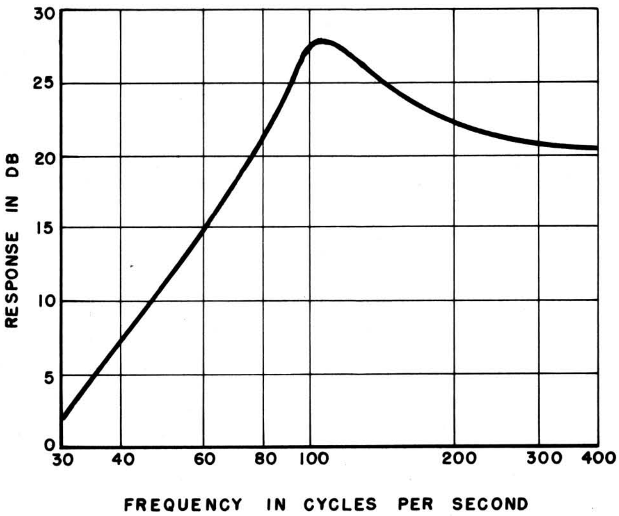


Fig. 4 – Theoretical response frequency characteristic of a twelve inch direct radiator loudspeaker mechanism mounted in a closed cabinet having a volume of two cubic feet.

The theoretically determined acoustical power output characteristic of the above mechanism operating in cabinet of two cubic feet is shown in Fig. 4. The corresponding experimentally determined acoustical output characteristic is shown in Fig. 5. The experimentally determined response of the same system but with damping material in the cabinet is shown in Fig. 6. Referring to Figs. 5 and 6 it will be seen that the combined resonant frequency of the cabinet and mechanism is 113 cycles. The response falls off quite rapidly below 90 cycles. Therefore, the low-frequency performance of the 12-inch direct radiator loudspeaker mechanism in a cabinet of two cubic feet is not satisfactory for a high quality reproducing system.

There are many expedients that may be employed to increase the low-frequency range of the combination of a direct radiator loudspeaker mechanism mounted in a completely enclosed cabinet. These systems will be described below.

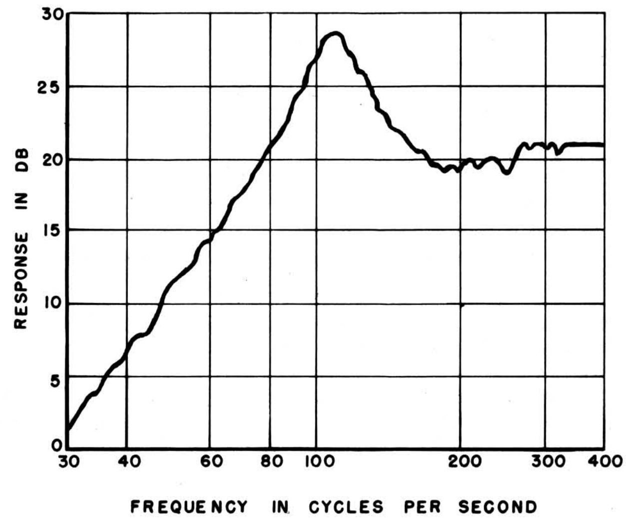


Fig. 5 – Measured response frequency characteristic of a twelve inch direct radiator loudspeaker mechanism mounted in a closed undamped cabinet having a volume of two cubic feet.

