Sound Pressure Levels in Rooms: A Study of Steady State Intensity, Total Sound Level, Reverberation Distance, a New Discussion of Steady State Intensity and Other Experimental Formulae

by

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ABSTRACT
In this publication we include all, or almost all, the valid formulas of sound levels in different types of rooms. We will explain all the theoretical basis of each of them, starting with reflected intensity, both classical and revised theories, the total sound level and its uses in concert venues. We will also deal with empirical formulas mainly for classrooms, churches and religious buildings and industrial use.

However, the main significance of this work is not only the wide range of formulas exposed but also that we have found the explanation of why the reverberation radius, or distance radius, cannot exist in the revised theory. This finding can help that the revised theory of M.Barron be slightly modified to apply it to any room for several uses, other than concerts

1. INTRODUCTION

In this publication we analyze all, or almost all, the valid formulas of sound levels in different types of halls. We will explain all the theoretical basis of each of them, starting with reflected intensity, both classical and revised theories, the total sound level and its uses in concert venues. We will also deal with empirical formulas mainly for classrooms, churches and religious buildings and industrial use.

However, the main significance of this work is not only the wide range of formulae exposed but also that we have found the explanation of why the reverberation radius, or distance radius, cannot exist in the revised theory. This finding can help that the revised theory of M.Barron be slightly modified to apply it to any room for several uses, other than concerts

2. STEADY STATE ENERGY IN ENCLOSURES

Perhaps the most basic quantity with we are closely concerned, in an enclosure, is sound power.This associated with the actual source of sound. The source radiates power which is transmitted in the form of sound. The sound power of a source is the total power coming from it. It is the rate at which energy is the form of sound leaves the source.

Now consider a point some distance from the source, and a small area perpendicular to the line joining the point to the source.

The some of power being generated by the source will be transmitted through the area, the exact amount depending not only on the sound power of the source, but also on its directional properties, the distance of the area from the source, and the presence of sound absorbing or sound reflecting materials.

If the power passing through an area A is w, we define the intensity as power per unit area, or:

$$I = wA$$

Although the intensity of a sound is an important quantity , it is difficult to measure because its vector properties. Whereas sound pressure can be measured quite readily due there is a relationship between two magnitudes. This is: $I = p^2_{rms}/\rho c$. Where I is the mean intensity of sound in a period:

$$I = 1/T\int_0^T I\,dt,$$

c ls the velocity sound in the medium and ρ is the density of the air. This last relation is good for all type waves: Plane, spherical.

The intensity, although fluctuating, is always positive. This is clear from a consideration of the physical meaning and from the mathematics. Since I is proportional to p^2_{rms} which must always be positive the time average of the intensity will also be positive. This mean value of the intensity is a useful quantity.

1. CLASSICAL APPROACH

The classic steady state sound intensity used in diffused fields is:

$$I_{diffuse} = 4wQ/A \qquad (1a),$$

$$I_{diffuse} = 25\ w\ Q\ (T/V) \qquad 1b)$$

where A, the equivalent absorption is normally: $A = [-S\ln(1-\alpha)+4mV]$, where: c = 345.5 m/s is sound velocity, V is the volume, T is the reverberation time and w is the sound power, m is the coefficient absorption of air and Q is directivity factor, normally in this paper is Q = 1.

2. NON-CLASSICAL APPROACH:

a) Revised Theory of M. Barron

The sound, emitted by a source emitting N pulse of waves transporting sound energy towards a receiver and producing integrated sound intensity in the room computed by M. Barron, [1], whose theory is based on the formulae derived by R.H. Bolt, P.E. Doak and P.J. Westervelt [2]. The equations derived by them, are applicable to values, l,m,n, large enough so that the details regarding source and receiver positions in the room can be disregarded. M.Barron recognised that the precise location of the source and receiver can be ignored. The sound ("integrated") intensity $\overset{\infty}{\underset{t}{I}}$, or $I_{diffuse}$, arriving after time t (the pulse from the source having been emitted at time t=0) is:

$$\overset{\infty}{\underset{t}{I}} = (w / V)\int_r^\infty e^{-(r/4V)A} \tag{3}$$

The equivalent formulae calculated by M.Barron solving this problem, are as follows:

$$I_{diffuse} = (4w/A).\ e^{-(r/4\ V)A}\ , \tag{3a}$$

$$I_{diffuse} = 25\ w\ (T/V).e^{-0.04\ r/T} \tag{3b}$$

$$I_{diffuse} = 312\ (w/4\Pi)(T/V).e^{-0.04\ r/T} \tag{3c}$$

Where r, is the source-receiver distance in meters. Barron-Lee examined the regression of measured sound levels against the source-receiver for 17 concert halls. There is a good agreement between experimental data and calculation.

