Some Notes On Sabine Rooms

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Abstract: First the classical derivation of the Sabine equation describing the decay of a diffuse sound field in a reverberant enclosed space is reviewed. Next a modal description of sound field decay is proposed and three alternative methods of solution are considered: (a) With appropriate simplifications the Norris-Eyering equation is derived. From the latter equation the Sabine equation is derived as a first approximation. (b) With alternative assumptions the Millington-Sette equation is derived and the open window dilemma, often cited, is resolved. (c) With further argument and one assumption the modal analysis leads to the Sabine equation but not as a first approximation. Experimental verification is demonstrated by making reference to data provided by a CSIRO round robin which was conducted and reported in 1980. It is shown that all of the data obtained in the latter investigation in the seven rooms ranging in size from 106 cubic meters to 607 cubic meters which had sufficient auxiliary diffusion and for all patch sizes tested may be reduced to one line in terms of the calculated statistical absorption coefficient for an infinite patch. A simple empirical expression based upon assumed edge diffraction effects is shown to fairly well describe the data in its mid range. Explanations for departures at low and at high frequencies from the proposed expression describing the results are suggested.

1. INTRODUCTION

When the reflective surfaces of an enclosure are not too distant one from another and none of the dimensions are so large that air absorption becomes of controlling importance, the sound energy density of a reverberant field will tend to uniformity throughout the enclosure. Generally, reflective surfaces will not be too distant, as intended here, if no enclosure dimension exceeds any other dimension by more than a factor of about three. As the distance from the sound source increases in this type of enclosure, the relative contribution of the reverberant field to the overall sound field will increase until it dominates the direct field (Beranek, 1971 see Ch, 9; Smith, 1971 see Ch 3). This kind of enclosed space, in which a generally uniform (energy density) reverberant field, characterised by a mean sound pressure and standard deviation, tends to be established, has been studied extensively because it characterises rooms used for assembly and general living and will be the subject of this paper. For convenience, this type of enclosed space will be referred to as a Sabine enclosure named after the man who initiated investigation of the acoustical properties of such rooms.

All enclosures exhibit low and high frequency response and generally all such response is of interest. However, only the high frequency sound field in an enclosure exhibits those properties which are amenable to the Sabine type analysis; thus, the concepts of the Sabine room are strictly associated only with the high frequency response. For more on this matter reference may be made to Bies and Hansen (1995).

2. TRANSIENT RESPONSE

If sound is introduced into a room, the reverberant field level will increase until the rate of sound energy introduction is just equal to the rate of sound energy absorption. If the sound source is abruptly shut off, the reverberant field will decay at a rate determined by the rate of sound energy absorption. The time required for the reverberant field to decay by 60 dB, called the reverberation time, is the single most important parameter characterising a room for its acoustical properties. For example, a long reverberation time may make the understanding of speech difficult but may be desirable for organ recitals.

As the reverberation time is directly related to the energy dissipation in a room, its measurement provides a means for the determination of the energy absorption properties of a room. Knowledge of the energy absorption properties of a room in turn allows estimation of the resulting sound pressure level in the reverberant field when sound of given power level is introduced. The energy absorption properties of materials placed in a reverberation chamber may be determined by measurement of the associated reverberation times of the chamber, with and without the material under test in the room. The Sabine absorption coefficient, which is assumed to be a property of the material under test, is determined in this way and standards (ASTM C423 - 1984a; ISO R354 - 1963; AS 1045 - 1971) are available which provide guidance for conducting these tests.

In the following sections two methods will be used to characterise the transient response of a room. The classical description, in which the sound field is described statistically, will be presented first and a new method, in which the sound field is described in terms of modal decay, will be presented second. It will be shown that the new method leads to a description in agreement with experiment.

