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# METHODS FOR DETERMINING SOUND TRANSMISSION LOSS IN THE FIELD [1]

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## ABSTRACT

In the customary method of determining the transmission loss of a wall or floor partition, it is necessary to measure the difference in sound levels existing in two rooms which have the partition as a separating wall or floor. Also the ratio $A_2/S$, where $A_2$ is the total sound absorption of the receiving room and $S$ the transmitting area of the partition, must be known. Difficulties are experienced in field measurements because of the nonuniformity of sound levels in the test rooms and an uncertain knowledge of $A_2$. Two new methods which eliminate these difficulties are described. In both of these methods the sound level on the quiet side is measured at the panel face, in the one method with a pressure microphone and in the other with a pressure gradient (ribbon) microphone. In the latter method, the transmission loss is independent of the value of $A_2/S$ if the panel face has little sound-absorptive value, while in the former it is possible, in most cases, to eliminate the necessity of measuring $A_2$ by determining in addition the average sound level in the receiving room.

Also, the possibility of using the ribbon microphone as a radiation pickup is indicated.

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## I. INTRODUCTION

This work was initiated with the purpose of developing a method of determining the sound-insulating efficiency of wall and floor partitions which would give results for field measurements comparable to those obtained in the laboratory. The method in most general use for laboratory determinations is one which consists in inserting the panel in an opening between two rooms in one of which a source of sound is located. The difference in sound level in the source and receiving room

[1] Presented in part at the twenty-third meeting of the Acoustical Society of America, April 29 and 30, 1940, under the title, *The Dependence of Sound Transmission Measurements on Microphone Position.*

may be related to give the efficiency of the construction in terms of the transmission loss, which is defined by the equation:

$$\text{Transmission loss} = L_1 - L_2 + 10 \log_{10} (S/A_2), \qquad (1)$$

where $L_1$ = average sound level in decibels in room 1, the source room,
$L_2$ = average sound level in decibels in room 2, the receiving room,
$S$ = total area of sound transmitting surface,
$A_2$ = total absorption in room 2, $A_2$ measured in same units as $S$.

If it is attempted to use eq 1 in field determinations of the transmission loss, one may meet with several difficulties of a more or less serious nature. The sound level in the rooms under question may vary considerably from point to point, so that just what the average sound level is may be highly indefinite. Means for determining $A_2$ may not be available, or even if available, a satisfactory field determination of the absorption in the receiving room may be difficult to make. To eliminate these and similar possibilities of error, two alternate methods have been developed, which, it is believed, are more suitable for field measurements.

## II. DESCRIPTION OF METHODS

### 1. USUAL METHOD

The term "usual method" refers to the procedure which is ordinarily used in our laboratory for the determination of the transmission loss. Since the results obtained by the alternate methods are to be compared with those obtained in the usual method, it will be of some interest to describe the latter also.

A description of the sound-transmission rooms has been given previously by V. L. Chrisler and W. F. Snyder.[2] It will suffice to say here that the receiving room (for wall panels) is about 9 ft. high, 12 ft. wide, and 16 ft. long. The opening between the two rooms will accommodate panels 7 ft. 4 in. high and 5 ft. 10 in. wide, while the dimensions of the sound-transmitting area of the panel are 6½ by 5 ft. There is no sound-absorption treatment in either of the rooms, the concrete walls being left bare.

In this same paper there are described some experimental devices which were used in the source room to obtain a diffuse sound field, that is, one in which the energy density is uniform at different regions in the room and the energy flow takes place equally in all directions. The necessity for doing this will be apparent from a perusal of a paper by Buckingham,[3] who gives the theoretical basis upon which eq 1 is founded. In this article a fundamental assumption is the uniformity of sound-energy densities in both the source and receiving room. To approach this ideal condition the following means are used:

1. As a source of sound, a warble note instead of a pure tone is used. The measurements are taken at nine different frequencies: 128, 192, 256, 384, 512, 768, 1,024, 2,048, and 4,096 c/s, the listed frequency being the center of the band; the band width is 36 percent of the band center at 128 and 256 c/s, and 18 percent at the seven other frequen-

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[2] J. Research NBS **14**, 749 (1935) RP800.
[3] Sci. Pap. BS **20**, 193 (1925) S506.

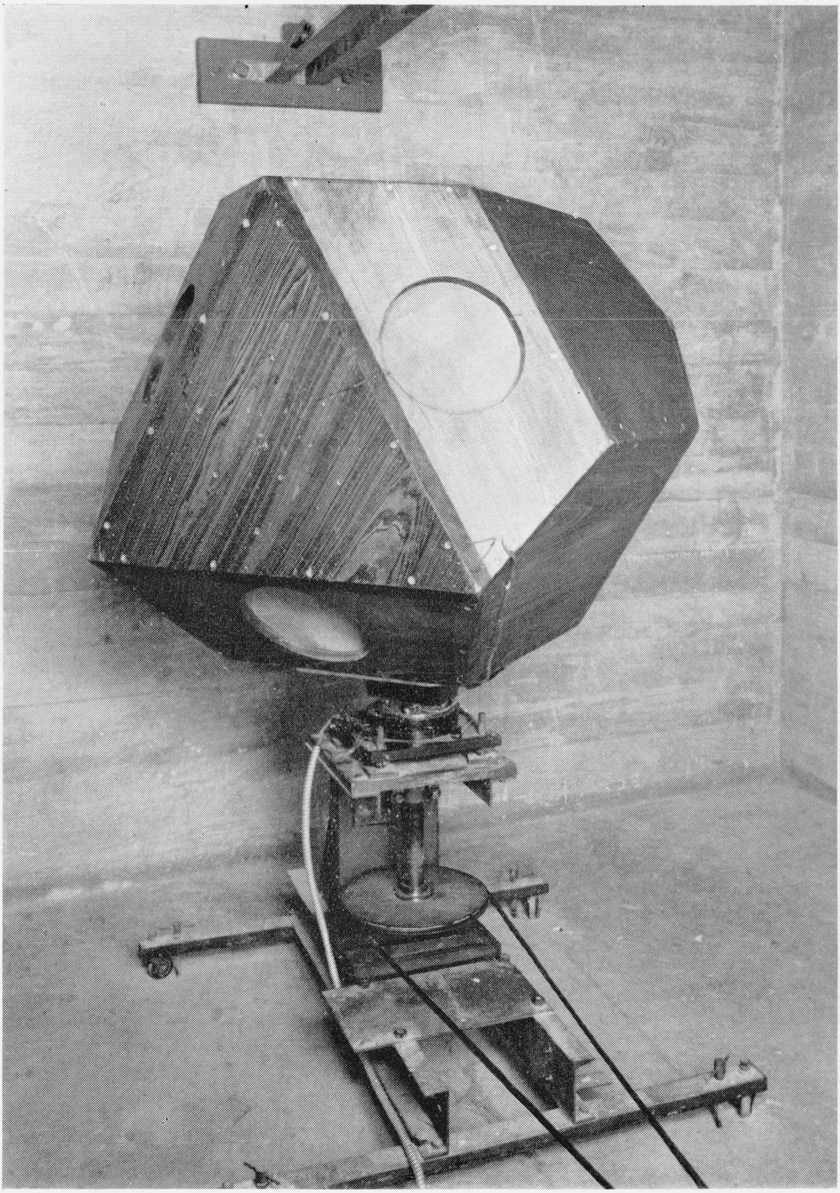


FIGURE 1.—*Multiple-loudspeaker unit.*

Only three of the loudspeakers are visible. Three others are located on the rear faces. Note that each speaker points in a different direction.

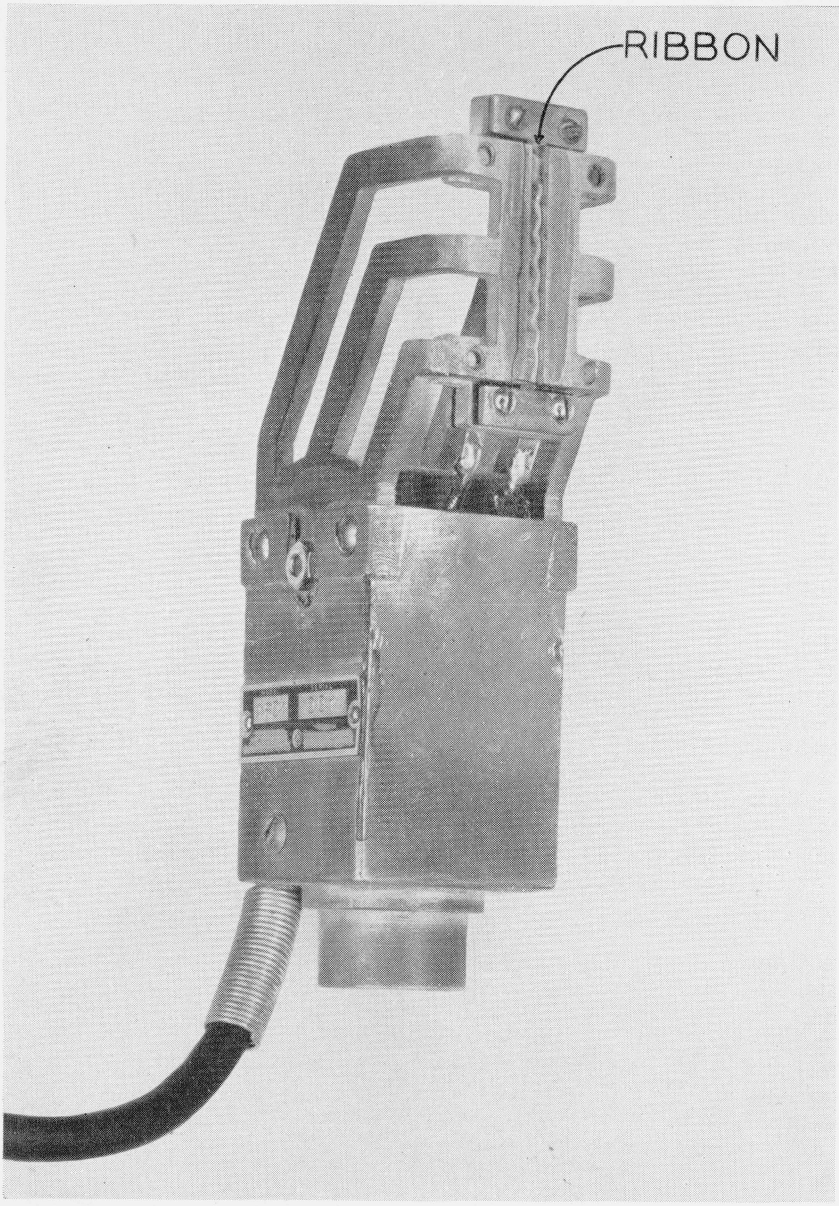



FIGURE 2.—*Microphone used in the ribbon-microphone alternate method.*

cies. Doubling the band width at the two lower frequencies reduces materially the scatter in the transmission-loss measurements while producing no significant change in the results.

2. The loudspeaker unit consists of a box (which rotates when in use) on which are mounted six loudspeakers. This device is pictured in figure 1. Three speakers each are mounted on opposite ends of the box, each one being directed into a different direction in the room. The net effect of the varied orientations of the speakers, in conjunction with the rotation of the box, is a considerable improvement in sound pattern. As compared with a rotating source consisting of one speaker, the spread in sound-pressure level over the panel face was reduced from 5 or 6 decibels to only 2 or 3 db (decibels). Also, the uniformity of sound-pressure distribution in both source and receiving room was considerably improved.

To minimize effects arising from fluctuations in the pressure level or from the sound pattern in the test rooms, the following devices are utilized:

1. The microphone signal is passed into an amplifier having at its output a thermoelement as a rectifier and a galvanometer as an indicator. The speed of response of this combination is somewhat sluggish, so that variations in signal level are effectively ironed out. Further details of this arrangement are given in Research Paper RP800 (see footnote 2).

2. Four nondirectional pressure microphones (Western Electric Type 633A, "salt shaker" type) are used in taking the measurements, two being used in the source room and two in the receiving room. The outputs of the two microphones are effectively averaged by a commutating device which switches rapidly from one microphone to the other. Thus the signal obtained at the amplifier output is a composite affair consisting of short samplings from the two microphones. This type of arrangement indicates a pressure level which is the average of two positions. The two microphones are arranged on a cross arm with a separation of about 2½ ft between them, and the latter is connected to a trolley which rides on a rail. Different microphone positions are obtained with the aid of a semiautomatic positioning device which is connected by a system of pulleys and cables to the trolley.

At the four lower frequencies at which measurements are taken, readings are made in both rooms at eight different positions 6 in. apart along a line perpendicular to the panel face. At the five upper frequencies, readings are taken only at four positions, at 1-ft intervals, because of the uniformity in sound level. In the noisy room all microphone positions were confined to distances greater than about 2 ft from the panel face, whereas in the quiet room all distances were greater than 3 ft. Reasons for these restrictions on the microphone positions will be evident when some of the experimental results are discussed.

After readings are taken on the one side with the two microphones, a similar set of readings is taken on the other side with the two other microphones. Another independent set of measurements is taken with the microphones interchanged so as to eliminate differences in response, although the four microphones have almost identical response curves.

### 2. ALTERNATE METHODS

A description of both alternate methods will be given here. However, a statement of the predisposing reasons favoring these methods for field measurements will be given in section III.

#### (a) PRESSURE-MICROPHONE ALTERNATE METHOD

The only detail in which this method differs from the usual method is the placement of the pressure microphones on the quiet side. In this case, the measurements in the receiving room are taken at the panel face. The two microphones are hung on a crossarm with a separation of about 2 ft between them. Eight readings are taken over the face of the partition at 6-in. intervals in a vertical direction (for wall panels) at the lower frequencies and four readings at 1-ft intervals for the higher frequencies. It is desirable that the microphones be placed as close as possible to the panel face without touching, although for the particular microphones which were used, no difficulties were encountered if the microphones were permitted to touch the panel loosely.

