THE EFFECT OF POSITION UPON THE EFFICIENCY OF ACOUSTICAL TREATMENT[1]

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In accoustical work it is assumed that the reverberation time is dependent upon two variables, namely, the total volume of the room and the total absorption of the surface exposed. This assumption leads to satisfactory results in the designing of new halls as well as in the correction of poor acoustics in old theaters, churches, lecture rooms, etc. The mathematical proof of the relation is direct and well known and the experimental derivation of the law was very ably contributed by W. C. Sabine in 1895. The rapid and rigorous development of the science of Architectural Acoustics since that time gives ample proof of the general accuracy of the Sabine Law. This law is expressed by the formula,

$$T = kV/A,$$

wherein, T is the reverberation time or the time required for the sound intensity to decrease sixty decibels, V is the total volume of the enclosed space, A is the total absorption present in the room, and k is a proportionality constant. This law requires a perfect diffusion of sound energy, a random distribution of the directions of the reflections, and no definite foci.

Now, even with the above enumerated conditions, are there not perhaps other factors which might affect the value of the reverberation time, T? Quite extensive researches have been made upon the effects of humidity, barometric pressure, temperature, pitch of sound, and other physical variations entering into the constant k. In fact these effects are quite definite and investigations are carried out with due regard for their constancy. Changes in volume, V, both in magnitude and in shape, have been exhaustively treated by many workers. Modern sound recording in the moving picture industry takes cognizance of the importance of size and shape in the designing of the studios to produce just the desired quality of music and depth of tone. The problem is reduced then to an investigation of the component parts of the factor A in the general equation. Until recently only one type of analysis has been made upon this factor and that is that the total absorption is equal to the arithmetical sum of the component parts, or,

$$A = a_1S_1 + a_2S_2 + a_3S_3 + \text{------}$$

wherein, a is the absorption coefficient of the sound-proofing material and S is the area of the surface covered. The absorption coefficients in sabines are taken from tables of physical constants and the areas are calculated for each type of treatment in the usual manner either from blue print specifications or from actual measurements. The numerical value of the constant k of the equation is equal to four times the natural

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logarithm of one millionth with this product divided by the velocity of sound in air.

The project discussed in this paper arose from the following general considerations: How does the coefficient of absorption depend upon the pressure of the incident sound energy? Will a given area of material separated into two parts produce the same correction as would the same area in a single unit? How does the efficiency of an absorber depend upon the direction and amplitude of the incident energy wave? Or, in short, is there an optimum position for the sound absorbing material? These problems are more or less involved and interdependent and hence have not been analyzed readily. James F. Mackell in 1931 completed a careful and conclusive determination of the effect of spacing upon the efficiency of absorbing material. C. A. Andree published in 1932 a mathematical projection of the problem of position of the material in correcting a cubical volume. This paper presents the results of tests made in variously designed rooms of different volumes upon the efficiency of a unit block of absorbing material when placed in different positions relative to the source, the reflecting walls, and the recorder. For each hall tested there will be found in Table A the average values of the reverberation time. A study of this table shows the apparently constant law of variation of efficiency with the position of the absorbing unit. In all tables and figures O designates the empty room, the letters a, b. - - - f show the successive positions of the absorbing unit, while the numbers 1, 2, and 3 designate the stations occupied by the investigator.

Preliminary Investigations. Before beginning the research various experiments were repeated in the reverberation room in Science Hall, Indiana University, hereafter referred to as Room No. 12. The source of sound was one of a series of rectangular wood organ pipes swinging from the ceiling and adjustable as to height and geometric location. These pipes were excited by means of a motor driven air compressor and the air pressure was controlled and measured in an anteroom adjoining the "live" room. When the organ pipe was excited by lung pressure the constancy of excitation was maintained by having a Thorpe Gauge properly connected to the mouthpiece of the pipe. A Jenkins and Adair condenser microphone was used as a sound detector. This was mounted upon a floor stand adjustable vertically and horizontally. The output of the one stage of amplification built into the microphone case was led to the anteroom where it was amplified and then measured with a vacuum thermocouple and microammeter. Observations were made using a battery operated amplifier as well as a Samson A. C. audio unit. A properly matched Brandeis headset could be substituted for the thermocouple-microammeter system when desired. Using this arrangement of apparatus and placing the microphone successively at the definite points marked in rectangular coordinates on the floor of Room No. 12 the factors governing the distribution of sound intensities in a room were studied. It was seen that definite standing wave patterns do exist under certain exact conditions. However, at some air pressures the quality and intensity of the sounds emitted by the organ pipe were so unstable as to cause the pattern to change or creep quite rapidly. The time lag in the amplifier-microammeter system was greater than the time required for this change of intensity and hence entirely vitiated the readings. It was noticed also that the sound intensity near the walls changed continuously showing that the conditions in this border region are unstable and hence that the angle of incidence of the pressure wave with the wall is a varying quantity. This then, while eliminating the standing wave pattern method as a recording scheme in this research, proved, nevertheless, the importance of determining the dependence of absorption efficiency upon the conditions of incidence. While taking data in Room No. 12 the masking effect of a second continuously emitting sound source was clearly demonstrated. When the power vacuum cleaner system was in operation the percentage decrease in the duration of sound after cut-off was very evident and quite constant. The other method of recording data was the ear-chronometer scheme where the observer is in the room and measures the time, by means of a manually operated stop watch, from the sound cut-off to the threshold of audibility. In any investigation the recorded value is the average of at least two hundred separate readings and each reading is the mean of ten successive reverberation periods. Many checks seem to prove the dependability of this ear-stop watch method of measurement. One such check was made in Room No. 12. The head set was substituted for the thermocouple-microammeter in the anteroom and a series of reverberation periods were taken with the observer in this anteroom. The mean value checked favorably with that determined when the observer was in the "live" room. Hence in the subsequent investigations the ear-stop watch method was used entirely. In presenting the results of the main researches no regard will be paid to their chronological order. In fact the entire mass of data for the first three halls had been recorded and studied over several times before the relation emphasized in this report was noticed. Then the investigation was carried to the Music Hall and from there to the Commerce Hall where an extensive and precise set of data was recorded, which when worked out two days later was in exact agreement as shown in Table A.