2.1. Classical Description

At high frequencies the reverberant field may be described in terms of a simple differential equation which represents a gross simplification of the physical process but none-the-less gives generally useful results. The total mean absorption coefficient $\overline{\alpha}$, including air absorption, m (dB per 1,000 m), may be written in terms of the volume, V, and total surface, S, of the room as follows.

$$\overline{\alpha} = \overline{\alpha}_w + 9.21x\,10^{-4} mV/S \tag{1}$$

Using the well known expression for the energy density, $\psi = \langle p^2 \rangle / (\rho c^2)$, where p is the root mean square sound pressure, ρ is the density and c the speed of sound in air the following equation may be written for the power, W_a, or rate of energy absorbed:

$$W_a = \psi S c \overline{\alpha} / 4 = \langle p^2 \rangle S \overline{\alpha} / (4 \rho c) \tag{2a,b}$$

Using the above equation and observing that the rate of change of the energy stored in a reverberant field equals the rate of supply, W_0, less the rate of energy absorbed, W_a, gives the following result.

$$W = V \partial \psi / \partial t = W_0 - \psi S c \overline{\alpha} / 4 \tag{3a,b}$$

Introducing the dummy variable,

$$X = [4 W_0 / S c \overline{\alpha}] - \psi \tag{4}$$

and using Equation 4 to rewrite Equation 3, the following result is obtained:

$$\frac{1}{X}\frac{dX}{dt} = -\frac{S c \overline{\alpha}}{4V} \tag{5}$$

Integration of the above equation gives:

$$X = X_0 e^{-S c \overline{\alpha} t / 4V} \tag{6}$$

where X_0 is the initial value.

Two cases will be considered. Suppose that initially, at time zero, the sound field is nil and a source of sound power W_0 is suddenly turned on. The initial conditions are time $t = 0$ and sound pressure $\langle p_0^2 \rangle = 0$. Substitution of Equation 4 into Equation 6 gives, for the resulting reverberant field at any later time t,

$$\langle p^2 \rangle = \frac{4 W_0 \rho c}{S \overline{\alpha}} \left(1 - e^{-S c \overline{\alpha} t / 4V}\right) \tag{7}$$

Alternatively, consider that a steady state sound field has been established when the source of sound is suddenly shut off. In this case the initial conditions are time $t = 0$, sound power $W_0 = 0$, and sound pressure $\langle p^2 \rangle = \langle p_0^2 \rangle$. Again, substitution of Equation 4 into Equation 6 gives, for the decaying reverberant field at later time t:

$$\langle p^2 \rangle = \langle p_0^2 \rangle e^{-S c \overline{\alpha} t / 4V} \tag{8}$$

Taking logarithms to the base ten of both sides of Equation 8 gives the following result.

$$L_{p0} - L_p = 1.086 S c \overline{\alpha} t / V \tag{9}$$

Equation 9 shows that the sound pressure level decays linearly with time and at a rate proportional to the Sabine absorption $S\overline{\alpha}$. It provides the basis for the measurement and the definition of the Sabine absorption coefficient $\overline{\alpha}$.

Sabine introduced the reverberation time, T_{60} (seconds), as the time required for the sound energy density level to decay by 60 dB from its initial value. He showed that the reverberation time, T_{60}, was related to the room volume, V, the total wall area including floor and ceiling, S, the speed of sound, c, and an absorption coefficient, $\overline{\alpha}$, which was characteristic of the room and generally a property of the bounding surfaces. Sabine's reverberation time equation, which follows from Equation 9 with $L_{p0} - L_p = 60$, may be written as follows

$$T_{60} = 55.25 V / S c \overline{\alpha} \tag{10}$$

2.2. Modal description

The discussion thus far suggests that the reverberant field within a room may be thought of as composed of the excited resonant modes of the room. This is still true even in the high frequency range where the modes may be so numerous and close together that they tend to interfere and cannot be identified separately. In fact, if any enclosure is driven at a frequency slightly off-resonance and the source is abruptly shut off, the frequency of the decaying field will be observed to shift to that of the driven resonant mode as it decays (Morse, 1948).