#### (b) RIBBON-MICROPHONE ALTERNATE METHOD

In this method the pressure microphones are entirely dispensed with and a single pressure gradient microphone is substituted. On the noisy side the microphone position is varied over exactly the same distance as in the usual method, while on the quiet side the measurements are taken at the panel face. As before, in the source room eight readings are taken at the lower frequencies and four at the upper frequencies. In the receiving room eight readings are taken over the panel face at all of the nine frequencies, the particle-velocity level indications at the higher frequencies varying somewhat more in this case than in the pressure-microphone alternate method. It is important that the microphone does not touch the panel, as "chattering" occurs and this results in an inordinate increase in level. The microphone used in these experiments is of the ribbon type and was built for us by Shure Bros. This is shown in figure 2. Its special design features will be indicated in section III–2. In use, the plane of the ribbon is placed parallel to the panel face, the face of the microphone being as close as possible without touching the panel.

## III. EXPERIMENTAL RESULTS

### 1. PRESSURE-MICROPHONE ALTERNATE METHOD

One of the important experimental phenomena associated with our problem is pictured in figure 3 ($A$ to $I$). There is shown in this series of curves the nature of the sound pattern in the receiving room and how it varies with distance from the face of the panel and with the amount of sound absorption in the receiving room. The curves, which are drawn through the experimental points, were obtained using four pressure microphones arranged to cover an area of about 2 sq ft, their outputs being commutated. The values of absorption range from that of the bare room ($A'_1$) to that when the room was as absorbent as it could be made conveniently ($A'_5$). The more promi-

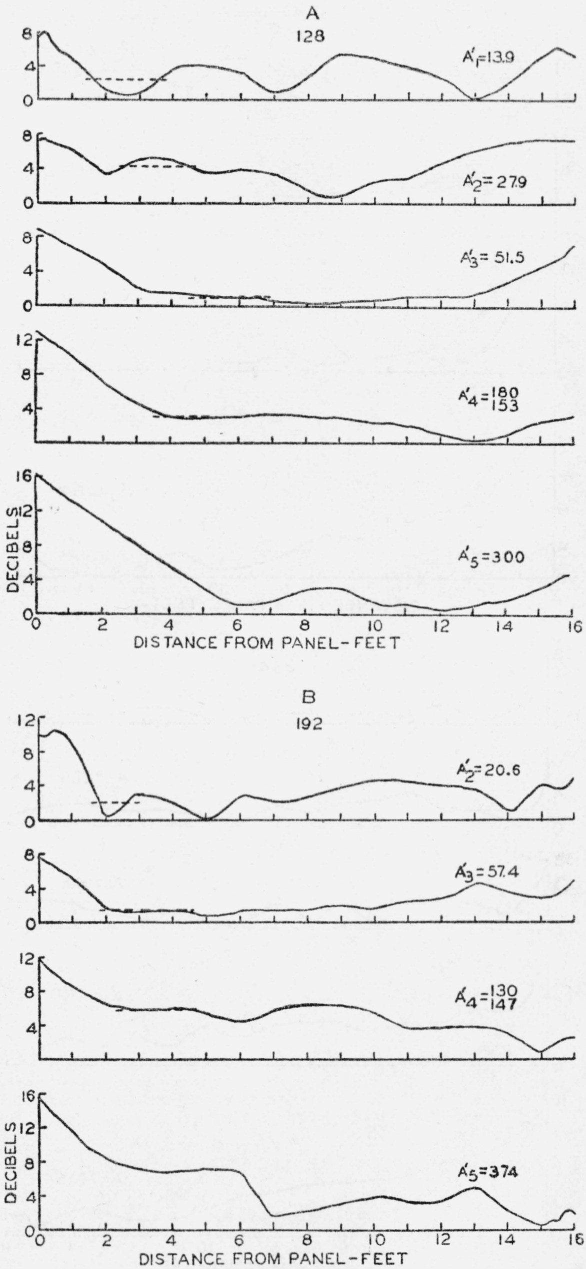



FIGURE 3.—*Variation in pressure level with distance from face of panel on quiet side.*

The total absorption of the receiving room is given in Sabins as $A'_1$, $A'_2$, $A'_3$, $A'_4$, and $A'_5$. Zero decibels for each curve is entirely arbitrary. Measurements were taken at nine different frequencies.

*A*, 128 c/s; *B*, 192 c/s.

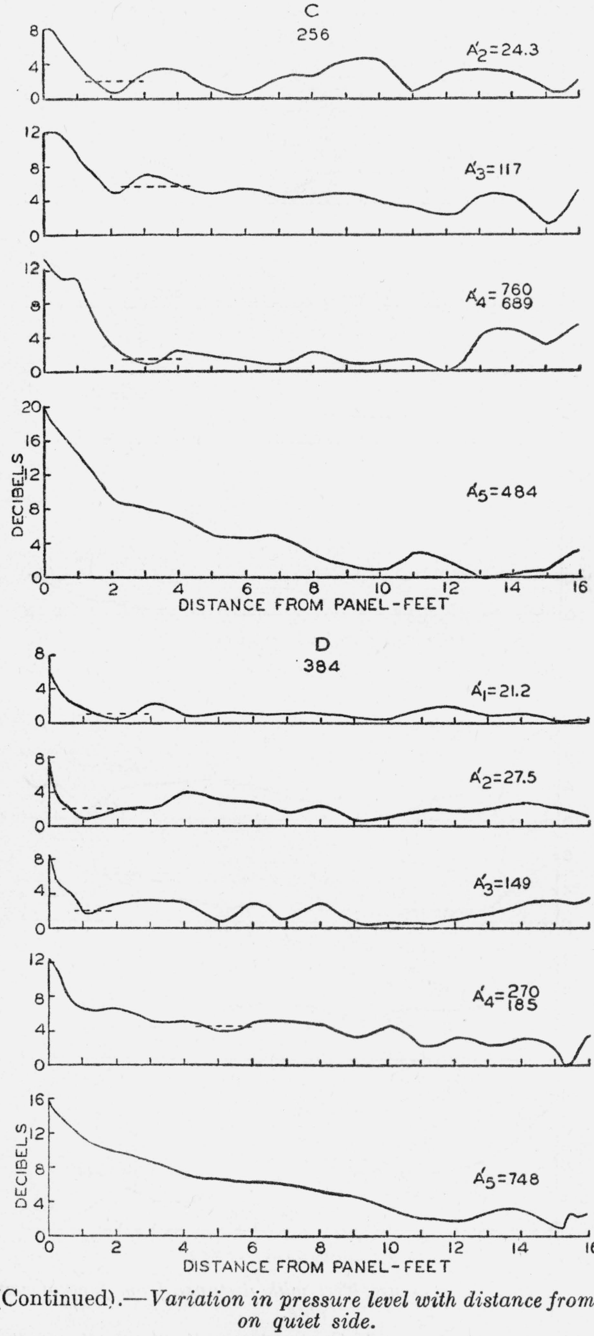
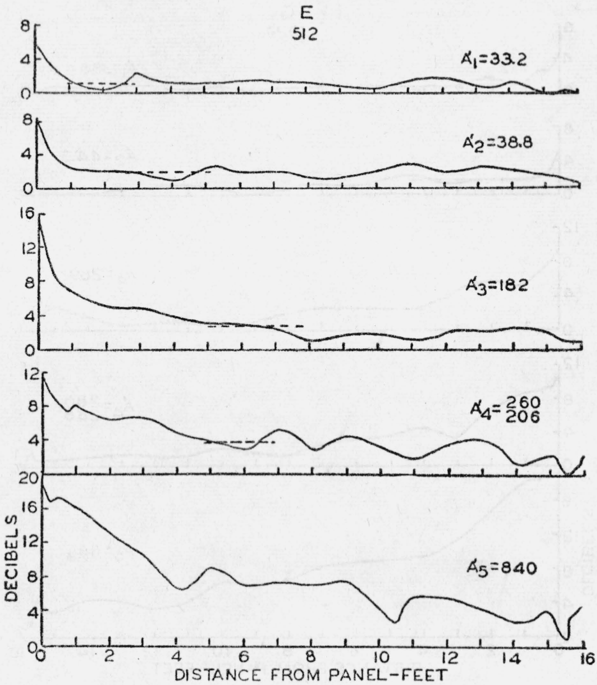



**Figure 3** (Continued).—*Variation in pressure level with distance from face of panel on quiet side.*

*C*, 256 c/s; *D*, 384 c/s.



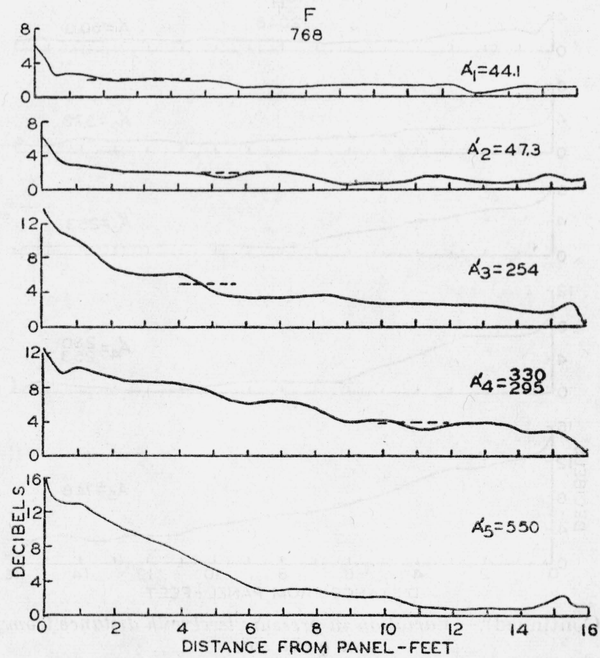




FIGURE 3 (Continued).—*Variation in pressure level with distance from face of panel on quiet side.*

*E*, 512 c/s; *F*, 768 c/s.

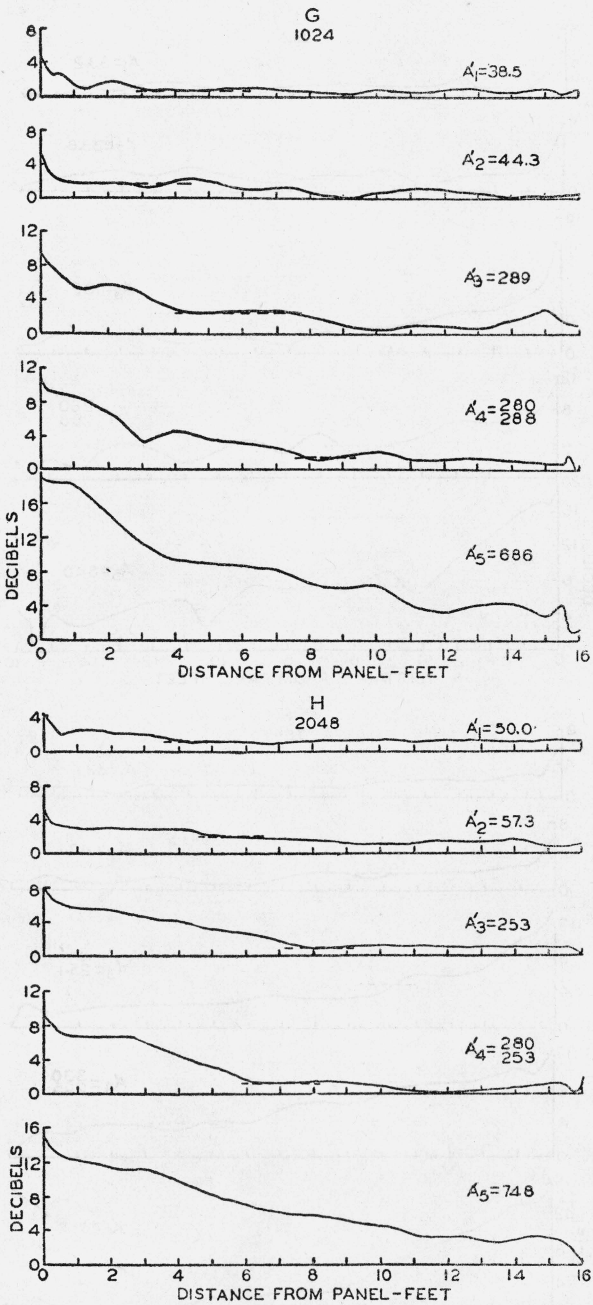



FIGURE 3 (Continued).—*Variation in pressure level with distance from face of panel on quiet side.*

*G*, 1,024 c/s; *H*, 2,048 c/s.

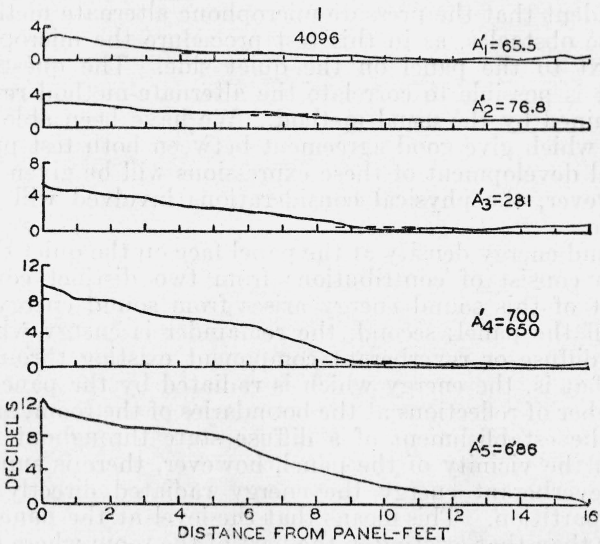



FIGURE 3 (Continued).—*Variation in pressure level with distance from face of panel on quiet side.*

*I*, 4,096 c/s.

nent features of the curves are the initial drop in sound-pressure level,[4] which occurs within a relatively short distance from the panel, and the flattening out of the curve to give a plateau with slight ridges and valleys. As the absorption increases, the initial drop becomes larger; further, the plateau is not quite established, the level dropping off slowly with increasing distance from the panel. For the highest values of absorption, that of $A'_5$ at the higher frequencies, there is really no leveling off of the curve anywhere in the room.