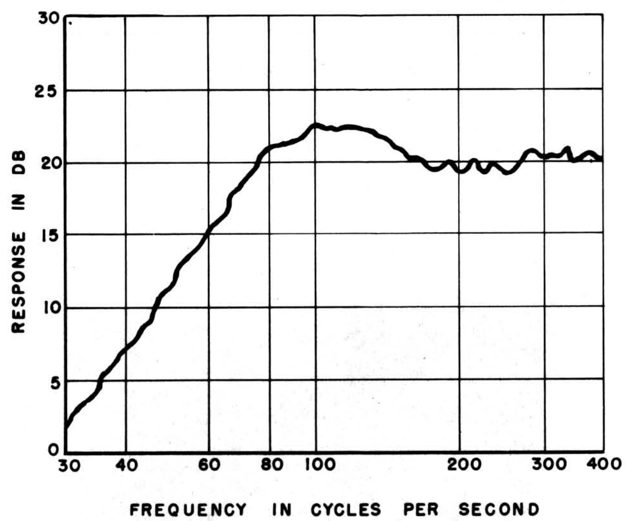


Fig. 6 – Measured response frequency characteristic of a twelve inch direct radiator loudspeaker mechanism mounted in a closed damped cabinet having a volume of two cubic feet.

Referring to Eq. (1) it will be seen that the resonant frequency of the combination of the mechanism and the cabinet can be lowered and hence the low-frequency response range extended by increasing the volume of the cabinet. However, as previously pointed out, a large cabinet is not suitable or possible for some applications.

The resonant frequency of the system consisting of the mechanism and cabinet can b

[1] Olson, ELEMENTS OF ACOUSTICAL ENGINEERING, D. Van Nostrand Company, New York, N. Y., 1947.

lowered by increasing the compliance of the suspension of the vibrating system of the mechanism. However, even if the stiffness of the suspension system were made zero, that is, an infinite compliance, the resonant frequency of the 12-inch loudspeaker mechanism described above operating in a cabinet of two cubic feet would still be 88 cycles. Obviously, this is not a satisfactory solution. Furthermore, decreasing the stiffness beyond a certain value leads to a ragged response frequency characteristic in the mid-frequency range due to "break up" of the limp suspension system.

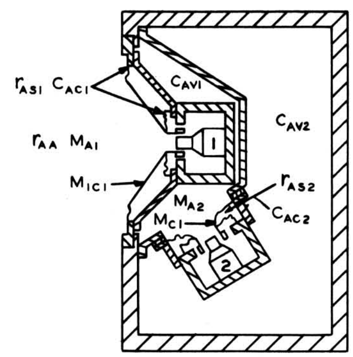
The resonant frequency of the combination of loudspeaker mechanism and cabinet can be lowered by increasing the inertance of the cone. The inertance of the cone of the mechanism described above can be increased by increasing the mass of the cone and voice coil. In order to obtain a resonant frequency of 72 cycles in a cabinet of two cubic feet with the same suspension system would require an increase in mass of 2½ times. Since the air load mass is unchanged this would require an increase in mass of the cone and voice coil of approximately 4 times. This system is impractical from the standpoint of efficiency and response.

The inertance of the cone can be increased by decreasing the diameter of the cone. Decreasing the diameter of the cone in the mechanism described above by a factor of one half but retaining the same voice coil will increase the inertance by 3.6 times. A mechanism employing this cone will give satisfactory response in the low-frequency range. However, for the same output the amplitude of the smaller cone will be four times that of the larger cone. If large outputs are not required this is a satisfactory solution.

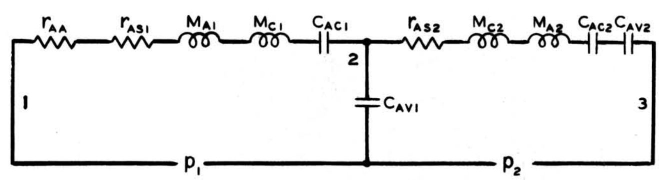
An examination of the above loudspeaker systems for improving the low-frequency response indicates that there is a deviation from the conventional systems. It appears that a practical solution for this problem would be the addition of some means to a conventional loudspeaker mechanism so that the performance would be equivalent to that of a large cabinet. It is the purpose of the next section to describe an adjunct which accomplishes this result.