In general, the reflection coefficient, β, (the fraction of incident energy which is reflected) characterising any surface is a function of the angle of incidence. It is related to the corresponding absorption coefficient, α, (the fraction of incident energy which is absorbed) as $\alpha + \beta = 1$. Let $\langle p(t)^2 \rangle$ be the mean square band sound pressure level at time t in a decaying field and $\langle p_k(t)^2 \rangle$ be the mean square sound pressure level of mode k. The decaying field may be expressed in terms of the sum of the time varying modal square pressure amplitudes $\langle p_k(t)^2 \rangle$, mean reflection coefficients β_k and modal mean free paths Λ_k as follows,

$$\langle p(t)^2 \rangle = \sum_{k=1}^{N} \langle p_k(t)^2 \rangle \beta_k^{ct/\Lambda_k} \tag{11}$$

where

$$\beta_k = \prod_{i=1}^{n} [\beta_{ki}]^{S_i/S_k} \tag{12}$$

In the above equations N is the number of modes within a measurement band. The quantities β_{ki} are the reflection coefficients and S_i are the areas of the corresponding reflecting surfaces encountered by a wave travelling around a modal circuit associated with mode k and reflection from surface i (Morse and Bolt, 1944). The S_k are the sums of the areas of the S_i reflecting surfaces encountered in one modal circuit of mode k.

The modal mean free path Λ_k is the mean distance between reflections of a sound wave travelling around a closed modal circuit and for a rectangular room is given by the following equation (Larson, 1978).

$$\Lambda_k = \frac{2 f_k}{c} \left[\frac{n_x}{L_x^2} + \frac{n_y}{L_y^2} + \frac{n_z}{L_z^2} \right]^{-1} \tag{13}$$

The quantities β_k are the reflection coefficients encountered during a modal circuit and the symbol $\prod_{i=1}^{n}$ represents the product of the n reflection coefficients where n is either a multiple of the number of reflections in one modal circuit or a large number. The quantity f_k is the resonance frequency given by the following equation for mode k of a rectangular enclosure, which has the modal indices n_x, n_y, n_z.

$$f_k = \frac{c}{2}\sqrt{\left[\frac{n_x}{L_x}\right]^2 + \left[\frac{n_y}{L_y}\right]^2 + \left[\frac{n_z}{L_z}\right]^2} \qquad (14)$$

In the above equation the subscript k on the frequency variable f indicates that the particular solutions or "eigen" frequencies of the equation are functions of the particular mode numbers n_x, n_y, and n_z.

The assumption will be made that the energy in each mode is on average the same, so that in Equation 11, p_k may be replaced with $p_0/\sqrt{N}$ where p_0 is the measured initial sound pressure in the room when the source is shut off. Equation 11 may be rewritten as follows.

$$< p(t)^2 > \; = \; < p_0^2 > \frac{1}{N}\sum_{k=1}^{N} e^{(ct/\Lambda_k)\log_e(1-\alpha_k)} \qquad (15)$$

A mathematical simplification is now introduced. In the above expression the modal mean free path length is replaced with the mean of all of the modal mean free paths, $4V/S$, and the modal mean absorption coefficient α_k is replaced with the area weighted mean statistical absorption coefficient $\overline{\alpha}_{st}$ for the room. The quantity V is the total volume and S is the total wall, ceiling and floor area of the room. In exactly the same way as Equation 10 was derived from Equation 8, the well known reverberation time equation of Norris - Eyring may be derived from Equation 15 giving an expression as follows.

$$T_{60} = -\frac{55.25V}{Sc\log_e(1-\overline{\alpha}_{st})} \qquad (16)$$

This equation is often preferred to the Sabine equation by many who work in the field of architectural acoustics. Note that air absorption must be included in $\overline{\alpha}_{st}$ in a similar way as it is included in $\overline{\alpha}$. It is worth careful note that Equation 16 is a predictive scheme based upon a number of assumptions that cannot be proven, and consequently inversion of the equation to determine the statistical absorption coefficient $\overline{\alpha}_{st}$ is not recommended. With a further simplification, the famous equation of Sabine is obtained. When $\overline{\alpha}_{st} < 0.4$, an error of less than 0.5 dB is made by setting $\overline{\alpha}_{st} \approx \log_e(1-\overline{\alpha}_{st})$ in Equation 16. Then by replacing $\overline{\alpha}_{st}$ with $\overline{\alpha}$, Equation 10 is obtained.