It is thus seen that considerable difficulty may be encountered in taking field measurements, since the amount of absorption in the receiving room may vary widely. In the first place, only in the case of rooms which are not too highly absorbent will a fairly uniform pressure level exist throughout most of the room. The position at which the pattern curve starts to flatten out and the average pressure level about which the level in the room fluctuates is indicated by the dotted line in figures 3 (*A* to *I*). The observer should keep away from positions very close to the panel if he wishes to use eq 1, as errors of 5 to 10 db, or even larger, may be involved. Furthermore, this requires an investigation of the variation of pressure level with distance from the panel face, so as to determine the positions in the room where the pattern has flattened out. In the case of highly absorbent rooms, such as a dead or moderately dead room, no uniform pressure level exists throughout any part of the room.

[4] The term "sound-pressure level" (abbreviated to pressure level) as used in this paper refers to the decibel reading of the thermoelement-galvanometer indicating system when a pressure microphone is used as a pickup. Similarly, if a velocity microphone is used, reference will be made to particle-velocity level, or velocity level. The reference level of zero decibels is entirely arbitrary, as of chief interest are differences of level.

It is evident that the pressure-microphone alternate method eliminates these obstacles, as in this test procedure the microphones are placed next to the panel on the quiet side. The question arises whether it is possible to correlate the alternate-method results with those obtained by the usual method. We have been able to derive equations which give good agreement between both test procedures. The actual development of these expressions will be given in section IV. However, the physical considerations involved will be briefly stated here.

The sound energy density at the panel face on the quiet side is considered to consist of contributions from two distinct components. First, part of this sound energy arises from sound energy radiated directly off the panel; second, the remainder is energy which arises from the diffuse or reverberant component existing throughout the room. That is, the energy which is radiated by the panel suffers a great number of reflections at the boundaries of the room, and the net effect is the establishment of a diffuse state throughout the whole room. In the vicinity of the panel, however, there is superimposed on this reverberant energy the energy radiated directly from the vibrating partition. This means that the level at the panel face will be greater than that existing in the part of the room where the diffuse sound field is present. The average pressure level caused by the latter is represented by the dotted lines of figure 3 (*A* to *I*).

As a consequence of these and other similar considerations, the following equations were derived for the pressure microphone alternate methods:

$$TL=(PL)_1-(PL)_{20}+10\log_{10}\left[\frac{1}{2}(1+2\sqrt{S/A_2})^2\right], \quad \nu=128 \text{ c/s}, \tag{2}$$

$$TL=(PL)_1-(PL)_{20}+10\log_{10}(1/2+2S/A_2), \quad \nu=192 \text{ to } 2{,}048 \text{ c/s}, \tag{3}$$

$$TL=(PL)_1-(PL)_{20}+10\log_{10}(3/8+S/A_2), \quad \nu=4{,}096 \text{ c/s}, \tag{4}$$

where

$TL$ = transmission loss in decibels.
$(PL)_1$ = average pressure level in the source room.
$(PL)_{20}$ = average pressure level at the panel face in the receiving room.
$S$ = total area of sound-transmitting surface
$A_2$ = total absorption in receiving room, $A_2$, measured in same units as $S$.
$\nu$ = frequency in cycles per second.

Equation 2 is to be used for measurements taken at 128 c/s, eq 3 for those taken at frequencies ranging from 192 to 2,048 c/s, and eq 4 for those taken at 4,096 c/s. It is seen that the transmission loss is given in each case by the difference in level which is observed, plus a correction term. The correction terms are plotted in figure 4 for different values of the ratio $A_2/S$.

In table 1 are presented results on 16 different measurements of transmission loss made on 9 different panels. For reference purposes, the absorption (in square feet) of the receiving room and the corresponding correction as determined from figure 4 with $S$=32.5 sq. ft (the sound-transmitting area of our panels) head the series of observations which were made at this value of absorption. Under "*TL*, usual" there is given the transmission loss as measured at the

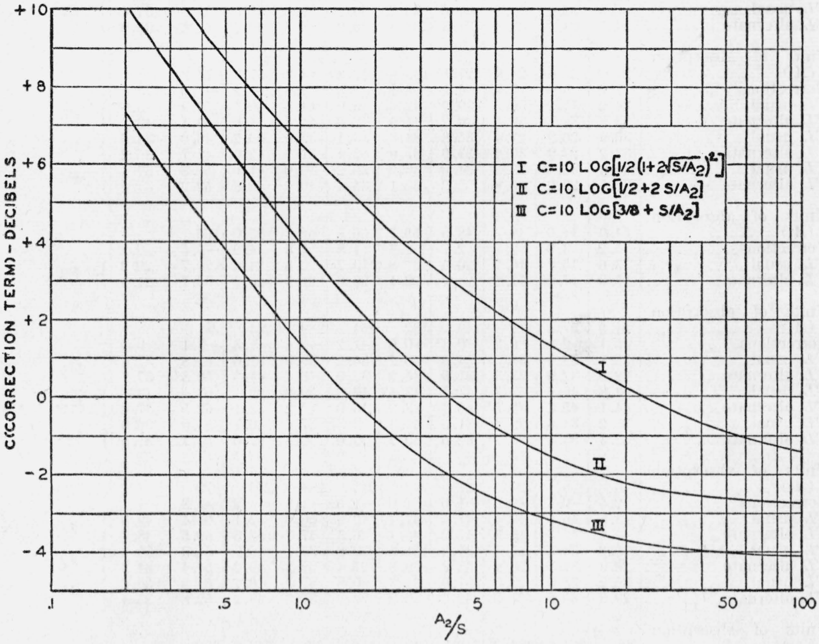



FIGURE 4.—*Dependence of the correction term, C, on the ratio $A_2/S$.*

Curve I is valid for a frequency of 128 c/s; curve II for 192 to 2,048 c/s; and curve III for 4,096 c/s.

different frequencies, 128 to 4,096 c/s, by the usual method, and "*TL*, alternate" gives the transmission loss determined by the alternate method. In the column captioned "average," the average transmission loss (average of the transmission loss measured at the nine different frequencies) is listed and opposite "correction," the average of the nine individual corrections. The panels measured had average transmission losses varying from about 10 to 50 db, and the types of construction represented include porous building block, porous building block with plastered surface, solid plaster on metal lath, and complex wood stud partition with very little tie between the two surfaces. There are thus included homogeneous, porous, and complex structures; thicknesses range from 2 to 12 in.

TABLE 1.—*Comparison between results obtained by usual and pressure-microphone alternate methods*

| Frequency, c/s: | 128 | 192 | 256 | 384 | 512 | 768 | 1,024 | 2,048 | 4,096 | Average | Test No. | Panel No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Units of absorption ($A_2$) | 13.9 | 14.4 | 19.7 | 21.2 | 33.2 | 44.1 | 38.5 | 50.0 | 65.5 | | | |
| Corrections | 9.1 | 6.9 | 5.7 | 5.4 | 3.8 | 3.0 | 3.4 | 2.6 | −0.6 | 4.4 | | |
| *TL*, usual | 34.2 | 41.2 | 39.7 | 39.7 | 42.6 | 43.9 | 44.6 | 50.1 | 58.9 | 43.9 | F4 | Z2 |
| *TL*, alternate | 32.7 | 38.4 | 39.2 | 40.0 | 41.6 | 42.5 | 44.9 | 50.9 | 60.2 | 43.4 | | |
| *TL*, usual | 32.3 | 32.4 | 33.5 | 34.0 | 36.2 | 36.2 | 39.0 | 41.6 | 51.8 | 37.4 | F7 | X2 |
| *TL*, alternate | 34.7 | 28.4 | 33.3 | 31.3 | 34.5 | 36.2 | 39.7 | 42.4 | 52.6 | 37.0 | | |
| Units of absorption ($A_2$) | 27.9 | 20.6 | 24.3 | 27.5 | 38.8 | 47.3 | 44.3 | 57.3 | 76.8 | | | |
| Corrections | 7.0 | 5.5 | 4.9 | 4.5 | 3.2 | 2.8 | 2.9 | 2.2 | −1.0 | 3.6 | | |
| *TL*, usual | 34.2 | 41.2 | 39.7 | 39.7 | 42.6 | 43.9 | 44.6 | 50.1 | 58.9 | 43.9 | F3 | Z2 |
| *TL*, alternate | 33.8 | 38.1 | 39.5 | 39.2 | 41.9 | 42.6 | 44.5 | 51.6 | 59.4 | 43.4 | | |
| *TL*, usual | 30.9 | 26.9 | 27.4 | 35.8 | 34.6 | 33.1 | 35.9 | 40.2 | 46.6 | 34.6 | F5 | X1 |
| *TL*, alternate | 33.2 | 27.9 | 30.4 | 37.6 | 35.9 | 32.4 | 37.1 | 42.9 | 48.7 | 36.2 | | |
| *TL*, usual | 32.3 | 32.4 | 33.5 | 34.0 | 36.2 | 36.2 | 39.0 | 41.6 | 51.8 | 37.4 | F6 | X2 |
| *TL*, alternate | 32.1 | 29.9 | 35.8 | 32.2 | 35.1 | 35.4 | 40.6 | 42.9 | 52.2 | 37.4 | | |
| Units of absorption ($A_2$) | 51.9 | 44.6 | 48.3 | 48.5 | 55.7 | 66.5 | 65.7 | 82.0 | 100 | | | |
| Corrections | 5.2 | 3.0 | 2.7 | 2.7 | 2.3 | 1.8 | 1.8 | 1.2 | −1.5 | 2.1 | | |
| *TL*, usual | 13.0 | 16.7 | 16.1 | 20.5 | 21.8 | 19.2 | 20.5 | 24.6 | 29.7 | 20.2 | F2 | Z1 |
| *TL*, alternate | 15.0 | 17.6 | 17.2 | 21.1 | 22.1 | 20.6 | 21.3 | 26.9 | 30.7 | 21.4 | | |
| Units of absorption ($A_2$) | 51.5 | 57.4 | 117 | 149 | 182 | 254 | 289 | 274 | 281 | | | |
| Corrections | 5.1 | 2.2 | 0.2 | −0.3 | −0.6 | −1.2 | −1.4 | −1.3 | −3.1 | 0 | | |
| *TL*, usual | 32.3 | 32.4 | 33.5 | 34.0 | 36.2 | 36.2 | 39.0 | 41.6 | 51.8 | 37.4 | H1 | X2 |
| *TL*, alternate | 32.5 | 32.9 | 33.3 | 31.5 | 35.2 | 36.0 | 40.4 | 41.3 | 50.8 | 37.1 | | |
| *TL*, usual | 43.8 | 46.6 | 47.4 | 47.7 | 47.4 | 49.9 | 50.0 | 52.1 | 63.4 | 49.8 | H2 | X3 |
| *TL*, alternate | 44.1 | 45.3 | 42.5 | 45.4 | 43.2 | 46.0 | 46.2 | 51.1 | 62.5 | 47.4 | | |
| *TL*, usual | 35.2 | 33.3 | 22.3 | 31.6 | 31.3 | 30.8 | 37.7 | 46.7 | 54.9 | 36.0 | H3 | X4 |
| *TL*, alternate | 32.3 | 33.3 | 25.7 | 32.5 | 30.2 | 29.0 | 36.8 | 47.0 | 53.1 | 35.5 | | |
| Units of absorption ($A_2$) | 166 | 138 | 724 | 227 | 233 | 313 | 284 | 266 | 675 | | | |
| Corrections | 2.5 | −0.1 | −2.2 | −1.0 | −1.0 | −1.5 | −1.3 | −1.2 | −3.8 | −1.1 | | |
| *TL*, usual | 43.8 | 46.6 | 47.4 | 47.7 | 47.4 | 49.9 | 50.0 | 52.1 | 63.4 | 49.8 | J1 | X3 |
| *TL*, alternate | 42.6 | 47.3 | 43.3 | 47.2 | 45.7 | 46.3 | 47.7 | 52.6 | 65.5 | 48.7 | | |
| *TL*, usual | 35.2 | 33.3 | 22.3 | 31.6 | 31.3 | 30.8 | 37.7 | 46.7 | 54.9 | 36.0 | J2 | X4 |
| *TL*, alternate | 26.9 | 31.5 | 20.4 | 32.2 | 29.8 | 27.4 | 37.3 | 49.2 | 54.4 | 34.3 | | |
| *TL*, usual | 35.2 | 33.3 | 22.3 | 31.6 | 31.3 | 30.8 | 37.7 | 46.7 | 54.9 | 36.0 | J3 | X4 |
| *TL*, alternate | 29.8 | 30.9 | 27.5 | 32.6 | 30.2 | 29.3 | 37.5 | 48.2 | 52.8 | 35.4 | | |
| Units of absorption ($A_2$) | 300 | 374 | 484 | 748 | 840 | 550 | 686 | 748 | 686 | | | |
| Corrections | 1.4 | −1.7 | −2.0 | −2.3 | −2.3 | −2.1 | −2.2 | −2.3 | −2.2 | −1.7 | | |
| *TL*, usual | 29.2 | 29.9 | 25.6 | 30.4 | 30.5 | 33.5 | 37.0 | 46.4 | 53.8 | 35.1 | F1 | Z5 |
| *TL*, alternate | 30.3 | 28.2 | 25.9 | 32.0 | 31.1 | 34.1 | 39.0 | 46.0 | 51.0 | 35.3 | | |
| *TL*, usual | 7.9 | 7.5 | 5.2 | 7.3 | 8.6 | 12.2 | 14.1 | 18.5 | 17.4 | 11.0 | F1 | Z4 |
| *TL*, alternate | 5.3 | 6.3 | 5.2 | 5.4 | 7.3 | 13.4 | 12.0 | 16.2 | 17.0 | 9.8 | | |
| *TL*, usual | 35.2 | 33.3 | 22.3 | 31.6 | 31.3 | 30.8 | 37.7 | 46.7 | 54.9 | 36.0 | K1 | X4 |
| *TL*, alternate | 30.1 | 30.5 | 23.0 | 31.7 | 30.6 | 28.0 | 36.2 | 47.1 | 54.0 | 34.6 | | |
| *TL*, usual | 34.3 | 26.4 | 33.0 | 36.8 | 34.6 | 37.4 | 43.2 | 50.5 | 56.9 | 39.2 | K2 | X5 |
| *TL*, alternate | 32.1 | 28.1 | 27.6 | 37.0 | 33.9 | 36.3 | 44.3 | 51.2 | 58.5 | 38.8 | | |

In table 2 the difference between the alternate *TL* and the usual *TL* is given. A minus sign indicates that the alternate *TL* was less than the usual *TL*.