Compound Direct Radiator Loudspeaker

One solution of the problem of maintaining adequate response in the low-frequency region in a small closed cabinet is to employ some means for reducing the stiffness presented to the cone of the loudspeaker mechanism by the cabinet. This can be accomplished by employing a second loudspeaker mechanism with a small cone coupled to the first loudspeaker mechanism with the large radiating cone. This system has been termed a compound direct radiator loudspeaker.



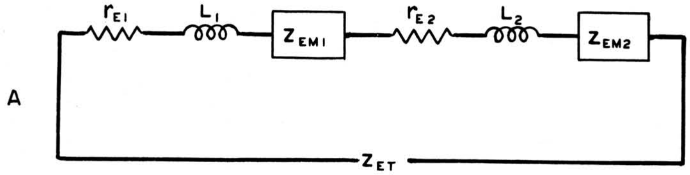
SECTIONAL VIEW



ACOUSTICAL NETWORK

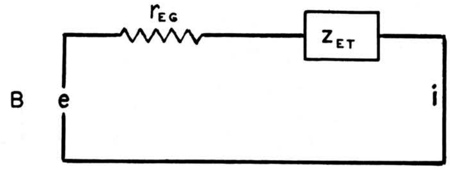
Fig. 7 - Sectional view and acoustical circuit of a compound direct radiator loudspeaker mounted in a closed cabinet. In the acoustical circuit: p_1 and p_2 = driving pressure of mechanism 1 and 2. r_{AA} = acoustical radiation resistance. r_{AC_1} and r_{AC_2} = acoustical resistance of the suspensions of mechanisms 1 and 2. M_{A_1} and M_{A_2} = inertances of cones and voice coils of mechanisms 1 and 2. C_{AS_1} and C_{AS_2} = acoustical capacitances of the suspensions of mechanisms 1 and 2. C_{AV_1} = acoustical capacitance of the volume between the loudspeaker mechanisms 1 and 2. C_{AV_2} = acoustical capacitance of the volume behind loudspeaker mechanism 2.

A sectional view and the acoustical network of the compound direct radiator loudspeaker system are shown in Fig. 7. The electrical circuits of the loudspeaker system of Fig. 7 are shown in Fig. 8. A photograph of the components of a compound direct radiator loudspeaker is shown in Fig. 9.



ELECTRICAL CIRCUIT

Fig. 8 (A) - Electrical circuit of the voice coils of mechanisms 1 and 2 of Fig. 7 connected in series. z_{ET} = total electrical impedance. r_{E1} = electrical resistance of the voice coil of mechanism 1. L_1 = inductance of the voice of mechanism 1. z_{EM1} = motional electrical impedance of the voice coil of mechanism 1. r_{E2} = electrical resistance of the voice coil of mechanism 2. L_2 = inductance of the voice coil of mechanism 2. z_{EM2} = motional electrical impedance of voice coil 2.



ELECTRICAL CIRCUIT

Fig. 8 (B) - Electrical circuit of the generator and voice coils. e = open circuit voltage of the generator. r_{EG} = electrical resistance of the generator. i = current in the circuit.

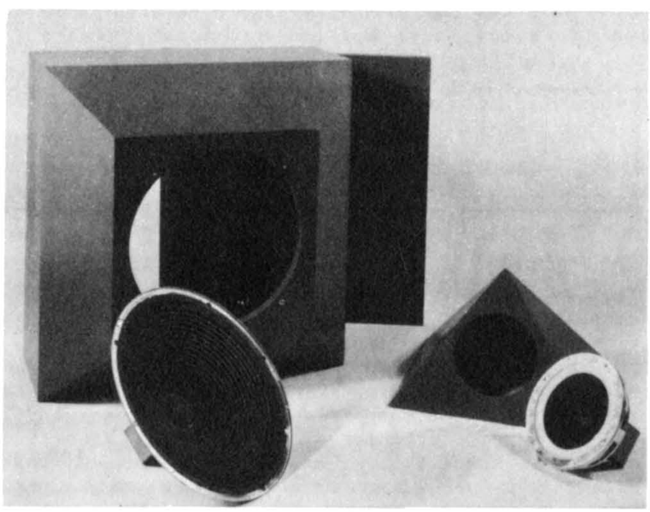


Fig. 9 - Photograph of the components of a compound direct radiator loudspeaker showing the 12-inch and the 5-inch loudspeaker mechanisms, the coupler and a closed cabinet having a volume of two cubic feet.