Alternatively, if in Equation 15 the $(1-\alpha_k)$ are replaced with the modal reflection coefficients β_k and these in turn are replaced with a mean value, called the mean statistical reflection coefficient $\overline{\beta}_{st}$, the following equation of Millington and Sette is obtained.

$$T_{60} = -55.25V/Sc\log_e\overline{\beta}_{st} \qquad (17)$$

The quantity $\overline{\beta}_{st}$ is given by Equation 12 but with changes in the meaning of the symbols. β_k is replaced with $\overline{\beta}_{st}$ which is now to be interpreted as the area weighted geometric mean of the random incidence energy reflection coefficients, β_i, for all of the room surfaces; that is,

$$\overline{\beta}_{st} = \prod_{i=1}^{n}\beta_i^{S_i/S} \qquad (18)$$

The quantity β_i is related to the statistical absorption coefficient $\alpha_{st,i}$ for surface i of area S_i by $\beta_i = 1-\alpha_{st,i}$. It is of interest to note that although taken literally Equation 18 would suggest that an open window having no reflection would absorb all of the incident energy and there would be no reverberant field, the interpretation presented here suggests that an open window must be considered as only a part of the wall in which it is placed and the case of total absorption will never occur. Alternatively, reference to Equation 11 shows that if any term β_i is zero it simply does not appear in the sum and thus will not appear in Equation 17 which follows from it.

3. NEW ANALYSIS

When a sound field decays all of the excited modes decay at their natural frequencies (Morse, 1948); the decay of the sound field is modal decay (Lawson, 1978). In the frequency range in which the field is diffuse it is reasonable to assume that the energy of the decaying field is distributed among the excited modes about evenly within a measurement band of frequencies. In a reverberant field in which the decaying sound field is also diffuse, as will be shown, it is also necessary to assume that scattering of sound energy continually takes place between modes so that even though the various modes decay at different rates scattering ensures that they all contain about the same amount of energy on average during decay. Effectively, in a Sabine room all modes within a measurement band will decay on average at the same rate, because energy is continually scattered from the more slowly decaying modes into the more rapidly decaying modes.

Let $\langle p(t)^2\rangle$ be the mean square band level at time t in a decaying field and $\langle p(0)^2\rangle$ be the mean square level at time t = 0. The decaying field may be expressed in terms of a time varying mean square pressure amplitude $p(t)^2$, modal mean square pressure amplitude $B_i(t)$, mean reflection coefficient β_i and modal mean free paths Λ_i. Equation 11 may be rewritten as follows.

$$\langle p(t)^2\rangle = \frac{\langle p(0)^2\rangle}{\Delta N}\sum_{i=N_1}^{N_2} B_j(t)\beta_i^{ct/\Lambda_i} \qquad (19)$$

In the above equation the number of modes within a measurement band bounded below by N_1 and above by N_2 is ΔN. The reflection coefficient β_i is given by Equation 12. It will be noted that Equation 19 is the same as Equation 15 with the exception of the introduction of the modal amplitudes $B_i(t)$.

It may readily be shown (Bies, 1984) that when a reverberant field is diffuse the mean of the modal mean free paths, Λ_i, is the mean free path of the room given by the following expression (Morse and Bolt, 1944).

$$\Lambda = \frac{4V}{S} \qquad (20)$$

Sabine observed that in a room in which the sound field is diffuse decay of the reverberant field is a linear function of time whatever the initial level when the sound source is abruptly shut off. Sabine introduced an absorption coefficient, α_{sab}, which is generally a property of the walls of the room relating the change in sound pressure level and the length of time of reverberation, t. For convenience, a room in which the sound field is diffuse and reverberant sound field decay is a linear function of time will be referred to here as a Sabine room (Fasold, Kraak, and Schirmer, 1984). The room reverberation decay may be written in terms of the room mean free path Λ and the Sabine absorption coefficient α_{sab} as follows.

$$\log_e \frac{\langle p(t)^2 \rangle}{\langle p(0)^2 \rangle} = -\frac{ct}{\Lambda}\alpha_{sab} \tag{21}$$

It will be instructive to consider first the decay of a single mode as given by Equation (19). In this case letting $\Delta N = 1$, $i = j$ and $B_i = 1$ Equation (19) may be rewritten as follows.

$$\log_e \frac{\langle p(t)^2 \rangle}{\langle p(0)^2} = \frac{ct}{\Lambda_j}\log_e \beta_j \tag{22}$$