The average deviation of the differences between the average *TL*'s as measured by the two methods is only 0.8 db, well within the experimental error. If these differences are averaged without disregarding their signs, the average difference of −0.4 db is obtained for the average *TL*'s. It should be pointed out that the possible error in determining the average transmission loss of a panel is about 1.5 db. Thus, tests J2 and J3 were made under identical conditions on the same panel, about 6 weeks apart. The two measurements differ by 1.1 db, perhaps owing to aging of the plaster. If two different panels nominally built in accordance with the same specifications are measured, the results may differ by as much as 2 db. In one extreme case at our laboratory there was a difference of 2.5 db.

TABLE 2.—*Figures give the difference between the transmission loss measured by the pressure-microphone alternate method and that measured by the usual method*

| Panel No. | Test No. | 128 | 192 | 256 | 384 | 512 | 768 | 1,024 | 2,048 | 4,096 | Difference between Avg. *TL*'s |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Z2 | F4 | −1.5 | −2.8 | −0.5 | +0.3 | −1.0 | −1.4 | +0.3 | +0.8 | +1.3 | −0.5 |
| X2 | F7 | +2.4 | −4.0 | −.2 | −2.7 | −1.7 | 0 | +.7 | +.8 | +0.8 | −.4 |
| Z2 | F3 | −0.4 | −3.1 | −.2 | −0.5 | +0.7 | −1.3 | −.1 | +1.5 | +.5 | −.5 |
| X1 | F5 | +2.3 | +1.0 | +3.0 | +1.8 | +1.3 | −0.7 | +1.2 | +2.7 | +2.1 | +1.6 |
| X2 | F6 | −0.2 | −2.5 | +2.3 | −1.8 | −1.1 | −.8 | +1.6 | +1.3 | +0.4 | 0 |
| Z1 | F2 | +2.0 | +0.9 | +1.1 | +0.6 | +0.3 | +1.4 | +0.8 | +2.3 | +1.0 | +1.2 |
| X2 | H1 | +0.2 | +.5 | −0.2 | −2.5 | −1.0 | −0.2 | +1.4 | −0.3 | −1.0 | −0.3 |
| X3 | H2 | +.3 | −1.3 | −4.9 | −2.3 | −4.2 | −3.9 | −3.8 | −1.0 | −0.9 | −2.4 |
| X4 | H3 | −2.9 | 0 | +3.4 | +0.9 | −1.1 | −1.8 | −0.9 | +0.3 | −1.8 | −0.5 |
| X3 | J1 | −1.2 | +.7 | −4.1 | −.5 | −1.7 | −3.6 | −2.3 | +.5 | +2.1 | −1.1 |
| X4 | J2 | −8.3 | −1.8 | −1.9 | +.6 | −1.5 | −3.4 | −0.4 | +2.5 | −0.5 | −1.7 |
| X4 | J3 | −5.4 | −2.4 | +5.2 | +1.0 | −1.1 | −1.5 | −.2 | +1.5 | −2.1 | −0.6 |
| Z5 | F1 | +1.1 | −1.7 | +0.3 | +1.6 | +0.6 | +0.6 | +2.0 | −0.4 | −2.8 | +.2 |
| Z4 | F1′ | −2.6 | −1.2 | 0 | −1.9 | −1.3 | +1.2 | −2.1 | −2.3 | −0.4 | −1.2 |
| X4 | K1 | −5.1 | −2.8 | +.7 | +0.1 | −0.7 | −2.8 | −1.5 | +0.4 | −.9 | −0.4 |
| X5 | K2 | −2.2 | +1.7 | −5.4 | +.2 | −.7 | −1.1 | +1.1 | +.7 | +1.6 | −.4 |
| Average deviation | | 2.4 | 1.8 | 2.1 | 1.2 | 1.2 | 1.6 | 1.3 | 1.2 | 1.3 | 0.8 |
| Average difference | | −1.3 | −1.2 | −0.1 | −0.3 | −0.9 | −1.2 | −0.1 | +0.7 | 0 | −0.4 |

It may therefore be said that all the deviations are within the error of measurement except for test H2, where the deviation is 2.4 db. This particular panel was constructed in two units with very little connection between the two. However, it is believed the difference is not due to this complexity of structure, since test J1 was made on the same panel and the deviation here was 1.1 db.

Resonance effects at the lower frequencies, 128, 192, 256 c/s, cause a greater scattering of the data, the average deviation being about 2 db. The value of the average difference indicates how well the individual differences scatter to either side of the usual value. The tendency to be a bit low is evident. On the average, however, eq 2, 3, and 4 may be said to give results in very good agreement with those obtained by the usual method.

Some important characteristics of the correction terms may now be considered. For example, for $A_2$=233 sabins and $S$=32.5 sq ft the correction is $-1.0$ db (from curve II, fig. 4). This is to be compared with the value of the correction one would need to use if the measurements were taken by the usual method. The correction from eq 1 has the value $-10\log_{10}(23.3/32.5)=-8.6$ db. It may be seen that the alternate-method correction in this case is much less than the usual-method correction. In fact, figure 4 shows that in the range of values 2 to 15 for $A_2/S$, the correction varies only between $+2$ and $-2$ db for curve II. For field measurements, where an accuracy of within 2 db is usually satisfactory, the correction term may be neglected. Furthermore, if one is interested chiefly in the average of the nine transmission losses and not in the individual values, it is possible to get good results by using correction curve II for all frequencies since curves I and III deviate in opposite directions relative to II.

When this is possible, a rough estimate of the ratio $A_2/S$ will suffice, as the correction term is relatively insensitive to errors in $A_2$/S. Another way of determining this ratio, without recourse to a reverberation method of measuring $A_2$, is to investigate the variation in pressure level with distance from the face of the panel (as in fig. 3, $A$ to $I$).

Equations (see section IV) may be derived which will give the difference in level between that at the face of the panel on the quiet side and the average level existing in the quiet room. These equations are:

$$(PL)_{20}-(PL)_2=10\log_{10}\left[\frac{1}{2}\frac{A_2}{S}\left(1+2\sqrt{\frac{S}{A_2}}\right)^2\right],\ \nu=128\ \text{c/s}, \tag{5}$$

$$(PL)_{20}-(PL)_2=10\log_{10}\left(1/2\frac{A_2}{S}+2\right),\quad \nu=192\ \text{to}\ 2{,}048\ \text{c/s} \tag{6}$$

$$(PL)_{20}-(PL)_2=10\log_{10}\left(3/8\frac{A_2}{S}+1\right),\quad \nu=4{,}096\ \text{c/s}, \tag{7}$$

where all symbols have been previously defined. To test the validity of eq 5, 6 and 7, a series of measurements were taken on a number of panels. In each case the pattern in the quiet room was observed, curves similar to figure 3 (*A* to *I*) being drawn. From these curves the differences in level between that at the panel face and the level about which the curves begin to flatten (indicated by the dotted lines of fig. 3, *A* to *I*) were obtained. These are indicated as the observed values of Δdb in table 3.

TABLE 3.—*Comparison between observed and calculated Δdb values*

[Δdb=difference in level between that at face of panel and the average level about which the pattern in the receiving room flattens out.]

| Panel No. | Absorption ($A_2$) | Δdb Observed | Δdb Calculated | Absorption ($A_2$) | Δdb Observed | Δdb Calculated | Absorption ($A_2$) | Δdb Observed | Δdb Calculated |
|---|---|---|---|---|---|---|---|---|---|
| | 128 | | | 192 | | | 256 | | |
| X5 | 13.9 | 4.9 | 5.4 | ------ | ------ | ------ | ------ | ------ | ------ |
| X5 | 27.9 | 3.1 | 6.3 | 20.6 | 8.0 | 3.6 | 24.3 | 6.0 | 3.8 |
| X5 | 51.5 | 8.0 | 7.3 | 57.4 | 5.3 | 4.6 | 117 | 6.3 | 5.8 |
| Z2 | 27.9 | 7.6 | 6.3 | 20.6 | 4.1 | 3.6 | 24.3 | 5.4 | 3.8 |
| X2 | ------ | ------ | ------ | 14.4 | 5.8 | 3.4 | 19.7 | 8.1 | 3.6 |
| X2 | 51.5 | 4.9 | 7.3 | 57.4 | 4.8 | 4.6 | 117 | 6.4 | 5.8 |
| X3 | 51.5 | 10.0 | 7.3 | ------ | ------ | ------ | 117 | 7.5 | 5.8 |
| X4 | 51.5 | 7.0 | 7.3 | 57.4 | 4.0 | 4.6 | 117 | 9.0 | 5.8 |
| | 384 | | | 512 | | | 768 | | |
| X5 | 21.2 | 4.8 | 3.6 | 33.2 | 4.8 | 4.0 | 44.1 | 4.1 | 4.3 |
| X5 | 27.5 | 6.0 | 3.9 | 38.8 | 4.3 | 4.2 | 47.3 | 4.2 | 4.4 |
| X5 | 149 | 6.5 | 6.3 | 182 | 12.3 | 6.8 | 254 | 9.0 | 7.8 |
| Z2 | 27.5 | 4.9 | 3.9 | 38.8 | 4.5 | 4.2 | 47.3 | 5.0 | 4.4 |
| X2 | 21.2 | 3.2 | 3.6 | 33.2 | 5.8 | 4.0 | 44.1 | 4.2 | 4.3 |
| X2 | 149 | 7.5 | 6.3 | 182 | 10.1 | 6.8 | 254 | 7.4 | 7.8 |
| X3 | 149 | 6.9 | 6.3 | 182 | 11.0 | 6.8 | 254 | 10.7 | 7.8 |
| X4 | 149 | 8.5 | 6.3 | 182 | 5.5 | 6.8 | 254 | 8.5 | 7.8 |
| | 1,024 | | | 2,048 | | | 4,096 | | |
| X5 | 38.5 | 4.5 | 4.2 | 50.0 | 3.3 | 4.5 | 65.5 | 1.0 | 2.4 |
| X5 | 44.3 | 3.5 | 4.4 | 57.3 | 3.2 | 4.6 | 76.8 | 1.5 | 2.8 |
| X5 | 289 | 6.7 | 8.1 | 253 | 7.0 | 7.7 | 281 | 5.2 | 6.2 |
| Z2 | 44.3 | 3.5 | 4.4 | 57.3 | 1.2 | 4.6 | 76.8 | 1.0 | 2.8 |
| X2 | 38.5 | 3.6 | 4.2 | 50.0 | 3.3 | 4.5 | 65.5 | 1.5 | 2.4 |
| X2 | 289 | 9.5 | 8.1 | 274 | 5.3 | 7.7 | 281 | 5.3 | 6.2 |
| X3 | 289 | 10.9 | 8.1 | 274 | 7.8 | 7.7 | 281 | 4.2 | 6.2 |
| X4 | 289 | 9.5 | 8.1 | 274 | 5.5 | 7.7 | 281 | 3.5 | 6.2 |

The calculated values of $\Delta$db were obtained by substituting $S=32.5$ sq ft and $A_2$ as determined from reverberation measurements in eq 5, 6, and 7; the three different room treatments represented in table 3 correspond to the values of absorption $A'_1$, $A'_2$, and $A'_3$ of figure 3 (*A* to *I*).

In table 4 there is listed for each frequency the average of the differences between the observed and calculated values of $(PL)_{20}-(PL)_2$ given in table 3. Under the column "average deviation" the absolute values of the differences have been averaged.

TABLE 4.—*Average deviation and difference for the data in table 3*

| Frequency | Average deviation | Average difference |
|---|---|---|
| c/s | | |
| 128 | 1.6 | +0.3 |
| 192 | 1.3 | −1.1 |
| 256 | 2.0 | −2.0 |
| 384 | 1.1 | −1.0 |
| 512 | 2.0 | −1.8 |
| 768 | 0.8 | −0.6 |
| 1,024 | 1.1 | −0.1 |
| 2,048 | 1.4 | +1.4 |
| 4,096 | 1.4 | +1.4 |

The similarity between the entries in table 2 and those in table 4 should be pointed out here. In table 2 there is listed the difference in transmission loss as obtained by the alternate method and that obtained by the usual method. Designate this quantity as $(TL)_A-(TL)_U$. For the middle range of frequencies one gets from eq 1 and 3

$$(TL)_A-(TL)_U=(PL)_2-(PL)_{20}+10\log_{10}\left(1/2+2\frac{S}{A_2}\right)-10\log_{10}\left(\frac{S}{A_2}\right)$$
$$=10\log_{10}\left(1/2\frac{A_2}{S}+2\right)-[(PL)_{20}-(PL)_2]$$

But $10\log_{10}\left(1/2\frac{A_2}{S}+2\right)$ is the calculated value of $\Delta$db, while $(PL)_{20}-(PL)_2$ would be the observed value of $\Delta$db were $(PL)_2$ obtained the same way in both sets of experiments. In the transmission measurements $(PL)_2$ is the average level existing between 3 and 6½ ft from the panel face on the quiet side, and it was observed only once under room treatment $A'_1$ and $A'_2$, while in the $\Delta$db measurements, $(PL)_2$ is obtained from the pattern curves and was observed over a wider range of variation in $A_2$. The conclusion one may draw from table 4 is that the average level which is to be used in eq 1 is that about which the pattern curve begins to flatten out. To determine the region in the room where this happens, it is necessary to explore the sound field. It is then possible to determine the correction terms for eq 2, 3, and 4 by utilizing 5, 6, and 7 to determine $A_2/S$ from a measurement of $(PL)_{20}-(PL)_2$. Thus, in figures 3 (A to I) the curves obtained for room treatment $A'_4$ were used to calculate the value of $A'_4$ and from this value of absorption the corrections to the alternate transmission measurements were obtained.