The main goal of M. Barron's theory is that the reverberant field decreases exponentially with the distance; something that is a new concept in relation to classical theory.

However seems that this formula is not very adequate for other spaces. Due to it other researchers have derived other experimental formulae by regression for other spaces of reverberation time very higher than concert halls. Also for theatres this formula is not good. In section 5 we carry out a discussion very important about this subject.

Knowing the following identities :
Eyring identity A = 0.16 V / T,
Sabine Identity, for α small, $\alpha < 0.2$, is A = 0.16 V/T.
r distance is r = ct, therefore the time is t = r/c.

<u>Others identities</u>: 0.04 r/T = 13.82 t/T and also 0.04 r = (-ct/4V)A,
25 (T/V) = (4/A) and also 25 (T/V) = (312/4Π)(T/V).

We can obtain other additional equivalent expressions for 3a), 3b), 3c).

When t = 0 or r =0 we obtain the <u>following classic expressions</u> from (3a,b,or c)):

$$I_{diffuse} = (4w/A) \quad (4)$$

$$I_{diffuse} = 25\ w\ (T/V) \quad (5)$$

Both classic formulae are well known and have been indicated in equation (1a) and (1b).

b) Alternative revised theory of M. VORLÄNDER

Subsequent to Barron's theory, M. Vorlander [3] investigated another approach considering that the lower limit integration is: lm/c, where lm is a mean free path, and also the average arrival time of the first reflection of rays on walls, running this lm. He derived:

$$I_{diffuse} = (4w/A)\ e^{-A/S}, \quad (6)$$

- Although the lm hypothesis is not coherent with the results found by Bolt, Doak and Westervelt, Vorlander admits that it is good for small rooms. However, by ignoring the coefficient m air absorption we have: $A_{m=0} = -S\ln(1-\alpha)$, a new expression is obtained using the following mathematical identity: $e^{\ln b} = b$:

$$I_{diffuse} = (4w/A)\ (1-\alpha), \quad (7)$$

This formula was proposed, by M.Vorländer, primarily for reverberation chambers.

For α low values, then is $(1-\alpha) \approx 1$ using (7) we obtain the classic expression: $I_{diffuse} = (4w/S\alpha)$

3. TOTAL SOUND FIELD IN ENCLOSURE

Main Equations

Total sound level intensity can be considered to be the sum of the direct sound intensity and the integrated, or diffuse intensity, from time t_0 to infinity.

The total sound intensity of the sound wave is the sum of two parts: Direct intensity I_{direct} and diffuse intensity $I_{diffuse}$, of one source that has a sound power w when travelling in a room, is as follows:

$$I_{total} = I_{direct} + I_{\ diffuse} \quad (8),$$

The total sound pressure level is:

$$L_p = L_I = 10 \log [I_{total}/I_{ref}] \quad (9a),$$

$$L_p = 10 \log (I_{direct} + I_{diffuse})/I_{ref} \quad (9b),$$

where I_{ref} is a reference intensity energy $I_{ref} = 10^{-12}$ watts/m^2 .

We know that $I_{direct} = Qw / 4\pi r^2$ is the direct component of the sound field, r is the distance source to receiver, where w is the sound power source.

1. CLASSIC FORMULAE:

First classic equation, [4], $I_{diffuse} = 4w/A$, (10a),

or other equivalent formula: $I_{diffuse} = 25\ w\ (T/V)$, (10b),

So, by applying (9b) equation for (10a) and (10b) we obtain the equivalent formulae:

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (4/A)) \quad (11a)$$

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (25(T/V)) \quad (11b)$$

Where A is equivalent absorption $A = [-S \ln (1-\alpha) + 4mv]$, with a representing the exponent absorption coefficient: $a = -\ln(1-\alpha)$ and where α is the absorption coefficient. When α is low and ignoring the absorption air coefficient m, then $A = S\alpha$, V is room volume, S is total surface of all walls and Q is the directivity factor. This formula is normally known as the Sabine formula. The reduction in sound pressure level as function distance r is very important when dealing with noise control in factories. We may check how much higher the sound absorption is in a room at full sound level. If the total absorption A is doubled, the sound pressure level is reduced by 3 dB.