Alternatively, if in Equation (22) $\beta_j = 1 - \alpha_j$ where α_j is small then

$$\alpha_j = -\log_e \beta_j \tag{23}$$

Substitution of Equation (23) into Equation (22) gives an equation formally the same as Equation (21). Evidently, in a Sabine room reverberant sound field decay is formally the same as that for any individual mode. Consequently, it will be convenient to extend the meaning of Equation (23) to define a Sabine reflection coefficient, β_{sab}, and to define the relationship between the Sabine reflection coefficient and a Sabine absorption coefficient. Reference to Equation (22) suggests that the associated Sabine reflection coefficient is a mean reflection coefficient of the excited and decaying modes of the room.

Solving Equation (21) for the Sabine absorption coefficient, a_{sab}, and introducing Equations (19) and (23) gives the following expression.

$$-\log_e \beta_{sab} = -\frac{\Lambda}{ct}\log_e \left[\frac{1}{\Delta N}\sum_{i=N1}^{N2} B_i(t)\,\beta_i^{ct/\Lambda_i}\right] \tag{24}$$

The following Equation is obtained from Equation (24).

$$\beta_{sab}^{ct\Lambda} = \frac{1}{\Delta N}\sum_{i=N1}^{N2} B_i(t)\,\beta_i^{ct/\Lambda_i} \tag{25}$$

Consideration of Equation (25) shows that in general β_{sab} is a function of time, and the reverberant field decay will not be linear with time. For example, consider the case that all $B_i = 1$ and no scattering of sound energy between modes takes place during sound field decay. If at time zero the amplitudes of all modes were approximately equal and subsequently the modes have all decayed independently of each other, those modes decaying most rapidly will determine the decaying field response initially while those modes decaying least rapidly will progressively dominate the remaining reverberant field response as the field decays. The latter effect is observed experimentally in a reverberant room unless sufficient diffusing elements are introduced in the room. Consequently, it is necessary to introduce the effect of scattering of sound energy from those modes more highly excited to those modes less excited.

In a Sabine room, however, experience shows that β_{sab} is a constant independent of time. For example, Equation (25) may be rewritten as,

$$\beta_{sab} = \left[\frac{1}{\Delta N}\sum_{i=N1}^{N2} (B_i\beta_i)^{ct/\Lambda_i}\right]^{\Lambda/ct} \tag{26}$$

Consideration of Equation (26) shows that in order that there be a solution it is necessary that all terms in the sum on the right hand side of the equation must be equal and in turn each must be equal to the term on the left hand side of the equation.

In the model which has been proposed it is assumed that sound energy is removed from modes least damped through scattering upon reflection at the boundaries and introduced into modes more heavily damped. The amplitude coefficients, B_i, of the latter quantities will be greater than 1 while the amplitude coefficients of the former quantities will be less than 1. Further consideration of Equation (26) shows that there will be some modes which will be unaffected by the assumed energy exchange and in their case the amplitude coefficients are 1. For such modes the above considerations lead to the following conclusion.

$$\beta_{sab} = \beta_i^{\Lambda/\Lambda_i} \tag{27}$$

If it is assumed that the unaffected modes are the modes whose reflection coefficients are the mean of the modal reflection coefficients then it is reasonable to assume that the modal mean free paths are also mean values of the modal mean free paths. In this case the Sabine reflection coefficient is simply equal to the modal mean reflection coefficient.

$$\beta_{sab} = \beta_{modalmean} \tag{28}$$

The modal mean reflection coefficient has the form given by Equation (12).

Consideration of Equation 23 suggests the following relation be assumed to hold for all values of α_{sab} and β_{sab}. That is, it will be assumed that Equation 23 constitutes a definition of α_{sab} in terms of β_{sab}.

$$\alpha_{sab} = -\log_e \beta_{sab} \tag{29}$$

Substitution of Equation 29 in Equation 22 leads to the famous equation of Sabine as follows.

$$T_{60} = \frac{55.25V}{Sc\,\alpha_{sab}} \tag{30}$$

The important difference in the equations derived earlier relating the Sabine absorption coefficient and the reverberation time and Equation 30 is to be noted. Although they are formally identical the earlier expressions are all based upon a number of assumptions which can not be proven while in the latter case the only assumption made is that Equation 23 is true. As will be shown the Sabine equation given by Equation 30 leads to agreement between measurement and prediction when edge diffraction is taken into account in the determination of the Sabine absorption coefficient.