The volume current $\dot{X}_1$, in cubic centimeters per second, in branch 1 of Fig. 7, is given by

$$\dot{X}_1 = \frac{p_1(z_{A2} + z_{A3})}{D} + \frac{p_2(z_{A2})}{D} \qquad (7)$$

where p_1 = pressure delivered by loudspeaker 1, in dynes per square centimeter,

p_2 = pressure delivered by loudspeaker 2, in dynes per square centimeter,

$D = z_{A1}z_{A2} + z_{A1}z_{A3} + z_{A2}z_{A3}$

$z_{A1} = r_{AA} + r_{AS1} + j\omega M_{A1} + j\omega M_{C1} - j/\omega C_{AC1}$

$z_{A2} = - j/\omega C_{AV1}$

$z_{A3} = r_{AS2} + j\omega M_2 - j/\omega C_{AC2} - j/\omega C_{AV2}$

r_{AA} = acoustical resistance due to the air load, upon the cone of loudspeaker 1, in acoustical ohms,

r_{AS1} = acoustical resistance of the suspension of loudspeaker 1, in acoustical ohms,

M_{A1} = inertance of the air load upon the cone of loudspeaker 1 in grams per (centimeter)^4,

M_{C1} = inertance of the cone and coil of loudspeaker 1, in grams per (centimeter)^4,

C_{AC1} = acoustical capacitance of the suspension system of loudspeaker 1, in (centimeter)^5 per dyne,

C_{AV2} = acoustical capacitance of the volume behind loudspeaker 2, in (centimeters)^5 per dyne.

r_{AS2} = acoustical resistance of the suspension system of loudspeaker 2, in acoustical ohms.

M_{C2} = inertance of the cone of loudspeaker 2, in grams per (centimeter)^4,

M_{A2} = inertance of the air load upon the cone of loudspeaker 1, in grams per (centimeter)^4,

C_{AC2} = acoustical capacitance of the suspension of loudspeaker 2, in (centimeters)^5 per dyne,

$p_1 = f_{M1}/A_1$ = driving pressure, in dynes per square centimeter,

$f_{M1} = B_1 l_1 i$ = driving force, in dynes,

B_1 = flux density in the air gap of loudspeaker 1, in gausses,

l_1 = length of the voice coil conductor of loudspeaker 1, in centimeters,

A_1 = area of the cone of loudspeaker 1, in square centimeters,

i = current in the voice coil, in abamperes,

$p_2 = f_{M2}/A_2$ = driving pressure, in dynes per square centimeter,

$f_{M2} = B_2 l_2 i$ = driving force, in dynes

B_2 = flux density in the air gap of loudspeaker 2, in gausses,

l_2 = length of the voice coil conductor of loudspeaker 2, in centimeters,

A_2 = area of the cone of loudspeaker 2, in square centimeter.

The volume current $\dot{X}_2$, in cubic centimeters per second, in branch 3 of Fig. 5 is given by

$$\dot{X}_2 = \frac{p_2(z_{A2} + z_{A1}) + p_1 z_{A2}}{D} \qquad (8)$$

Since the electrical current is the same in the voice coils of loudspeaker mechanisms 1 and 2, there follows the relation

$$p_1/p_2 = B_1 l_1 A_2 / B_2 l_2 A_1 = K \qquad (9)$$

where K = constant given by Eq. 9.