Second classic formula, [5], of diffuse field is: $I_{diffuse} = 4w/R$, (12a)

where $R = \alpha S/1-\alpha$ (R is a constant room), therefore this can also be written as follows:

$$I_{diffuse} = 4w(1-\alpha)/S\alpha \quad (12b)$$

where w represents sound power, Q the source directivity and r the distance between source and receiver, S total surface of walls in a room and _ the mean coefficient absorption of walls.

The total sound level for both expressions are:

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (4/R)) \quad (13a)$$

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (4(1-\alpha)/\alpha S)) \quad (13b)$$

This last formula is known as Sabine-Franklin-Jaeger.

2. NON-CLASSICAL FORMULAE:

a) Revised Theories M. Barron and alternative M. Vorlander

1. First- Barron [6], [7], [8], we have:

$$I_{diffuse} = 312.(w/4\pi)(T/V).e^{-0.04\ r/T}, \quad (14a)$$

$$I_{diffuse} = 25.w\ (T/V)e^{-0.04\ r/T} \quad (14b)$$

$$I_{diffuse} = (4w/A)e^{-(r/4V)A}, \tag{14c}$$

where A is: $A = [-S\ln(1-\alpha)+4mv]$, r is the distance, $r = ct$, t is the time (lower limit integration), S is the overall surface of a room, _ is the average coefficient absorption, T is the reverberation time, V is the volume of the room and m is the absorption coefficient of air. Barron's equation was developed for concert halls originally. The total sound level, applying (9b) is:

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (312/4\pi)(T/V).e^{-0.04\ r/T}, \tag{15a}$$

$$L_p = L_w + 10 \log(Q/4\pi r^2 + 25(T/V).e^{-0.04\ r/T}), \tag{15b}$$

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (4/A).e^{-(r/4V)A}, \tag{15c}$$

Total sound level up to 10 m from source, is:

$$L_{p10} = L_w + 10 \log [Q/\pi\ 400 + 25\ (T/V)\ e^{-0.04\ r/T}] \tag{16}$$

The strength G is the level measured at a direct level position, 10 m from an nondirectional source, Q=1, in an anechoic environment: $G = L_{p10} - L_{d=10\ (anechoic)}$,

$$\begin{aligned} G &= 10 \log \{[1/\pi 400 + 25\ (T/V)\ e^{-0.04\ r/T}]/1/\pi 400\} = \\ &= 10 \log \{100/r^2 + 31200\ (T/V)\ e^{-0.04\ r/T}] \end{aligned} \tag{17}$$

The early reflected (I_{er}) and late reflected (I_l) intensities, for 80 ms and 50 ms respectively.

$$(I_{er})_{80} = 25\ (T/V)\ e^{-0.04\ r/T}.(1- e^{-1.11/T}) \tag{18a}$$

$$(I_{er})_{50} = 25\ (T/V)\ e^{-0.04\ r/T}.(1- e^{-0.69/T}) \tag{18b}$$

$$(I_l)_{80} = 25\ (T/V)\ e^{-0.04\ r/T}.e^{-1.11/T} \tag{19a}$$

$$(I_l)_{50} = 25\ (T/V)\ e^{-0.04\ r/T}.e^{-0.69/T} \tag{19b}$$

From here and (9b) to L_{p10} we obtain several G_i, i= 50 or 80 ms, Q=1:

$$(G_{er})_{80} = 10\log\{100/r^2 + 31200\ (T/V)\ e^{-0.04\ r/T}\ (1- e^{-1.11/T})\} \tag{19a}$$

$$(G_{er})_{50} = 10 \log\{100/r^2 + 31200\ (T/V)\ e^{-0.04\ r/T}\ (1- e^{-0.69/T})\} \tag{19b}$$

$$(G_l)_{80} = 10 \log \{31200\ (T/V)\ e^{-0.04\ r/T}.e^{-1.11/T}\} \tag{19c}$$

$$(G_l)_{50} = 10 \log \{31200\ (T/V)\ e^{-0.04\ r/T}.e^{-0.69/T} \tag{19d}$$

2. Second- Nijs et al.,[9]: Here, T is reverberation time of Eyring formula: $T_{Eyring} = -0.04\ l_m / \ln(1-\alpha)$. On substituting this formula in (13b) they obtained the following simplified expression, using the following mathematical identity: $e^{\ln b} = b$.