4. CALCULATION OF THE SABINE ABSORPTION COEFFICIENT

It is customary, following Sabine, to calculate absorption as proportional to the area of an absorbing patch of material. On the other hand, where there is a large difference in surface impedances between the absorbing patch and the adjacent wall or floor on which it is mounted, as in the case of the usual reverberation room test, large diffraction effects will take place which in the case of the reverberation room have the effect of considerably adding to the effective area of the patch (Morse & Bolt 1944). Where A_p is the physical area of the patch and A_e is the effective additional area due to edge diffraction the Sabine absorption may be written as follows.

$$A_p \alpha_{sab} = \alpha_\infty (A_p + A_e) \tag{31}$$

In the above equation a_{sab} is the measured Sabine absorption coefficient and a_∞ is the calculated statistical absorption coefficient for an unbounded surface.

Various authors have considered the calculation of the effective area Ae (Pellam 1940, Morse and Bolt 1944, Levitas and Lax 1951, Northwood et al. 1959, Northwood 1963) with various degrees of success but none are convenient to use and only that of Northwood considers the rectangular patch as considered in the CSIRO tests which will be considered here (see below). The approach which will be taken will be empirical but guided by the observations of Morse and Bolt (1944) and will be limited to showing that a consistent relationship exists between the measurements and theory when diffraction is taken into account.

Following Morse and Bolt (1944) the effective area will be assumed proportional to an effective perimeter of the patch $P' = P - a$, where P is the physical perimeter and a is a constant that is assumed to account for the corners of the patch, multiplied by a wavelength written in terms of the speed of sound c and frequency f as c/f. Equation 31 gives the following postulated functional relationship which will be shown empirically to exist.

$$\left(\frac{\alpha_{sab}}{\alpha_\infty} - 1\right) = F\left(\frac{cP'}{A_p f}\right) \tag{32}$$

5. COMPARISON OF MEASUREMENTS AND THEORY

In 1980 CSIRO-Division of Building Research published a report describing the results of a round robin conducted in Australia and New Zealand in which the Sabine absorption coefficients of samples of Sillan were determined using the standard reverberation decay method (Davern & Dubout 1980). In all, twenty one reverberant rooms were involved in the tests. The test material, a rock wool batt material of density 100 kg/m^3 made by Grunzweig-Hartmann of Germany, was similar to that used in an earlier round robin in Europe (Kosten 1960).

A principal conclusion of the latter report was that those rooms with auxiliary diffusing surfaces equal to or greater than 1.4 times the floor area of the reverberant room gave results consistent among themselves whereas those rooms with less or no auxiliary diffusing surfaces gave results which where inconsistent with all other rooms. Seven rooms ranging in volume from 106 to 607 cubic meters were identified as meeting the diffusing surfaces criterion which gave consistent results for samples ranging in size from 5.0 to 22.5 square meters. Sample sizes were chosen consistent with the size of the room and a sample of 10.5 square meters was tested in all rooms. The data obtained in the latter seven rooms provides the basis for a comparison with prediction.

The referenced report provides four measurements of a 5.0 m^2 sample, six measurements of a 7.5 m^2 sample, seven measurements of a 10.5 m^2 sample, three measurements of a 16.0 m^2 sample, and one measurement of a 22.5 m^2 sample in all one third octave bands from 100 Hz to 5,000 Hz. For the purposes of the proposed comparison average values have been determined and recorded in Table 1. Also recorded in the table for convenience of later comparison are calculated values of the statistical absorption coefficient. The statistical absorption coefficient is shown for an infinite locally reactive surface. However, calculations for a bulk reacting surface are only slightly greater at frequencies greater than about 2000 Hz and thus the difference between the two types of surfaces is considered negligible.