Two values of $A'_4$ are given, the upper one being obtained from the curves of figure 3 ($A$ to $I$), the lower one from data taken on a different panel. The values check closely enough for the purpose desired, since the transmission loss corrections are relatively insensitive to small changes in absorption. Note, in particular, in figure 3 ($B$) the measurement of $A'_4$ at a frequency of 256 c/s. The absorption so determined seems considerably out of line with other values; however, as far as the transmission loss correction is concerned, the error made in it will be relatively small and unimportant.

In section IV–1, expressions are given, eq 42, 43, and 44, in which $A_2/S$ already has been eliminated from the equation for the transmission loss, so that the latter is only a function of the readily observable quantities $(PL)_1-(PL)_{20}$ and $(PL)_{20}-(PL)_2$.

In table 1, the corrections as determined from the $A'_4$ curves were used in tests J1, J2, and J3. Also in table 1 the tests F1, F1′, K1, and K2 were made when the quiet side had the room treatment $A'_5$.

To get $A'_5$, the absorption when the room was as absorbent as it could be made, the Norris-Andree [5] method was used. The decay curves so obtained could not be taken over a range greater than about 30 db, the reverberation time being about 0.1 or 0.2 second. In most of the $A'_5$ curves, there is very little evidence of flattening out, indicating that a reverberant condition is not really formed. It was not possible to get agreement between the absorption as measured by the Norris-Andree method and from $(PL)_{20}-(PL)_2$ of the pattern for the few curves which did seem to level off. This disagreement is probably due to the insecure basis on which both types of measurement rest, in the case when the room is so absorbent.

So far there have been discussed only modifications in the usual method which are necessitated by the possibility of a nonuniform sound energy distribution on the quiet side. The noisy side has been neglected because it is usually possible to obtain a fairly diffuse sound field in the source room. However, under certain field conditions it may be somewhat difficult to do this. The pattern due to furniture or obstacles may be erratic, or absorption on the noisy side may perturb the uniformity of sound level in the room. It would then be of advantage to restrict measurements on the noisy side to positions at the panel face. The question arises as to what correction should be applied in this case.

Kellogg [6] has shown that a sound-level measuring arrangement—such as a pressure microphone, amplifier, and square-law rectifier (in which the deflection of the output meter is thus proportional to the square of the pressure amplitude of the sound wave)—would give, at a perfectly reflecting wall, a deflection twice as great as at a position away from the wall where a diffuse sound field exists. Thus a meter calibrated to read in decibels would read 3 db higher at the wall. To establish the validity of this conclusion, a series of measurements were taken on the noisy side in which the variation of pressure level with distance from the face of the panel was investigated.

Figure 5 shows the results of this set of experiments. Four pressure microphones arranged to cover an area of about 2 sq ft were used, their outputs being commutated. There is still in evidence in the

[5] J. Acous. Soc. Am., **3**, 361 (1932).
[6] J. Acous. Soc. Am., **4**, 61 (1932).

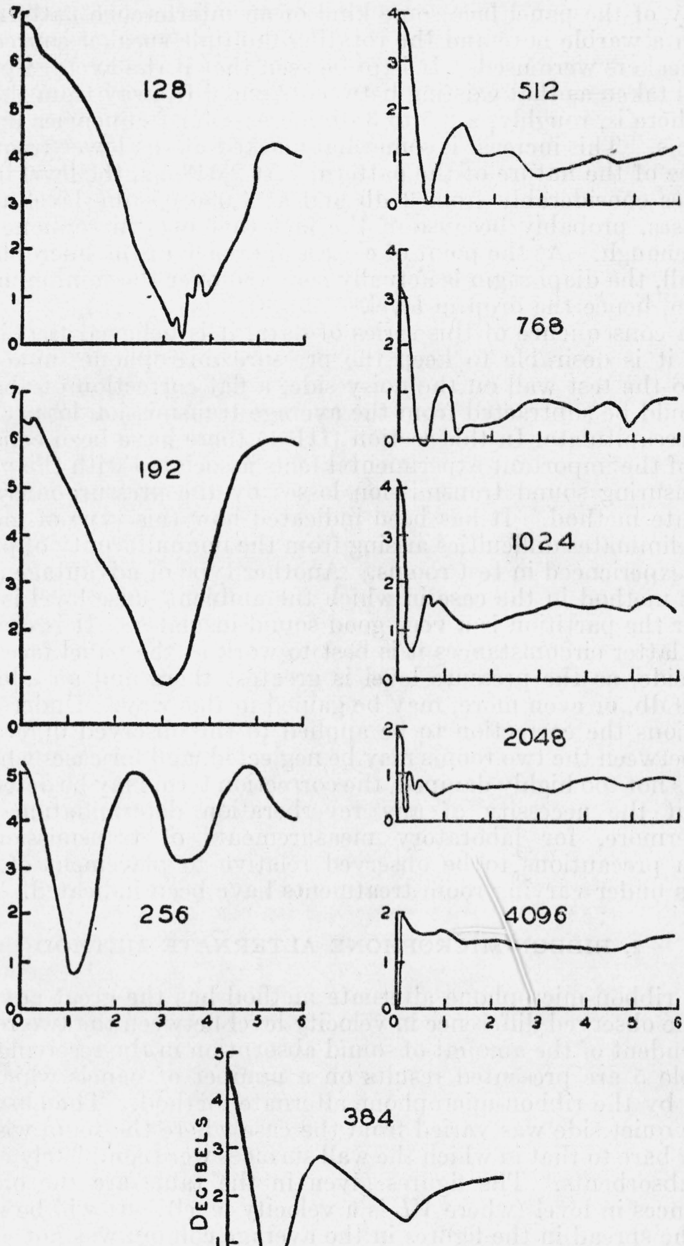



FIGURE 5.—*Variation in pressure level with distance from face of panel on noisy side*

Zero decibels for each individual curve is entirely arbitrary. Frequency concerned is given with each curve.

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vicinity of the panel face some kind of an interference pattern, even though a warble note and the rotating multiple speaker source of six loudspeakers were used. It is to be seen that if the average pressure level is taken as that existing between 2 and 6 ft away from the panel then there is, roughly, a 2.5 to 3 db increase for frequencies up to $\nu=$ 1,024 c/s. This increase is somewhat masked at the lower frequencies because of the nature of the pattern. At 2,048 c/s, the level increase deviates considerably from 3 db and at 4,096 c/s the level actually decreases, probably because of the fact that our microphone is not small enough. At the point of closest approach of the microphone to the wall, the diaphragm is actually centered over the minimum in the pattern, hence the drop in level.

As a consequence of this series of data, it is believed that in tests where it is desirable to keep the pressure microphone immediately next to the test wall on the noisy side, a flat correction of about 2.5 db should be subtracted from the average transmission loss.

To recapitulate: In this section (III–1) there have been considered some of the important experimental facts associated with the problem of measuring sound transmission losses by the pressure-microphone alternate method. It has been indicated how this type of measurement eliminates difficulties arising from the nonuniformity of pressure levels experienced in test rooms. Another type of advantage accrues to this method in the case in which the ambient noise level is rather high or the partition is a very good sound insulator. It is clear that in the latter circumstances it is best to work at the panel face on the quiet side, as the pressure level is greatest there and an additional 3 to 10 db, or even more, may be gained in this way. Under certain conditions the correction to be applied to the observed difference in level between the two rooms may be neglected, and for cases where the room is not too highly damped, the correction term may be determined without the necessity of any reverberation determination of $A_2$. Furthermore, for laboratory measurements of transmission loss, certain precautions to be observed relative to placement of microphones under varying room treatments have been indicated.

### 2. RIBBON-MICROPHONE ALTERNATE METHOD

The ribbon-microphone alternate method has the great advantage that the observed difference in velocity level between the two rooms is independent of the amount of sound absorption in the receiving room. In table 5 are presented results on a number of panels which were tested by the ribbon-microphone alternate method. The absorption on the quiet side was varied from the case where the room was completely bare to that in which the wall surfaces were completely covered with absorbents. The figures given in the table are the observed differences in level (where *VL* is a velocity level). It will be noticed that the spread in the figures in the average column was not as great as 1 db even though the absorption was varied through this wide range. To indicate the amount of absorption in the room, only the absorption at 512 c/s is listed. Under similar circumstances the observed level differences would have differed by 6 db in the case of the pressure-microphone alternate method. This is indicated in the column labeled "average pressure-microphone alternate method correction". (Compare average correction in table 1.)

TABLE 5.—*Independence of* $(VL)_1-(VL)_{20}$ *when measured by the ribbon-microphone alternate method of absorption in the receiving room*

| Panel No. | Test No. | Absorption at 512 c/s in sabins | Average pressure-microphone alternate method correction (db) | Frequency (c/s) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 128 | 192 | 256 | 384 | 512 | 768 | 1,024 | 2,048 | 4,096 | Avg. |
| X9 | S8 | 33.2 | +4.4 | 26.1 | 30.6 | 29.9 | 32.6 | 31.8 | 33.0 | 34.8 | 41.6 | 44.3 | 33.9 |
| | S9 | 233 | −1.1 | 26.2 | 32.2 | 28.0 | 32.4 | 31.7 | 32.7 | 35.2 | 41.6 | 46.3 | 34.0 |
| X10 | S13 | 33.2 | +4.4 | 19.4 | 20.0 | 23.2 | 26.4 | 29.4 | 34.0 | 38.1 | 42.6 | ------ | 29.1 |
| | S11 | 233 | −1.1 | 19.9 | 21.2 | 23.4 | 27.9 | 30.4 | 34.8 | 38.8 | 43.6 | ------ | 30.0 |
| X11 | S16 | 33.2 | +4.4 | 21.2 | 18.3 | 20.2 | 31.4 | 27.4 | 34.6 | 37.4 | 37.6 | 50.1 | 30.9 |
| | S17 | 182 | 0 | 18.9 | 17.1 | 19.9 | 31.0 | 27.4 | 33.5 | 37.0 | 40.0 | 52.4 | 30.8 |
| | S19 | 840 | −1.7 | 19.6 | 17.2 | 20.0 | 32.4 | 28.5 | 34.7 | 37.6 | 39.8 | 53.6 | 31.5 |
| X12 | S21 | 33.2 | +4.4 | 13.3 | 19.3 | 23.2 | 28.0 | 30.4 | 36.2 | 41.6 | 45.6 | 61.2 | 33.2 |
| | S20 | 840 | −1.7 | 10.8 | 20.2 | 23.3 | 27.4 | 30.6 | 35.8 | 41.1 | 47.0 | 61.6 | 33.1 |

The results of the experiments listed in table 5 may be readily explained. As has been indicated before, the sound energy density at the face of the panel on the receiving side may be considered to consist of two components, the direct component arising from sound energy radiated directly off the panel, and the reverberant component due to the reverberant energy existing throughout the room. This latter component may be considered to consist of a great number of waves which strike the panel at random angles of incidence with random phases. For each wave which strikes a perfectly reflecting rigid wall, its component of particle velocity normal to the wall becomes zero at the surface of the wall. Hence when the ribbon (particle velocity) microphone is placed next to the panel face, the reverberant component will be attenuated, while the response to the direct component will not be affected. The diffuse component is discriminated against to such an extent that what the ribbon microphone measures is a function only of the sound radiated from the panel.

This discrimination is of the order of 18 to 20 db for most of the frequencies concerned, as a perusal of figure 6 shows. This series of curves was obtained by investigating the variation in velocity level with distance from the face of the panel on the noisy side, using the ribbon microphone of figure 2. It will be seen that at the panel face the response of the ribbon microphone to the reverberant sound field of the source room is greatly diminished. The noisy side is used in these experiments simply because in this case there is present only a diffuse component, so that this discriminatory effect may be investigated without the disturbing effect of the direct component.