$$I_{diffuse} = (4(1-\alpha)^{r / lm}/S\alpha) \qquad (20)$$

The total sound level is:

$$L_p = L_w + 10 \log \{Q/4\pi r^2 + [4(1-\alpha)^{r/lm}]/S\alpha\} \qquad (21)$$

3. Third- H. Arau ,[10], in rooms with asymmetric absorption distribution:

$$I_{diffuse} = 25w(T/V)\ (0.9.e^{-0.04\ r/EDT} + 0.1.\ e^{-0,04\ r/T}) \qquad (22a)$$

$$I_{diffuse} = 25w(T/V)\ (0.9.e^{-13,82/EDT} + 0.1.\ e^{-13.82\ t/T}) \qquad (22b)$$

$$I_{diffuse} = 312(w/4\pi)((T/V)\ (0.9.e^{-0.04\ r/EDT} + 0.1.\ e^{-0.04\ r/T}) \qquad (22c)$$

This expression could be applicable to spaces with asymmetric absorption distribution..

4. Fourth- M.Vorlander, [3]:

$$I_{diffuse} = (4w/A)\ e^{-A/S} \qquad (23a)$$

$$I_{diffuse} = (4w/A).(1-\_) \qquad (23b),$$

In this case, he assumed that m of air is m=0.
The total sound level of these expressions is:

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (4/A)\ e^{-A/S}) \qquad (24a)$$

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (4/A)\ (1-\alpha) \qquad (24b)$$

For α low values and ignoring m air coefficient the formula (24b) is converted to expression (11a), when $A=S\alpha$, $(1-\alpha) \approx 1$. The expression most typically used for room reverberation is:

$$L_p = L_w + 10 \log (Q/4\pi r^2 + (4/S\alpha) \qquad (25)$$

4. RADIUS, OR DISTANCE, OF REVERBERATION

Here, our aim is to obtain the radius of reverberation of the main formulae shown above. To find the "reverberation distance" r_{rev} we can carry out the following equality (26), to see if from this equality we can meet the reverberation distance. This distance is that at which the direct sound reaches the same level as the reverberant or diffuse field.

$$Idirect = I\ diffuse \tag{26}$$

Classical Formulae:
Matching the corresponding term of the direct sound with the term of the diffuse sound field of the formulae (11a), (11b), (13a), (13b), (15a) and (15b) and solving for r, we obtain r_H ,for each case.

$$r_H = (QA/16\pi)^{1/2} \tag{27a}$$

$$r_H = (QV/T100\pi)^{1/2} \tag{27b}$$

$$r_H = (Q\alpha S/16\pi\ (1-\alpha))^{1/2} \tag{27c}$$

$$r_H = (QA/16\pi)^{1/2} \tag{27d}$$

where: A= [-Sln(1-α)+4mv], but when α is a low value then A= Sα and ignoring m, then the formula (27d) is equal to (27c) being (1-α) ≈ 1 .

Non-Classic Formulae:
Matching the corresponding term of the direct sound with the term of the diffuse sound field for formulae (15b), (15c), (21), (24a) and (25b) and (13b) solving for r we obtain the following for each case:

a) Barron
From (15b): $$Q/4\pi r^2 = 25(T/V).e^{-0.04\ r/T} \tag{28a}$$

From (15c): $$Q/4\pi r^2 = (4/A).e^{-(ct/4V)A} \tag{28b}$$

Therefore r in equations (28a) and (28b) only can be solved by iteration. Iteration means that the left term value is equal to the right term for one r searched by computation.