Union Hall. The auditorium in the Student Union Building at Indiana University (Union Hall) is a rectangular room with a high, beamed ceiling, a small balcony, and an entrance vestibule. This room is quite live, even when filled with leather upholstered chairs, as it was when these data were taken. The three positions of the observer were: (1) standing at the rear of the hall near the entrance, (2) standing at the front stage at the speaker's position, and (3) sitting on a chair placed upon the absorbing unit. Of course it is to be remembered that the absorption represented by the observer's body changed position in each case, which might account for some of the general variation. However, since each separate set of data shows approximately the same variation as does the set of average values this change is immaterial. Other positions were tried, but owing to the geometric cross-section of the hall direct echoes interferred with the determination of the period by affecting the k of the Sabine equation rather than the A.

The absorbing unit used in this hall was composed of thirty square feet of asbestos wool in metal sections and fifty pieces of Quietile in one-foot squares. The large volume of the room reduced the percentage effect of the additional absorption introduced. Hence the unit had to be relatively large.

Room No. 12. In the "live" room in Science Hall, Room No. 12, besides the preliminary researches discussed in the introduction, two sets of data were recorded following the general scheme used in Union

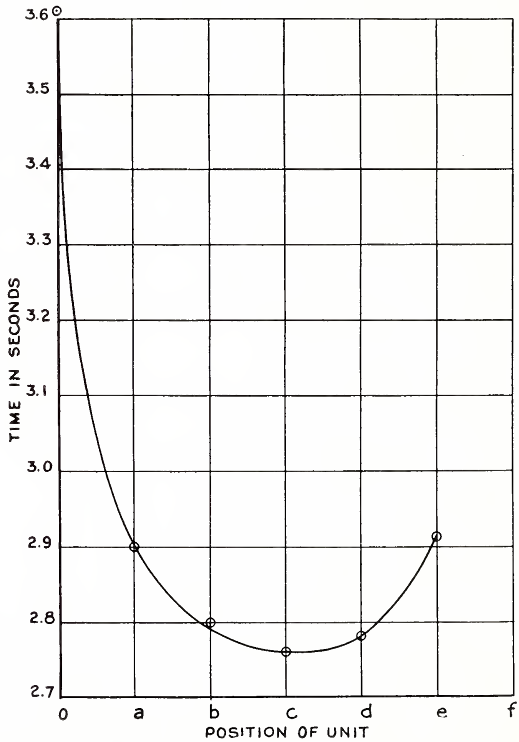

Fig. 1. Average reverberation time, room No. 12, empty.

Hall. The first observations were made using the room with no additional absorption present except the unit, which was placed upon the concrete floor. This arrangement gave the data tabulated in the second column of Table I and graphically presented in figure 1. Then the room was treated with hair felt, distributed as uniformly as possible, in order to bring the free period down to a value comparable, relative to the room size, with the free period of Union Hall. The data obtained then gave a curve with the same characteristics as that of figure 1. In this room the observer stood at a point near the east wall corresponding to the speaker's position if the room were to be used as a lecture hall.

TABLE I

Composite table of mean values of reverberation time.

Position of unit	Union Hall	Room No. 12	LeFer No. 500	Music Hall	Commerce Hall
o	3.87 s.	2.28 s.	3.11 s.	4.71 s.	4.31 s.
a	3.66 s.	1.63 s.	2.50 s.	4.38 s.	3.89 s.
b	3.59 s.	1.40 s.	2.32 s.	4.58 s.	3.76 s.
c	3.63 s.	1.43 s.	2.24 s.	4.38 s.	3.54 s.
d	3.63 s.	1.48 s.	2.18 s.	4.44 s.	3.57 s.
e	3.74 s.	1.49 s.	2.28 s.	4.62 s.	3.73 s.
f	3.83 s.	1.75 s.	2.44 s.	....	3.82 s.