It will be noticed that the attenuation at 2,048 and 4,096 c/s is somewhat less than that obtained at the other frequencies. This is because the plane of the ribbon of the microphone should be relatively closer to the wall for the high frequencies, in order to obtain the same attenuation as at the lower frequencies. For example, some measurements with and RCA 44–A ribbon microphone, in which the ribbon element is mounted 2 in. from the external protective screen,

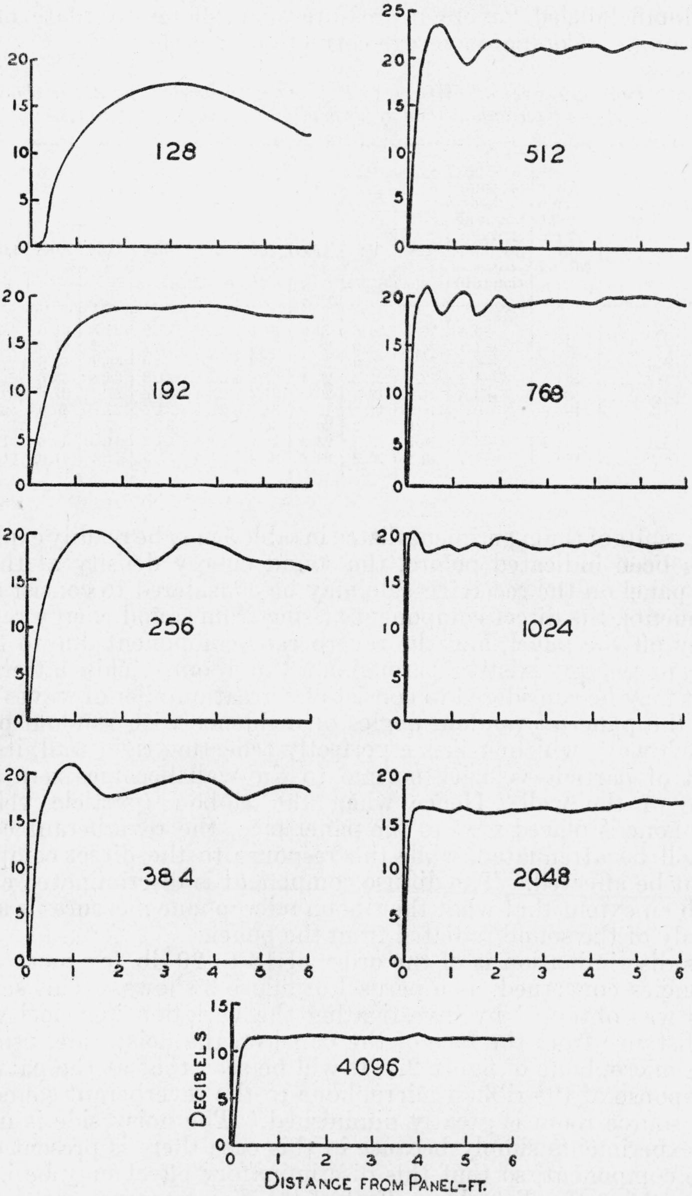


FIGURE 6.—*Variation in velocity level with distance from face of panel on noisy side.*

Zero decibels for each individual curve is entirely arbitrary. Frequency concerned is given with each curve.

showed that the reverberant component is only diminished to the extent of 10 db for the lower frequencies. It is also important that the sound waves have free access to both the front and back of the ribbon. Thus, in the RCA lapel microphone type MI-4001-A, in which the ribbon is mounted about one-fourth inch from its face, partial screening of the ribbon occurs at the back of the ribbon by the permanent magnet of the microphone, so that only 2- to 4-db reductions are obtained at 2,048 and 4,096 c/s. The ribbon microphone used to obtain figure 6 was designed to overcome these objections. The ribbon is mounted about one-eighth inch from the face of the microphone and the back is entirely open, so that screening of the ribbon is reduced to a minimum. These features are readily apparent in figure 2.

The question next arises as to the relationship between the difference in level observed in the ribbon-microphone alternate method and the transmission loss of the panel. Table 6 furnishes experimentally determined corrections to be applied to the observed differences in level.

TABLE 6.—*Correction to be added to $(VL)_1-(VL)_{20}$ observed in the ribbon-microphone alternate method, to obtain transmission loss*

| Frequency | Correction | Frequency | Correction |
|---|---|---|---|
| *c/s* | *db* | *c/s* | *db* |
| 128 | +8.2 | 768 | +1.4 |
| 192 | +6.7 | 1,024 | +0.4 |
| 256 | +6.6 | 2,048 | −2.9 |
| 384 | +4.4 | 4,096 | −2.0 |
| 512 | +3.6 | | |
| Correction for average transmission loss=+2.9 | | | |

If the corrections given in table 6 are used, the ribbon-microphone alternate method will give transmission losses which are in agreement with those obtained by the usual method. The number of ribbon-microphone transmission-loss measurements involved in the preparation of table 6 is 18, while the number of panels is 11. However, since three of the panels were similar to each other, the number of independent types of panels considered to be represented in the table is 9. These figures are given on a tentative basis, as it will be possible to obtain a more accurate set of corrections only after testing a larger number of panels.

In the nine panels so tested, the average transmission loss of these panels as determined by the ribbon microphone (using the corrections of table 6) exceeded the usual transmission-loss determinations by the following number of decibels: +3.4, +0.8, +0.1, +0.1, +0.1, −0.7, −1.4, −1.5, −1.8. The average deviation of these nine results is 1.2 db. The reason for the somewhat large deviation of 3.4 db is not clear.

Of course the corrections have been established only for the particular ribbon microphone used for these experiments, so that one may ask whether they will hold for any other ribbon microphone. It is believed that they are valid for any microphone in which the ribbon is mounted so that it may approach sufficiently close to the vibrating wall. The criterion for being "sufficiently close" is determined by the amount of attenuation the reverberant component will suffer (see fig. 6). For most rooms this discrimination should amount to no less than 10 db. To check this point, some *TL* measurements were taken with a quite different type of ribbon microphone, the RCA lapel microphone (type MI–4001–A). It is clear that from the objections, described previously, to the use of this microphone in the alternate method, the *TL* measurements at 2,048 and 4,096 c/s would not be reliable. In table 7 the results obtained with the two ribbon microphones are compared.

TABLE 7.—*Comparison of results obtained with two different ribbon microphones*

| Frequency | Shure Bros. ribbon | Lapel ribbon |
|---|---|---|
| *c/s* | *db* | *db* |
| 128 | 5.2 | 5.5 |
| 192 | 17.0 | 14.4 |
| 256 | 19.9 | 21.6 |
| 384 | 26.7 | 28.0 |
| 512 | 27.8 | 27.4 |
| 768 | 36.4 | 35.4 |
| 1,024 | 38.1 | 37.4 |
| 2,048 | 46.6 | 49.0 |
| 4,096 | 47.2 | 40.8 |
| Average--- | 29.4 | 28.8 |

Significant differences occur only at 2,048 and 4,096 c/s. The average transmission loss for the frequencies 128 to 1,024 c/s is for the Shure Bros. ribbon 24.4 db and for the lapel ribbon 24.2 db, which is excellent agreement.

The results of this section may be summarized thus: With the use of the ribbon-microphone alternate method it is possible to determine the transmission loss of partitions without a determination of the ratio $A_2/S$. Experimental evidence has been presented to show that the ribbon-microphone measurements are independent of $A_2$. Of course this holds only when the panel in question does not have a sound-absorbing treatment on its face, since in this case the amount of attenuation the reverberant component will suffer may be reduced considerably. The independence of the results of variations in the value of $S$ follows from the fact that, because of the directional characteristics of the ribbon microphone and its proximity to the panel face, the response of the microphone arises from sound being radiated from a small area centered about the microphone. This point will be considered further in section V.

With the aid of table 6, the observed difference in level $VL_1 - VL_{20}$ may be corrected to give transmission losses in agreement with the usual method.

## IV. INTERPRETATION OF RESULTS

### 1. PRESSURE-MICROPHONE ALTERNATE METHOD

In this section it is proposed to derive eq 1 to 7.

Let us consider the deduction of eq 1.

Assume a reverberant room in which there is a uniform energy density, $E$. At what rate will energy strike a unit area of the wall? The total amount of energy contained in $dV$ (fig. 7) is $EdV$, and this amount of energy is radiated by $dV$ in all directions. Hence the amount of energy which will ultimately reach $dS$ is

$$\frac{d\Omega}{4\pi}EdV, \tag{8}$$

where $d\Omega$ is the solid angle subtended by $dS$ at point $P$.

$$d\Omega = \frac{dS \cos\theta}{R^2} \tag{9}$$

$$dV = R \sin\theta \, d\phi \, R d\theta dR \tag{10}$$

The rate at which energy strikes $dS$ is given by

$$\frac{EdS}{4\pi dt}\int_0^{cdt}\int_0^{2\pi}\int_0^{\pi/2} \cos\theta \sin\theta d\theta d\phi \, dR, \tag{11}$$

since all the energy within a distance $cdt$, where $c$ is the velocity of sound, will hit $dS$ in time $dt$. Upon carrying out the integration of eq 11 and dividing by $dS$, one obtains the amount of energy, $J$, which hits a unit area of the wall in unit time

$$J = \frac{Ec}{4}. \tag{12}$$

Thus, if $E_1$ is the sound-energy density in the source room, then the rate at which energy is incident on the panel on the noisy side is $(E_1cS)/4$. The rate of energy transmission into the receiving room is $(\tau E_1cS)/4$, where $_1$ is the transmissivity—that is, the fraction of energy incident on $S$ in the source room, which is transmitted into the receiving room.

If a room has a source of power, $P$, present, then in the steady state the amount of sound energy absorbed by the walls per second must equal the rate at which sound energy is introduced into the room—that is, $JA = P$, where $A$ is the total absorption of the room. Thus, from eq 12 the energy density in the steady state is

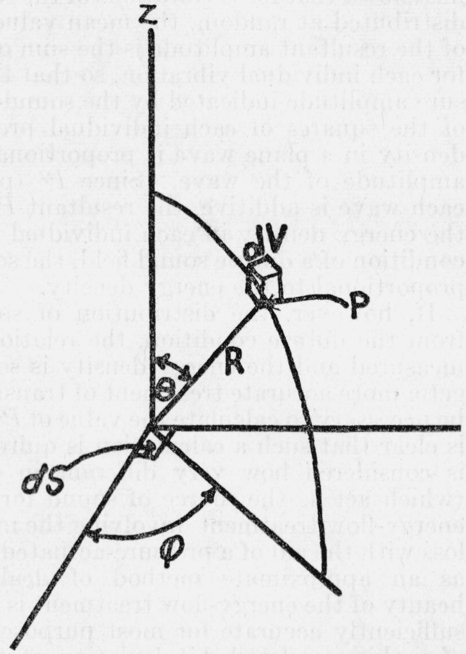


FIGURE 7

$$E = \frac{4P}{cA}. \tag{13}$$

The energy density in the receiving room, $E_2$, is then

$$E_2 = \frac{4}{cA_2} \cdot \frac{\tau E_1 cS}{4} = \frac{\tau E_1 S}{A_2}. \tag{14}$$

The deduction of eq 14 is similar to one given by Buckingham.[7] Equation 14 may be put in the form

$$10 \log_{10}\left(\frac{1}{\tau}\right) = 10 \log_{10}\left(\frac{E_1}{E_2}\right) + 10 \log_{10}\left(\frac{S}{A_2}\right). \tag{15}$$

[7] Sci. Pap. BS 20, 193 (1925) S506.

The term 10 $\log_{10}$ $(1/\tau)$ is the transmission loss, and 10 $\log_{10}$ $(E_1/E_2)$ is equal to $L_1-L_2$, the difference in sound level between the two rooms, so that eq 15 is just eq 1 written in a somewhat different fashion.

It is to be noted that in setting $L_1-L_2=10\ \log_{10}(E_1/E_2)$ we have assumed that the sound lever meter indications are proportional to the energy density in the sound field. Of course, what is really measured, if a pressure microphone is used, is the time average of the square of the excess pressure. However, if the sound field is truly diffuse—that is, uniform energy-density distribution exists—then the disturbance at any point may be considered to arise from the superposition of a large number of plane wave trains with random phases and with all directions of propagation equally probable. Rayleigh [8] has shown that for $n$ vibrations of the same frequency, and with phases distributed at random, the mean value to be expected for the square of the resultant amplitude is the sum of the squares of the amplitudes for each individual vibration, so that the square of the resultant pressure amplitude indicated by the sound-level meter is equal to the sum of the squares of each individual pressure amplitude. The energy density in a plane wave is proportional to the square of the pressure amplitude of the wave. Since $P^2$ (pressure amplitude squared) of each wave is additive, the resultant $P^2$ is proportional to the sum of the energy density in each individual wave train. Hence, under the condition of a diffuse sound field, the sound-level meter indications are proportional to the energy density.

If, however, the distribution of sound energy is much different from the diffuse condition, the relationship between the $P^2$ which is measured and the energy density is somewhat difficult to state. To get a more accurate treatment of transmission problems, it would then be necessary to calculate the value of $P^2$ for each point in the room. It is clear that such a calculation is quite formidable, especially when it is considered how very different in physical properties the panels (which act as the source of sound for the quiet side) may be. The energy-flow treatment involving the measurement of the transmission loss with the aid of a pressure-actuated device is then to be considered as an approximate method of dealing with this problem. The beauty of the energy-flow treatment is that it gives an answer which is sufficiently accurate for most purposes, and eliminates the necessity of making a detailed calculation of the pressure wave in both the source and receiving rooms. In the development of equations 2 to 7 the energy-flow method will be used.

First, the energy density at the panel face due to the energy radiated from the panel will be calculated.

As the simplest assumption to make, it will be assumed that the panel radiates in such a fashion that the energy density is uniform over its face, except at the boundary edges of the panel. A more extreme case of this assumption is that of an infinite panel which may be assumed to radiate so that the whole (free) space which it bounds has a uniform energy-density distribution. Such a sound field, however, is not entirely diffuse, since only half the total possible directions of flow are permitted; that is, the energy can flow away from the panel only. This means that the total amount of energy which will strike unit area per second when placed in such a sound field will be $Ec/2$ as

[8] Theory of Sound, vol. 1, 2d ed., sec. 42a, p. 36–42 (Macmillan and Co., London, 1894).

compared to $Ec/4$ for a completely diffuse field; an element of volume such as $dV$ can radiate into a solid angle of $2\pi$ for the former as compared to $4\pi$ for the latter.

Hence,

$$J' = \frac{E'c}{2}, \tag{16}$$

the primes referring to the state in which the energy flow is "half" diffuse. This immediately leads to the conclusion that if the panel radiates $J'$ units of energy per unit area per second, the energy density will be $E' = 2J'/c$.

For a panel of finite size, if $E_0$ is the energy density at the panel face, and $J_0$ is the rate of energy emission per unit area, then

$$E_0 = \frac{2J_0}{c} \tag{17}$$

for positions not too close to the edges of the panel.