Additionally, from equation (28a) for Q=1, we have obtained:

$$r = (1/100\pi)(V/T)e^{-0.04\ r/T}, \tag{29a}$$

If in equation (28b) we write $ct = l_m = 4V/S$ in exponent terms, then r is:

$$r_H = \{[AQ/16\pi]\ e^{A/S}\}^{1/2} \tag{29b}$$

this last equation is equal to (31a) according to Vorländer.

b) Nijs et al
From (24) if $I_{diff} = I_{dir}$ we obtain: $$Q/4\pi r^2 = [4(1-\alpha)^{r/lm}]/S\alpha \tag{30}$$

This equation is derived also from Barron's equation; therefore r is only solved by iteration.

c) Vorlander

From (24a) we obtain: $r_H = \{[AQ/16\pi]\ e^{A/S}\}^{1/2}$ (31a)

And from (24b): $r_H = \{[AQ/16\pi\ (1-\alpha)]^{1/2}$ (31b),

5. COMPARISON BETWEEN SEVERAL REVERBERATION RADIUS FORMULAE r_H. A NEW DISCUSION ABOUT STEADY STATE ENERGY IN ENCLOSURES

1) Concept:

The Euclidean distance between sound source and receiver is a scalar quantity between two points in same medium and does not depend on any external influence that exist in the same medium.

We imagine that the sound from a source propagates in a room. In this room the sound is transmitted directly between the sound source and a receiver. But we also know that the sound collides against the walls surrounding the room. These walls can have low or high absorption. The reflected sound from the walls creates a diffused sound field or a reverberated sound field. The receiver gets the direct sound first and shortly afterwards the reflections that collided against the walls reach the receiver. Usually, at first the direct sound level is more intense than the reverberated sound level that is practically silenced, but gradually the reverberated sound increases while the direct sound fades away when moving away from the sound source.

The distance between the sound source and the receiver is very important and it is called reverberation distance or reverberation radius. The reverberation distance r_H is the distance from a sound source and a receiver, where the direct sound pressure level of the direct sound field becomes equal to the reverberated sound field. This distance is the minimum distance between source and receiver where all the sound pressure levels of different nature become equal.

The different types are the direct sound field, (which are free of propagation, and its pressure level decrease 6 dB to the square of the distance), and the reverberated sound field (caused by the reflections from the walls that produce the reverberation of the room).

Initially the direct sound level is high and conceals the reverberated sound. Our hearing, during a lapse of time, cannot hear the reverberated sound although the first sound reflections have already been formed on the walls of the room. In our ear the reverberation it is only produced when we are able to hear it. If the room is very reverberant we will hear the reverberated field almost instantly. But if the space is very dry or with low reverberation it will be a lot harder to hear the reverberated sound field.

Therefore, we perceive the reverberation when it reaches us but not when the first sound reflections are produced against the walls of the room.

2) Comparison between distance, or radius, of reverberation

For comparison purposes, we are using a theoretic space of volume V=400 m^3, with a variable reverberation time. First the radius of reverberation $r = r_H$ of the enclosure is calculated using the classical theory (27b), Barron's equation (28b) and Vorländer's equation (31a), for the following directivity factors of sound source Q: 1, 5, 10 and several reverberation times T= 0.5, 1, 3, 10 s, for a room of dimensions 10 x 8 x 5 m. The calculated values for each case of T and Q, are displayed in Table 1:

Table 1. Analysis of the reverberation radius rH using several methods.

Room: 10 m x 8 m x 5 m, S=260 m^2, **T=0.5 s**

Example 1	**Radius reverberation**	**rH (m)**	
(**Q)**	**Classical (33b)**	**Barron**	**Vorlander**
1	1.60	1.71	2.04
5	3.57	4.23	4.56
10	5.05	6.56	6.45

Room: 10 m x 8 m x 5 m, S=260 m^2, **T=1 s**

Example 2	**Radius reverberation**	**rH (m)**	
(Q)	**Classical (33b)**	**Barron**	**Vorlander**
1	1.13	1.15	1.28
5	2.52	2.66	2.85
10	3.75	3.85	4.04

Room: 10 m x 8 m x 5 m, S=260 m^2, **T=3 s**

Example 3	**Radius reverberation**	**rH (m)**	
(Q)	**Classical (33b)**	**Barron**	**Vorlander**
1	0.65	0.65	0.68
5	1.46	1.47	1.52
10	2.06	2.09	2.15

Room: 10 m x 8 m x 5 m, S=260 m^2, **T=10 s**

Example 4	**Radius reverberation**	**rH (m)**	
(Q)	**Classical (33b)**	**Barron**	**Vorlander**
1	0.36	0.36	0.36
5	0-80	0.80	0.81
10	1.13	1.13	1.14

In reality, not have been possible, experimentally to show the difference of reverberation distance r_H between classical and revised theories. In next paragraph 3), we explain the reason because these calculations are unsuccessful.