Table 1. Absorption Coefficients

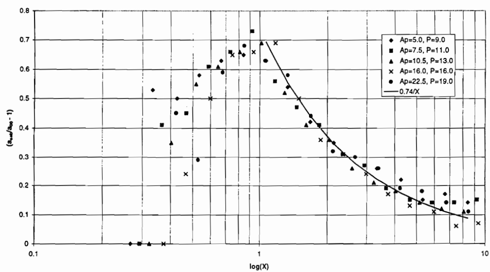
f (Hz)	5.0 m^2	7.5 m^2	10.5 m^2	16.0 m^2	22.5 m^2	α_∞
100	0.07	0.11	0.11	0.10	0.16	0.1
125	0.26	0.24	0.23	0.21	0.22	0.17
160	0.33	0.32	0.34	0.33	0.35	0.22
200	0.49	0.50	0.50	0.51	0.52	0.31
250	0.67	0.68	0.68	0.68	0.67	0.41
315	0.86	0.90	0.88	0.88	0.82	0.52
400	1.04	1.00	0.97	0.96	0.92	0.64
500	1.14	1.09	1.04	1.01	0.98	0.74
630	1.15	1.14	1.10	1.06	1.05	0.81
800	1.16	1.13	1.08	1.07	1.08	0.86
1000	1.17	1.14	1.09	1.05	1.07	0.90
1250	1.15	1.08	1.07	1.03	1.07	0.91
1600	1.12	1.06	1.05	1.02	1.05	0.92
2000	1.07	1.06	1.04	0.99	1.03	0.93
2500	1.10	1.07	1.04	1.01	1.03	0.94
3150	1.07	1.08	1.05	0.99	1.06	0.94
4000	1.08	1.08	1.05	1.01	1.08	0.94
5000	1.12	1.06	1.05	1.00	1.08	0.94

Use of the data in Table 1 has allowed construction of Figure 1. In turn the figure has allowed determination of an empirical function $F(P'c/A_p f)$ which seems to fairly well describe the data. The empirically determined relationship is,

$$\left(\frac{\alpha_{sab}}{\alpha_\infty} - 1\right) = \frac{0.74}{X} \tag{34}$$

where

$$X = \frac{A_p f}{c(P - 3.55)} \tag{35}$$



Plot of measured and normalized sabine absorption coefficients (Table 1) as a function of normalized frequency (equation 35.) See text for discussion.

Consideration of the figure shows generally good agreement over the decade range of the parameter X from about 1.0 to about 10. Above 10. one would expect the edge correction to diminish to zero. It is suggested that the evident departure from the latter expectation at high frequencies may be due in part to the discontinuity in height at the edge between the surface of the absorptive patch and the concrete floor which increases as the ratio of sample thickness to wavelength increases. This has not been considered in any analysis.

Departure at the low frequency end is probably due to failure at long wavelengths of the reverberant rooms to meet the conditions for a diffuse field implicit in the Sabine formulation. At very low frequencies the wide scatter is due to the difficulty of making the necessary reverberation measurements with sufficient accuracy. However, even though the data become quite scattered as the frequency decreases a generally consistent trend can be identified suggesting the possibility of an analytic solution.

6. CONCLUSION

An analysis has been presented which shows that the Sabine equation is correct if it is accepted that the mean modal reflection coefficient and the statistical absorption coefficient are related as proposed. In support of this conclusion the relationship between the calculated statistical absorption coefficient of an unbounded porous material, Silan, and the measured absorption coefficient has been demonstrated in the case that adequate diffusion has been achieved in the test chambers used for the measurements. The demonstration has shown the importance of adequate diffusion and edge diffraction for the determination of the sound absorptive properties of a test material in a reverberation chamber. Conversely, by implication the importance of diffusion and edge diffraction for application of absorptive materials in a Sabine type room have also been demonstrated.

For application to the practice of room acoustics a quantitative measure of diffusion is required which besides identifying adequate diffusion would also identify degree of partial diffusion (Bodlund 1976, 1977a,b). In turn, further investigation is required to determine the quantitative effect of partial diffusion on sound absorption so that it may be taken into account in practice. Additionally, simple procedures are required which will allow estimation of the effect of edge diffraction on sound absorption (Pellam 1940, Morse and Bolt 1944, Levitas and Lax 1951, Northwood et al. 1959, Northwood 1963).

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