What has been assumed then is that the uniform and diffuse energy density on the noisy side, after being attenuated by the panel, reappears on the quiet side as a uniform and "half" diffuse energy density. That this is a plausible assumption is evident from a theorem first proved by Schoch,[9] which states that for sufficiently high frequencies above the fundamental frequency of a vibrating plate, the distribution of amplitude of vibration over the face of the plate is directly proportional to the distribution of driving pressure. Any diffuse distribution of energy incident on the panel face causes an exact image displacement of the panel so that a uniform energy density at the noisy face of the panel is duplicated at the quiet face. Of course, the use of this assumption at low frequencies and on complex partitions is justifiable only if the equations derived agree with the experimental results.

A modification of eq 11 gives as the rate at which energy is incident on $dS$ from the solid angle included between $\theta$ and $\theta + d\theta$, in a uniform, "half" diffuse sound field

$$\frac{EcdS}{2\pi} \cos\theta \, 2\pi \sin\theta d\theta. \tag{18}$$

The solid angle included between $\theta$ and $\theta + d\theta$ has the value $2\pi \sin\theta \, d\theta$. Hence the total amount of energy reaching $dS$ per second from the solid angle included between $\theta$ and $\theta + d\theta$ is proportional to $\cos\theta$. If one reverses the reasoning and thinks of the area $dS$ as radiating to reproduce this uniform "half" diffuse sound field, then it follows that the amount of energy radiated between $\theta$ and $\theta + d\theta$ is proportional to $\cos\theta$. This is the analog of Lambert's law in optics, which states that a glowing plate must emit energy proportional to $\cos\theta$, at an angle $\theta$, in order to look equally bright in all directions.

Using Lambert's law, eq 17 may be derived now in a more direct manner.

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[9] Akustische Z. **2**, 113 (1937). See also English summary in J. Acous. Soc. Am. **9**, 168 (1937).

Consider the element of area $dS$ radiating according to the $\cos\theta$ law (fig. 8).

Let $J_\Omega=\frac{dJ}{d\Omega}$=energy radiated per second per unit area per unit solid angle between $\Omega$ and $\Omega+d\Omega$,

$J_0$=total energy radiated per unit area per second,
$B$=a constant to be determined.

Then

$$J_\Omega d\Omega=B\cos\theta\, 2\pi\sin\theta d\theta, \tag{19}$$

$$J_0=\int J_\Omega d_\Omega=B2\pi\int_0^{\pi/2}\cos\theta\sin\theta d\theta, \tag{20}$$

so that

$$B=\frac{J_0}{\pi} \tag{21}$$

Therefore,

$$J_\Omega d\Omega=2J_0\cos\theta\sin\theta d\theta \tag{22}$$

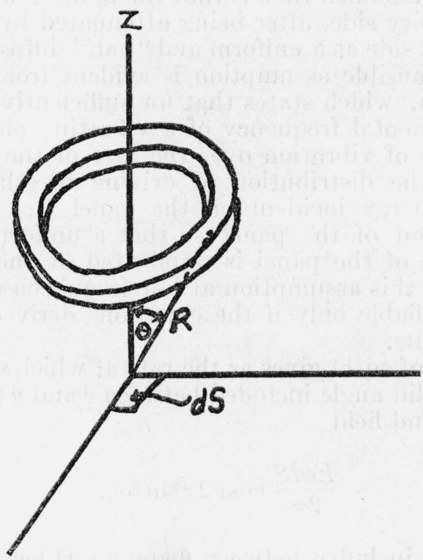


FIGURE 8

The contribution of $dS$ to the energy density $E_{ds}(R,\ \theta)$ at point $P(R,\ \theta)$ is the total amount of energy which flows into the volume of the ring, $2\pi\ R^2\sin\ \theta\, d\theta\, dR$ in the time $dR/c$, from the elementary area $dS$.

$$E_{ds}(R,\theta)=\frac{J_\Omega d\Omega}{2\pi R^2\sin\theta\, d\theta\, dR}\frac{dR}{c}\,dS,$$

or

$$E_{ds}(R,\theta)=\frac{J_0\cos\theta}{\pi cR^2}\,dS. \tag{23}$$

Consider a vibrating, circular plate (fig. 9) of radius $a$. The total energy density, at a point $Q$ located on the polar axis of the disk, due to contributions from all elements is

$$E(Z) = \frac{J_0}{\pi c} \int_0^a \frac{\cos\theta}{R^2} 2\pi r\, dr, \tag{24}$$

But

$$R^2 = r^2 + Z^2.$$

Whence,

$$2RdR = 2rdr$$

$$E(Z) = \frac{2J_0}{c} \int_Z^{\sqrt{a^2+Z^2}} \frac{Z}{R} \cdot \frac{1}{R^2} RdR;$$

so that,

$$E(Z) = \frac{2J_0}{c} \left[ 1 - \frac{Z}{a\sqrt{1+\frac{Z^2}{a^2}}} \right]. \tag{25}$$

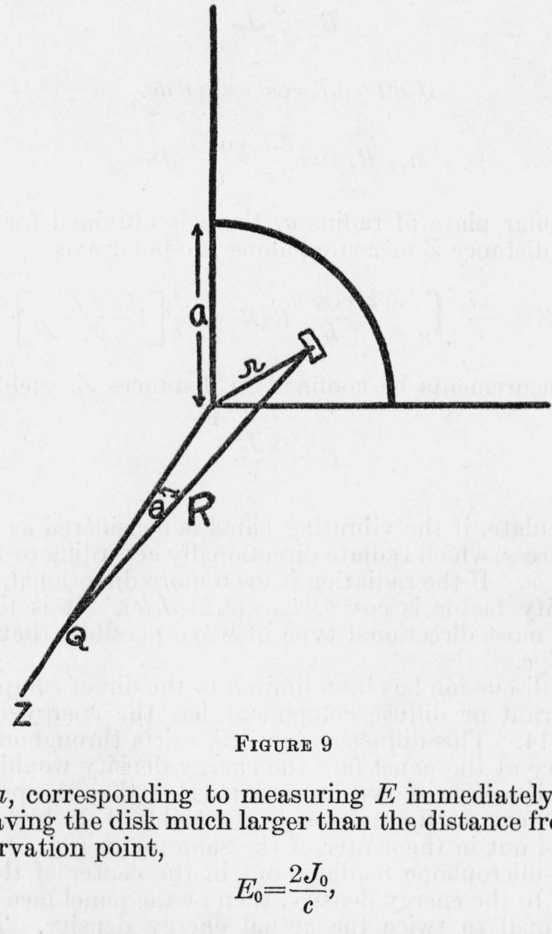


FIGURE 9

For $Z \ll a$, corresponding to measuring $E$ immediately next to the panel, or having the disk much larger than the distance from the panel to the observation point,

$$E_0 = \frac{2J_0}{c},$$

which is identical with eq 17. If the energy density is measured at $Z=0$, the result may be expected to be the same no matter what the boundary is—circular, rectangular, or otherwise. Also, positions not too far removed from the polar axis should give approximately the same value for $E_0$.

For high-frequency excitation of the panel, in the neighborhood of 4,000 c/s, it was found that the Lambert law does not hold. To get agreement with experiment, it was found necessary to assume that the radiation follows a more directional law, the directionality factor being $\cos^2\theta$, instead of $\cos\theta$. Equations analogous to those derived for the Lambert source (eq 19 to 25) will be derived now.

The amount of energy radiated per second per unit area in the solid angle between $\Omega$ and $\Omega+d\Omega$ is given by

$$J_\Omega d\Omega = 2\pi B \cos^2\theta \sin\theta \, d\theta \tag{26}$$

$$J_0 = 2\pi B \int_0^{\pi/2} \cos^2\theta \sin\theta \, d\theta$$

Whence

$$B = \frac{3}{2\pi} J_0, \tag{27}$$

or

$$J_\Omega d\Omega = 3J_0 \cos^2\theta \sin\theta \, d\theta. \tag{28}$$

So

$$E_{dS}(R, \theta) = \frac{3J_0}{2\pi c} \frac{\cos^2\theta}{R^2} dS. \tag{29}$$

For a circular plate of radius $a$, there is obtained for the energy density at a distance $Z$ measured along the polar axis

$$E(Z) = \frac{3J_0}{c} \int_Z^{\sqrt{a^2+Z^2}} \frac{\cos^2\theta}{R^2} R dR = \frac{3}{2} \frac{J_0}{c} \left[1 - \frac{Z^2}{a^2+Z^2}\right]. \tag{30}$$

If the measurements be confined to distances $Z$, such that $Z \ll a$, then

$$E_0 = \frac{3}{2} \frac{J_0}{c}. \tag{31}$$

To recapitulate, if the vibrating panel is considered as a collection of simple sources, which radiate directionally according to a $\cos\theta$ law, then $E_0 = 2J_0/c$. If the radiation is even more directional, that is, the proportionality factor is $\cos^2\theta$, $E_0 = (3/2)(J_0/c)$. It is to be noted that for the most directional type of wave possible, that is, a plane wave, $E_0 = J_0/c$.

So far the discussion has been limited to the direct component only. The reverberant or diffuse component has the energy density, $E_2$, given by eq 14. This diffuse energy, $E_2$, exists throughout the whole room. Hence at the panel face the energy density would be $E_0 + E_2$. However, it has been shown in section III–1 that the pressure level at the panel face on the noisy side is roughly 3 db higher than the pressure level out in the center of the same room (fig. 5). Hence, if the pressure-microphone readings out in the center of the room are proportional to the energy density, then at the panel face its readings are proportional to twice the actual energy density. This is also true for the diffuse component on the quiet side. Hence if $E_{20}$ is the energy density *indicated* by the pressure microphone at the panel face on the quiet side, one obtains

$$E_{20}=E_0+2E_2. \tag{32}$$

Thus, for the Lambert region where eq 17 holds,

$$E_{20}=\frac{2J_0}{c}+2E_2. \tag{33}$$

But $J_0$, the amount of energy emitted per unit area per second from the radiating surface, is given by

$$J_0=\frac{\tau E_1 c}{4} \tag{34}$$

where $E_1c/4$ is the rate at which energy is incident on unit area of the panel on the noisy side. Substituting for $J_0$, and for $E_2$ from eq 14, one gets

$$E_{20}=\frac{\tau E_1}{2}+\frac{2\tau S}{A_2}E_1,$$

or

$$\frac{1}{\tau}=\frac{E_1}{E_{20}}\left(\frac{1}{2}+\frac{2S}{A_2}\right). \tag{35}$$

Taking 10 $\log_{10}$ of both sides, there is obtained

$$10\log_{10}\left(\frac{1}{\tau}\right)=10\log_{10}\left(\frac{E_1}{E_{20}}\right)+10\log_{10}\left(\frac{1}{2}+2\frac{S}{A_2}\right). \tag{36}$$

10 $\log_{10}(1/\tau)$ is the transmission loss, and 10 $\log_{10}$ $(E_1/E_{20})$ is the observed difference in pressure level $(PL)_1-(PL)_{20}$. Hence eq 36 is identical with eq 3. For the $\cos^2\theta$ region where eq 31 is valid, the microphones are too large to be able to get sufficiently close to the panel to have the sound level of the diffuse component increase by 3 db (Compare $\nu=4{,}096$ c/s of fig. 5). Therefore,

$$E_{20}=\frac{3}{2}\frac{J_0}{c}+E_2 \tag{37}$$

and

$$\frac{1}{\tau}=\frac{E_1}{E_{20}}\left(\frac{3}{8}+\frac{S}{A_2}\right). \tag{38}$$

Taking 10 $\log_{10}$ of both sides of eq 38, eq 4 is obtained. As already indicated in section III–1, best agreement is obtained with experiment by using eq 3 at frequencies ranging from 192 to 2,048 c/s, and eq 4 at the frequency of 4,096 c/s.

The lowest frequency, $\nu=128$ c/s, is in a difficult region where the radiated wavelength is comparable to the dimensions of the panel and the dimensions of the room. The wavelength at 128 c/s is 8.8 ft; dimensions of the sound-transmitting surface about 6½ by 5 ft; dimensions of the receiving room about 9 by 12 by 16 ft. The mean free path $\left(4\frac{\text{volume of room}}{\text{total wall area}}\right)$ is thus less than the wavelength, being 7.7 ft.

One might, therefore, expect very little randomness in the resultant steady state in the room. In deriving eq 2, it is assumed that conditions deviate from random to such an extent that the pressure wave radiated from the panel is in phase with the pressure wave which originates in the room proper. If $P_R$ is the pressure amplitude at the panel face of the resultant wave, $P$ that of the direct wave, and $p$ that of the "diffuse" wave, then

$$P_R^2=(P+\sqrt{2}p)^2. \tag{39}$$

The factor $\sqrt{2}$ in front of $p$ is in accord with Kellogg's [10] result that for a diffuse component the square of the pressure amplitude is twice as great at the wall as that at a position away from the wall. It is assumed that $P_R^2$ is proportional to $E_{20}$, $P^2$ to $E_0=\tau E_1/2$ of the direct component and $p^2$ to $E_2=\tau E_1 S/A_2$ of the diffuse component, the proportionality constant being the same for all three.

Thus,

$$E_{20}=\left(\sqrt{\frac{\tau E_1}{2}}+\sqrt{2\tau E_1\frac{S}{A_2}}\right)^2$$

or

$$\frac{1}{\tau}=\frac{1}{2}\frac{E_1}{E_{20}}\left(1+2\sqrt{\frac{S}{A_2}}\right)^2. \tag{40}$$

Equation 40 is to be considered as an attempt to weight properly the relative influence of the standing wave system in the room and the diffusing nature of the many reflections the sound experiences at the walls of the room. Other attempts to take into account these two factors were not as successful as eq 40 insofar as agreement with experiment is concerned.