From Eqs. 7 and 9, the acoustical impedance, in acoustical ohms, at p_1 of Fig. 7 is

$$z'_{A1} = \frac{p_1}{\dot{X}_1} = \frac{D}{z_{A2} + \frac{z_{A2}}{K} + z_{A3}} \qquad (10)$$

From Eqs. 8 and 9, the acoustical impedance, in acoustical ohms, at p_2 of Fig. 7 is

$$z'_{A2} = \frac{p_2}{\dot{X}_2} = \frac{D}{z_{A1} + z_{A2} + K z_{A2}} \qquad (11)$$

The motional electrical impedance z_{EM1}, in abohms, of the voice coil of loudspeaker mechanism 1 is given by

$$z'_{EM1} = (B_1 l_1)^2 / z_{A1} A_1^2 \qquad (12)$$

The motional electrical impedance z_{EM2}, in abohms, of the voice coil of loudspeaker mechanism 2 is given by

$$z'_{EM2} = (B_2 l_2)^2 / z_{A2} A_2^2 \qquad (13)$$

The electrical circuit consisting of the voice coils of loudspeaker mechanisms 1 and 2 is shown in Fig. 8A. The total electrical impedance z_{ET}, in abohms, of the voice coils of loudspeaker mechanisms 1 and 2 in series is given by

$$z_{ET} = r_{E1} + j\omega L_1 + z_{EM1} + r_{E2} + j\omega L_2 + z_{EM2} \qquad (14)$$

where r_{E1} = electrical resistance of the voice coil of loudspeaker 1, in abohms,

L_1 = inductance of the voice coil of loudspeaker 1, in abhenries,

r_{E2} = electrical resistance of the voice coil of loudspeaker 2, in abohms,

L_2 = inductance of the voice coil of loudspeaker 2, in abhenries

The electrical circuit of the voice coils and generator is shown in Fig. 8B. The electrical current i, in abamperes, is given by

$$i = \frac{e}{r_{EG} + z_{ET}} \qquad (15)$$

where e = voltage of the generator, in abvolts and

r_{EG} = electrical resistance of the generator, in abohms.

The acoustical output is produced by loudspeaker mechanism 1. The acoustical power output P, in watts, is given by

$$P = r_{AA} \dot{X}_1^2 \cdot 10^{-7} \qquad (16)$$

The performance of the compound direct radiator loudspeaker can be determined from Eqs. 7 to 16 inclusive. To demonstrate the effectiveness of the compound loudspeaker in extending the low frequency range, the loudspeaker mechanism described in the preceding section was used as the radiating loudspeaker and designated as 1 in the compound loudspeaker system of Fig. 7. The total cabinet volume was two cubic feet. The volume behind the loudspeaker mechanism was 1.8 cubic feet. The specifications of the loudspeaker mechanism 2 are as follows: Effective diameter of the cone = 5 inches. Length of the voice coil conductor = 321 centimeters. Electrical resistance of the voice coil = 7×10^8 abohms. Inductance of the voice coil = 2.2×10^4 abhenries. Flux density in the air gap = 11,250 gausses. The acoustical capacitance of the suspension = 0.049 $(\text{centimeters})^5$ per dyne. Mass of the cone, air load and voice coil = 4 grams. The acoustical resistance of the suspension system = 0.0015 to 0.003 acoustical ohm. The generator electrical resistance = 1.7×10^9 abohms. From the above data the performance of the compound direct radiator loudspeaker may be predicted.

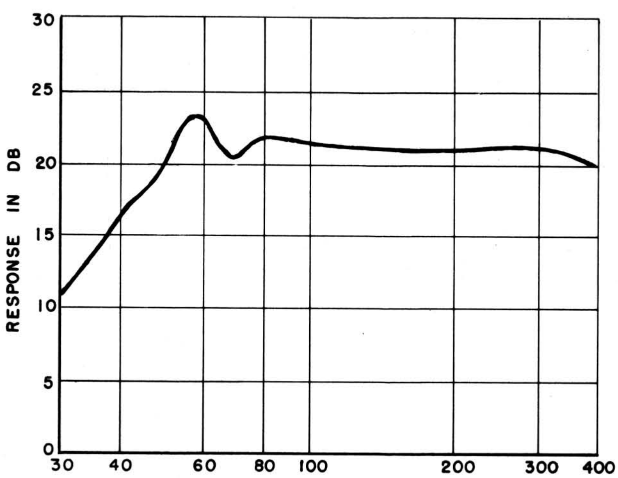


Fig. 10 – Theoretical response frequency characteristic of a compound direct radiator loudspeaker mechanism mounted in a closed cabinet of two cubic feet. The radiator is a twelve-inch mechanism.