3) A new discussion about steady state energy in enclosures

We know that radius or distance of reverberation is the distance at which the direct and reverberant levels become equals.

Before of this distance r_H, the direct sound level is masking the reverberant sound level. Is by this question that the reverberant sound is not perceived our ear. It is in this point that defines the distance r_H to source. In this point the reverberant sound subjectively is borning to our ears.

Therefore is required that the lower limit of integral of reflected intensity must start with $t_d = t - t_H$ or $r_d / c = r/c - r_H/c$, where r_H , $r_H = (QA/16\pi)^{1/2}$, for Q = 1 normally.

So the revised theory of Mike Barron must be corrected in this sense but to do it in the Michael Vorländer formula is not possible.

We know that the sound ("integrated") intensity $\overset{\infty}{\underset{t}{I}}$, or $I_{diffuse}$. In this case we write:

$$\overset{\infty}{\underset{t}{I}} = (w / V)\int_{td}^{\infty} e^{-(c(t-t_H)/4v)A} \cdot dt \qquad (32)$$

Where now the lower limit must be $t_d = t - t_H$, for $t_d \geq 0$, where t_H is the interval of time of the distance of reverberation r_H,

The equivalent formulae calculated by M.Barron solving this integral, are as follows:

$$I_{diffuse} = (4 /A).e^{-((r - r_H)/4 V)A} \qquad (33a)$$

$$I_{diffuse} = 25 \text{ w } (T/V).e^{-0.04 (r - r_H)/T} \qquad (33b)$$

$$I_{diffuse} = 312 \text{ } (w/4\pi)(T/V).e^{-0.04 (r - r_H)/T} \qquad (33c)$$

If any formula (33a," or, b, or c") is $t_d = 0$ then $t = t_H$ or $r/c = r_H/c$. Therefore for $t_d = 0$ we obtain that the equation (33a), (for example), is became to classical equation (10a). Using now the formula (27a) we obtain r_H , This r_H is the classical distance reverberation $r_H = (A /16\pi)^{1/2}$, for Q = 1..

This shows that the revised theory must not have a r_H value different than the classical expression therefore the several values of distance of reverberation computed by revised theories in 5 section are wrong. Only is possible to find the distance r_H from the classical formula.

This correction is not possible in the formula of M.Vorlander because his formula would lose its identity by becoming to revised formula of M.Barron modified.

We remark that r_H increase, when the reverberation time decrease, or when the absorption units A increases. Therefore $t_d = t - t_H$ change with reverberation time (or absorption A) of hall.

This means that the value t_H produces a time delay of the reflected intensity field arises, in the hall, after that the sound has been produced by the source in time t=0 s.

Here only we have solved one small aspect of revised theory. This perhaps may to solve the calculation for all types of usages of rooms with reliability, and no only for concerts.

Many years ago, after 1995, we thought that the theory of M.Barron was true if radius reverberation calculated from his theory was checked experimentally. ¡But do not we get it never!

Here we have finished many years of research, [11], always occupied in obtaining the radius of reverberation of revised theories, but our experiments were useless. Now theoretically we know this is not possible.

We remark that r_H increase, when the reverberation time decreases, or when the absorption units A increase. Therefore $t_d = t - t_H$ change with reverberation time (or absorption A) of hall.

This means that the value t_H produces a time delay of the reflected intensity field arises, in the hall, after that the sound has been produced by the source in time t=0 s.