Upon taking 10 $\log_{10}$ of both sides of eq 40, eq 2 is obtained. It is to be remembered that in accordance with its method of derivation, eq 2 only holds when the mean free path of the receiving room is of the same order of magnitude as the wavelength of the sound emitted; if the room is quite large, it is probable that eq 3 should be used.

Substituting for $E_1$ in terms of $E_2$ from eq 14, one obtains from eq 40

$$\frac{E_{20}}{E_2}=\frac{1}{2}\frac{A_2}{S}\left(1+2\sqrt{\frac{S}{A_2}}\right)^2, \tag{41}$$

which is simply a different form of eq 5. Similarly, eq 6 and 7 may be obtained by using eq 14 to eliminate $\tau E_1$ from eq 35 and 38, respectively.

If $S/A_2$ is eliminated from eq 40 with the aid of eq 14, one obtains an expression for $1/\tau$ (eq 42) which is a function of two readily observable ratios, namely, $E_1/E_{20}$ and $E_2/E_{20}$. Similarly, from eq 35 and 38, eq 43 and 44, respectively, are obtained.

$$\frac{1}{\tau}=\frac{1}{2}\frac{\dfrac{E_1}{E_{20}}}{\left(1-\sqrt{\dfrac{2E_2}{E_{20}}}\right)^2} \qquad \nu=128\ c/s. \tag{42}$$

[10] J. Acous. Soc. Am. 4, 61 (1932).

$$\frac{1}{\tau}=\frac{1}{2}\frac{\frac{E_1}{E_{20}}}{\left(1-2\frac{E_2}{E_{20}}\right)}\qquad \nu=192\text{ to }2{,}048\ c/s. \tag{43}$$

$$\frac{1}{\tau}=\frac{3}{8}\frac{\frac{E_1}{E_{20}}}{\left(1-\frac{E_2}{E_{20}}\right)}\qquad \nu=4{,}096\ c/s. \tag{44}$$

Equations 42, 43, and 44 are the analytic formulation of the experiments in section III–1, in which it is pointed out that transmission-loss measurements could be made without a knowledge of $A_2/S$ if, in addition, the quantity $(PL)_{20}-(PL)_2$ is measured.

### 2. RIBBON-MICROPHONE ALTERNATE METHOD

The fundamental problem here is to calculate the correction terms given in table 6. Is it possible to compute the correction terms by a procedure analogous to that used in deriving eq 2, 3, and 4? Such a calculation must first compute the response of a ribbon microphone when used in a reverberant room, and second, its response when used in a position adjacent to the panel on the quiet side.

The first calculation has appeared elsewhere in several places.[11] The essential point is that for sound originating at an angle $\theta$, the ribbon microphone will generate a voltage proportional to $\cos\theta$. The response of the ribbon to the energy in the wave will therefore be proportional to $\cos^2\theta$, since the energy in the wave is proportional to the square of the particle velocity. Hence, if the energy density in the room is $E$, the rate at which energy is indicated by the ribbon as striking the ribbon area $dS$, is

$$\frac{EdS}{4\pi}\int_0^c\int_0^{2\pi}\int_0^{\pi}\cos^2\theta\sin\theta\,d\theta\,d\phi\,dR=\frac{Ec}{3}\,dS \tag{45}$$

Hence, if the energy density $E$ is measured by a nondirectional microphone, a ribbon microphone will record it as $E/3$.

For the second part of the calculation, reference is made to eq 23, which gives the energy density at a distance $R$ and an inclination $\theta$ due to a radiating element $dS$. If a ribbon microphone is situated at the point $(R,\theta)$, it will indicate the energy density $\overline{E}_{dS}(R,\theta)$ where

$$\overline{E}_{dS}(R,\theta)=\cos^2\theta\,E_{dS}(R,\theta)=\frac{J_0\cos^3\theta}{cR^2}\,dS. \tag{46}$$

Consider now a vibrating circular plate. In a manner similar to eq 24, one obtains

$$\overline{E}(Z)=\frac{J_0}{\pi c}\int_Z^{\sqrt{a^2+Z^2}}\frac{\cos^3\theta}{R^2}\,2\pi R dR. \tag{47}$$

[11] See, for example, Olson and Massa, Applied Acoustics, 1st ed., p. 133 (P. Blakiston's Son & Co., 1012 Walnut St., Philadelphia, Pa., 1934).

For the position immediately next to the panel the energy density indicated by the ribbon is

$$\overline{E}_{20}=\frac{2}{3}\frac{J_0.}{c} \tag{48}$$

From eq 34 $J_0=(\tau E_1 c/4)$.
Furthermore, the energy density $\overline{E}_1$ indicated by the ribbon on the noisy side is

$$\overline{E}_1=\frac{E_1,}{3} \tag{49}$$

so that

$$\overline{E}_{20}=\frac{1}{2}\tau\overline{E}_1 \tag{50}$$

or

$$10\log_{10}\left(\frac{1}{\tau}\right)=10\log_{10}\left(\frac{\overline{E}_1}{\overline{E}_{20}}\right)+10\log_{10}\left(\frac{1}{2}\right) \tag{51}$$

The first term on the right-hand side of eq 51 is the actual difference in level observed, while the second term is a correction term and is equal to −3.0 db. Of course, this equation should be valid only for the Lambert frequency region; in the $\cos^2\theta$ region the correction term turns out to be $-10\log_{10}(16/9)=-2.5$ db. It will be observed that the figure −2.5 db agrees well with the −2.0 db given in table 6 for the frequency 4,096 c/s. However, in the Lambert region (the range from 128 to 2,048 c/s according to our pressure-microphone alternate-method measurements) there is only one frequency, 2,048 c/s, which agrees with the −3.0 db calculated. All of the other corrections of table 6 are definitely in disagreement with the theoretical values.

There are two possible sources of error in the above calculations. Equation 49, $\overline{E}_1=E_1/3$, may be in error. Fortunately, it is possible to check the validity of eq 49. The response of a nondirectional microphone, such as a sound-pressure microphone, may be compared to the response of the ribbon microphone, when both are placed in a reverberant room. If both microphones have the same response to a plane wave, the ribbon microphone should indicate the velocity level to be $10\log_{10}3=4.8$ db lower than the corresponding pressure level. The experiment was carried out by comparing the response of the ribbon microphone with a pressure microphone (Western Electric Type 633A) under free-field, plane-wave conditions in the dead room at the National Bureau of Standards. From this the relative frequency-response characteristic of the two was determined. The two microphones were then placed on the noisy side of our transmission rooms and the difference in sound level indicated by the two was measured. The number of decibels by which the ribbon read less than the pressure microphone after correction was made for the differing response-frequency characteristics is as follows:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Frequency, c/s | 128 | 192 | 256 | 384 | 512 | 768 | 1, 024 | 2, 048 | 4, 096 |
| Decibels | 2.8 | 4.5 | 3.0 | 4.5 | 5.2 | 4.8 | 3.6 | 2.2 | 2.5 |

Measurements at frequencies up to 384 c/s have a possible error of about ±1.5 db; while the possible error for the other frequencies is about ±0.5 db. Thus all the figures are in rough agreement with the value 4.8 db except those at 2,048 and 4,096 c/s. Best agreement is to be anticipated at these higher frequencies, since it is then that the sound field approaches the diffuse condition most closely. The explanation may be that at these frequencies the pressure microphone is becoming directional and its response is 5 to 10 db down for waves too far off from normal incidence.

In attempting to account for the results in table 6, an impasse has been reached. While the sound-pressure data seem to be well-behaved (in the sense that they accord with our analysis), the same cannot be said of the particle velocity measurements. One qualitative explanation is suggested by a perusal of table 6. The correction factor diminishes with increasing frequency, which corresponds to the fact that the velocity level as indicated by the ribbon when placed adjacent to the panel on the quiet side is greater than it should be, its excessive value also diminishing with increasing frequency. This is just the behavior one gets from a ribbon microphone when one approaches a point source with it. There is an inordinate increase in the particle velocity of a spherical wave over the pressure in the wave for positions close to the source, especially for the low frequencies.[12] It is thought that possibly a similar phenomenon is occurring here, even though the source is of such an extended nature as a wall. Different elements of the panel emit spherical waves, but the vibration of the panel is of such a complex nature that a quantitative elaboration of this idea would seem to be difficult.

## V. FURTHER APPLICATIONS OF THE RIBBON-MICROPHONE ALTERNATE METHOD

From the discussion in section IV, it will be evident that of the two components, direct and diffuse, only the latter depends on the ratio $A_2/S$, the former being independent of this ratio. Since in the ribbon-microphone alternate method the response of the ribbon on the quiet side depends only on the direct sound, it follows that by this method it is possible to make transmission-loss measurements without considering complications arising from the size of the wall or the nature of the receiving room. The room may be extraordinarily large, say the size of a large auditorium, in which case the wall under test will be large also. The wall may be even discontinuous in nature with different sections differing in construction. It will still be possible to determine the transmission loss, but the different sections will give different results.

It is necessary to qualify the last statement somewhat. If two adjacent sections are too different in insulating efficiency, it is possible to obtain erroneous results. For example, suppose the energy radiated from one area is 30 db greater in level than that from another area. The energy radiated from the wall forms a reverberant sound field out in the center of the room, which, let us say, is 5 db less in level than the direct component. This means that at the face of the section which is a poorer radiator, the reverberant energy will be 25 db larger than the direct energy. If the ribbon microphone attenuates the reverberant component to the extent of 20 db, the result is that there will be a 5-db error in the transmission loss for the poorer section. In case the room is relatively bare, the error will be even greater.

[12] Olson and Massa, Applied Acoustics, 1st ed., p. 9 (P. Blakiston's Son & Co., 1012 Walnut St., Philadelphia, Pa., 1934).

The decibel difference between the direct and reverberant component may be readily shown to be 10 $\log_{10}$ $(A_2/2S)$. With the aid of this formula it is possible to determine the difference in level between different sections whose transmission losses may be ascertained without error. The more absorbent the room or the smaller the area in question, the larger the difference in transmission loss which can be measured. For an untreated room a common condition is one in which the ratio of absorption to surface area is equal to 1. In this case the direct component is 3 db less than the reverberant component. If the ribbon microphone discriminates against reverberant energy to the extent of 20 db, the resultant discrimination will be 17 db. This means that the transmission loss of sections differing by as much as 17 db may be determined. This figure holds only where there is no appreciable direct feeding of sound into the microphone from the poorer section. These quantitative calculations will be wrong to the extent to which this phenomenon takes place.

All of the above figures have to be modified because of a factor which has not yet been taken into account, namely, the fact that the discrimination of the ribbon microphone in favor of the direct sound is increased even more because the velocity level due to the direct sound is considerably greater than it should be, as the figures in table 6 show. Since the theoretical value of these corrections in table 6 is $-3.0$ db ($\nu$=128 to 2,048 c/s), the velocity level indications at the panel face on the quiet side are $+3.0$ db higher than the correction terms given in table 6 (relative to the predicted velocity level). Thus at 128 c/s there is an additional discrimination in favor of the direct sound of 11.2 db, which must be added to 15 db obtained at 128 c/s from figure 6, making a total discrimination of about 26 db. Similarly, at the other frequencies, 192, 256, 384, 512, 768, 1,024, 2,048, and 4,096 c/s, the discrimination in favor of the direct sound is 28, 27, 25, 28, 24, 21, 16, 12 db, respectively. No experiments have been carried out as yet to check these figures.

Within the limitations indicated in the foregoing, the ribbon microphone may be used as a radiation pickup,[13] with certain obvious advantages over a vibration pickup. At no time does the microphone touch the radiator, so that the vibration characteristics of the body are not disturbed as sometimes happens in using a vibration pickup. What is measured is the sound radiated directly from the vibrating body, which is usually a quantity of primary interest. On the other hand, a determination of the vibration amplitude, velocity, or acceleration has an uncertain relationship to the sound which is radiated.

The ribbon microphone when used as a radiation pickup has one other advantage over a vibration pickup. The variation in velocity level between different positions over the panel face is much less than variations in level indicated by a vibration pickup. Thus, as a general observation, it may be stated that over the whole frequency range the maximum spread in velocity level obtained at the panel face with the ribbon microphone was usually less than 4 db but sometimes as large as 6 or 7 db. This is to be compared with the vibration pattern obtained on a 9-in. brick wall by Constable and Aston [14] with

[13] Paul Huber, of the General Motors Corporation, in an oral observation at the 23d meeting of the Acoustical Society indicated a similar use for a ribbon microphone in studying the radiation from the panels of automobile bodies.
[14] Proc. Phys. Soc. (London) 48, 919 (1936).

a vibration pickup. Using a warble tone, the maximum spread in results was 13 db at 100 c/s, 12 db at 500 c/s, 21 db at 1,600 c/s, and 16 db at 4,000 c/s. The ribbon microphone thus acts somewhat like an averaging device in that its response depends on a region of the panel somewhat larger than that which influences the response of a vibration pickup.

One proposed application of the ribbon microphone is concerned with its use in evaluating the resistance of floor construction to transmitting impact noises. No completely satisfactory method of determining this physical quantity is now in use, as all measurements depend to some extent on room conditions. It is suggested that this type of measurement might rest on a more satisfactory basis if the ribbon microphone were used to measure the energy radiated directly from the panel, making appropriate use of the corrections of table 6. Of course, it would be necessary to take a frequency analysis of the noise resulting from the mechanical impact caused by the tapping machine, in order to use these correction terms. The efficiency of the panel might be defined in terms of the ratio of the sound energy emitted on the noisy side to the mechanical energy of the exciting hammer blow. Further work in this direction is contemplated. P. Haller [15] has given a discussion of this question along similar lines.

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The development of the multiple loudspeaker unit and the commutating device used with the amplifier is due in large part to V. L. Chrisler and W. F. Snyder. S. Greenman assisted in carrying out some of the measurements.

WASHINGTON, January 31, 1941.

[15] Akustische Z. 4, 370 (1939).