LeFer No. 500. The reverberation room of the physics department of St. Mary-of-the-Woods College (LeFer No. 500) is rectangular with the west wall, just a trifle higher than the east. It was possible in this room to make a check of each set of readings by taking advantage of the symmetrical design of the floor. With the absorbing unit, fifty square feet of Quietile, in a given position readings were taken with the observer first at position (1) and then at position (2). Then the final value of reverberation time taken at 1- -a should be the same as that taken at 2- -f, 1- -b as 2- -e, etc. (see figure 2). These expected checks were realized exactly.

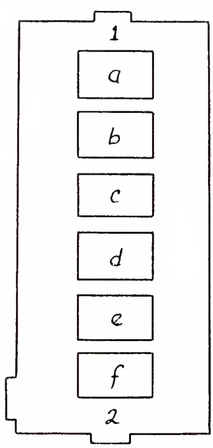

Fig. 2. Floor plan, LeFer No. 500.

Music Hall. Next a series of measurements was made in the Cecilian Auditorium, St. Mary-of-the-Woods College (Music Hall). This room is of a rather striking and very beautiful design. The floor plan is practically square. The pillars, built-in boxes, sloping floor, large curved balcony, and particularly the dome-shaped, stained glass ceiling make an effective combination for producing the acoustical qualities desirable for instrumental music. The room is fairly "live" for speaking, but this fault is partly overcome by the good sound distribution. The data recorded in the fourth column of Table I were taken with the doors closed and the stage cut off by the heavy asbestos curtain. The absorbing unit was a large pile of various types of material moved from post to post with no change of arrangement within the unit. There is one point to be noted in particular and that is the unusual behavior at position b (see figure 3). After working up this data and noticing the eccentricity of this point b a second visit was made to the auditorium, and it was observed that there is an apparent loud area across the hall at b caused probably by the focussing of the reflected sound from the sloping balcony to this position. This is again an effect upon the constant k of the equation and the point b will have to be ignored in studying the effect of position upon the absorption A. The main point to be noted in this set of readings is that even with the odd ceiling and other features which might change the behavior of this room from that of the regular rectangular volumes studied before the variations of the average reverberation time with the position of the unit follows the same general law.

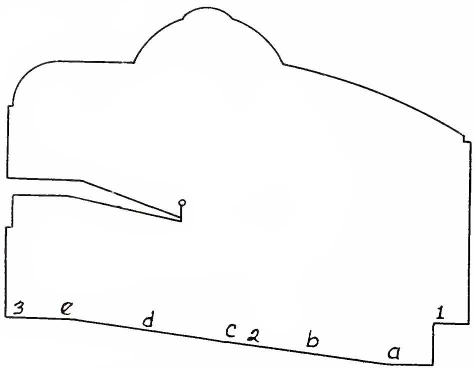

Fig. 3. Longitudinal section through center, Music Hall.

Commerce Hall. As a final check upon this position effect a very thorough test was carried out in the auditorium of the Commerce Building at Indiana University (Commerce Hall). In this investigation the absorbing unit was made up by arranging upon the seats and across the backs of the seats, in each position, a large amount of material of various types and coefficients. This arrangement took advantage of spacing effect, the exposure of all edges and both sides of each piece, and the effective "suspension in mid-air" of the unit instead of using it to cover a surface. It is evident then that if any change in the absorbing power is observed it must surely be due to the relative position of the unit, the reflecting walls, the source, and the observer. Column 5 in Table I shows the remarkable agreement of this data with that obtained in the other halls.

Summary. Even though the positions a, b, etc., are not absolutely identical in the several columns of Table I, a study of this table will facilitate the detection of the similarity of changes in the reverberation times recorded. A general statement of this agreement would be that absorbing material is most efficient when placed in a position midway between opposite reflecting surfaces. The check is sufficiently complete with the unit placed upon the floor to imply that it would be the same if the symmetry were maintained and the unit placed upon the side walls or the ceiling. The observations made in Commerce Hall would seem to show that the most efficient position of the unit in the cases studied would be in the geometric center of the room.

In conclusion I wish to express my gratitude to Doctor Arthur L. Foley for his willing and helpful suggestions in the selection of this project and during the subsequent research. Thanks are due and gladly given Indiana University for the use of the facilities necessary to the experimental investigations. I wish to thank Doctor R. R. Ramsay for his suggestion in the arrangement of electrical apparatus and all other members of the physics department for innumerable hints and suggestions. And since it is impossible to measure the amount of assistance I have received from the many articles and books I have read I want to show my gratitude to some authors by the appended bibliography and to those unintentionally omitted by a sincere apology.

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