Therefore we write the new formulae of revised theory of Barron-Lee, so:

$$d = 100/r^2,$$
$$e = (31200\ T/V)\ e^{-0.04\ (r-rH)/}T.\ (1 - e^{-1.11/T}),$$
$$l = (31200\ T/V)\ e^{-0.04\ (r-rH)/}T.\ e^{-1.11/T},$$

Thus we can to write:

$$C_{80} = 10 \log (d + e)/l$$
$$G = L - L_0 = 10 \log (d+e+l),$$

which is equal to:

$$G = 10 \log \{\ 100/r^2 + 31200\ (T/V)\ e^{-0.04\ (r-rH)\ /\ T}] \qquad (34)$$

When $r = r_H$, we obtain the classical expression:

$$G = 10 \log \{\ 100/r^2 + 31200\ (T/V),$$

6. OTHER EXPERIMENTAL EQUATIONS

Classrooms

Sato and Bradley [12] recently proposed the following experiment:

$$I_{diffuse} = (4w/\alpha S)(1-\alpha)^{\varepsilon..r/lm} \qquad (35)$$

Factor ε here represents order 2. This factor was introduced in a study carried out in classrooms.

The total sound level of this expression is:

$$L_p = L_w + 10 \log \{Q/4\pi r^2 + (4/\alpha S)(1-\alpha)^{\varepsilon..r/mfp}\} \qquad (36)$$

From expression (15c), formula Eyring, and (21) we can derive:

$$L_{p\ early} = L_{w\ speech} + 10\log\ (Q/4\pi r^2 + (4(1-\alpha)^{\ r/lm}/\alpha S).(1-e^{-0.69/T}) \quad (37)$$

$$L_{p\ late} = L_{w\ speech} + 10\ \log\ (4(1-\alpha)^{r/lm}\ /\alpha S).(e^{-0.69/T}) \quad (38)$$

C_{50} (without noise) is defined by the difference between two values:

$$L_{p\ early} - L_{p\ late} \quad (39)$$

It is sometimes necessary to introduce noise in this last expression to account for noise made by traffic or ventilation systems, therefore for (15a) the following formula can be written:

$$L_p\ noise = L_w\ noise + 10\ \log\ (4/A) \quad (40)$$

From formula (39) and (40) we have:

$$L_{p\ late+noise} = L_{w\ speech} + 10\ \log\ (4(1-\alpha)^{\ r/lm}/\alpha S).(e^{-0.69/T}) + (4.10^{-S/N/10})/\alpha S \quad (41)$$

where SN is SN = $L_{w\ speech} - L_{w\ noise}$.

Churches and Religious Buildings

Several recent measurement exercises carried out in religious buildings,[12],[13], show that diffuse sound levels generally decrease when distance r increases between source and receiver.

In these cases the formula is corrected by empirical measurements:

$$I_{diffuse} = (4w/A).e^{-0.04\ \beta\ r/T} \quad (42)$$

β are experimental values.

The total sound level of this expression is:

$$L_p = L_w + 10\ \log\ \{Q\ /4\_r^2 + (4/A)\ e^{-0.04\ \_\ r/T}\} \quad (43)$$

Industrial Enclosures

In this case we write the complete formula L_p in each case:

Kuttruff Models [15]:

Kuttruff proposed one model for predicting octave band sound propagation which only applies to wide and long fitted workrooms. The models are based on the assumption that workrooms with floor fittings can be modelled as an empty workroom with a diffuse reflecting floor.

One model further assumes that the ceiling is also diffuse reflecting. This diffuse model can be expressed as follows:

$$SP_{tot}(r) = 10\ \log\ [(1/4\pi r^2)+(1-\alpha)\{[1+r^2/h^2)^{1.5} + b(1-\alpha)(b^2+r^2/h^2)^{1.5}/\alpha]/\pi h^2\}] \quad (44)$$

in which h=H, the room height, r is the source-receiver distance, α is the average surface absorption coefficient and β is a tabulated factor, with β representing a constant value 3 for a rectangular halls.

Osipov,Sergei and Shubin Model [16]:
This model assumes that sound propagation is cylindrical but that the room geometry is rectangular.

$$L_p = L_w + 10 \log [1/2\pi r^2 + ((1-\alpha)(r+W) J(\alpha,\rho)) HW(r+H)] \quad (45)$$

where $J(\alpha,\rho)) = 0.1/\alpha^2+\rho^2 e^{0.65\rho}$, in which is: $\rho =- r S \ln(1-\alpha)/4V$ is a dimensionless distance, r is the distance from source- receiver and α is the average absorption coefficient of the room surfaces, as the room was empty for the purposes of Table 1. The empty factory values are used for the walls and ceiling; the values for the appropriate industry are used for the floor. Here, m is air absorption in Np/m. H is room height, W is room width.