The theoretically determined acoustical output characteristic of the compound direct radiator loudspeaker is shown in Fig. 10. The experimentally determined characteristic is shown in Fig. 11. Comparing Figs. 10 and 11 with Figs. 4, 5 and 6 it will be seen that for the same cabinet volume the low frequency range is extended by the use of the compound direct radiator loudspeaker system. As a matter of fact, the output characteristic of the compound direct radiator loudspeaker system operating in a cabinet of two cubic feet is the same as that of the single loudspeaker system operating in a very large cabinet of several cubic feet. The efficiency of the compound system in the high-frequency range is practically the same as that of loudspeaker mechanism 1 alone because the electrical impedance of loudspeaker mechanism 2 is small compared to that of loudspeaker 1 in the region above 300 cycles. Below 300 cycles the combined characteristics of the two mechanisms conspire to extend the low-frequency range and smooth out the response.

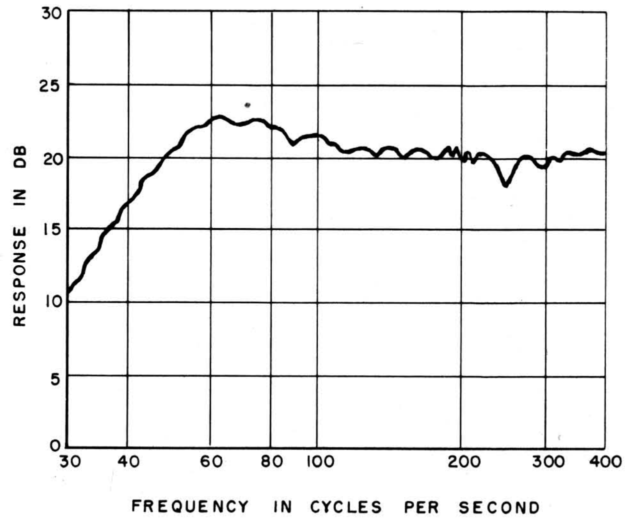


Fig. 11 – Measured response frequency characteristic of a compound direct radiator loudspeaker mechanism mounted in a closed cabinet of two cubic feet. The radiator is a twelve-inch mechanism.

The loudspeaker mechanism 2 must be capable of executing excursions four times that of loudspeaker 1 in order that the power handling capacity of the compound system will not be limited by the loudspeaker mechanism 2. Above 400 cycles mechanism 2 does not influence the response of the system. Therefore, the performance of the loudspeaker mechanism 2 in the region above 400 cycles is of no consequence. Under these conditions the entire attention as to performance of loudspeaker mechanism 2 can be confined to the low frequency region. For example, the breakup of the limp suspension system in the loudspeaker mechanism 2 in the mid and high frequency ranges is not important as would be the case if it were the radiating loudspeaker. A consideration of Fig. 7 and Eqs. 7 to 16 inclusive shows that a small amount of distortion in loudspeaker mechanism 2 will be reduced to a negligible amount by the radiating loudspeaker. These factors conspire to make the design of loudspeaker mechanism a rather simple task.