Table 1. Absorption coefficients for typical factories and furnished factories (several authors)

Frequency Hz	250	500	1000	2000	4000
Empty factories	0.09	0.09	0.09	0.08	0.09
Textile Industry	0.25	0.29	0.40	0.40	0.43
Print industry	0.31	0.27	0.26	0.31	0.31
Metal work	0.32	0.30	0.34	0.34	0.38
Low freq. fittings	0.20	0.10	0.10	0.10	0.10
Mid freq. fittings	0.35	0.30	0.25	0.15	0.10

Thompson et al. [16] Model:
They proposed a modification to the existing steady sound level formula:

$$L_p = L_w + 10 \log [(e^{-mr}/4\pi r^2) + 4V/rS(\alpha S+4mV)] + 10 \log\{(t^0 + 460)/527 + 30/p^0\} \quad (46)$$

where: t_0 is temperature in ^{0}C and p^0 is the barometric air pressure.

R.E. Jonckheere, F. Verbandt Model [18]
They described a new model based on the classic general formula (19b), developing it until the experimental result fitted best with the calculated values.

The final model established is:

$$L_p = L_w + A \log ((C/r^2)+(D/r^B)+(E/r^F)) \quad (47)$$

with, L_p: Sound pressure level dB at a distance r from source.
L_w Sound power level of the source.
r distance between source and receiver.
A = -5.9407 logH + 5.8267 logSg-3.0125 log Sw -2.5933 log T-1.9651 log + λ 8.3711,
B = -0.84669 log H + 0.0099740 log Sg-0.027103 log Sw + 0.14816 log T-0.025967 log + λ 1.0898
C = +0.31944 log H - 0.20796 log Sg + 0.25196 log Sw - 0.025819 logT - 0.12450 log - λ 0.14910
D = -072493 logH + 0,071599 log Sg - 0.0504311 log Sw - 0.0035823 logT + 0.0058199 log + λ 0.7056,
E = +031220
F = +1.5302
H = room height, Sg= floor area, Sw = Total area of all surfaces T= Reverberation Time, λ sound wave length.

The mean deviation of the measured and the calculated values amounts to 1.24 dB for 88000 measurements. The application range of this formula is between 400 and 14000 m3, absorption coefficients between 0.07 and 0.21, frequencies between 500 and 5000 Hz. This method allows us to make a prediction with a mean accuracy of 1.8 dB.

C.Bodrone-Sacerdote and G.Sacerdote [19] ,reference A.Cops [20], model

If the dimensions of the floor of a closed room are more than five times the height of the ceiling, the reflections of the walls are negligible. In this circumstance, the diffuse sound field is reduced. The reflected sound pressure level is no longer uniform and decreases with the increasing distance. A theoretical approximation based on image points, gives the following relationship between the sound pressure level. L_p, the sound power level L_w, the absorption coefficient _ of ceiling and the relation number x=r/d, with r representing the distance between source and receiver and d, the height of ceiling:

$$L_p = L_w + 10 \log (1.05/4\pi d^2) + 10\log \{\sum_n (1-\alpha)^{n/2} [(2/(n^2+x^2) + ((2-\alpha)/(x^2+(n+1)^2] - (1/x^2)\} \quad (48)$$

Where n is the number of sources.

The reflected sound pressure level is not constant at considerable distances from the sound sources, as located in a diffuse sound field.

1. We see in example 1, that when the reverberation time T is low, the radius of reverberation increases with the factor directivity of source. In this case, we can see an important discrepancy between classical and non classical theories where the directivity factor increases.
2. When the reverberation time is increased, the radius of reverberation of all theories is similar. Where reverberation time is very high, we see that all theories studied are equal for each directivity factor analysed.

7. CONCLUSIONS

The objective of this paper was to present many theories and empirical formulae of interest in the field of architectural acoustics, developing the full range of equations that may be of interest for technical studies in areas such as classrooms, churches, concert halls, industrial enclosures, restaurants, …...

We have analized a new aspect of the refllected intensity finding a new lower limit of the integral. We have found the explanation of why the reverberation, or distance, radius, cannot exist in the Revised theory.

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