The compound direct radiator loudspeaker may be used with a closed cabinet equipped with a port and thereby increase the amplitude of the response over a portion of the low-frequency region at the expense of a higher low-frequency

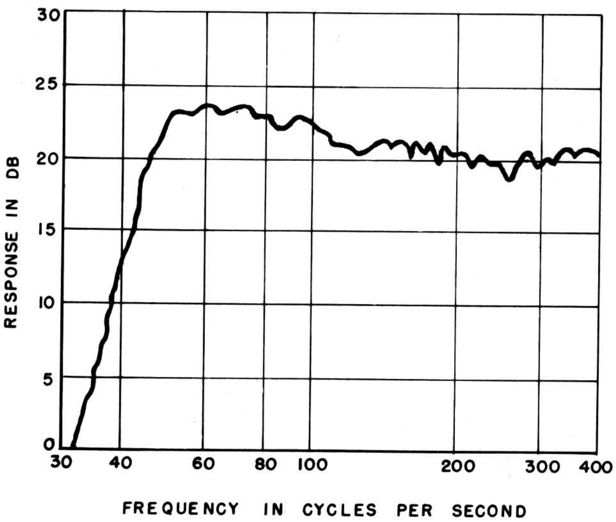


Fig. 12 - Measured response frequency characteristic of a compound direct radiator loudspeaker mechanism mounted in a closed cabinet of two cubic feet equipped with a port. The radiator is a twelve inch mechanism.

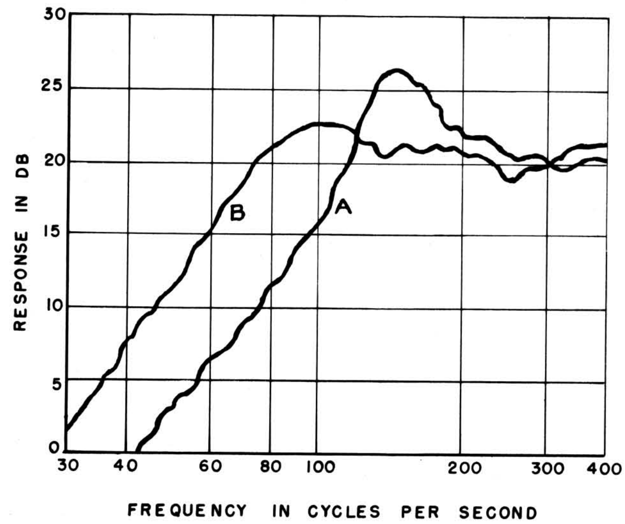


Fig. 13 (A) - Measured response frequency characteristic of a ten inch direct radiator loudspeaker mechanism mounted in a closed cabinet having a volume of one cubic foot.

Fig. 13 (B) - Measured response frequency characteristic of a compound direct radiator loudspeaker mounted in a closed cabinet having a volume of one cubic foot. The radiating mechanism is a ten inch mechanism.

cutoff. The experimentally determined response frequency characteristic of the compound direct radiator loudspeaker operating in a closed cabinet equipped with a port is shown in Fig. 12. It will be seen that the output is increased over a closed cabinet in the region from 45 to 150 cycles. However, the low-frequency cutoff is sharper than that of a closed cabinet.

In a second application of the compound direct radiator loudspeaker, a 10-inch loudspeaker was used as the radiating loudspeaker. The total cabinet volume was one cubic foot. The response frequency characteristic of the ten inch loudspeaker mechanism mounted in a closed cabinet of one cubic foot is given by the curve A of Fig. 13. The response frequency characteristic of a compound loudspeaker system consisting of the same ten-inch loudspeaker mechanism as the radiating loudspeaker, a small second mechanism and a cabinet with a volume of one cubic foot is given by the curve B of Fig. 13.

The compound direct radiator loudspeaker as described above, provides a system for obtaining adequate low-frequency response in a cabinet of small volume. In other words, if the cabinet is restricted to a relatively small volume, the addition of a second smaller direct radiator loudspeaker mechanism supplies an adjunct, which in combination with a conventional direct radiator loudspeaker mechanism, makes it possible to obtain the same low-frequency response in a small cabinet as would be obtained with the conventional mechanism operating alone in a relatively large cabinet.

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